**Analysis of Space Weather Impacts
on the Terrestrial Ionosphere
and
Development and Testing of a Coronagraph
for Space Weather Forecasts**

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Abstract

The ionosphere is a conductive layer of the Earth's atmosphere, characterised by the presence of free electrons. Through interaction with electromagnetic waves, it influences a wide spectrum of radio wave communications, including short-wave communication between stations across the globe as well as Ultra-High Frequency (UHF) from ground to satellites. The ionosphere is generated mainly by solar Extreme Ultraviolet (EUV) radiation, but also subject to changes due to a range of different phenomena, most importantly the effects of solar activity and space weather. Changes in the solar EUV output across the solar activity cycle affect its ground state, while transient events such as solar flares and geomagnetic storms introduce strong, short term disturbances that in turn can affect wireless communications and the precision of Global Navigational Satellite Systems (GNSS). The strongest effects are caused by Coronal Mass Ejections (CMEs), large outbursts of solar coronal plasma travelling with velocities of up to 3500 km s^{-1} that can be observed and tracked in space using white-light coronagraphs. The continuously growing use of technological systems affected by ionospheric disturbances increases the need to develop space weather forecasting models, as well as dedicated instrumentation to provide the required input data.

In the first part of this dissertation, I investigate the response of the global ionosphere to different phenomena of solar activity, and discuss their application to forecasting models based on my work in the national German research project Operational Tool for ionosphere Mapping and Prediction (OPTIMAP). Global maps of the Vertical Total Electron Content (VTEC) from the Center for Orbit Determination in Europe (CODE) between 2003 and 2018 were processed together with solar EUV irradiance measured by the Solar Dynamics Observatory (SDO), solar X-Ray irradiance measured by the Geostationary Orbital Environmental Satellites (GOES) as well as solar wind data from the OMNI data set. The long duration of the time series allowed me to analyse all effects across a full solar cycle, and include extreme events like the Halloween storms of 2003. A high correlation around $r = 0.88$ was found between EUV and global mean VTEC, and $r > 0.7$ for the medium-term trend of the 27-day solar rotation, both following a linear relationship across the last solar cycle. Due to a seasonal trend, the lowest relative global TEC values were observed in summer, and the highest in spring and autumn. An analysis of regional correlation coefficients revealed the highest correlations just after sunrise and around the dayside magnetic equator. The delayed response of the ionosphere was measured at 20 hours on the global scale, with only weak patterns and a wide range of delays up to several days in the regional and seasonal analysis. For the X17 flare of 2003-10-28 and the X28-flare of 2003-11-04, regional TEC enhancements of around 10 TECU and 3 TECU were measured, which is lower than values reported by studies using single-station data. A superposed epoch analysis was performed for 7838 C-, 752 M- and 73 X-flares between 2003 and 2014. The results were used to formulate a mean- and worst-case scaling law. For the study of CMEs and CIRs, two separate selections of a total of 46 events were made, one including events of all magnitudes and one events with strong geomagnetic impact. The VTEC profiles of these events were again studied on

global and regional scales. A good correspondence was found between the time of peak global TEC and strong southward turnings of the solar wind $v \cdot B_z$ parameter. Negative storm phases, which were identified for 13 events, were found to be restricted to the southern hemisphere in winter and the northern hemisphere in summer. A comparison between intra-day fluctuations of TEC and $v \cdot B_z$ during periods of low geomagnetic activity showed only very low correlation coefficients of $r \leq 0.2$.

In the second part of the dissertation, I describe the design and tests of an optical prototype of a new solar coronagraph, developed within the European Space Agency's (ESA) Solar Coronagraph for OPERation (SCOPE) project. SCOPE follows a design known as compact coronagraph, which tries to reduce the complexity of the baffle system required by the classical Lyot design. Optical performance tests of the prototype have been conducted after manufacturing at the University of Göttingen, followed by tests at Centre Spatial de Liege, Belgium, and RAL Space, UK. The 5-disc external occulter showed levels of diffracted light about a factor of 1.5 lower than numerically predicted in tests with monochromatic light sources. Strong diffractive stray light originating on circular baffles limited the performance to a relative brightness of $10^{-9} B_\odot$ across the field of view. A test with an altered setup at RAL Space achieved values below $10^{-11} B_\odot$, but with remaining differences to a final design. Rough edges of the spider-arms, which hold the external occulter of the instrument, also produced stray light around $10^{-9} B_\odot$. In a systematic test of 5 different models, I demonstrated that polished edges can deliver a rejection ratio close to $2 \cdot 10^{-12} B_\odot$ near the inner field of view boundary, below the defined requirements at this location.

The results of this work show that different space weather impacts on the ionosphere can be quantified and implemented in forecasting models. For CMEs, a scheme based on prototypic events was suggested that can be validated and expanded according to operational requirements. Further developments are required to provide accurate forecasts of the input parameters. A new generation of space-borne coronagraphs is required to maintain the capability of detecting and modelling the propagation of CMEs. The development of SCOPE has been an important step towards the development of a European coronagraph. The test results have already demonstrated the performance goals for some of its components, giving confidence that further developments can be concluded successfully.

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List of Acronyms

AC	Analysis Centre
ACE	Advanced Composition Explorer
ADS	Airbus DS Space Systems
ADU	Analog-to-Digital-Units
AIA	Atmospheric Imaging Assembly
AR	Anti-Reflective
ASPIICS	Association de Satellites Pour l’Imagerie et l’Interferometrie de la Couronne Solaire
CAD	Computer Aided Design
CCOR	Compact CORonagraph
CIR	Corotating Interaction Region
CLIMSO	CLIchées Multiples du SOleil
CME	Coronal Mass Ejection
CODE	Center for Orbit Determination in Europe
CSL	Centre Spatial de Liège
DGAC	Direction Générale de l’Aviation Civile
DGFI-TUM	Deutsches Geodätisches Forschungsinstitut der Technischen Universität München
DRAO	Dominion Radio Astrophysical Observatory
DSCOVr	Deep Space Climate Observatory
EEB	EVE Electronics Box
EIA	Equatorial Ionospheric Anomaly
EO	External Occulter
EOF	Empirical Orthogonal Functions
ESA	European Space Agency
ESP	EUV-Spectro-Photometer
EUV	Extreme Ultraviolet
EVE	EUV Variability Experiment
FOV	Field of View
GFZ	Geomagnetisches ForschungsZentrum
GIC	Geomagnetically Induced Current
GIM	Global Ionospheric Map
GLE	Ground Level Enhancement
GNSS	Global Navigational Satellite Systems
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
GSTP	General Support Technology Programme
HF	High Frequency
HI	Heliospheric Imager
HMI	Helioseismic and Magnetic Imager

HRM	Heat Rejection Mirror
HRO	high-resolution-OMNI
HWN	Hurricane Weather Net
HXR	Hard-X-Ray
IAG	Institut für Astrophysik Göttingen
ICME	Interplanetary Coronal Mass Ejection
IFOV	Inner FOV
IGRF	International Geomagnetic Reference Field
IGS	International GNSS Service
IMF	Interplanetary Magnetic Field
IO	Internal Occulter
IONEX	IONospheric map EXchange format
IRI	International Reference Ionosphere
ISR	Incoherent Scatter Radar
LASCO	Large Angle and Spectroscopic COronagraph
LASP	Laboratory for Atmospheric and Space Physics
LEO	Low Earth Orbit
LOS	Line Of Sight
LRO	Low-Resolution OMNI
LT	Local Time
MC	Magnetic Cloud
MEGS	Multiple EUV Grating Spectrograph
MLSO	Mauna Loa Solar Observatory
MSB	Mean Solar Brightness
NCEI	National Centers for Environmental Information
OBB	Optics BreadBoard
OFOV	Outer FOV
OPTIMAP	Operational Tool for Ionosphere Mapping and Prediction
OSO	Orbiting Solar Observatory
PSP	Parker Solar Probe
QD	Quasi-Dipole
RAL	Rutherford Appleton Laboratory
ROB	Royal Observatory of Belgium
SAA	South Atlantic Anomaly
SAM	Solar Aspect Monitor
SCOPE	Solar Coronagraph for OPErations
SDO	Solar Dynamics Observatory
SECCHI	Sun Earth Connection Coronal and Heliospheric Investigation
SEE	Single Event Effect
SEP	Solar Energetic Particle
SID	Sudden Ionospheric Disturbance
SILSO	Sunspot Index and Long-term Solar Observations
SIR	Stream Interaction Region
SMEI	Solar Mass Ejection Imager
SNR	Signal-to-Noise Ratio

SOHO	Solar and Heliospheric Observatory
SoIO	Solar Orbiter
SSC	Storm Sudden Commencement
SSN	Sunspot Number
STEC	Slant TEC
STEREO	Solar Terrestrial Relations Observatory
SXR	Soft-X-Ray
TEC	Total Electron Content
TECU	TEC Unit
UHF	Ultra-High Frequency
UV	UltraViolet
WDC	World Data Center
WISPR	Wide Field Imager for Solar Probe
WrLageZ	WeltraumLageZentrum
XRS	X-Ray- and EUV-sensor
ZGeoBw	Zentrum für Geoinformationswesen der Bundeswehr

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Chapter 1

Introduction

Around the year 1900, technology was developed to enable long range radio communication, pioneered by Guglielmo Marconi, who won the Nobel Prize for his work in 1909 (Marconi, 1909). As part of his development of transatlantic communication, Marconi performed systematic range tests with a receiver placed on a ship, and as a result noticed a dependence on the time of day. As we know today, this is due to electromagnetic-waves being guided and reflected by the *ionosphere*, an electrically conductive layer of the Earth's atmosphere. Following Marconi's observations, theoretical predictions about the ionosphere were made independently by Arthur Kennelly and Oliver Heaviside in 1902 (Kennelly, 1902; Heaviside, 1902). The experimental verification of the existence of the ionosphere was finally made in 1924 by Edward Appleton, who received the Nobel Prize in 1947. Shortly after, Breit and Tuve (1926) measured the altitude where waves are reflected and found that it varied between approximately 80 km and 220 km. During the second world war, many radio stations were installed around the globe, which were subsequently used to map global patterns in the ionosphere. Using this data, Appleton (1946) found the *equatorial anomaly* and described its dependence on magnetic latitude. Nowadays, wireless communication uses a wide range of electromagnetic frequencies for different applications. Among the most important systems affected by the ionosphere are High Frequency (HF; $f = 3 \text{ MHz} - 30 \text{ MHz}$) communications with aircraft, and Global Navigational Satellite System (GNSS) positioning services (Cannon et al., 2013).

The ionosphere is the layer of the atmosphere with the highest density of free electrons. As the electron density profile as a function of height is not always obtained directly, the integrated Total Electron Content (TEC) is often used. The first method to determine the electron density was the so called Ionosonde used by Breit and Tuve (1926), which measures the vertical electron density profile up to the peak of the electron density. In the 1960s, the Incoherent Scatter Radar (ISR) technique was introduced (Gordon, 1958), which can measure the electron density at all altitudes, as well as arbitrary lines of sight, and yield other properties like the electron and ion temperatures through spectral measurements. The ISR in particular has the disadvantage that very high power transmitters of the order of a few MW are required, and as a consequence only about a dozen

stations exist worldwide. For Ionosondes, the initial conditions were similar, but systems have since become more compact, portable and efficient (Bibl, 1998). The newest technique is the use of GNSS-based measurements. In contrast to the other techniques, GNSS only measures the integrated TEC along a line-of-sight (LOS), but each ground station only needs a small, inexpensive receiver. Additionally, it does not suffer as much degradation during geomagnetic activity as the other two techniques (Mendillo, 2006). GNSS-stations have been installed all over the world to form networks from which Global Ionospheric Maps (GIMs) can be computed (Hernández-Pajares et al., 2009).

Figure 1.1 shows an example of a GIM on 2012-03-21 12:00 UT, a geomagnetically quiet day during solar activity maximum, plotted on a global map outline for reference. The data is from the Centre for Orbit Determination in Europe (CODE; Schaer et al. 1996b). The Figure shows the typical Vertical Total Electron Content (VTEC) morphology, given in TEC Units (TECU), where $1 \text{ TECU} = 10^{16} \text{ e}^- \text{m}^{-2}$. The highest electron content is found in the two bands of the equatorial anomaly, at geomagnetic latitudes of $\pm 15^\circ$, and peaking in the early afternoon sector.

Figure 1.1: Example of a global ionospheric map (GIM) on 2012-03-21 12:00 UT, using data from CODE. An outline map of countries is included for reference.

The ionosphere changes not only with time of day, seasons or magnetic latitude, but is also strongly influenced by solar activity and the subsequent *space weather* effects (Schlegel et al., 2007). The primary source of ionisation in the atmosphere, thus determining its ground state, is solar *Extreme UltraViolet* (EUV) emission (Prölss, 2013). The solar EUV output varies over the course of the 11-year solar cycle, as well as the rotation of the Sun with a period of 27 days as seen from Earth. A delayed response of the ionosphere to EUV has been found as a result of chemical and transport processes in the atmosphere (Jakowski et al., 1991; Jacobi et al., 2016). During *solar flares*, the emission of EUV and particularly X-Rays by the Sun is suddenly enhanced for a short time, leading to increased TEC-levels on the dayside of the ionosphere for a few hours (Tsurutani et al., 2009; Zhang and Xiao, 2005). The ionosphere is also impacted by geomagnetic storms, initiated by fast streams of the *solar wind* and, most importantly, *Coronal Mass Ejections* (CMEs; Mendillo 2006). CMEs are massive outbursts of plasma launched from the Sun with velocities up to 3500 km s^{-1} (Webb and Howard, 2012).

In the first part of this thesis, I investigate the ionospheric impact of space weather events by using GIMs. The work presented is based on analyses performed in the *Operational Tool for Ionosphere Mapping and Prediction* (OPTIMAP) project, with additional analysis to expand on the results found during the project phase. OPTIMAP was commissioned by the Zentrum für Geoinformationswesen der Bundeswehr (ZGeoBw) and the German Weltraumlagezentrum (WrLageZ). The Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (DGFI-TUM) and the Institute für Astrophysik at the Georg-August-Universität Göttingen (IAG) were involved as research institutions. The goal of the project is to provide a novel, state-of-the-art prediction service of GIMs to be implemented for automatic operational use at WrLageZ that includes space weather data and forecasts to improve the prediction model. Here, I will address the following questions:

- What are the quantitative impacts of EUV radiation, solar flares, the solar wind and CMEs on the ionosphere?
- What are the temporal and spatial characteristics of the different effects?
- How well can the different phenomena be separated in space and time?
- How can we use these results to establish forecasting methods?

Today, it is well known that CMEs are a cause of strong ionospheric effects (Mendillo, 2006; Prikryl et al., 2014). Being able to observe, study and forecast CMEs is thus a paramount task of space weather operations. CMEs are observed visually as brightness enhancements of the solar K-corona, which is formed by Thomson-scattering of light on free electrons. The total coronal brightness, which includes also the F-corona formed by light scattered on dust particles, is much fainter than the Sun, so it can not easily and accurately be observed through the Earth’s atmosphere and the blue Sky. During a solar eclipse, part of the corona becomes visible for a brief moment, but eclipses are rare and too short to detect the dynamics of CMEs, so that they were not recognized as a phenomenon before systematic observations with dedicated instruments (Hansen et al., 1971).

In 1930s, the French astronomer Bernard Lyot invented such an instrument, called the *coronagraph*, to be able to observe and study the corona outside of eclipses (Lyot, 1932). In a coronagraph, direct solar light is blocked by a so called *occulter* and several baffles to reduce stray light to below the coronal brightness. With a coronagraph placed high on a mountain, where the atmospheric effects are reduced, the near-Sun corona can be observed, although still only over a Field of View (FOV) of a few solar radii ($R_{\odot}$). CMEs were first identified in the early 1970s (Gopalswamy, 2016), around the same time when the first space-borne coronagraph was launched on board the OSO-7 satellite (Koomen et al., 1975). Space-borne coronagraphs do not suffer from background stray light of the Earth’s atmosphere and can observe the corona in higher detail out to much larger elongations from the Sun, as well as continuously due to the absence of clouds or the day and night cycle. Space-borne coronagraphs thus form the state-of-the-art technology to observe, analyse and predict the dynamics of CMEs.

At the time of writing, operational activities of space weather forecasting relies mainly on the data provided by two missions. The first is the *Solar and Heliospheric Observatory* (SOHO; Domingo et al. 1995), located at the Lagrange-point L1, which features (among other instruments) a package of three coronagraphs, C1, C2 and C3, in the *Large Angle and Spectroscopic CO*ronagraph (LASCO) suite (Brueckner et al., 1995). The second mission is the *Solar Terrestrial Relations Observatory* (STEREO; Kaiser et al. 2008), consisting of two nearly identical satellites that orbit the Sun in Earth-like orbits with a varying angular separation to Earth. Each STEREO satellite features two coronagraphs, COR1 and COR2, in the *Sun Earth Connection Coronal and Heliospheric Investigation* (SECCHI) instrument package (Howard et al., 2008; Eyles et al., 2009). An example of a CME recorded by the SOHO/LASCO/C3 coronagraph on 1998-04-20 is shown in Figure 1.2.

The biggest challenge that space weather forecasting currently faces with these two missions is their age. SOHO was launched in 1995, and STEREO in 2006. The harsh radiation environment found in space leads to gradual degradation of system components to varying degrees, and so gradually increases the risk of failure. Both missions have already suffered from partial losses. On SOHO, the C1 coronagraph

Figure 1.2: Observation of a large CME by SOHO/C3 on 1998-04-20. Image courtesy of SOHO (ESA & NASA).

is lost since 1998 during a deep-freeze of the satellite (Fleck, 2018). One of the STEREO satellites, STEREO-B, has been lost since 2014 during a test for solar conjunction operations, due to a loss of attitude control. This situation creates demand for a new coronagraph to ensure our current capabilities of forecasting CMEs in the future (Kraft et al., 2017).

With the advancement of technology, we now have many systems that are vulnerable to space weather effects. This includes national power grids, satellites and communication, and has further consequences for aircraft operations, global navigational services as well as astronaut health and safety (Reitz et al., 2007; Cannon et al., 2013). The cause of the strongest impacts with highest potential for severe damage are CMEs. Two events often referenced as prototypes of so called *superstorms* are the “Carrington Event”, which occurred on 1859-09-01 (Carrington, 1859; Hodgson, 1859), and a CME observed on 2012-07-23 (Riley et al., 2018). At the time of the Carrington event, there was no significant electrical infrastructure, but operators of telegraph lines reported electric shocks and sparks (Boteler, 2006) and aurora were seen as close to the equator as Colombia (Cárdenas et al., 2016). The 2012-07-23 event did not hit Earth, but was recorded in-situ by the STEREO-A spacecraft (Temmer and Nitta, 2015). A study performed by the insurance market Lloyd’s of London (Lloyd’s, 2013) has estimated, for the U.S. alone, an economic damage between 600 and 2600 billion US Dollars as a result of wide-spread power outages from a superstorm. In the UK’s National Risk Register of Civil Emergencies 2017 (Cabinet Office, 2017), space weather in general was ranked at 3 out of 5 on an impact severity scale and 4 out of 5 on a likelihood of occurrence scale, where 5 is the highest (i.e. worst) in each case. For comparison, heatwaves and poor air quality received the same ratings, and a pandemic influenza received also a likelihood of 4, but is rated with impact severity of 5. This underlines the need to not only research and understand all aspects of space weather and their solar origins, but also to develop forecasting capabilities, risk mitigation strategies, disaster management plans, and to educate the general public and spread awareness of this “modern form” of natural hazards (Bingham et al., 2019). Specifically, it requires operational coronagraphs to detect and track CMEs.

Thanks to the scientific advancements made using the data from SOHO, STEREO, and other solar and heliospheric physics missions, it is now the next logical step to develop a coronagraph that is optimised for operational space weather purposes. It would also create new research opportunities by providing a new data set for the development and testing of space weather prediction services. There is an ongoing effort in several countries to develop a new generation of coronagraphs with an advanced design for use on various missions. For example, the U.S. Naval Research Laboratory develops the Compact CORonagraph (CCOR), intended to be launched on the next generation Geostationary Operational Environmental Satellite (GOES) in 2024¹. Another development is targeted at using the International Space Station to host a coronagraph (Cho et al., 2017). The European Space Agency (ESA) is planning to operate a future space weather mis-

¹https://www.goes-r.gov/featureStories/CCOR_feature.html, 27.04.2020

sion at the Sun-Earth Lagrange point L5 (Kraft et al., 2017). A mission at this location would provide a unique view of the Sun to enhance forecasting accuracy through 3D-observations of CMEs as well as providing information of the solar far side rotating into view of Earth (Schmidt and Bothmer, 1996).

In the second part of this thesis, I describe the development and testing of the *Solar Coronagraph for OPERations* (SCOPE) instrument. The SCOPE project was funded under ESA’s General Support Technology Programme (GSTP), and performed by a consortium of Rutherford Appleton Laboratory Space (RAL Space - lead institution), the Institut für Astrophysik at the Georg-August-Universität Göttingen (IAG), the Royal Observatory of Belgium (ROB), the Centre Spatial de Liège (CSL) and Airbus DS Space Systems (ADS) (Middleton, 2017). Its technical specifications are tailored for operational forecasting purposes. Like the CCOR and ISS-coronagraph developments, SCOPE follows a new and improved coronagraph design, called the compact coronagraph. The goal of this development is to reduce the complexity of the baffle system that constitutes the Lyot-design, on which the coronagraphs on board SOHO and STEREO are based, and thus significantly reduce the size and mass of the instrument. I will describe my contribution to the following development questions:

- What are the important design aspects of the compact coronagraph?
- Does the current design achieve the defined stray light rejection?
- What are the requirements to successfully test a coronagraph under laboratory conditions?

The thesis is structured as follows:

In chapter 2, the basic theoretical knowledge about the Sun and solar activity is presented, including a description of the coronagraph instrument to observe the solar corona. The basic theoretical knowledge about the Earth and ionosphere, as well as space weather impacts at Earth are presented in chapter 3. In chapter 4, I describe the different data sets used for the analysis of ionospheric impacts. Further processing steps, as well as the analysis methods are presented in chapter 5. The results of these analyses are then presented in chapter 6 and discussed in chapter 7. In chapter 8, design of the SCOPE instrument and the construction of a test model to verify its optical properties is described. In chapter 9, the basic requirements for a coronagraph test facility are discussed, followed by a description of the test setups used to analyse the stray light properties of SCOPE. The results of these tests are presented in chapter 10 and discussed in chapter 11. Finally, the thesis is closed with a summary and outlook to future activities in chapter 12.

Chapter 2

Basic Knowledge of the Sun, Solar Activity, and the Coronagraph

In this chapter, I present the basics of the Sun and solar activity as a theoretical background for the following chapters. First, the basic characteristic of the Sun and its atmospheric structure are presented, followed by the solar activity cycle and phenomena that form the cause of space weather effects at Earth and in the ionosphere. Finally, the principle of the coronagraph instrument, which is used to observe the white-light solar corona and CMEs, is explained.

2.1 The Sun and its Corona

The Sun is the central object of our solar system, and the source of the majority of space weather phenomena and effects. In short, the Sun is a large sphere composed of mostly Hydrogen and Helium in the form of hot, ionised plasma. It has a radius of 696,000 km at its equator, a mass of $1.99 \cdot 10^{30}$ kg and outputs a luminous power of $3.8 \cdot 10^{26}$ W in the form of photon radiation (Stix, 2004, pp. 3-6). This enormous amount of energy is created by nuclear fusion in its core. Figure 2.1 shows the structure of the Sun.

The innermost layer, the *core*, extends to about 25% of the radius. In the core, Hydrogen gas undergoes nuclear fusion, creating Helium. As a result of the equilibrium that forms between gravity and energy production, the density in the core lies around 150 g cm^{-3} , the pressure around $2.5 \cdot 10^{11}$ bar and the temperature around $1.5 \cdot 10^7$ K (Guzik and Lebreton, 1991).

The second layer is called the *radiation zone*. In this region, energy production by fusion has mostly ceased, but the density and pressure are still high enough to balance the temperature gradient and inhibit convection. Energy is thus transported outward via thermal conduction and radiation transport, with the latter dominating under these specific conditions (Stix, 2004, pp. 237-239).

Beyond the radiation zone lies the *convection zone*. Here, the temperature gradient is high enough compared to the density gradient to drive convective motion, transporting heat more quickly. The convection itself shows turbulence and forms a substructure with convective granules of different size, visible at the photosphere through meso- and supergranulation (Stix, 2004, pp. 265-269).

Ultimately, when the conditions reach a temperature of around 5800 K and 10^4 Pa, the opacity of the solar plasma drops below 1 within a relatively narrow zone of only around hundred kilometres (Stix, 2004, p.149, 174). The energy can quickly escape this layer, forming the visible "surface" of the Sun called the *photosphere*.

Figure 2.1: Schematic of the interior structure of the Sun and its atmosphere. The green letters indicate the convention for labelling direction. The image textures of the photosphere, chromosphere and corona are observations of the SDO/AIA and SDO/HMI instruments (see section 4.2).

Inside the Sun, there is more motion than just the convective flow from the inside to the outside. The convection zone and photosphere exhibit differential rotation, i.e. a different rotation period at the equator and poles. In the photosphere, the sidereal rate varies between about 24.5 d at the equator and about 34.2 d at the poles (Snodgrass and Ulrich, 1990). The difference changes throughout the convection zone, until it ceases in the boundary region called *tachoclyne* (Thompson et al., 2003). The resulting plasma movements due to the differential rotation and the convection are the origin of a magnetic dynamo, which generates and maintains the magnetic field of the Sun. Important dynamo mechanisms are the α -effect, ω -effect and the Babcock-Leighton mechanism (Ossendrijver, 2003; Charbonneau, 2012).

The outward transport of magnetic field occasionally causes such strong bundles of field lines to cross the photosphere that the convection is locally inhibited. With the main energy transport mechanism eliminated, the photosphere locally cools and the temperature drops to around 4000 K, which is still hotter than the filament of an incandescent lightbulb, but as thermal radiation increases with the fourth power of temperature and the peak of the spectrum shifts towards the infrared, these regions appear dark. This is what we know as *sunspots* (Stix, 2004).

Above the photosphere follows the solar atmosphere. The first layer of the atmosphere, directly above the photosphere, is called the *chromosphere*. Its temperature lies between about 4000 K and 25000 K and is characterised by spectral line emission and absorption, most prominently in the H_α -line at 656.3 nm (Stix, 2004, pp. 389-392). An image of the Sun in H_α , taken by myself at the Institut für Astrophysik Göttingen, is shown in Figure 2.2, where different structures like sunspots and prominences are visible. At a height of about 2000 km, the conditions change rapidly in the so called *transition region*. Over this narrow region of only about 100 km, the temperature increases up to over 10^6 K (Aschwanden, 2005b, pp. 26-28) in the uppermost layer, the *corona*. At these high temperatures, heavy atoms like Iron are present in highly ionised states. These states absorb and emit light at different characteristic wavelengths in the extreme ultraviolet (EUV) portion of the electromagnetic spectrum and are hence used as a means to study the coronal temperature and structure. EUV is defined as the part of the electromagnetic spectrum ranging from a wavelength of 124 nm down to 10 nm. Figure 2.3 shows a comparison of the solar corona observed by the Atmospheric Imaging Assembly (AIA; Lemen et al. 2011) on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012) at two different wavelengths of 171 and 193 Å. The 171 Å channel shows light from Fe IX lines (8-times ionised iron), probing temperatures of 50,000 K and lower atmospheric layers, where magnetic loops and active regions are clearly visible. The 193 Å channel (Fe XII, Fe XXIV) probes higher regions at temperatures of up to 20,000,000 K. How energy is transported to and dissipated in the corona to generate these high temperatures is one of the fundamental open question in heliophysics research (Fox et al., 2016).

Figure 2.2: Image of the solar disc in the H_α emission line at 656.3 nm, showing sunspots and a prominence. Image taken by the author at the Institut für Astrophysik Göttingen on 2015-09-29.

Figure 2.3: SDO/AIA observations on 2017-01-03 at wavelengths of 171 Å (left) and 193 Å (right). Courtesy of NASA/SDO and the AIA, EVE, and HMI science teams.

Figure 2.4 shows a measured spectrum of sunlight from the X-Ray regime at $\lambda < 1$ nm up to the infrared at $\lambda > 100$ μm . In the visible and infrared, the spectrum is approximated well by a black body spectrum of temperature $T = 5762$ K emitted from the photosphere. In the ultraviolet and below, the spectrum shows a plateau due to the combined emission from the chromosphere and corona.

Figure 2.4: Measured spectrum of sunlight, together with a computed black body spectrum of $T = 5762$ K. Reproduced from Aschwanden (2005a) with permission.

It is not only possible to observe the solar corona in EUV, but also in white-light. The latter is caused partly also by spectral line emission, but mostly by the processes of Thomson-scattering on free electrons and Mie-scattering on dust particles. The corona is commonly classified into the following three different components (Aschwanden, 2005b, pp. 25-26):

- L(ine)-Corona (also E[mission]-Corona): Quantum-mechanical absorption and emission by ions and atoms at specific wavelengths. The strongest emission line in the visible is the Fe XIV-line at $\lambda = 530.3$ nm (Woolley and Allen, 1948).
- F(raunhofer)-Corona: Mie-scattering by dust particles. Identical spectrum to the solar photosphere; the Fraunhofer-absorption-lines are visible.
- K(ontinuum)-Corona: Thomson scattering by free electrons. Also similar to the photospheric spectrum, but additionally Doppler-broadened by the higher velocity of electrons compared to dust particles; the Fraunhofer-lines are not visible.

The profile of the coronal brightness as a function of elongation from the Sun, measured at 1 AU relative to the brightness of the solar disc centre ($B_{\odot}$), is shown in Figure 2.5. The profile by Baumbach (1937) was derived from total brightness measurements of several solar eclipses, while Saito et al. (1977) used space-borne measurements from Skylab and calculated the K- and F-components using polarisation data. The two profiles are in good agreement, and show that the F-corona dominates above approximately $3 R_{\odot}$. The Figure also includes reference brightness values of the daytime Sky (recorded at Mauna Loa observatory; Garcia and Yasukawa 1983), the Sky during a solar eclipse (Pramudya and Muchlas, 2016) and the nighttime Sky (Falchi et al., 2016). Even during a solar eclipse, the corona is darker than the Sky above about $5 R_{\odot}$, and therefore ground-based observations will be limited by atmospheric stray light.

Figure 2.5: Brightness of the solar corona relative to the solar disc centre brightness ($B_{\odot}$) between the solar limb and $35 R_{\odot}$ according to the models by Baumbach (1937) and Saito et al. (1977). Values for the Day Sky, Eclipse Sky and Night Sky are included for reference (Garcia and Yasukawa, 1983; Pramudya and Muchlas, 2016; Falchi et al., 2016).

2.2 The Solar Cycle and Solar Activity

The Sun undergoes periodic changes in an 11-year long *solar cycle*. These changes affect both the appearance of the Sun and its corona, as well as the occurrence of several activity phenomena, which will be discussed in this section.

Visually, the cycle is quantified by the number of the photospheric sunspots. They are counted daily by a number of observatories across the globe, and are usually measured in the International Sunspot Number (SSN) S_n , originally defined by Wolf (1851), and most recently revised by Clette et al. (2014). In the SSN, not only the number of spots N_s is considered, but also the number of sunspot groups N_g , as these usually cause a larger activity. It is calculated using the formula

$$S_n = k \cdot (10 \cdot N_g + N_s) \quad (2.1)$$

where k is called “personal scaling coefficient”, and is used to account for the different numbers counted by different observers. A systematic record of sunspots is maintained by the Sunspot Index and Long-term Solar Observations¹ (SILSO) operations at the Royal Observatory of Belgium (ROB) and is available as monthly mean data from 1749, and as daily data from 1818 onward. Following the work of Wolf, sunspot cycles are continuously numbered (from minimum to minimum) with cycle 1 beginning in 1755. The last cycle, number 24, began in December 2008². At the time of writing, the transition to cycle 25 is in progress, but an official date has not yet been published.

Figure 2.6 shows the monthly-averaged sunspot number, together with a 13-month smoothed average over the last five solar cycles. It can be seen that there is a significant variation between individual cycles. In cycle 24, the 13-month average peaked just above $S_n = 100$, while cycle 19 peaked around $S_n = 275$. This behaviour is attributed to the superposition with longer duration cycles of 88 years and above (Hathaway, 2015).

Sunspot groups with particularly strong magnetic fields and complex field configurations often show enhanced brightness in EUV-bands and are associated with the occurrence of other activity phenomena described below. Such regions are also called *active regions*.

Another, often used measure for the solar cycle is the *F10.7-index* (Tapping, 2013). It is the solar radio flux at 2800 MHz, equivalent to a wavelength of 10.7 cm. Its official data source is the Dominion Radio Astrophysical Observatory (DRAO) in Penticton, Canada³. Here, the F10.7 index is measured three times per day, at 18:00, 20:00 and 22:00 UT time in winter, and 17:00, 20:00 and 23:00 UT time in summer. F10.7 correlates strongly with SSN, although the relationship is slightly non-linear, and is still used as an input parameter for atmospheric models (e.g. Meng et al. 2020).

¹<http://sidc.be/silso/home>, 27.04.20

²<http://sidc.be/silso/cyclesmm>, 27.04.2020

³<https://www.spaceweather.gc.ca/solarflux/sx-en.php>, 27.04.2020

Figure 2.6: The monthly mean sunspot number (blue) and 13-month smoothed sunspot number (red) over the last five solar cycles. Image credit: SILSO data/image, Royal Observatory of Belgium, Brussels, licensed under CC BY 4.0

As described in the previous section, the solar corona with its many different ion species and high temperature is a source of EUV and X-Ray radiation. Like SSN and the F10.7 index, this radiation also strongly varies across the solar cycle. At a wavelength of 30.4 nm, the variability across the solar cycle is around a factor of 2, as can be seen in Figure 2.7, which shows the irradiance in this spectral band measured between May 2010 and December 2018 by the EUV Variability Experiment (EVE, Woods et al. 2012) on board SDO. The data has been smoothed to show daily average values. Around the peak of solar cycle 24, in 2014, the irradiance is around $1 \cdot 10^{-3} \text{ W m}^{-2}$, and has dropped to between $5 - 6 \cdot 10^{-3} \text{ W m}^{-2}$ near the minimum in 2018. In addition to the solar cycle trend, additional variability with a period of 27 days and changing amplitude can be seen. This variability is due to the radiation originating from active regions rotation in and out of view of Earth.

The effects listed above describe changes to the electromagnetic radiation output on medium and long time scales. There are also shorter, transient phenomena of solar activity. A *solar flare* is a sudden, short lived and local increase of the brightness of the solar surface, usually observed near a sunspot group. Flares are generated during events of magnetic reconnection (Parker, 1957), where electrons are accelerated to high energies and flow along the magnetic field lines towards the photosphere, forming two flare ribbons (Schmieder et al., 2015). The electrons then heat up a part of the photosphere to extremely high temperatures, thus emitting EUV- and X-Ray radiation. The onset time, i.e. the time between the beginning and the peak intensity, is around 15 min to 30 min, and they decay back to the background level in approximately 60 min to 120 min (see section 4.3). Woods et al. (2005) have studied the spectrum of X17-flare of 2003-10-28, and derived variability between 10% above wavelengths of 150 nm, 100% at wavelengths down to 30 nm and up to 10000% at X-Ray wavelengths around 1 nm, so similar to the solar cycle variations above 30 nm, but much stronger at shorter wavelengths.

Figure 2.7: Variability of the solar EUV irradiance in the 30.4 nm spectral band, measured between May 2010 and December 2018 by SDO/EVE. The data has been smoothed to show daily average values.

In the radio part of the solar spectrum, transient effects are called *radio bursts*. They are subdivided into 5 types, type I to type V in Roman numerals, which differ in terms of the duration between seconds and days, and frequency range between 10 kHz and 2 GHz (Antar et al., 2014). The different types also originate in a range of different sources, from active regions up to CME shock waves (see below).

Besides radiation in different spectral regions, the Sun emits a continuous stream of magnetised plasma, known as the *solar wind*. It was predicted theoretically in early works by Biermann (1951) and Parker (1959), who first used the term solar wind. The experimental confirmation followed closely after with the Russian Luna 1 spacecraft (Gringauz et al., 1960). Since then, many missions were flown to measure and characterise the solar wind. For example, the Helios 1 and 2 spacecraft, launched in 1974 and 1976, measured the properties of the solar wind over elliptical orbits between 0.29 and 1 AU (Rosenbauer et al., 1977). The solar wind is divided into two categories, *slow* and *fast* solar wind, which are mainly distinguished by a threshold proton velocity of $v_p = 450 \text{ km s}^{-1}$. Table 2.1 lists typical parameters of the slow and fast solar wind at 1 AU.

The origin of the fast solar wind lies in coronal holes, where particles can easily escape into interplanetary space along the “open” magnetic field lines (Wang and Sheeley, 1990). The origin of the slow solar wind is not yet fully proven, and may be a combination of several sources. The proposed mechanisms include ejection from the top of coronal streamers, expanded fast stream from polar coronal holes, as well as multi-scale reconnection processes (Cranmer et al., 2017).

Table 2.1: Typical values of the proton velocity v_p , proton density n_p , proton temperature T_p and magnetic field strength B of the slow and fast solar wind at a heliocentric distance of 1 AU (Rosenbauer et al., 1977; Bothmer et al., 2007).

Solar Wind type	v_p	n_p	T_p	B
slow solar wind	300 to 450 km s ⁻¹	10 cm ⁻³	5 · 10 ⁴ K	4 nT
fast solar wind	450 to 800 km s ⁻¹	3 cm ⁻³	2 · 10 ⁵ K	5 nT

Interactions between fast solar wind streams and the ambient slow solar wind lead to the formation of compression regions ahead and rarefactions behind the fast stream (Gosling et al., 1972). The compression regions are called *stream interaction regions* (SIRs) or, when the underlying source region is stable over several solar rotations so that a recurring compression region is observed every 27 days, *co-rotating interaction regions* (CIRs). These compressions are characterised by an enhanced density and magnetic field strength, and can form a shock wave in extreme cases.

Coronal Mass Ejections (CMEs) are very strong outbursts of plasma from the solar corona that travel with velocities of, potentially, over 3500 km s⁻¹ (Webb and Howard, 2012; Riley et al., 2018), and are generally associated with the strongest space weather effects. The occurrence of CMEs is often connected to the disappearance of filaments or prominences in the lower corona (Bothmer and Schwenn, 1994), with underlying bipolar regions in the photosphere (Cremades and Bothmer, 2004). The large amount of energy required to launch a large amount of plasma is believed to be generated in the process of reconnection of the strong magnetic fields in complex sunspot groups (see e.g Schmieder et al. 2015 for a recent review of the trigger mechanisms). Like the solar wind, CMEs carry a magnetic field into interplanetary space, which can reach a total field strength of around 100 nT at 1 AU (Riley et al., 2018).

CMEs can be detected in white-light coronagraph observations (see the following section for a detailed description), or in the solar wind parameters measured near Earth. In the latter case, the detected structures are called *Interplanetary Coronal Mass Ejections* (ICMEs). Figure 2.8 shows a schematic of the typical structure of a CME (left side of the Figure), and measured data of an ICME observed on 2004-07-27 by the Advanced Composition Explorer (ACE; Stone et al. 1998; right side of the Figure). Three phases of a typical strong CME/ICME event are labelled: A (1) A magnetohydrodynamic *shock wave* travels ahead of the ICME, characterised by abrupt jumps in (some of) the measured quantities, most importantly the velocity and the strength of the interplanetary magnetic field (IMF). Shock-waves are present only in the faster ICMEs that fulfil the conditions of the Rankine-Hugoniot equations. (2) Next follows a so called *sheath region*. It is a turbulent region of compressed solar wind ahead of the ICME. It is characterised by a heavily fluctuating magnetic field vector, a high temperature around 10⁶ K and an enhanced density compared to the solar wind before the shock. (3) The main phase of the ICME is the passage of a *magnetic cloud* (MC). Its characteristics were first described by Burlaga et al. (1981): a smooth rotation of the magnetic field direction, as seen the B_z -component in Figure 2.8; a total magnetic field

strength inside the MC that is stronger than the average solar wind; and a lower temperature than the average solar wind. MCs were then identified as magnetic *flux tubes* of CMEs (Bothmer and Schwenn, 1994), which form as helically wound magnetic field lines in a cylindrical cross section. Bothmer and Schwenn (1994) have also introduced a scheme of the configurations of MCs according to their helicity and polarity.

Figure 2.8: Schematic of the typical CME structure (left) and an ICME signature in solar wind data measured by ACE-MAG and -SWEPAM on 2004-07-27 (right).

Finally, a phenomenon often associated with strong CMEs and flares are *Solar Energetic Particles* (SEPs). These are high energy particles (electrons, ions, and protons) accelerated to energies between tens of keV and a few GeV (Bothmer et al., 2007). In solar flares, the acceleration of the particles is thought to occur at the top of magnetic loops, where energy is released by magnetic reconnection, while in CMEs the particles are accelerated most strongly in shock fronts (Klein and Dalla, 2017).

2.3 The Solar Coronagraph Instrument

In this section, I present the basic design characteristics of the white-light coronagraph, with particular emphasis on the subclass of externally-occulted coronagraphs.

A solar coronagraph is a special type of telescope designed to observe the faint outer atmosphere of the Sun, the solar corona. A conventional telescope or imaging camera, pointed at the Sun, can not be used to perform this task. The main reasons for this can be explained with the help of the plot of relative brightness of the solar corona in Figure 2.5. The coronal brightness is below $10^{-5} B_{\odot}$ even just above the solar limb at $1 R_{\odot}$. The first issue stemming from this is that a camera with a large enough light collecting power to collect a sufficient number of photons of the corona would create a very bright image of the solar disc. This can result in thermal damage to the image sensor or surrounding electronics. Secondly, even without damage, the imaging contrast will likely be too low due to optical effects such as scattering on lens surface errors, surface roughness, glass inhomogeneity, and particularly image ghosts - i.e back-and-forth reflections between lens surfaces including the detector. Further scattering can occur on structural parts of the telescope and even in the form of diffractive stray light.

2.3.1 Classical Coronagraph Designs

To overcome the stray light limitations, French astronomer Bernard Lyot designed the coronagraph in the 1930s. Figure 2.9 shows the schematic presented in his original publication (Lyot, 1932). In this design, an image of the Sun and corona is formed by an objective lens (A). At the centre, the image of the Sun is reflected out of an exit window (K) by a small, angled mirror (J). The image of the corona is then re-imaged onto a detector (or film, at the time of publication; B'/B'') by a field lens (C) and a relay lens (F). The field lens furthermore serves to create an intermediate image of the entrance aperture around the objective lens and block the diffracted light from this aperture on a second aperture stop (D). At the same location, a small spot (E) on the optical axis is used to catch Poisson-spot diffraction and ghost images of the Sun formed in the first lens. These two elements of a coronagraph have subsequently received the names *Lyot stop* and *Lyot spot*.

Figure 2.9: Schematic of the internally occulted coronagraph proposed by Bernard Lyot. Reproduced from Lyot (1932).

Lyot's design is known as an *internally occulted* coronagraph, because the occulter is placed behind the first optical element, the objective lens. It allowed him to observe the inner corona from ground based observatories and study phenomena such as prominences (Lyot, 1939). Lyot's design was later developed into the second design type, called *externally occulted* coronagraph, by Evans (Evans, 1948), where the occulter is placed in front of the first optical element to further reduce stray light. Further important development on the externally occulted design was made by Newkirk and Bohlin (Newkirk and Bohlin, 1963, 1964), who improved the design for use in space-borne observatories that had then become a possibility.

Figure 2.10 shows a side-by-side comparison of the basic, simplified optical principles of the internally and externally occulted coronagraphs, together with the ray paths for solar disc rays (red) and coronal rays (blue). In the internally occulted coronagraph, shown at the top of the Figure, the solar rays are focused by an objective lens to form an intermediate image plane, where the occulter is placed. In the externally occulted coronagraph, shown at the bottom of the Figure, the occulter is placed at some distance in front of the objective lens. It is oversized relative to the lens aperture, so that the latter lies inside the shadow cast by the occulter (red dotted lines).

Figure 2.10: Schematic comparison of the internally occulted (top) and externally occulted (bottom) coronagraph, showing the main components and ray paths for sunlight (red) and coronal light (blue). The grey, dotted line indicates the optical axis of the system.

The two types of coronagraphs have different advantages and disadvantages, making them suitable to observations of different parts of the corona. The first difference concerns the image resolution. In the internally occulted coronagraph, the occulter creates a sharp cut-off because it is placed in the image plane of the Sun and corona. The external occulter, on the other hand, is not located in any image plane, and thus creates a vignetted image area around its inner Field Of View (FOV) angle. This in turn imposes a diffraction-limited degradation of resolution close to the inner FOV limit (Born and Wolf, 1999). The second difference lies in the stray light performance that can be achieved. The internally occulted design is limited primarily by the properties of the objective lens, which is illuminated directly by sunlight. Even the most perfect lens (or mirror) will scatter light because of surface roughness, as well as imperfections in the bulk glass such as bubbles (Nelson, 2006). In the externally occulted coronagraph, the objective lens is not illuminated directly, and thus the main source of stray light is eliminated. In combination, these two differences make internally occulted coronagraphs well suited to observations of the innermost corona at high resolution, and the externally occulted coronagraph to observations up to several $10 R_{\odot}$.

Both coronagraph types have been used by several observatories and missions in the past and present. Notable examples of operational, ground-based coronagraphs are the K-COR instrument at the Mauna Loa Solar Observatory (MLSO) in Hawaii, which observes in polarised light to extract electron density information of the K-corona de Wijn et al. (2012), and the *CLIchés Multiples du SOleil* (CLIMSO) instruments at Pic-du-Midi, which observes at five emission lines between 393.4 nm (Ca II) and 1083 nm (He I) to achieve a better contrast (Koechlin et al., 2019).

The first space-borne coronagraph was flown in September 1971 on board the seventh Orbiting Solar Observatory (OSO-7) (Koomen et al., 1975). It was externally occulted and observed within a FOV of $2.8 R_{\odot}$ to $10 R_{\odot}$. Further instruments were then used on the Skylab Apollo Telescope Mount (MacQueen et al., 1974), the *Solwind* coronagraph on the U. S. Department of Defense Space Test Program Satellite P78-1 (Sheeley et al., 1980), a Lyman-alpha and white-light coronagraph on Spacelab (Kohl et al., 1981) and a coronagraph observing in seven spectral band on the Solar Maximum Mission (MacQueen et al., 1980).

At the present, coronagraphs are featured on three active missions. First, the Solar and Heliospheric Observatory (SOHO) (Domingo et al., 1995). It was launched in 1995 and is located at the Sun-Earth Lagrange-point L1. SOHO originally featured three coronagraphs C1, C2 and C3 as part of the Large Angle and Spectroscopic Coronagraph (LASCO) instrument-package (Brueckner et al., 1995). C1 is internally occulted, but used reflective primary objectives as well as an “inverse occulter” realised as a fold mirror with a central hole. Its FOV is $1.1 - 3 R_{\odot}$, and observations are made in a narrow wave band using a tunable Farby-Perot filter. C1 has not been operational since 1998, when SOHO had suffered from a pointing error and went into a deep freeze (Fleck, 2018). The C2 and C3 coronagraphs are still operational and serve as the main “workhorse” for operational space weather purposes today. They are both externally occulted and observe in white light,

with FOVs of $1.5 - 6 R_{\odot}$ and $3.7 - 30 R_{\odot}$, respectively. The design of the C3 instrument is shown in Figure 2.11. Second, the Solar Terrestrial Relations Observatory (STEREO) (Kaiser et al., 2008). This mission consists of two nearly identical spacecraft, STEREO-A and -B, that were launched in 2006 into 1 AU heliocentric orbits. Each satellite features two coronagraphs, COR1 and COR2, as part of the Sun-Earth Connection Coronal and Heliospheric Investigation (SECCHI) instrument package (Howard et al., 2008). Both observe in white-light with FOVs of $1.4 - 4 R_{\odot}$ and $2.5 - 15 R_{\odot}$, respectively. COR1 is a classical, internally occulted coronagraph, while COR2 is externally occulted. STEREO also features two so called heliospheric imagers (see section 2.3.3). Third, the Solar Orbiter (SolO) spacecraft, which was launched in February 2020, now features the METIS coronagraph (Antonucci et al., 2019), although the instrument has not yet been commissioned. The mission concept is quite different here, as SolO has an elliptic orbit with a minimum perihelion of 0.28 AU and a maximum aphelion around 1.3 AU, which change over the course of several Venus swing-by maneuvers (Müller et al., 2013). The FOV of METIS will span between $1.7 R_{\odot}$ and $9 R_{\odot}$ (Antonucci et al., 2019). Because of the elliptic orbit, the thermal load on the instrument varies strongly, and METIS therefore uses a so called “inverse external occulter” scheme to reject as much direct solar radiation as possible.

Figure 2.11: Design of the SOHO/C3 coronagraph. Adapted from Brueckner et al. (1995) with permission.

An important upcoming mission featuring an externally occulted coronagraph is the PROBA-3 mission with the *Association de Satellites Pour l’Imagerie et l’Interferometrie de la Couronne Solaire* (ASPIICS) coronagraph. As an ESA technology-demonstration mission, PROBA-3 explores the feasibility of fine formation flight through a large-scale version of the externally occulted coronagraph: One spacecraft contains the camera, one spacecraft holds the external occulting disc (Plessier et al., 2013). This disc is 1400 mm in diameter, and located at a distance of approximately 150 m from the camera spacecraft. This way, it achieves an inner FOV limit as close as $1.04 R_{\odot}$. PROBA-3 will fly in a highly elliptical orbit with a period of 19.7 hours. The formation flight and observation phase will last for several hours during each orbit.

2.3.2 Design of the Externally Occulted Coronagraph

In this section, I present the design of the externally occulted coronagraph in detail. The design of the SCOPE coronagraph, which is presented in chapter 8, is a further development of this design. Furthermore, the STEREO/COR2 and SOHO/C3 instruments, which are the most similar existing coronagraphs compared to SCOPE, also follow this design.

As mentioned in the previous section, the externally occulted coronagraph traditionally follows the design by Evans, Newkirk and Bohlin (Evans, 1948; Newkirk and Bohlin, 1963, 1964). The detailed design is more complicated than that shown in Figure 2.10 and involves further optical elements and baffles. Figure 2.12 shows a more detailed schematic drawing with some additional components and ray paths compared to Figure 2.10, which are a core part of the original coronagraphs stray-light reduction mechanism.

Figure 2.12: Schematic of the externally occulted coronagraph, showing the main components and ray paths for coronal light (blue), as well as ray paths for light diffracted off the external occulter (green) and lens aperture (orange). The grey, dotted line indicates the optical axis of the system.

The design consists of two occulters, one external occulter (EO) and one internal occulter (IO), three groups of lenses (O1 - O3), baffles and apertures (A0-A3) and a detector at the final focal plane (F). In the following, only the term “lens” will be used for simplicity, where in a real system a complex group of several individual lenses would usually be used.

At the very front of the instrument, the EO and the baffle aperture (A0) are located, followed next by the aperture of the lens system (A1). Here, the first difference to the simple scheme can be seen, namely that the external occulter consists of more than one disc. The reason for this is the fact that light, due to its wave-properties, gets diffracted around solid boundaries and there are thus no perfect shadows (Born and Wolf, 1999). For the stray light rejection ratios required to observe the outer corona, together with typical restrictions in size of a satellite (resulting in ~ 0.5 m EO-A1 and $\varnothing \sim 40$ mm EO), the amount of diffracted light arriving at the A1 aperture from a single disc is too large. The efficiency of the

EO must hence be improved by using a geometry other than a single, circular disc. One common option is to use a series of discs that become successively smaller towards the lens aperture. The individual disc sizes are chosen so that each disc, and finally the optics aperture, lies in the shadow cast between the previous two discs, thus effectively apodising the diffraction pattern. The principle is shown schematically in Figure 2.13. Both LASCO/C3 and SECCHI/COR2 have used 3-disc EOs. The heliospheric imagers on STEREO used 5 linear baffles following the same principle. Halain (2012) has described a formula to compute the individual baffle heights for the case of HI. Other options that have been studied and used include a conical occulter with a smooth or threaded surface, and a serrated disc (Fort et al., 1978; Bout et al., 2000). The LASCO/C2 coronagraph used a single, thick disc with 160 threads (Brueckner et al., 1995).

Figure 2.13: Sketch of the multi-disc occulter principle, outlined with a 3-disc occulter. The lens aperture, at the right end of the sketch, lies inside the shadow of the final disc.

The dimensions of the EO and A0 aperture also define some FOV limits of the system. Four limits can be defined, accounting for the vignetting they introduce. If the radii of the EO, A0 and A1 apertures are given by r_{EO} , r_{A0} and r_{A1} , and D_{EO} and D_{A0} define the distance between the final disc of the EO and A0 to A1, the limits for the inner FOV (IFOV) and outer FOV (OFOV) can be computed as follows:

$$\alpha_{\text{IFOV,limit}} = \arctan \left(\frac{r_{EO} - r_{A1}}{D_{EO}} \right) \quad (2.2)$$

$$\alpha_{\text{IFOV,unvignetted}} = \arctan \left(\frac{r_{EO} + r_{A1}}{D_{EO}} \right) \quad (2.3)$$

$$\alpha_{\text{OFOV,unvignetted}} = \arctan \left(\frac{r_{A0} - r_{A1}}{D_{A0}} \right) \quad (2.4)$$

$$\alpha_{\text{OFOV,limit}} = \arctan \left(\frac{r_{A0} + r_{A1}}{D_{A0}} \right) \quad (2.5)$$

Behind the A1 aperture follows first lens, the objective lens (O1). It first forms an intermediate image plane of the corona, where a field stop (A2) is placed to sharply limit the coronal image, i.e. before $\alpha_{\text{FOV,limit}}$. The O1 lens also forms an intermediate image of the EO, which lies slightly further inside the instrument. In this image plane, a single IO disc is placed, which is slightly oversized w.r.t. the image of the EO so that the first few diffraction rings are blocked from propagating further down the system and being scattered or reaching the detector focal plane (F). The A0 aperture also diffracts light towards the lens system according to Babinet’s principle (Born and Wolf, 1999), which is caught on the field stop.

Next follows the second lens, the field lens (O2). In conjunction with O1, it forms another intermediate image plane, specifically of the A1 aperture, which is illuminated by the diffracted light from the EO and A0. This baffle has been named *Lyot-stop*, as it was one of the most important elements in Lyot’s original internally occulted coronagraph, where the fully illuminated A1 aperture presented an even stronger source of diffracted light.

The final optical elements are the relay lens (O3), which forms the final image of the corona in the detector focal plane (F).

There are still two important elements worth noting that are not included in the schematic: The *spider-arms*, or *pylons*, holding the EO and IO at the centre of the instrument, and the *heat rejection mirror* (HRM), which is located just before and around the A1 aperture.

The pylon can also be a source of scattered or diffracted light, while spanning the entire FOV from its inner to its outer limit in at least one part of the image. In the specific design case of SCOPE, it was found to be a particularly important object to control, and the effort to investigate its behaviour and design requirements is presented in this thesis.

The HRM is needed in the externally occulted coronagraph to remove the sunlight that enters between the EO and A0 and hits the structure of the instrument around A1. If the structure is diffusely scattering light, it will be scattered partly towards the rear-side of the EO and A0, which then re-scatter on towards the first lens, which will again re-scatter towards the detector. Given the high contrast required, even this 3-scatter-process can be significant. A good black paint diffusely reflects $\sim 1\%$ of the incident light, which may offer a sufficient reduction. However, black paint has the added side-effect of absorption of a large amount of sunlight, and can consequently lead to thermal management issues. The solution is to place a concave mirror at the rear of the instrument that focuses the incoming sunlight between the external occulter and the baffles and so directs it back out of the instrument.

2.3.3 Further Related Instrument Concepts

In this section, I want to briefly present further instrument concepts similar to the solar coronagraph, which take the coronagraph development to a broader range of scales.

One such instrument is called *heliospheric imager*, which was first used on the STEREO mission with two cameras, HI1 and HI2 (Eyles et al., 2009). The heliospheric imager is designed to observe the corona even further away from the solar limb than externally occulted coronagraphs. On STEREO, they bridged the gap to observe the entire distance between the Sun and the Earth, and allowed to track CMEs until their arrival and measurement in solar wind data at L1 (Davis et al., 2009). Heliospheric imagers are not designed to observe 360 degrees around the Sun, but only in one direction. This allows for a different optical design of the straylight-rejection features, e.g. the occulter is replaced by a series of linear baffles. Figure 2.14 shows an overview of the FOVs of the different cameras on STEREO, and Figure 2.15 the schematic design of STEREO/HI.

Figure 2.14: FOV of the STEREO/SECCHI cameras. Image credit: NASA/STEREO.

Figure 2.15: Schematic design of the heliospheric imagers on STEREO. Adapted from Eyles et al. (2009) with permission.

Another pair of heliospheric imagers are the two cameras of the Wide Field Imager for Solar Probe (WISPR; Vourlidas et al. 2015) suite on board Parker Solar Probe (PSP; Fox et al. 2016). The orbit of PSP is elliptic, and so the combined FOV of WISPR will vary between $2.2 - 20 R_{\odot}$ at the closest perihelion of 0.044 AU and $9.5 - 83 R_{\odot}$ at aphelion of 0.25 AU. The SolO mission also features a heliospheric imager in addition to the METIS coronagraph, called SoloHI (Howard et al., 2013). Its FOV, at perihelion, will be between $5.25 - 47.25 R_{\odot}$.

A similar instrument, the Solar Mass Ejection Imager (SMEI) was launched in January 2003 on board the Coriolis spacecraft (Eyles et al., 2003; Jackson et al., 2004). The spacecraft is located in a LEO orbit with a period of 102 minutes. SMEI features three wide angle cameras with a FOV of $3^{\circ} \times 60^{\circ}$. Over each orbit, the three cameras mapped the entire sky from an elongation of 20° outward.

Furthermore, the coronagraph design has been adapted to the use on stars, where it is used for the search of exoplanets. One type already used successfully for this purpose is the *phase mask coronagraph* (Roddier and Roddier, 1997). It follows the design of the internally occulted coronagraph, but with a phase mask deposited onto a clear glass window replacing the internal occulter, which partially shifts the phase of the incoming light and so cancels the stellar light. This is possible for stellar coronagraphy because stars are effectively a point sources w.r.t. the diffraction limit of the telescope aperture. This method achieves a better contrast very close to the star than would be possible with a simple occulting mask. Another concept, which so far has only been proposed, follows the externally occulted design as an even larger version of the formation-flight concept used with PROBA-3. It is often labelled as *starshade* coronagraph. The FOV that needs to be occulted in case of a star is on the order of few arcseconds, meaning that a “relatively small” occulting disk at a very large distance is required. To give some example values from Glassman et al. (2009), the starshade diameter for a full-scale mission is 50 m, and the spacecraft separation 67000 km to reach a working angle of 77 mas.

Chapter 3

Basic Knowledge of the Ionosphere and Space Weather

Following the basic knowledge of the Sun and solar activity in the previous chapter, I here present the relevant basics about the Earth, ionosphere and space weather impacts. First, a description of the Earth's atmospheric structure and the magnetosphere surrounding it is presented. Afterwards follows a detailed description of the ionosphere, its chemical composition and the dynamics due to coupling with the other layers. Finally, the impacts of space weather phenomena at Earth are described, with an emphasis of the effects on the ionosphere.

3.1 The Earth's Atmosphere and Magnetosphere

The Earth is surrounded by a gaseous atmosphere, composed of roughly 78% Nitrogen, 21% Oxygen, 1% Argon plus some minor constituents (Schubert and Walterscheid, 2002). At the surface of the Earth, the mean pressure is $p = 1013 \text{ hPa}$, which decreases with increasing altitude to form a hydrostatic equilibrium. The pressure at altitude z is described by the barometric formula:

$$p(z) = p_0 \cdot e^{\int_0^z (Mg)/(RT) dz} \quad (3.1)$$

where p_0 is the pressure at a reference altitude $z = 0$ and R the universal gas constant. The molar mass M , the temperature T and the gravitational acceleration g in general have to be treated as a function of altitude. The extent of the atmosphere is difficult to quantify because, as a result, the pressure slowly and continuously decreases. One definition, the *Kármán line*, made by the Fédération Aéronautique Internationale sets the boundary to space at an altitude of 100 km above the surface, where pressure and density have dropped by a factor of 10^{-6} and aerodynamic lift drops to be dominated by the orbital centrifugal force¹.

¹<https://web.archive.org/web/20110809093537/http://www.fai.org/astronautics/100km.asp>, 27.04.2020

A common stratification, shown in Figure 3.1, is based on the temperature of the atmosphere, which shows a more complex behaviour with two inversions at characteristic heights. This is indicated on the right side of the Figure with data taken from the NRLMSISE00 model (Picone et al., 2002), accessed through the *msise00*-module² for python, for a time of 12 UT during solar maximum. The layers are called troposphere up to a height of ~ 15 km, stratosphere up to a height of ~ 50 km, mesosphere up to a height of ~ 100 km and finally thermosphere above ~ 100 km. The exact altitudes vary depending on the time of day or the phase of the solar cycle, and the values given here correspond to figure 3.1.

Figure 3.1: Thermal stratification of the atmosphere. The temperature profile is computed using the NRLMSISE00 model for a time of 12 UT during solar maximum.

The troposphere is characterised by a decline in temperature from 288 K on the ground to just above 200 K at its top. The chemical composition is very homogeneous, with the exception of water vapour, as can be seen e.g. from the variable cloud coverage. In the stratosphere, the temperature again increases due to absorption of UV radiation by ozone. With increasing height, absorption becomes weaker and thermal IR-emission, e.g. by carbon dioxide, dominates, so that the temperature drops. Finally, the balance shifts back to being dominated by absorption, leading to an even stronger rise in temperature up to an asymptotic temperature of 1000 K at altitudes above 300 km, coining the name thermosphere.

²<https://github.com/space-physics/msise00>, 27.04.2020

Other layers are defined e.g. by chemical composition into homo- and heterosphere; by vertical transport mechanism into turbosphere, diffusosphere and effusosphere; by gravitative binding into barosphere and exosphere; and, most importantly in the context of this thesis, by the degree of ionisation into the neutral atmosphere, ionosphere and plasmasphere (Prölss, 2013, p. 32). The ionosphere is described in greater detail below in section 3.2.

The Earth sustains a magnetic field through dynamo processes in its liquid outer core (Roberts and Glatzmaier, 2000). The mechanism of this dynamo is different from that of the Sun, as are the specific conditions in the Interior, and therefore the resulting field at the surface differs. Figure 3.2 shows a global map of the magnetic field strength at the Earth’s surface. The data is from the *International Geomagnetic Reference Field* (IGRF, Thébaud et al. 2015) and was accessed through the pyIGRF-module³ for python. The field is dominated by a dipole component, but shows distortions from higher order terms as well as non-centricity of the dipole axis with the Earth’s axis of rotation. The mean dipole axis of the magnetic field is currently tilted by about 10° relative to the rotation axis, with the north pole leaning towards North America. The south magnetic pole is deflected more strongly, and shows a higher peak field strength than the north pole. Another important feature is the so called *South Atlantic Anomaly* (SAA), exemplified in Figure 3.2 by the very low field strength over South America.

Figure 3.2: Magnetic field strength at the Earth’s surface. The data is computed using the IGRF model for the year 2020.

The Earth’s magnetic field also shows reversals, which are chaotically distributed with timescales around $2 \cdot 10^5$ years to 10^7 years, during which it enters a phase of more chaotic field whose strength is reduced by a factor of 3 to 10 (Stacey and Davis, 2008, pp. 427-432). Currently, the polarity of the field is such that the north pole is actually a magnetic south pole and vice versa. This has developed from historic definitions: The north pole of a magnetic compass needle points towards the Earth’s north pole, while it is truly attracted by a magnetic south pole.

³<https://github.com/zzyztyy/pyIGRF>, 27.04.2020

The region around Earth where its magnetic field dominates the movement of charged particles is called the *magnetosphere* (Kivelson and Bagenal, 2014). Beyond the magnetosphere, the Sun's magnetic field, carried by the solar wind, dominates. Figure 3.3 shows a schematic drawing of the magnetosphere's structure. The shape is distorted from the approximate dipolar field near the surface due to compression by the inflowing IMF carried by the solar wind. Two distinct boundaries are formed: the *bow shock* and the *magnetopause*, separated by the *magnetosheath*. The bow shock is formed because the solar wind is a supersonic flow that changes to subsonic conditions at the interaction with the Earth's magnetosphere. Behind the shock follows the sheath region characterised by turbulent field. At the magnetopause, the turbulent fields abruptly change to smooth conditions when the Earth's field fully dominates.

Inside the magnetosphere, a *polar cusp* forms where the field lines diverge between the sunward side and the tail. It opens magnetic connections to solar wind particles in the magnetosheath, which can flow down the cusp and penetrate into the ionosphere (Russell, 2000). It is quite narrow, with a width of only about 5 degrees in longitude and 90 degrees in latitude (Zhang et al., 2013).

Under quiet geomagnetic conditions, the extent of the magnetosphere in the sunward direction is about 10 Earth-radii (R_E). On the night side, a long *magnetotail* is formed, with an extent of several 100 R_E (Prölss, 2013, pp. 265-266).

Figure 3.3: Schematic structure of the magnetosphere.

When the conditions of the inflowing solar wind change, particularly toward a southward polarity of the IMF, field lines at the front of the magnetosphere undergo magnetic reconnection. This in turn leads to additional compression of the magnetic field in the tail, where further reconnection takes place in crossover points at the centre of the tail lobe. The energy released in those processes accelerates electrons and ions to high energies of several keV. These particles then flow along the magnetic field lines towards the night side polar regions, where they penetrate down into the ionosphere and excite molecules, causing strong aurora.

On short timescales of minutes or hours, the magnetic field at the surface shows fluctuations of a few nT during normal conditions, but can reach a few 100 nT in extreme cases. These fluctuations are caused by interactions of the Earth's magnetosphere with the solar wind, as well as changes of electrical current systems in the ionosphere.

These fluctuations are being measured continuously to derive index values for the magnetic activity. The most popular index is the K-index, which was introduced by Bartels et al. (1939), and its global average Kp, where the index p stands for planetary, which followed in 1949. The planetary index is determined from 13 stations, which are distributed in Europe, North America, Australia and New Zealand. Each station records the maximum variations of the horizontal magnetic field component H in 3-hour intervals. The values are then presented on a logarithmic scale from 0 to 9, with $\frac{1}{3}$ stepping, denoted as 0, 0+, 1-, 1, 1+, etc. Sometimes, the full numbers are additionally appended by a small letter o, i.e. the sequence becomes 0o, 0+, 1-, 1o, etc. The distinction between quiet and disturbed geomagnetic conditions is not a hard boundary, but somewhat flexible. For example, the so called *international quiet days* are assigned for $Kp \leq 3o$, while the NOAA space weather scales begins with minor disturbances for $Kp = 5o$. Conditions of $Kp = 9o$ occur around 4 times per solar cycle (Lloyd's, 2013). The official data source for the Kp-index is the Geomagnetisches Forschungszentrum (GFZ) in Potsdam, Germany⁴. Another important index is the Dst-index (Sugiura and Kamei, 1991). It also measures variations in the horizontal magnetic field component H , but using stations closer to the equator and using mean values instead of fluctuations (Le Mouél et al., 2012). It is given in units of nT. The Dst index is a measure of the strength of the the equatorial ring current that flows in the ionosphere (see the following sections). The ring current induces a magnetic field opposite to that at the Earth's surface. Thus, a negative Dst-index is an indication of a strong ring current. A typical limit for quiet conditions is $Dst > -30$ nT, and the strongest storms have reached $Dst < -500$ nT (Riley et al., 2018). Both the Kp and the Dst index have specific applications, and neither correlates with all effects (Borovsky and Shprits, 2017). The Dst-index is provided by the World Data Center (WDC) for geomagnetism in Kyoto, Japan⁵. Both the Kp and Dst-index are available in “quicklook” as well as “final” format. The final data is postprocessed with long-term data, and delayed by a month in case of the Kp-index, and several years in case of the Dst-index.

⁴<https://www.gfz-potsdam.de/kp-index/>, 27.04.2020

⁵<http://wdc.kugi.kyoto-u.ac.jp/dst/dir/>, 27.04.2020

3.2 The Ionosphere and its Coupling to Other Layers

The ionosphere is the ionised part of the upper atmosphere, characterised by the presence of a large number of free electrons (Prölss, 2013, p. 165). Solar EUV radiation is the main cause of ionisation, but other spectral bands, particularly X-ray-radiation, also play an important role. Furthermore, there is some ionisation by cosmic rays and, at times, SEPs. Cosmic rays can reach the highest energies up to 10^{21} eV and are predominantly important in the generation of the lower ionosphere below 100 km (Velinov et al., 2013). Figure 3.4 shows the electron density as a function of altitude for the day (12:00 UT) and night (00:00 UT) ionosphere in the northern midlatitudes during high solar activity. The data is taken from the *International Reference Ionosphere* model (IRI; Bilitza et al. 2017), accessed through the *iri2016*-module for python⁶. The Figure also indicates three different layers that are commonly distinguished: The F-region above an altitude of about 170 km, the E-region between about 90 km and 170 km, and the D-region below 90 km, although these numbers should only be taken as a coarse reference (Prölss, 2013, p. 168). The E-region is named for the reflections of electromagnetic waves, as were first observed by Guglielmo Marconi and Edward Appleton in the early 20th century. The other layers subsequently received adjacent letters. In the D- and E-regions, the electron density is greatly reduced at night, while it only drops by about a factor of 2 in the upper F-region.

Figure 3.4: Structure of the ionosphere, indicating typical profiles of the electron density. The data is taken from the IRI2016 model.

⁶<https://github.com/space-physics/iri2016>, 27.04.2020

Figure 3.5: Density of the major ions in the ionosphere for a mid-latitude, daytime, solar maximum ionosphere. Values are computed from the IRI2016 model.

Figure 3.6: Density of the major neutrals in the ionosphere for a mid-latitude, daytime, solar maximum ionosphere. Values are computed from the NRLMSISE-00 model.

The major constituents of the ionosphere are shown in detail in Figure 3.5 for ionised and Figure 3.6 for the neutral components, again for a mid-latitude ionosphere during solar activity maximum. The numbers for the ions are taken from the IRI model, and the numbers for the neutrals are taken from the NRLMSISE00 model. In the neutral gas, the onset of the ionosphere is visible by the sudden appearance of large quantities of monatomic H, N and O, which are formed by photodissociation due to EUV radiation (He is a noble gas and thus naturally monatomic). Monatomic O becomes the dominant neutral constituent above ~ 200 km, while He dominates above 600 km to 800 km. At F-region altitudes, the ions are dominated by O^+ . In the E-region, O_2^+ and N_2^+ show the biggest contribution. In the D-region, the density of O_2^+ drops more rapidly than N_2^+ , and cluster-ions as well as negative ions (not included in these models) become important as well. Ionisation and formation of molecular ions occurs down to the ground as a result of mostly cosmic rays and radioactive radiation (Velinov et al., 2013). However, there is no significant number of free electrons below the ionosphere, and so this does not contribute to the data analysed in this work. It will thus not be considered further. Finally, at an altitude of about 1000 km, depending on the phase of the solar cycle, H^+ begins to dominate the ion constitution. By definition, this marks the end of the ionosphere and the start of the plasmasphere.

As can be seen from comparing Figure 3.5 to Figure 3.6, the ion and electron density is more than an order of magnitude below the neutral density even at an altitude of 1000 km. In other words, the ionosphere - despite being defined as a region with a significant number of free electrons - is mostly neutral. For this reason, the study of the ionosphere does not only require knowledge of plasma physics, but also of the behaviour of the neutral atmosphere due to interaction between the species.

The compositions shown above are the result of a number of physical and chemical processes of ion production and loss. The main production mechanism is, as mentioned before, ionisation of atoms or molecules by EUV photons. In the case of molecules, this can also occur together with dissociation of the molecule. Some of the most important reactions are (Prölss, 2013, pp. 170-180):

Furthermore, the electrons generated from the highest energy photons can have a sufficient kinetic energy to generate secondary electrons:

where X can be any atom or molecule that is not fully ionised. This process is not limited to primary photoelectrons, but can also be caused by external electrons and other high-energy particles like cosmic rays.

Once ions have been generated, charge can also be transferred between atoms and molecules, which, again, can be dissociative, and even form new molecules in the same step. The latter is the source of NO^+ ions, which, as discussed above, are a significant contributor to the D- and E-regions. Some important reactions here are:

Finally, the production of ions and electrons must be balanced by losses. The most important mechanism here is dissociative recombination, where the energy from recombination is released by breaking up a molecular ion. Recombination with atomic ions will lead to the emission of a photon:

Recombination of atomic ions is less important however, as conservation of momentum and energy, together with quantisation of energy levels, favours only few situations. Compared to the dissociative processes, the efficiency is about 5 orders of magnitude lower (Prölss, 2013, p. 176), and the loss of atomic ions thus governed primarily by charge transfer from O^+ to N_2 or O_2 and subsequent recombination. The intermediate charge transfer is also slow, so that the total recombination timescale is much higher for monatomic ions. This also explains why the F-region is sustained through the night despite the absence of ionising radiation, but the E- and D-regions are reduced by orders of magnitude.

As the full 3D-distribution of the electron density can not easily be measured, the ionosphere is often characterised in terms of the integrated column density. This quantity is called the total electron content (TEC), and can either be evaluated

vertically (VTEC) or along any arbitrary line, e.g. between a satellite and a ground station, called slant TEC (STEC). It is typically given in *TEC Units* (TECU), where $1 \text{ TECU} = 10^{16} \text{ e}^- \text{ m}^{-2}$. Figure 3.7 shows a global VTEC map, for a quiet day near solar maximum (2012-03-21 12:00 UT). The dashed lines indicate lines of constant magnetic latitude in the so called *Quasi-Dipole* (QD) system (Emmert et al. 2010, see also section 5.1). Around the poles and on the night side, VTEC is below 30 TECU. On the dayside, there are two maxima of about 80 TECU, which lie around $\pm 15^\circ$ magnetic latitude, and are delayed behind the subsolar point by around 2 hours. The fact that the electron density is higher around the equator than at the equator is called *Equatorial Ionospheric Anomaly* (EIA), and its underlying mechanism the ionospheric fountain effect (Prölss, 2013, p. 201). The eastward directed electric field $\vec{E}$ of the equatorial ring current, plus the northward directed magnetic field $\vec{B}$ produce an upward $\vec{E} \times \vec{B}$ drift. Plasma is moved to higher altitudes, where it is surrounded by lower density and thus expands laterally.

Figure 3.7: Global VTEC map for 2012-03-21 12:00 UT. The dashed lines show constant magnetic latitude in QD coordinates.

The ionospheric chemistry has also been linked to a delayed response between TEC and EUV. Jakowski et al. (1991) derived an accumulation of atomic oxygen at an altitude of 180 km, which is generated at lower altitudes by photodissociation and transported upwards by diffusion. The delay has been studied by several groups (e.g. Lee et al. 2012; Jacobi et al. 2016; Vaishnav et al. 2018) using global averaged, daily TEC, and found to be in the range of 1-2 days.

Both during and outside of space weather events, the ionosphere is a highly dynamic medium. At an altitude of 300 km, the mean free path of the particles is 3 km (Prölss, 2013, p.12) and collisions can not be neglected yet at this altitude, although this becomes the case at higher altitudes as the mean free path increases sharply in this region. This makes the ionosphere subject to neutral winds. At low latitudes, the velocity u of these winds is dominated by the Earth's rotation translated into the upper atmosphere through friction (Prölss, 2013, p. 138):

$$u = \Omega_E (1 R_E + h) \cos(\Theta) \quad (3.14)$$

where Ω_E is the Earth's angular rotation rate, h the altitude and Θ the geographic latitude. This wind component is zonal, i.e. along lines of constant latitude. At the equator and thermospheric altitudes this velocity is around 500 km s^{-1} . Near the poles, the velocity due to co-rotation vanishes as a result of the $\cos(\Theta)$ -term. The next important component is a daily variation. Absorption of sunlight heats the dayside atmosphere, which develops a temperature and pressure distribution that peak just after 12 local time (LT), with a minimum around 3 LT. This generates a velocity field including also a meridional component, i.e. along lines of constant longitude. There is hence a flow across the poles. The zonal flow is furthermore inhibited by an ion drag force. This is because ions can move freely only along the magnetic field lines, which are approximately meridional in the dipole-dominated field.

The interactions between neutral gas flows, as well as magnetic field fluctuations induced by the solar wind generate a number of current systems in the ionosphere and plasmasphere. Charged particles inside a magnetic field do not move in straight lines, but gyrate around the field-line with a gyro-radius of:

$$r_B = \frac{mv_{\perp}}{|q|B} \quad (3.15)$$

where m is the mass of the particle, $v_{\perp}$ the velocity component perpendicular to the magnetic field B and q the charge. In the ionosphere, electrons have a much smaller gyro-radius than the much heavier ions. The action of the magnetic field leads to an asymmetry of the conductivity. Three components are distinguished: the Hall-, Pedersen- and Birkeland-conductivity (and correspondingly -current). The Birkeland-conductivity is along the direction of the magnetic field. The Pedersen-conductivity along the component of the electric field perpendicular to the magnetic field, and the Hall-conductivity closes the system. The total current density $\vec{j}$ can thus be expressed by (Prölss, 2013, p. 372):

$$\vec{j} = \sigma_B \vec{E}_{\parallel} + \sigma_P \vec{E}_{\perp} + \sigma_H \vec{B} \times \vec{E}_{\perp} / B \quad (3.16)$$

Figure 3.8 shows a schematic overview of the electric current systems in the polar ionosphere. Field-aligned Birkeland currents flow along the field lines into and out of the auroral oval, separated into two regions west and east of 12 LT, as well as the inside of the oval (region 1) close to the pole and the outside (region 2). On the morning side, the Birkeland current flows towards Earth in region 1 and away in region 2, with the opposite behaviour on the evening side. The currents are closed across the poles and inside the auroral oval by Pedersen-currents that flow from morning to evening in the polar cap and opposite in the auroral oval. There is also a system of horizontal “convection” of Hall-currents. these flow from the night- towards the day-side over the polar cap, and close along the auroral oval in the form of the so called *auroral electrojet*.

Figure 3.8: Schematic of the polar ionospheric current systems. Reproduced from Le et al. (2010) with permission.

Important current systems are also formed in the equatorial region of the ionosphere and magnetosphere. When the gyration around a magnetic field is combined with a perpendicular force field, e.g. gravity and horizontal magnetic field lines at the equator, the gyration becomes asymmetric due to a change of the gyro-radius across a full gyration. This in turn leads to a net flow of positive and negative particles in opposite directions, forming a *ring current* around the equator. Such a current flows in the magnetosphere from East to West at variable altitudes between $2 R_E$ to $9 R_E$ (Daglis et al., 1999). In the ionosphere itself, dynamo currents are generated as the result of the drag forces from neutral winds. At altitudes below the D-region, the collision frequency is higher than the gyrofrequency and both electrons and ions follow the neutral wind, with no resulting currents. In the F-region and above, the collision frequency is low so that both electrons and ions drift perpendicular to the wind and magnetic field, again with no net current. In the central region around ~ 100 km, the collision frequency of ions is higher than the gyrofrequency, while it is lower for electrons. This results in different motion for the two particle species, dominated by the drift of ions with the neutral gas (Prölss, 2013, p.416). Under solar quiet (Sq) conditions, such currents are generated as the result of tidal effects. It is most strongly pronounced in a small region around the magnetic equator, the *equatorial electrojet*. The effects under disturbed conditions can be quite complex, and are usually separated into low-, mid- and high-latitudes (Prölss, 2013, pp. 418-427).

3.3 Space Weather Impacts at Earth and in the Ionosphere

The changing conditions on the Sun due to its activity, and the associated phenomena described in section 2.2, lead to variable conditions in the interplanetary space and at planets, where they in turn induce changes and effects on planetary magnetospheres, ionospheres, or technological systems. These changing conditions and effects are collectively known under the term *space weather*, and are an important branch of modern space research. Figure 3.9 shows an illustration of the most important affected systems at Earth. This includes the generation of strong currents in pipelines and power grids, which can lead to severe power outages (Lloyd's, 2013). For satellites, astronauts, as well as aircraft crew and passengers, enhanced radiation levels due to SEP events are a serious threat (O'Sullivan, 2004). Furthermore, long distance communication with electromagnetic waves, e.g. at HF frequencies, or positioning accuracy of GNSS-systems can be impacted through changes of the ionosphere. In this section, I will present an overview of space weather effects at Earth and in the ionosphere.

Figure 3.9: Illustrative overview of the most important space weather effects. Adapted from https://www.nasa.gov/images/content/607989main_FAQ13-orig_full.jpg. Image Credit: NASA.

Solar radio emission during radio bursts can lead to direct interference with radar systems if certain conditions are met. On 2015-11-04, such an event led to issues with air traffic control radar across Europe, with severe disruptions of service in Sweden that led to partial closures of airspace and delays of flights (Marqué et al., 2018).

The enhanced solar radiation in EUV and X-Ray during solar flares causes enhanced ionisation of all layers of the ionosphere. Tsurutani et al. (2006) and Sahai et al. (2008) have studied the effects of the X17 flare on 2003-10-28, one of the strongest flares ever recorded, using GNSS-derived TEC for single station in Africa (close to noon) and in Brazil, respectively. Both have shown an increase of about 25 TECU, or a relative increase of $\approx 30\%$ for the data reported by Sahai et al. (2008), that then decayed back to the background values over period of approximately 3 hours. The regional distribution of TEC enhancements was also studied using data from GNSS stations (Zhang and Xiao, 2005; Hernández-Pajares et al., 2012) as well as using model calculations (Qian et al., 2012). They found increases of TEC due to solar flares out to 15° behind the day-night terminator, i.e. up to solar zenith angles of $\chi = 105^\circ$, and TEC change rates on the dayside as a function of the cosine of χ .

$$\frac{dTEC}{dt}(\chi) = \begin{cases} \frac{dTEC}{dt}_0 \cdot \cos(\chi \cdot \frac{90}{105}) & \text{for } \chi \leq 105^\circ \\ 0 & \text{for } \chi > 105^\circ \end{cases} \quad (3.17)$$

where $dTEC_0$ is the enhancement at the subsolar point and χ the solar zenith angle.

The abrupt changes in the ionosphere caused by flares leads to disruption of high frequency communications, known as *Sudden Ionospheric Disturbance* (SID). A recent example is given by the X9.3 and X8.2 flares on 2017-09-06 and 2017-09-10, which happened at the time of hurricane relief efforts in the Caribbean and caused communication issues for the Hurricane Weather Net (HWN), and the French Civil Aviation Authority (DGAC) (Redmon et al., 2018; Bingham et al., 2019).

Strong SEP events pose a threat for radiation damage to electronic systems as well as human health (Cannon et al., 2013). The effects are fundamentally the same as for cosmic rays, but with cosmic rays being present as a relatively constant background, while SEPs occur in far more intense transient events. In computer electronics, this can lead to so called single event effects (SEE), where a single bit (or sometimes multiple bits) is flipped by an ionising particle, with random effects up to a full system shutdown, requiring a reboot of the system. The effects are usually not immediately destructive, although the lattice displacements in semiconductors accumulate over time, leading to degradation. This is measurable for example on the efficiency of solar arrays. Curdt and Fleck (2015) have calculated that 38% of the degradation of the SOHO solar panels over 17 years between the launch in 1996 and 2013 was caused by transient SEP events.

A specific impact of SEPs is the release of charge in image sensors such as CCDs, which can lead to a strong amount of noise in the images as individual pixels are fully saturated. Particles entering at shallow angles, or causing secondary electrons, will show as elongated streaks. Figure 3.10 shows an example from the eruption of a fast CME on 2003-10-28, which was accompanied by strong SEPs. During the first images at 11:41UT and 12:17UT, the images are still clean and the CME appears bright close to the Sun. In the following frame at 12:41UT, a larger number of bright pixels and streaks are seen in the image until finally, at

13:43UT, it is almost impossible to observe the CME above the noisy background.

Figure 3.10: Series of SOHO-LASCO-C3 running difference images on 2003-10-28 during the eruption of a fast CME. The final image at 13:43:39UT shows strong SEP noise.

In terms of human health, SEPs are of immediate consequence to astronauts during extra-vehicular activities (Malandraki and Crosby, 2018, p. 20). While SEPs can not directly penetrate the atmosphere down to altitudes of e.g. commercial aircraft operations, the high energies cause nuclear chain-reactions that generate secondary particles which may lead to significantly enhanced radiation levels at lower altitudes, particularly in polar regions. Particles with energies of GeV-energies also cause so called ground level enhancements (GLEs), measured on ground by neutron monitors (Aschwanden, 2012). As a consequence, aircraft operators may divert aircraft to routes to lower latitudes and/or altitudes, both of which has economic impacts due to e.g. enhanced fuel costs. For these kind of events, energies above (a few) 100 MeV would be better suited as an indicator rather than the 10 MeV currently used most frequently (Cannon et al., 2013).

The solar wind and CMEs interact with the Earth primarily through the magnetosphere. As CMEs reach the highest velocities and magnetic field strengths, they are generally responsible for the strongest magnetic fluctuations. The compression of the magnetic field generates or alters the ionospheric current system.

An example is the ionospheric ring current, which is increased at times of strongly magnetised and/or fast solar wind flows and characterised by negative values of the Dst index. In the ionosphere, the increased ring current leads to an enhancement of the ionospheric fountain effect, sometimes called the superfountain (Tsurutani et al., 2004). This leads to TEC enhancements as the existing plasma is transported to higher altitudes with longer recombination times, and new ionisation by EUV occurs at lower altitudes. The plasma is also transported to higher latitudes than by the quiet-time fountain. A review of geomagnetic storm effects on ionospheric TEC is given by Mendillo (2006). It is noted that thermospheric composition changes, perturbations by neutral wind and electric fields generated in the magnetosphere are the main drivers of ionospheric changes. The enhancement or decrease of monatomic Oxygen plays an important role in the formation of positive and negative storm phases, respectively.

In addition to the magnetically induced ion and electron transport, dissipation of energy in the enhanced current systems leads to heating of the atmosphere. The density in the upper ionosphere and thermosphere, the location of Low Earth Orbit (LEO) satellites, can be increased by around 1600% (Doornbos and Doornbos, 2012), which in turn causes increased drag and a disturbance of the satellite orbit. Thermospheric winds driven by heating also lead to changes in the neutral gas composition at high and mid-latitudes. In these regions, the atomic oxygen density in the F-region can be lowered by over 50%, leading to negative TEC excursions (Prölss, 2013, pp. 442-444). Large changes in TEC affect the accuracy of GNSS-positioning services, with a common translation being 1 m of error for 6 TECU.

The changing magnetic field on the ground also has significant impacts on technical systems, most importantly power grids. In electric conductor loops, a change in magnetic flux Φ causes the induction of a voltage according to Faraday's law:

$$V = -\frac{d\Phi}{dt} = -\int_A \frac{d\vec{B}}{dt} \cdot d\vec{A} \quad (3.18)$$

where $\vec{B}$ is the magnetic field, and the integration is over the loop surface A . This voltage is the source of *geomagnetically induced currents* (GICs) in loops formed between the ground and electrically conducting materials such as pipelines and power grid lines. The latter are typically grounded at the respective ends, and thus form very long loops. GICs are DC currents that can reach values of over 100 A (Girgis and Vedante, 2012). In large transformer units, which operate on AC, a DC offset leads to a loss in efficiency as they drive transformers into part-cycle semi-saturation, and in turn overheating. The most well-known event is that of March 1989, where 6 million people were affected by long-lasting power outages in Canada (Allen et al., 1989).

Chapter 4

Data Sources for the Ionospheric Impact Analysis

In this chapter I describe the main data sources used for the analysis of ionospheric space weather impacts. Section 4.1 starts with a description of GNSS-based global ionospheric maps and the product from the Centre for Orbit Determination in Europe. EUV data from the Solar Dynamics Observatory is described in section 4.2. Next, in section 4.3, I introduce the X-Ray measurements from the Geostationary Operational Environmental Satellites, which is used to classify solar flares. And finally, solar wind data at Earth from the OMNI data set is described in section 4.4.

4.1 Global Ionospheric Maps

The electron content of the ionosphere can be measured with different techniques, which are based on its effects on radio-wave propagation. The two techniques used historically are ionosondes, starting in the 1930s based on the work of Breit and Tuve (1926), and incoherent scatter radar starting in the 1960s (Gordon, 1958). Both measure reflected radio-wave signals emitted from ground-based antennas and yield an electron density profile. In case of the ionosonde, the profile is only measured up to the height of peak electron density (called the bottomside ionosphere), and modelling is required to estimate the electron density above it (the topside ionosphere). Most recently, GNSS-based techniques have been introduced, where the electron content is inferred from positioning errors caused by deflections of the signal in the ionosphere (Schaer et al., 1996b). Because here the transmitter and receiver are located on opposite sides of the ionosphere and the direct signal instead of a weak scattered component is measured, much lower power needs to be transmitted, and each ground station requires only a relatively inexpensive receiver. This allows to cover a much larger spatial grid across the globe and compute full ionospheric maps. Unfortunately, GNSS-measurements do not provide a direct measurements of the electron density, but only the integrated TEC along the signal path. GNSS-based TEC does not suffer as much degradation during geomagnetic activity as the other techniques (Mendillo, 2006).

Figure 4.1 shows a 2-dimensional schematic of the GNSS-positioning principle. A receiver, in this example an airplane, determines its location by triangulating using the distances r_i to a number of satellites. The orbital locations of the satellites are continuously monitored using radar or laser ranging, and thus known with very high accuracy. The satellites furthermore carry atomic clocks for precise knowledge of time. These clocks are also regularly synchronized from ground, keeping them accurate to a level of a few ns (Kaplan and Hegarty, 2006, p.305). Each satellite continuously broadcasts messages composed of the current time and corresponding orbital location of the satellite, which are encoded in a so called *navigation message* onto a radio-wave carrier frequency. The receiver records at which time it has received the messages from each satellite, computes the difference between the recorded time and that contained in the message, $\Delta t = t_{\text{received}} - t_{\text{broadcast}}$, and then the distances r_i (also called *ranges* in GNSS theory) between itself and a satellites by assuming that the signal has travelled at the speed of light c :

$$r_i = c \cdot \Delta t \quad (4.1)$$

Figure 4.1: Schematic principle of localisation using GNSS in 2D. The position of a receiver (airplane) is triangulated using the distances r_1 and r_2 to two GNSS-satellites.

In the example of Figure 4.1, this constrains the receiver location to two circles of radii r_1 and r_2 . Two circles generally overlap with two intersection points. In three dimensions, three satellites are required, and the location is then computed from the overlap of three spherical shells, which again results in two intersection points. This remaining ambiguity is resolved automatically, because four satellites are required in practice due the most important error source of this technique, the *receiver clock bias*. In equation 4.1, a clock error in Δt of 10 ns translates into a position error of 3 m. The satellite clocks are synchronised to this level, but it is impractical to provide this for the receiver in most applications. The simpler solution is to introduce a receiver clock error σ_{clock} into the equation:

$$r_i = c \cdot (\Delta t + \sigma_{\text{clock}}) \quad (4.2)$$

and solve for the four unknowns (three for position and one for receiver clock error) by using at least four satellites. There are further potential error sources related to the electronic design of the receiver, which will not be discussed in this thesis. The absolute satellite clock error can contribute a significant error, and the navigation messages contain a near-real-time estimate for a rough correction to keep it within a few ns as mentioned above.

As mentioned in chapter 3, the free electrons in the ionosphere cause a deflection of radio waves. The effect on GNSS signals is illustrated schematically in Figure 4.2. The ionosphere has a different refractive index n_{iono} compared to the Plasmasphere above (n_{plasma}) and the Troposphere below (n_{tropo}). The Stratosphere is not shown in the schematic, as its contribution is often assumed negligible in GNSS-signal propagation theory. The effective signal path length from satellite to receiver increases, introducing an additional position error.

The tropospheric refractive index is constant for the different GNSS-frequency-bands, and composed of a dry and wet component (Hopfield, 1969). The ionosphere, on the other hand, is a dispersive medium, i.e. its refractive index is a function of frequency (Hofmann-Wellenhof et al., 2007). The refractive index of the ionosphere with respect to the carrier phase velocity, $n_{ph.}$, and group velocity, $n_{gr.}$, is to first-order approximation given by (Hofmann-Wellenhof et al., 2007, p.118):

$$n_{ph.} = 1 + \frac{c_2}{f^2} \quad (4.3)$$

$$n_{gr.} = 1 - \frac{c_2}{f^2} \quad (4.4)$$

As the two equations only differ in the sign of the second term, I will use $n = n_{gr.}$ as an abbreviated notation from here on. The coefficient $c_2 \approx -40.3 N_e \text{ Hz}^2$ is dependent on the electron density N_e . According to Fermat's principle, the signal path is found by minimizing the integral along the path ds :

$$s = \int n ds = \int \left(1 + \frac{40.3 N_e}{f^2}\right) ds \quad (4.5)$$

Figure 4.2: Schematic principle of deflection of GNSS-signals by the ionosphere. The Stratosphere, which lies between the Troposphere and ionosphere, is not shown as it is often assumed negligible in GNSS-signal theory.

Similarly, the undisturbed geometric path s_0 is given by assuming $n = 1$:

$$s_0 = \int 1 \, ds_0 \quad (4.6)$$

The ionospheric range error Δ_{iono} is the difference of the two equations. By furthermore assuming that the real path s is similar to the geometric path s_0 , this difference becomes:

$$\Delta_{\text{iono}} = \int \left(1 + \frac{40.3N_e}{f^2}\right) ds_0 - \int 1 \, ds_0 = \frac{40.3}{f^2} \int N_e \, ds_0 \quad (4.7)$$

$$\Rightarrow \Delta_{\text{iono}} = \frac{40.3}{f^2} \text{STEC} \quad (4.8)$$

where the integrated electron density along a signal path has been defined as the so called *slant total electron content* (STEC).

$$STEC = \int N_e ds_0 \quad (4.9)$$

Of the different sources of error, like the tropospheric error or clock errors, only the ionospheric delay significantly depends on frequency, and STEC can be calculated if simultaneous measurements at different frequencies are available for a satellite-receiver pair. Collecting all other errors in the variable ϵ , we can write for the measured ranges r :

$$r_1 = \rho + \epsilon + \frac{40.3}{f_1^2} STEC \quad (4.10)$$

$$r_2 = \rho + \epsilon + \frac{40.3}{f_2^2} STEC \quad (4.11)$$

$$(4.12)$$

STEC is then computed through the linear combination:

$$r_1 - r_2 = 40.3 \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right) STEC \quad (4.13)$$

$$\Rightarrow STEC = \frac{r_1 - r_2}{40.3} \frac{f_1^2 f_2^2}{f_2^2 - f_1^2} \quad (4.14)$$

All GNSS satellites broadcast on multiple frequencies. Traditionally the L1- and L2-band frequencies at 1575.42 MHz and 1227.60 MHz, respectively, of the American Global Positioning System (GPS) were used most commonly. Until around 2008, the L2-frequency was restricted to military users by encryption, and any civilian use otherwise restricted to single-frequency services using the L1-band. However, receivers were developed that could make use of the L2-signal phase information in so called “codeless” or “semi-codeless” approaches, so that ionospheric information could be extracted from the L2-band (Keegan, 1990). In recent years, this scheme has been abandoned towards providing civilian multi-frequency services, both with updated generations of GPS satellites, as well as the Russian GLONASS and the newer Chinese Beidou and European Galileo systems. All of these services are not yet fully operational, however, with e.g. the GPS civilian L2C-signal planned to reach operational availability in 2020¹. An additional broadcasting at the L5-frequency of 1176.45 MHz will also be made available² and is also available via Galileo³.

¹see <https://www.navcen.uscg.gov/pdf/FederalRadionavigationPlan2019.pdf>, page 62; 27.04.2020

²<https://www.gps.gov/systems/gps/modernization/civilsignals/>, 27.04.2020

³https://gssc.esa.int/navipedia/index.php/Galileo_Signal_Plan, 27.04.2020

The STEC computed from dual frequency measurements is mapped to VTEC to provide a more universal and comparable value, as the slant path is different for every measurement. This mapping is often performed with the assumption of a thin, single-layer ionosphere, because its extent is small compared to the satellite-receiver distance (Schaer et al., 1996a).

GNSS-based VTEC is publicly and operationally provided in the form of *Global Ionospheric Maps* (GIMs). Several global institutions compute and provide such maps, and distribute them through the International GNSS Service (IGS; Hernández-Pajares et al. 2009). The individual institutions are also called the associated *Analysis Centres* (ACs) of the IGS. Each AC computes its maps with a different selection of receiver stations as well as underlying modelling techniques. A combined product is computed by the IGS. All GIMs are currently provided in the *IONospheric map EXchange* format (IONEX; (Schaer et al., 1998)) with a spatial sampling of $5^\circ \times 2.5^\circ$ in longitude and latitude respectively, with an underlying VTEC-modelling in a solar-geomagnetic reference frame and using a spherical harmonic series of degree $n=15$ to interpolate between the irregularly spaced receiver locations. This spherical harmonic degree, however, corresponds to only a resolution of approximately $12^\circ \times 12^\circ$.

The analyses presented in this thesis were performed using the “codg” product provided by the Centre for Orbit Determination in Europe (CODE; Schaer et al. 1996b), one of the ACs of the IGS. The data was downloaded in IONEX-format from CODE’s ftp-server⁴. The decision to use this particular product was based on an assessment made during the initial part of the OPTIMAP project (internal communications), where the codg-maps showed the smallest and most consistent difference to the IGS final product, and I continued to use it for this thesis. Using maps computed by a single method was preferred over using a combination that changes over time, as is the case with the IGS final product. Recent studies have compared different GIM products (e.g. Roma-Dollase et al. 2018), showing differences of about 10% between different products. This also includes a newer, higher resolution product with e.g. 15 min sampling. A similar development is made by DGFI-TUM (Goss et al., 2019) and will be used in the OPTIMAP implementation. This will also be based on B-spline modelling instead of spherical harmonics. They find improvements of 26% compared to the codg-product. However, these GIMs are not yet operationally available and could not be used in this work.

An important aspect of the computation of GIMs is the spatial coverage of GNSS receivers. Figure 4.3 shows an example of receiver locations listed in the header information of the codg-IONEX file of 2019-01-01. Due to the location of the majority of these receivers, there is good coverage of Europe, North America as well as Australia and Japan. The least coverage is given over the oceans and central Africa. Handling of such data gaps is one of the motivations for moving from spherical harmonic modelling to B-Spline approaches, as described in Goss et al. (2019). The number of stations has also increased over time, as can be seen in Figure 4.4, which shows the number of stations reported in the codg-IONEX-headers between 2003 and 2018.

⁴<ftp://ftp.aiub.unibe.ch/CODE/>, 27.04.2020

Figure 4.3: Map of the GNSS receiver stations used for the codg maps of 2019-01-01.

Figure 4.4: Number of GNSS-stations reported in the codg-data headers between 2003 and 2018.

4.2 EUV Observations by the Solar Dynamics Observatory

The Solar Dynamics Observatory (SDO; Pesnell et al. 2012) is a major scientific mission for solar observations of recent years. It was launched in 2010 into a geosynchronous orbit, and features three instrument suites: the Advanced Imaging Assembly (AIA; Lemen et al. 2011), taking high-resolution images of the full solar disk in EUV and UV; the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012), taking white-light observations and computing the photospheric magnetic fields from polarisation data; and the Extreme Ultraviolet Variability Experiment (EVE; Woods et al. 2012), which measures EUV-spectra as well as high-resolution time-series in selected EUV-bands with a long-term absolute calibration

Figure 4.5: The EVE experiment on board SDO, showing the different instruments and the EVE Electronics Box (EEB). Reproduced from Woods et al. (2012). Licensed under CC BY-NC-2.0.

EVE, shown in Figure 4.5, consists of two sub-instruments, the EUV-Spectrophotometer (ESP) and the Multiple EUV Grating Spectrograph (MEGS). ESP is a transmission-grating spectrometer with a set of photodiodes as detectors. It provides measurements of four EUV-bands, centred at 18.2 nm, 25.7 nm, 30.4 nm and 36.6 nm, with a spectral bandwidth of approximately 4 nm. Additionally, a 0.1–7 nm “quad-diode” observes four quadrants of the solar surface in the 0th-order of the grating. Besides the diffraction grating, spectral filtering is performed with a thin-film Aluminium-filter at the instrument entrance aperture, and a Titanium-filter for the quad-diode. The Aluminium filter is placed in a filter-wheel with a triple-redundancy to provide two spares (Didkovsky et al., 2012). The cadence of each diode is 0.25 s. MEGS consists of two grating spectrometers, MEGS-A and MEGS-B, observing from 5 to 37 nm, and 35 to 103 nm, respectively, with a resolution of 0.1 nm. The instrument box is furthermore shared with the Solar

Aspect Monitor (SAM), an X-Ray pinhole camera used mainly to provide pointing reference. MEGS-A was lost in May 2014 due to a capacitor failure. The cadence of all spectra is 10 s. Observations are not made continuously, but only for about 3 hours per day to reduce degradation of the detectors. EVE was calibrated on ground prior to launch (Didkovsky et al., 2007, 2012), together with an identical flight-spare. The flight-spare is launched into the upper atmosphere about once a year on a sounding-rocket to provide an inter-calibration measurement to account for the degradation of the primary instrument on-board SDO. The long-term absolute accuracy was estimated after pre-flight calibration at 21.3%, but an improvement was expected after a few sounding-rocket calibration flights (Didkovsky et al., 2012) because the major factor was an estimated sensitivity degradation of 15.9%, which is corrected for by the sounding rocket flights.

Resolved images of the solar disk, chromosphere and lower corona are recorded by the AIA instrument. It provides measurements with a very high resolution of 4096×4096 pixels, or 0.6 arcsec per pixel. Observations are taken in a total of 10 UV and EUV channels. The cadence for the EUV-bands is 12 s. Compared to EVE, AIA does not have the same scheme for absolute calibration. Inter-calibration was performed mainly using the MEGS-A spectra until its failure (Boerner et al., 2014), and uses a proxy model since then (Chamberlin et al., 2007).

Because of the long term calibration, EVE data is used in this thesis. Specifically, the ESP diode measurement in the 18.2 nm, 25.7 nm and 30.4 nm bands are used. The 36.6 nm channel shows a large error and is officially not recommended for scientific purposes⁵, while the 0th-order channel is very similar to GOES-flare data and hence did not provide any specific benefit for the impacts investigated.

The ESP data is of calibration Level 1, from data release version 6 (2017-06-15), provided by the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado⁶ and is available starting 2010-05-01. Level 1 data provides fully calibrated irradiance at the full temporal resolution of 0.25 s, which I average to a resolution of 1 min for consistency with the other data sets. Level 1 data is also corrected for the orbit of SDO, i.e. normalized to 1 AU. This is actually not desirable for the analysis of impacts on Earth, as the real irradiance at the Earth is of interest. The data is thus adjusted again using DE430 ephemeris data (Folkner et al., 2014) and accessed through the python-module *jplephem*⁷. Further calibration is performed to remove artefacts of eclipses, i.e. when SDO passes through the Earth's shadow, as well as times of calibration maneuvers. Data of these maneuvers is available⁸, but it does not fully cover all effects seen in EVE. The data was filtered with the official list, and then scanned manually to remove remaining signatures of eclipses and spacecraft maneuvers.

⁵http://lasp.colorado.edu/eve/data_access/evewebdata/products/level1/esp/EVE_ESP_L1_V6_README.pdf, 27.04.2020

⁶http://lasp.colorado.edu/eve/data_access/evewebdata/products/level1/esp/, 27.04.2020

⁷<https://pypi.org/project/jplephem/>, 27.04.2020

⁸<https://aia.lmsal.com/public/SD0calendar.html>, 27.04.2020

4.3 Solar X-Ray Data from the Geostationary Operational Environmental Satellites

Solar Flares are commonly detected and classified in X-Ray irradiance measured by satellites of the Geostationary Operational Environmental Satellite programme (GOES, Nat 2005). GOES is a series of satellites, operated by the US agency NOAA, used mainly for the purpose of environmental and meteorological observations of the American continents. The first satellite, designated GOES-1, was launched in 1975. Since then, regular updates and replacements were launched. At any time, there are two active satellites, also called GOES-East and GOES-West, located in geostationary orbits over the US-East- and -West-Coast. The latest satellite, designated GOES-S (during development) or GOES-17 (on orbit), was launched in 2018 and is currently active in the West-slot. Each satellite features two instrument suites: First, an Earth-facing platform, hosting visible and infrared-imagers and sounders, as well as relay services for search & rescue purposes; Second, a Sun-facing platform, hosting an X-Ray-imager to observe the full solar disc, energetic particle sensors and an X-Ray- and EUV-sensor (XRS). X-Ray irradiance data is recorded in two spectral bands: The soft-X-Ray (SXR) band between 0.1 nm - 0.8 nm, and the hard-X-Ray (HXR) band between 0.05 nm - 0.4 nm. The temporal resolution of the measurements is 2 seconds, but more commonly, the data is used with a resolution of 1 minute.

In this work, I use X-Ray data between 2003 and 2018. As stated above, different GOES-satellites were regularly launched and used as the primary and secondary data source, so that no single satellite provides data over the entire time range. For this reason, X-Ray data from GOES-10 to GOES-15 is used. Unfortunately, X-Ray data from the re-designed XRS-successor, EXIS, on GOES-16 and -17, has only been made available recently and could not yet be considered for this work. The data from GOES-15 is used as the primary source where data is available. Data gaps are then filled with observations made by GOES-14, remaining data-gaps with data from GOES-13 and so forth down to GOES-10. The data of these GOES generations was downloaded from the NOAA National Centers for Environmental Information (NCEI⁹), using the 1-minute resolution data set.

The classification of solar flares is done by means of the SXR-irradiance and using the GOES-flare-class scheme listed in Table 4.1. In this scheme, 5 classes are defined (A,B,C,M and X), where each class is subdivided further according to the exact value of the peak irradiance. For example, a flare with an irradiance $I = 3.5 \cdot 10^{-5} \text{ W m}^{-2}$ would correspond to a class M3.5. For the highest class, X, this subdivision is open-ended, e.g. a flare with an irradiance $I = 3.5 \cdot 10^{-3}$ would correspond to class X35. Intensities below the lowest class A are in practice below even the solar minimum background values, as well as the instrument dynamic range.

⁹<https://satdat.ngdc.noaa.gov/sem/goes/data/avg/>, 27.04.2020

4.3. SOLAR X-RAY DATA FROM THE GEOSTATIONARY OPERATIONAL ENVIRONMENTAL SATELLITES

Table 4.1: Irradiance boundaries defined in the GOES-flare-class-scheme.

GOES class	GOES 0.1 nm-0.8 nm irradiance I (W m^{-2})
A	$10^{-8} \leq I < 10^{-7}$
B	$10^{-7} \leq I < 10^{-6}$
C	$10^{-6} \leq I < 10^{-5}$
M	$10^{-5} \leq I < 10^{-4}$
X	$10^{-4} \leq I$

The scheme presented above contains a calibration error for historic reasons: The first satellites through GOES-7 were spin-stabilised, and it was later found that the measured irradiance was incorrect by a factor of 0.85 for HXR and 0.7 for SXR. Data of the later generations (8-15) has the same scaling factor applied to provide consistency of the flare-class definition. To get true irradiance, the data must be divided by the aforementioned scaling factors¹⁰. For data from GOES-16 onward, it is intended to drop the scaling and move to the use of the correct irradiance data. As I only use data up to GOES-15 in this thesis, I have not applied the scaling factors and use the incorrect, “traditional” irradiance.

The detection of flares follows the algorithm described by NOAA/NCEI¹¹:

1. The start of a flare is detected when there is a monotonic increase in irradiance of at least 40% over consecutive data points at 1 min resolution.
2. The peak time is recorded when the irradiance reaches its maximum.
3. The flare ends when the irradiance falls back below a threshold of 1/2 the difference between peak-irradiance and the irradiance at the start of the event.

¹⁰See the GOES-XRS Readme file, https://www.ngdc.noaa.gov/stp/satellite/goes/doc/GOES_XRS_readme.pdf, 27.04.2020

¹¹<https://www.ngdc.noaa.gov/stp/solar/solarflares.html>, 27.04.2020

4.4 Solar Wind Data from the OMNI Data Set

The properties of the solar wind are measured by in-situ instruments outside of the Earth's magnetosphere, as the latter interacts with and thus disturbs the solar wind plasma. Solar wind instruments have been included on many different missions since the early 1960s. This includes the two Helios probes, which were launched in 1974 and 1976 into elliptic orbits and measured the solar wind properties down to 0.29 AU, or the two Voyager missions, both launched in 1977, which are still active today and have left the Heliosphere in 2013, providing the first data of the the interstellar medium (Gurnett et al., 2013).

The most important missions in recent years to provide operational data for space weather purposes at Earth are the missions Wind (Lepping et al., 1995), launched in 1994; the Advanced Composition Explorer (ACE; Stone et al. 1998), launched in 1997; and the Deep Space Climate Observatory (DSCOVR; Burt and Smith 2012), launched in 2015. All missions are located in halo-orbits around the Sun-Earth Lagrange-point L1. At this location, they measure the solar wind conditions 1.5 million kilometres upstream of Earth, not disturbed by the Earth's magnetosphere. Depending on the velocity of the solar wind plasma, this provides an advanced warning time for the arrival at Earth between 15 and 60 minutes.

The instrumentation is typically separated into magnetometers and plasma instruments. The type of magnetometers used are usually fluxgate magnetometers (Smith et al., 1998), which measure the magnetic field by observing an asymmetric saturation in a pair of coils, with one pair needed for each component. The plasma parameters are measured with different ion sensors. For example, ACE uses electrostatic analysers (McComas et al., 1998), while DSCOVR uses a Faraday Cup. Figure 4.6 shows three instruments on board DSCOVR: The Faraday cup, the electron spectrometer, and the magnetometer (from left to right).

Figure 4.6: Three solar wind instruments of DSCOVR. From left to right: Faraday cup, electron spectrometer, and magnetometer. Image credit: NASA/DSCOVR.

The data from several missions that measured the conditions near the Earth, including Wind, ACE and DSCOVR, are collected in the so called OMNI dataset (King and Papitashvili, 2005), which I use as the primary solar wind data set for this work. OMNI further distinguishes a high-resolution-OMNI (HRO) and low-resolution-OMNI (LRO) dataset, with temporal sampling of 1-minute and 1-hour respectively. All data is processed to account for the distance to L1 and so is mapped to the arrival time at Earth, which makes it ideal for the study of the impacts at Earth. The LRO dataset is available from 1963, while the HRO dataset begins in 1981. I use only the HRO dataset, because the temporal structure of solar wind parameters is important regarding its effects on the ionosphere. In the period between 2003 and 2018, the HRO data is composed of measurements by the WIND, ACE and DSCOVR. The data is extracted from the OMNI data set through the OMNIWeb interface¹².

For a few individual events, I will additionally use a direct Level-2 dataset from the ACE spacecraft, because the OMNI dataset shows a few large data gaps for important events where the ACE-Level 2 data does not, and thus adds important information. The ACE Level 2-data represents fully calibrated science data and is supplied with 16 s cadence for the magnetometer data and 64 s cadence for the plasma data, which I again interpolate to a resolution of 1 min for consistency. ACE data is accessed through the ACE Science Center located at the California Institute of Technology¹³.

¹²https://omniweb.gsfc.nasa.gov/form/omni_min_def.html, 27.04.2020

¹³<http://www.srl.caltech.edu/ACE/ASC/level2/index.html>, 27.04.2020

Chapter 5

Data Processing and Analysis of Ionosphere Data

In this chapter, I present the methods for the analysis of ionospheric impacts of space weather phenomena. First, in section 5.1, I describe the coordinate systems in which the GIMs are studied. In section 5.2, I present the methods of subtracting backgrounds from the different data sets where applicable. Filtering of the data according to geomagnetic activity defined by the Kp-index is presented in section 5.3. Afterwards, the individual analyses and correlations with EUV-irradiance, solar flares, geomagnetic storms and the solar wind are described in section 5.4 to section 5.7. This includes the selection criteria used to compile event lists for the analyses.

5.1 Coordinate Systems for the Global Ionospheric Maps

Different coordinate systems need to be considered in an analysis of global TEC maps, due to the complex interaction of the driving forces originating from the Sun, and the atmospheric and magnetospheric dynamics, rotating with the Earth and showing variations with the seasonal cycle. Here, three coordinate systems are considered: 1) The geographic, 2) a sun-fixed, and 3) a sun-fixed-magnetic coordinate system.

The first coordinate system is the simple geographic coordinate system, i.e. where any location on the Earth's surface has a fixed longitude and latitude. The GIMs from CODE used in this work are provided in the geographic coordinate system, so no further processing needs to be applied. I do, however, not use the geographic coordinates in my analyses, as the global ionosphere is to first order better described by the other systems.

The second coordinate system is a sun-fixed coordinate system. It is defined so that the subsolar point, i.e. the point on the Earth's surface where the Sun is exactly overhead, has the coordinates (0,0) at any given time. In my implementation used

here, the geographic poles are furthermore kept on the 0° - and 180° -longitude meridians, meaning that the sunrise and sunset terminators lie fixed at the -90° - and $+90^\circ$ -meridians, respectively. This coordinate system is most relevant to EUV- and X-ray-radiation, as these originate from the Sun and travel unaffected by the Earth's magnetic field.

The third coordinate system is based on a magnetic coordinate system, which is used to describe the large-scale features in the ionosphere like the equatorial anomaly, which follows the magnetic equator (compare Figure 3.7 in chapter 3). The specific coordinate system used here is the so called "quasi-dipole" (QD) coordinate system as defined by Richmond (1995) and implemented in the apexpy-package¹ for python (Emmert et al., 2010). Figure 5.1 shows lines of constant latitude of the QD-coordinate system overplotted on a world map. large deviations from geographic coordinates can be seen especially for the south pole and near South America, corresponding with the South Atlantic magnetic anomaly (Figure 3.2). One property of the QD-system is that it is bijective to the geographic coordinate system. More complex magnetic coordinate systems exist, but a benefit is not expected for the analyses in this thesis. The magnetic system is furthermore combined with the sun-fixed system by adjusting the longitude for the magnetic longitude of the subsolar point. This provides the coordinate system where the ionospheric features like the EIA are most stable over time. For the rest of this thesis, this sun-fixed-magnetic coordinate system will be referred to simply as "magnetic" coordinate system.

Figure 5.1: Lines of constant latitude in the Quasi-Dipole coordinate system (red lines), plotted over a world map and the corresponding geographic latitudes (dashed grey lines).

¹<https://github.com/aburrell/apexpy>, 27.04.2020

5.2 Background Subtraction for the Data Sets

The ground state of the ionosphere is strongly correlated with variations of solar EUV radiation on timescales of the solar cycle, seasons and the 27 d rotation of the Sun (see the results presented in section 6). Other effects, e.g. of solar flares or CMEs, are transient in nature, and their impact on the ionosphere lasts between a few hours and a few days. A background subtraction is thus necessary to separate the effects of transients, which cause the disturbances in technical applications, from periodic trends and compute accurate dTEC levels in each case. Background subtraction is performed here for VTEC- and EUV data. For the X-Ray-irradiance and solar wind data, background subtraction is not required for the following reasons: Solar flares, especially X-class events, already have a very high contrast ratio over the background, so a subtraction will have no measurable impact on the results. In case of the solar wind, the effects are driven strongly by the B_z -component of the magnetic field, which shows regular polarity reversals during quiet times or in the sheath regions of CMEs, so that a mean or median value is often close to zero.

Different techniques can be used and are found in literature, depending also on the available data. One method used in other studies is to subtract the data from the previous day to construct running differences (e.g. Tsurutani et al. (2009)). Fourier- or wavelet-transforms can also be used to remove effects with specific periods (e.g. Jacobi et al. (2016)). For this work, the primary method for both VTEC and EUV is the subtraction of 27-day median values. This removes long-term trends due to the solar cycle and seasons, but leaves the sinus-like signature of the solar rotation. For the VTEC-maps, the values are generated separately for each time of day to avoid influences from effects due to the Earth's rotation. Secondly, where effects with time-scales of a few days are not important, e.g. for the much shorter solar flares, moving-median values with a 2-day window will be subtracted. This effectively removes the 27-day signal and provides a better direct access to the dTEC values caused by the events. Finally, a discrete pre-/post-event subtraction is used as the final step in some of the analysis steps for flares and geomagnetic storms. Because such times can be classified for these events, this can be used in certain cases to remove effects from other geomagnetic events within a 2-day window.

Regarding the nomenclature for the following sections and chapters, the term VTEC will be used whenever data without background subtraction are used, and the term dTEC will be used whenever subtraction has been applied. If the term TEC, i.e. without any prefix, is used, the statements apply to both cases. Likewise, the prefix “d” is used to distinguish absolute EUV-irradiance I and background-subtracted dEUV-irradiance dI .

5.3 Filtering for Geomagnetic Activity

Because the full dynamics of the ionosphere is a result of the superposition of several factors, it is important to distinguish between the effects and avoid misidentification or contamination in computation of average values. Effects driven by geomagnetic storms cause disturbances in the magnetic field and will show elevated Kp-levels. I evaluate the parameters with thresholds of $Kp \leq 3$ and $Kp \leq 6$ to define magnetically quiet times and medium active times. The threshold of 3 ensures good margins to recovery phases of activity, but is also not too low to cause frequent data gaps due to fluctuations during quiet periods. In the time interval from 2003 to 2018, this definition corresponds to 85% of the 3-hour intervals, and thus appears to be a good compromise between not removing a significant amount of data from the statistics and avoiding strong geomagnetic activity. However, this depends strongly on the type of event considered, as can be seen from the number of flares presented below in section 5.5, because they appear mostly during solar maximum, when active geomagnetic conditions also occur more frequently. In the following sections, it will be stated where this type of event-filtering is used, and which temporal margins around the events are considered.

5.4 Correlation Between the Total Electron Content and EUV Radiation

The first step of the analysis is to quantify the correlations between TEC and EUV. For this, the EUV data is rebinned to the time resolution of the corresponding TEC data of 2 hours or 1 hour. The time series are compared to identify long-term and seasonal variations. Correlation coefficients are computed in each spectral band for global mean as well as dayside mean TEC, for the full year as well as the seasons. For the global mean TEC, linear and quadratic fits are computed to identify any non-linear relationship and extrapolated behaviour outside the dynamic range of the last solar cycle.

As has been shown by several studies (e.g. Jacobi et al. 2016), there is a delayed response of the ionosphere to EUV, which is explained mostly with the transport of neutral, monatomic oxygen generated by photodissociation. These groups studied the delay using daily and global mean averages of TEC over time spans of a few years. I will make use of the full temporal resolution of the data and compute the delayed response with a resolution of 2 hours. I also compute the correlation coefficients and delayed responses on a regional grid. For this regional analysis, both the sun-fixed as well as the magnetic coordinate systems are investigated. The sun-fixed system is better related to the EUV-irradiance, as each coordinate corresponds to a fixed solar zenith angle and EUV radiation is not deflected by the Earth's magnetic field. The magnetic coordinate system is of course important because the main ionospheric features are most stable there. For the computation of correlation coefficients, the data was rebinned slightly in latitude into a resolution of $5^\circ \times 5^\circ$. As outlined in section 4.1, the underlying spherical harmonics have a lower inherent resolution than the maps. The rebinning was simply applied to

reduce computation time, which became significantly large for the full time series. Further reduction, e.g. to $10^\circ \times 10^\circ$, was not used to maintain some interpolation.

To determine the delayed response, a Pearson correlation coefficient is computed with time shifts from -144 hours (VTEC leading EUV) to +144 hours (VTEC trailing EUV). Figure 5.2 shows an example for one grid point of the regional analysis around the equator and near noon. Near the peak, the correlation coefficient only changes slowly with time shift, but also exhibits some random fluctuations. To obtain consistent estimates for the peak time shifts at all grid points, the curves are fitted in three iterations. First, the entire data series is fitted with a 3rd-order polynomial to obtain a rough peak position. The fit is then performed again using a 2nd-order polynomial with windows of ± 24 h and finally ± 18 h around the previously fitted peak. The windows and polynomial order were determined empirically to obtain the best results across regions with different correlation coefficients. The second and third iteration improved the accuracy of the fit, but could show large errors for regions with low correlation. An example is shown in Figure 5.3, where the correlation coefficients show a flat top and, as a result, a flipped second and shifted third iteration. In case an issue with the fits was detected, the 3rd-order polynomial from the first iteration was used for the final result. For the computation of the global delayed response, only a single iteration 3rd-order fit between -48 hours and +96 hours was used to account for the specific fluctuations observed in this case.

Figure 5.2: Example of how regional time shifts between EUV and VTEC are determined. The data was computed for the time series between 2010-05-15 and 2018-12-15 in the sun-fixed coordinate system between longitude 0° and 5° and latitude -2.5° to 2.5° .

Figure 5.3: Example of a problematic fit of time shifts between EUV and VTEC. The second iteration showed a flipped direction, resulting in the third iteration fitting the wrong segment.

5.5 Analysis of Solar Flare Impacts

In the entire time series covering 2003 to 2018, 11229 C-flares, 1117 M-flares and 104 X-flares were detected. Figure 5.4 shows the occurrence of the different flare-classes between 2003 and 2018. The majority of flares in cycle 24 occurred between the years 2011 and 2015. In 2008, only 8 C- and no M- or X-class-flares were detected in the data. The occurrence of X-flares is very rare overall, and confined mostly to around the solar maximum. Unfortunately, this means that only 8 X-flares lie within the period where GIMs with a temporal resolution of 1 h are available. A high resolution is important because the duration of 91% and 71% of all M- and X-class flares between 2003 and 2018 is below 1 hour and 2 hours, respectively, and this duration even includes the slow decay phase at the end of a flare. For comparison, the time between the start of a flare and its peak is below 30 minutes for 92% and below 15 minutes 68% of all M- and X-class flares, respectively.

Table 5.1 lists the times and GOES-class of the 10 strongest flares. The lowest GOES-class is X6.9, and the highest, on 2003-11-04, is estimated between X28 and X48 (see e.g. Brodrick et al. 2005 and references therein), because the dynamic range of the GOES-XRS-Sensor peaks at around X17 Machol and Viereck (2016). 8 of the 10 strongest flares occurred before November 2014, i.e. when the time resolution of CODE TEC-maps was 2 hours.

Because of the relatively short duration of flares, background subtraction using 2-day moving median values can be used for the TEC data. However, this processing may still not result in accurate dTEC readings for individual events because of overlaying intra-day fluctuations, and a pre-/post-event average is additionally subtracted. As the times of the flare do not coincide exactly with the times of

Figure 5.4: Number of C-, M- and X-class flares per year between 2003 and 2018. The number above each column denotes the number of flares of the respective column.

the TEC maps, I assume that the last TEC-data point before the flare peak time already includes effects of the flare, and consequentially use the value two data points before the peak as the pre-event value. In case of the 2 h-data, this results in a pre-event value 4 h before the peak. The post-event time is also chosen as 4 h as a consequence of the estimated 3 h decay time from other studies (Tsurutani et al., 2006). For the data with 1 h resolution, I use the same definition for consistency. This results in the following formula, where t_{peak} is the time of the observed dTEC-peak:

$$dTEC_{\text{peak}} = dTEC(t = t_{\text{peak}}) - \frac{1}{2}[dTEC(t = t_{\text{peak}} - 4\text{h}) + dTEC(t = t_{\text{peak}} + 4\text{h})] \quad (5.1)$$

The analysis of TEC-effects of the strongest flares listed in Table 5.1 revealed a significant dTEC only for the two strongest events of 2003-10-28 and 2003-11-04. Therefore, I perform a superposed epoch analysis as a second approach. This way, the large number of weaker M- and C-class events can also be used to try and extract values for weaker events and derive - if not direct results - constraints for their impact on TEC. To align the events for superposition, the peak times of all X-, M- and C-class flares are first identified in the time series. They are then filtered for coinciding geomagnetic activity, Using the Kp-index with thresholds of $Kp \leq 3$ and $Kp \leq 6$ in a window of 48 hours before and 12 hours after the X-Ray peak time. Filtering for a short time after the flare ensures clearance of impact from beginning geomagnetic storms (and thus voiding the pre/post-event subtraction), while a longer window is necessary before the events to avoid recovery phases of strong geomagnetic storms. For each flare, dTEC-averages are computed globally,

Table 5.1: List of the 10 strongest solar flares in the time series, covering the years 2003 to 2018. The GOES-class for the strongest event of 2011-11-04 is an estimate, because the GOES detector is saturated at this flux.

Date	GOES-Class
2011-08-09 08:05:00	X6.9
2005-01-20 07:01:00	X7.1
2017-09-10 16:06:00	X8.2
2003-11-02 17:25:00	X8.3
2006-12-05 10:35:00	X9.0
2017-09-06 12:02:00	X9.3
2003-10-29 20:49:00	X10.1
2005-09-07 17:40:00	X17.0
2003-10-28 11:10:00	X17.2
2003-11-04 19:44:00	(X28-X45)

over the dayside and in the “subsolar” region of up to 45° solar zenith angle. The curves are then aligned to the data-point closest to the peak-time of the flare and averaged. The resulting superposed values are compared with the mean peak X-Ray flux for the respective set of flares.

Table 5.2 lists the number of events in the time series with and without the filtering described above. The weaker criterion of $K_p \leq 6o$ only removes few events from the statistics, and all cases are covered with a high number of events, except for X-class flares in the period after November 2014, where the unfiltered number is already low. The stronger criterion of $K_p \leq 3o$ further reduces the number of events by about 60% in the period before November 2014 and about 80% after 2014. In the latter case, only relatively few events remain considering the expected dTEC and the observed intra-day fluctuations that act as noise. Results will be presented only for the 2003-2014 and $K_p \leq 6o$ set.

Table 5.2: Number of Flares in the time series for the periods of different temporal resolution of the GIMs, and with filtering for $K_p \leq 6o$ and $\leq 3o$ applied.

	2003-2014		
Flare Class	Unfiltered	$K_p \leq 6o$	$K_p \leq 3o$
C	8614	7821	3258
M	868	750	305
X	90	73	24
	2014-2018		
Flare Class	Unfiltered	$K_p \leq 6o$	$K_p \leq 3o$
C	2384	2193	519
M	204	182	37
X	8	6	2

Finally, for the strongest event of 2003-10-28, an additional regional analysis is performed by averaging dTEC-values in rings around the subsolar point. Different angular widths of the rings were tested, and the results are presented with a width of $\Delta\chi = 10^\circ$ as a compromise between resolution and noise from averaging too few data points in the inner rings. The results are compared to the cosine-of-zenith-angle law, equation 3.17, described in section 3.3.

5.6 Impacts of Geomagnetic Storms

ICMEs and fast solar wind streams, including CIRs, occur at all times of the solar cycle with variable distribution, and exist in the form of very weak as well as strong events. There are also great differences between individual events regarding the morphology of the solar wind parameters over the duration of the events. For this reason, events must be analysed individually to identify key features and link them to the resulting TEC effects.

A selection of events must be made, because there are too many events between 2003 and 2018 to make an individual analysis feasible. For this analysis, two sets of events were selected by two approaches. The first selection was made during the OPTIMAP project. Here, solar wind data in the 18-month period between 2014-11-01 and 2016-04-30 were analysed for the passage of ICMEs, HSSs and CIRs. This identification was performed mainly by M. Venzmer and V. Bothmer. 22 ICMEs, 54 HSSs and 61 SIRs/CIRs were identified. An initial analysis showed that global TEC effects could be observed for almost all of the ICMEs, but for only one of the other events. Here, I hence use only the list of ICMEs.

Table 5.3 lists the identified ICMEs in the OPTIMAP timeseries. Two events occurred in while overlapping with a CIR. For these events, I also inspected SOHO/LASCO observations with the help of N. Mrotzek, to identify corresponding Earth-directed CMEs in the preceding days. For three events, denoted in parentheses, no CME could be identified, which is possible if the CMEs are very weak. There are three cases of multiple events occurring in close proximity: event #1 to #3; #6 and #7; and #11 to #13. In case of event #2, it was impossible to unambiguously detect effects caused it. I have kept it in the list for completeness as this list represents a full selection of all events in the time series.

The OPTIMAP-timeseries includes only a few strong events, with the strongest on 2015-Mar-17 causing a Kp-index of 8-. To expand the analysis and include more severe events, a second selection was made. This was performed automatically using threshold values for the Kp-index, global mean dTEC (after subtraction of 2-day moving-median background) and the solar wind magnetic B_z -component. These threshold values were evaluated per day, i.e. computing the maximum Kp and dTEC as well as the minimum B_z for each day and comparing with the threshold values. For the combined result, only days where all three threshold values are met were selected, allowing for occurrences of B_z and Kp on the day before dTEC. Using these criteria, only events are selected that have significant and measurable effects on TEC, with a link to strong geomagnetic activity. The threshold values were then increased until a comparable number of events to the OPTIMAP time

series was returned. Table 5.4 lists the detected days for each criterion, as well as the total number of events for the combined selection. The events themselves are listed in Table 5.5. As can be seen, the criterion on dTEC was the most selective, while the criteria for Kp and B_z produced a similar number of days. The list of events produced by this algorithm might be slightly incomplete due to data gaps in the OMNI-dataset. For example, there is a large data gap on 2003-10-29 and -30, the strongest storm in the entire time series. An ACE/MAG and SWEPAM Level2-dataset was used to cover this event instead, and I added it to the list. The type of event listed in Table 5.5 was again inferred from SOHO/LASCO observations and an inspection of the solar wind signatures.

Table 5.3: List of ICMEs identified in solar-wind data in the OPTIMAP-timeseries between 2014-11-01 to 2016-04-30. For the three events marked in parentheses, the solar wind structure was identified as a ICME, but no corresponding CME was found in SOHO/LASCO coronagraph observations.

Event #	Date	Type of Event
1	2014-12-21	ICME
2	2014-12-22	ICME
3	2014-12-23	ICME
4	2015-01-07	(ICME)
5	2015-03-17	ICME
6	2015-03-29	ICME
7	2015-03-31	ICME + CIR
8	2015-04-10	(ICME)
9	2015-05-06	ICME
10	2015-05-10	(ICME)
11	2015-06-22	ICME
12	2015-06-24	ICME
13	2015-06-27	ICME
14	2015-07-13	ICME
15	2015-08-15	ICME
16	2015-08-28	ICME + CIR
17	2015-09-08	ICME
18	2015-10-24	ICME
19	2015-11-06	ICME
20	2015-12-19	ICME
21	2015-12-30	ICME
22	2016-01-18	ICME

Table 5.4: Threshold values of K_p , dTEC and B_z for the selection of geomagnetic storm events, together with the number of days identified before and after the OPTIMAP-timeseries.

Parameter	2003-01-01 to 2014-10-31	2016-05-01 to 2018-12-31
$K_p \geq 6$	129	20
dTEC ≥ 4 TECU	39	2
$B_z < -15$ nT	122	19
Combined events	22	2

Table 5.5: Strong geomagnetic storm events identified between 2003 and 2018, excluding the OPTIMAP-timeseries between 2014-11-01 to 2016-04-30. The type of event has been identified using SOHO/LASCO observations and an inspection of solar wind data.

Event #	Date	Type of Event
23	2003-06-18	CME + CIR
24	2003-08-18	CME
25	2003-10-24	CME?
26	2003-10-29	CME
27	2003-11-04	CME
28	2003-11-20	CME
29	2004-02-11	CIR
30	2004-07-22	CME
31	2004-07-24	CME
32	2004-07-26	CME
33	2004-11-07	CME
34	2004-11-09	CME
35	2005-08-24	CIR
36	2011-08-05	CME
37	2011-09-26	CIR
38	2011-10-24	CME
39	2012-03-12	CME
40	2012-07-14	CME
41	2012-11-12	CME
42	2013-05-31	CIR
43	2013-10-02	CME
44	2014-02-19	CME
45	2017-05-27	CME
46	2017-09-07	CME

For the identified events, the solar wind $v \cdot B_z$ and global mean dTEC (with 27-day backgrounds subtracted) were inspected to characterise the following times:

1. The start time of the event in the solar wind.
2. Distinct polarity changes from positive to negative in $v \cdot B_z$ (alternatively B_z).
3. Positive and negative peaks in global mean dTEC and the onset of the corresponding rising phase.

In $v \cdot B_z$, the start time can be marked by a shock, an increase in the amplitude of fluctuations or a sudden turning towards a single polarity. The negative polarity changes are recorded at the polarity crossing before an extended period of strong mean negative polarity. In some cases, there were frequent polarity changes of different duration or strength, making it difficult to define exactly which is the “first significant”. For some events, the magnetic field showed mostly northward polarity before the first dTEC-peak, and the identified start time was used instead. In dTEC, the onset was recorded as the first significantly increasing data point prior to the peak. This was difficult to determine in some cases because there is a rise due to regular intra-day fluctuations just prior to the start of the event. If there was a sudden change in gradient approximately correlated to one of the identified solar wind features, the corresponding time was chosen as the onset of the rise. Figure 5.5 shows an example for event #40. In the solar wind, the onset is defined by a sudden onset of fluctuations on 2012-07-15, with initial mean negative $v \cdot B_z$. For this event, the start time was thus not distinguished from the first southward turning. Shortly after, dTEC shows a very weak first peak (almost a plateau). On 2012-07-16, a stronger rise phase and peak are associated with a change to smooth, negative conditions, indicated by the red dashed lines, corresponding to the passage of a magnetic cloud. No global minimum of dTEC is seen in this event.

The analysis of features in the global average dTEC showed at least one positive peak for all events in the time series. A second global peak was identified for 28 out of the 46 events, and a global minimum was identified for 13 events. Regarding the solar wind data, an event start time and first B_z -turning was identified for all events, and a second B_z -turning for 23 events, with the ambiguities of counting B_z -turnings as mentioned above.

The differences between the identified timings are analysed to find the best temporal correlations between features. Most importantly I analyse if the observed peaks correspond better to the solar wind event start times, or the first southward turning. To compare the strength of the events, the peak dTEC is evaluated with a pre-event subtraction using the identified rise-onset time.

One attempt to evaluate regional characteristics I made during the OPTIMAP project was the use of empirical orthogonal functions (EOFs), where spatio-temporal data is separated into orthogonal spatial modes and a corresponding time-factor. The original data at any point in time is reconstructed by summing each mode multiplied by the time-factor at the given time. This EOF-analysis unfortunately

Figure 5.5: Example of the identified timings in dTEC and $v \cdot B_z$. In the upper panel, the blue dashed lines mark the first rise and peak of dTEC, while the red lines mark the second rise and peak. In the middle panel, the blue dashed line indicates the start of the event, and the red dashed line indicates a strong southward turning of the IMF. The bottom panel shows the Kp-index for comparison.

did not yield conclusive results because of the spatio-temporal dynamics of the effects. The features I observed are not stationary in any of the used coordinate systems. Any visible effects were spread out over a few EOF-modes, with the remaining modes showing only noise. Furthermore, only for the strongest events of the OPTIMAP-time series could any effects be observed at all, as the weaker events showed no clear features in any mode. Another complication of the procedure was that the results depend on the length of the time series given as input, which due to the weak separation of components showed a significant impact on the result. As part of forecasting-routines created for OPTIMAP, where a few events were used as prototypes for geomagnetic storm forecasts, the EOF-technique was actually implemented as an option to filter noise, but no validation of its usefulness has so far been made. Results of the EOF analysis are thus not presented in this thesis.

Instead, I focus on a few broader regions to determine regional patterns, all evaluated in the magnetic coordinate system. I average dTEC, with 27-day background subtraction, in the latitude bands between 0° to 30° (low latitudes), 30° to 60° (mid-latitudes) and 60° to 90° (high latitudes), as well as between 10° and 20° , corresponding to the crests of the EIA. As noted by Mendillo (2006), GNSS-TEC might suffer from low satellite elevation angles and few stations in this region, but the behaviour during geomagnetic storms is an important question. To study

the effects in longitude, I evaluate dTEC in bands of 30° -width. To compare the curves for different events, I apply a pre-event subtraction using the mean dTEC in the interval between 36 and 12 hours before the first global dTEC peak. Using a longer period as an average gave a similar level for all events and did not result in artefacts from intra-day fluctuations.

5.7 Correlation with the Solar Wind

The TEC data, both in global or regional averages, show regular fluctuations on intra-day timescales. To investigate if the fluctuations can be explained by the regular fluctuations in solar wind, I correlate dTEC and $v \cdot B_z$ for periods of low geomagnetic activity. For the latter, I again apply the selection criterion of $K_p \leq 3$ as described in section 5.3, but without the use of special temporal margins.

Outside of magnetic flux tubes commonly found in ICMEs, which are characterised by a smooth rotation of the magnetic field vector, the solar wind magnetic field is characterised by frequent polarity changes. These changes typically happen at timescales of below 15 minutes, so they are much shorter than the temporal resolution of the TEC maps. The solar wind $v \cdot B_z$ must thus be processed further to extract parameters for comparison. Identifying distinct southward turnings and corresponding dTEC peaks, as described in the previous section for strong geomagnetic storms, is not possible for the same reason. Here, I compute minimum, maximum, mean and standard-deviations of both variables in a window of 1 day. Because of the subtraction of 2-day backgrounds, mean dTEC should be close to zero and show very little correlation. It is included in the results for completeness and comparison. In the solar wind, significant mean-values over these timescales can occur.

For the computation of these values, especially the standard deviation, it is important to have a significant number of data points. As the time series is very long, I further limit the selection in this regard to improve the data quality. First, only days where all K_p -values satisfy the threshold are selected, i.e. there are at least 12 or 24 dTEC-data points depending on the resolution. For the solar wind data, which has frequent short data gaps, I set the requirement that at least 50% of the data must be present, i.e. 720 data points at the resolution of 1 minute.

As there is a general dependence of all parameters on the solar cycle, it must be considered whether any observed correlation is merely a product of solar cycle trends rather than an actual physical effect. To take this into account, I compute all correlation coefficients also after normalising dTEC by dividing with 2-day median smoothed global mean VTEC to remove most of the observed variation of the amplitude of the fluctuations.

Chapter 6

Results of Ionospheric Space Weather Impact

In this chapter, I present the results of the analysis of space weather impacts on the ionosphere, following the methods and goals presented in the previous chapter. In section 6.1, I first present the correlations between solar EUV irradiance and global as well as dayside average TEC, including a separation by identified seasonal pattern. Afterwards, regional correlations are analysed and presented. Next I present the analysis of solar flare effects in section 6.2, where the impact of the strongest individual events is presented first, followed by a superposed epoch analysis of a large number of events. In section 6.3, I show the impacts of geomagnetic storms. Again, global characteristics are presented first, followed by regional patterns. Finally, the correlation between fluctuations of TEC and the solar wind during periods of low geomagnetic activity is shown in section 6.4.

6.1 Ground State Correlations with Extreme Ultraviolet Radiation

The solar EUV irradiance from SDO was correlated against global mean and dayside mean values of absolute VTEC and dTEC after subtraction of 27-day backgrounds. The EUV data was binned to the temporal resolution of the corresponding VTEC-maps, i.e. 2 hours before 2014-11-01 and 1 hour starting 2014-11-01. Table 6.1 lists the resulting correlation coefficients. Across the spectral bands, the correlation coefficients are very similar. The same is true comparing the dayside and global averages. The correlation coefficients between the absolute VTEC is higher at around $r = 0.88$ than after background subtraction at around $r = 0.7$. Because of the similarity between the different spectral bands, which was also observed for other results, I will show only the results of the 30 nm band for the remainder of this section.

Table 6.1: Correlation coefficient between the different SDO/ESP wavelength bands and TEC, averaged averaged globally and over the dayside.

Spectral Band	VTEC		dTEC	
	Global	Dayside	Global	Dayside
18 nm	0.877	0.882	0.710	0.697
26 nm	0.888	0.892	0.735	0.724
30 nm	0.861	0.866	0.736	0.724

Figure 6.1 shows the time series of global mean VTEC and the 30 nm-irradiance plotted together. Both curves were smoothed to a resolution of 2 days to improve visibility of the medium- and long-term trends. The two curves show good correspondence over timescales of the solar cycle, as well as the 27-day solar rotation. The latter is shown magnified for a portion of the time series in the zoomed inset. However, there is a periodic discrepancy between the curves on the seasonal timescale. The highest VTEC values in relation to EUV are observed around the equinoxes (i.e. during spring and autumn), while the solstices (summer and winter) show lower values. Additionally, the global mean VTEC appears lower during the northern summer months than during winter, while no systematic pattern is observed between spring and autumn. In the following, whenever the seasons are referred to by name (Spring, etc.), the corresponding months of the northern hemisphere season are implied (e.g. around March for Spring, June for Summer, etc.).

Figure 6.1: Comparison of the ESP 30 nm band and global mean VTEC over the time series. The data has been smoothed with a 2-day moving average.

I computed the mean date of the four extrema to assess how the observed seasonal changes align with the calendarian equinox and solstice dates. Each peak was estimated by eye, as it is very difficult to obtain them numerically due to the superposed variations of the 27-day cycle. The accuracy of each peak is hence assumed to be half a solar rotation, i.e. ± 13 d, consistent with the observed standard deviations of the dates ranging from ± 8 d to ± 13 d. Table 6.2 shows the mean observed dates of the four peaks together with the calendarian dates. The given errors are the result of the aforementioned numbers and averaging of 8 values in each case. All fitted dates lag behind the calendarian dates, with only spring showing relatively small difference of 9 days, compared with the estimated fitted error of 7 days. Summer and winter show a deviation of about 3 weeks, while the fitted date of the autumn peak disagrees with the calendarian date by over a month.

Table 6.2: Comparison of fitted VTEC season dates and calendarian dates. Note that the season names (Spring, etc.) refer to the northern hemisphere seasons.

Season	Fitted Date	Calendarian Date
Spring	Mar-29 ± 7 d	Mar-20
Summer	Jul-14 ± 6 d	Jun-21
Autumn	Oct-31 ± 7 d	Sep-23
Winter	Jan-18 ± 6 d	Dec-21

To analyse the relationship between EUV and TEC further, Figure 6.2 shows a scatter plot of global mean VTEC vs 30 nm-EUV, and Figure 6.3 the same after subtraction of 27-day backgrounds (note that 2-day smoothing, as in Figure 6.1, was not applied here). Both Figures include a linear as well as quadratic fit to the data, indicated in the upper left corners of the plots. With background subtraction applied, both fits are very similar, which can also be seen by the similarity of the linear and constant coefficients. For the absolute values in Figure 6.2, there is a significant difference, affecting the extrapolation of the data. The linear fit has a large negative constant coefficient, i.e. at zero EUV, it predicts (strongly) negative VTEC, which is unphysical. The quadratic fit predicts a positive value of 3.6 TECU. A small positive value would be expected due to e.g. the presence of cosmic rays, although I do not know how high the contribution is exactly.

As shown above, there is a systematic seasonal effect in VTEC. To investigate the impact of this on the linear or quadratic fitting, they were evaluated separately for each season. The linear and quadratic fits for the 30 nm spectral band and global mean TEC are listed in the following. Tables 6.3 and 6.4 list the correlation coefficients for global and dayside TEC, analogous the data in Table 6.1 presented above.

Figure 6.2: Scatter plot between the SDO/ESP 30 nm band and global mean VTEC, together with a linear and quadratic fit.

Figure 6.3: Scatter plot between the SDO/ESP 30 nm band and global mean dTEC after subtraction of 27-day background values, together with a linear and quadratic fit.

Linear Fits

$$VTEC = (38700 \pm 100)I_{30} - (11.3 \pm 0.1) \quad \text{Full Year} \quad (6.1)$$

$$VTEC = (43400 \pm 150)I_{30} - (12.3 \pm 0.1) \quad \text{Spring} \quad (6.2)$$

$$VTEC = (30000 \pm 100)I_{30} - (9.1 \pm 0.1) \quad \text{Summer} \quad (6.3)$$

$$VTEC = (43000 \pm 150)I_{30} - (12.8 \pm 0.1) \quad \text{Autumn} \quad (6.4)$$

$$VTEC = (37000 \pm 150)I_{30} - (8.8 \pm 0.1) \quad \text{Winter} \quad (6.5)$$

$$dTEC = (24000 \pm 100)dI_{30} + (0.18 \pm 0.01) \quad \text{Full Year} \quad (6.6)$$

$$dTEC = (28200 \pm 200)dI_{30} + (0.25 \pm 0.01) \quad \text{Spring} \quad (6.7)$$

$$dTEC = (19200 \pm 100)dI_{30} + (0.11 \pm 0.01) \quad \text{Summer} \quad (6.8)$$

$$dTEC = (27300 \pm 200)dI_{30} + (0.22 \pm 0.01) \quad \text{Autumn} \quad (6.9)$$

$$dTEC = (24900 \pm 250)dI_{30} + (0.12 \pm 0.01) \quad \text{Winter} \quad (6.10)$$

Quadratic Fits

$$VTEC = (25.6 \pm 0.6)10^6 I_{30}^2 + (-1300 \pm 900)I_{30} + (3.6 \pm 0.3) \quad \text{Full Year} \quad (6.11)$$

$$VTEC = (18.0 \pm 0.9)10^6 I_{30}^2 + (15000 \pm 1300)I_{30} - (2.1 \pm 0.4) \quad \text{Spring} \quad (6.12)$$

$$VTEC = (-16.2 \pm 0.6)10^6 I_{30}^2 + (56000 \pm 900)I_{30} - (19.3 \pm 0.3) \quad \text{Summer} \quad (6.13)$$

$$VTEC = (18.2 \pm 0.8)10^6 I_{30}^2 + (14000 \pm 1300)I_{30} - (2.0 \pm 0.4) \quad \text{Autumn} \quad (6.14)$$

$$VTEC = (7.0 \pm 0.7)10^6 I_{30}^2 + (26000 \pm 1100)I_{30} - (5.0 \pm 0.4) \quad \text{Winter} \quad (6.15)$$

$$dTEC = (5.9 \pm 0.8)10^6 dI_{30}^2 + (24000 \pm 100)dI_{30} + (0.16 \pm 0.01) \quad \text{Full Year} \quad (6.16)$$

$$dTEC = (9.0 \pm 2.0)10^6 dI_{30}^2 + (28100 \pm 200)dI_{30} + (0.22 \pm 0.01) \quad \text{Spring} \quad (6.17)$$

$$dTEC = (4.4 \pm 0.8)10^6 dI_{30}^2 + (19200 \pm 100)dI_{30} + (0.10 \pm 0.01) \quad \text{Summer} \quad (6.18)$$

$$dTEC = (0.9 \pm 1.8)10^6 dI_{30}^2 + (27300 \pm 200)dI_{30} + (0.20 \pm 0.01) \quad \text{Autumn} \quad (6.19)$$

$$dTEC = (-5.7 \pm 2.8)10^6 dI_{30}^2 + (24900 \pm 250)dI_{30} + (0.13 \pm 0.01) \quad \text{Winter} \quad (6.20)$$

Table 6.3: Correlation coefficients between the different SDO/ESP wavelength bands and global mean TEC.

	VTEC			
Spectral Band	Spring	Summer	Autumn	Winter
18 nm	0.920	0.956	0.956	0.946
26 nm	0.937	0.957	0.956	0.956
30 nm	0.924	0.934	0.937	0.941
	dTEC			
Spectral Band	Spring	Summer	Autumn	Winter
18 nm	0.724	0.743	0.700	0.670
26 nm	0.756	0.757	0.715	0.719
30 nm	0.757	0.758	0.723	0.703

Table 6.4: Correlation coefficients between the different SDO/ESP wavelength bands and dayside mean TEC.

	VTEC			
Spectral Band	Spring	Summer	Autumn	Winter
18 nm	0.921	0.954	0.955	0.948
26 nm	0.939	0.966	0.955	0.956
30 nm	0.926	0.933	0.937	0.942
	dTEC			
Spectral Band	Spring	Summer	Autumn	Winter
18 nm	0.707	0.730	0.692	0.653
26 nm	0.742	0.745	0.709	0.705
30 nm	0.740	0.746	0.721	0.687

Figure 6.4 shows the correlation coefficients r as a function of time shift between dEUV and dTEC, with subtraction of 27-day backgrounds. Negative values of the time shift indicate that dEUV lags dTEC, while positive values indicate that dTEC lags dEUV. The correlation coefficients were fitted with a 3rd-order polynomial to determine the peak location, which is found to be at a delay of 20 hours.

Figure 6.4: Correlation coefficients between the SDO/ESP 30 nm band and global mean VTEC. Negative values of the time shift indicate that dEUV lags dTEC, while positive values indicate that dTEC lags dEUV. The peak of the 3rd-order polynomial fit lies at a time shift of 20 hours.

Next, I present the results of the regional evaluation of correlations between EUV and TEC. Figure 6.5 shows the map of r between dTEC and dEUV for the entire time series in $5^\circ \times 5^\circ$ elements of the sun-fixed coordinate system. The corresponding plots for the four seasons can be found in Appendix A, Figures A.4 to A.7. A clear jump in r is visible across -90° longitude, i.e. across the sunrise terminator in this coordinate system. The values peak at around $r = 0.58$, near the equator and a longitude of -60° . The regional values are thus lower than the global average of $r = 0.736$, see Table 6.1. The correlation then gradually decreases with increasing longitude from the sunrise terminator. There is also an asymmetry between the northern and southern hemispheres, with slightly larger values of r in the north at night and in the south during the day.

The seasonal maps show the same jump of r across the sunrise terminator. The pattern for spring looks similar to the full-year pattern, with a slightly wider range of correlation coefficients across the map. In autumn, high correlation is found also around altitudes of $\pm 50^\circ$ in the dayside. Summer and winter show a clear asymmetric behaviour, with a band of high r values following the location of the magnetic equator in this coordinate system. Summer shows the highest correlation coefficients of the seasons.

Figure 6.6 shows the correlation coefficients r for absolute VTEC and EUV. The corresponding plots for the four seasons can be found in Appendix A, Figures A.8 to A.11. The peak values of r are closer to the global mean values in this case. The sunrise terminator is again visible, but the sunset terminator is also more pronounced. Across all seasons, there are consistently high correlation coefficients at the north pole of this coordinate system.

Figure 6.5: Regional correlation coefficients between the SDO/ESP 30 nm band and dTEC with 27-day background values subtracted. The values were computed in the sun-fixed coordinate system and in $5^\circ \times 5^\circ$ patches.

Figure 6.6: Regional correlation coefficients between the SDO/ESP 30 nm band and VTEC over the entire time series. The values were computed in the sun-fixed coordinate system and in $5^\circ \times 5^\circ$ patches.

Figure 6.7 shows the correlation coefficients r in the magnetic coordinate system for dTEC and dEUV. The corresponding plots for the four seasons can be found in Appendix A, Figures A.12 to A.15. Here, the sunrise- or sunset-terminators are not as clearly defined, because they are not stationary features over time. They are visible most prominently at low- and mid-latitudes for summer and winter, where they appear tilted. Besides this, a consistent pattern is observed at the dayside magnetic equator as a band between $\pm 10^\circ$ latitude. No features are observed at the crests of the equatorial anomaly, however, which are located around latitudes of $\pm 15^\circ$ and longitude $= 30^\circ$.

Figure 6.7: Regional correlation coefficients between the SDO/ESP 30 nm band and dTEC, with 27-day background values subtracted, over the entire time series. The values were computed in the magnetic coordinate system and in $5^\circ \times 5^\circ$ patches.

The delays associated with the regional correlation coefficients are shown in Figures 6.8, 6.9 and 6.10, corresponding to Figures 6.5, 6.6 and 6.7 above. The patterns look very different to the correlation coefficients, but it should also be kept in mind that many regions show very low correlation coefficients, so the time delay might generally be inaccurate there. No significant change is observed across the sunrise terminator, with only a slight effect seen in the full year and autumn cases. For spring and autumn, the regions of highest correlation coefficients around the equator correspond to the regions of lowest time delays. For autumn, there is a difference between the day and night-side, with delays of under 20 h observed only on the dayside. a region of low correlation on the night side corresponds to high time shifts. For spring, in contrast, there is no general difference between day and night, with high delays at high latitudes and low delays as low latitudes with some shift towards southern latitudes. For summer and winter, there are again structures along the longitudes that correspond to the patterns observed in the correlation coefficients. In summer, the entire northern high latitudes show low delays below approximately 12 h, but the same is not observed in winter for the south pole. The plots for the four seasons corresponding to Figure 6.8 can be found in Appendix A, Figures A.16 to A.19, for completeness. The seasonal plots of the other cases are not shown because of the little additional information they present.

Figure 6.8: Regional time delays of the correlation coefficients between the SDO/ESP 30 nm band and dTEC, with 27-day background values subtracted, over the entire time series. The values were computed in the sun-fixed coordinate system and in $5^\circ \times 5^\circ$ patches.

Figure 6.9: Regional time delays of the correlation coefficients between the SDO/ESP 30 nm band and VTEC over the entire time series. The values were computed in the sun-fixed coordinate system and in $5^\circ \times 5^\circ$ patches.

Figure 6.10: Regional correlation coefficients between the SDO/ESP 30 nm band and dTEC, with 27-day background values subtracted, over the entire time series. The values were computed in the magnetic coordinate system and in $5^\circ \times 5^\circ$ patches.

6.2 Impacts of Solar Flares

Figures 6.11 and 6.12 show plots of dTEC (top panels) and GOES SXR irradiance (bottom panels) for the two strongest flares of the time series on 2003-10-28 and 2003-11-04. The curves in the top panels show global mean, dayside mean, as well as the subsolar mean values of dTEC. The latter in this case includes all values up to 45° solar zenith angle. In both cases, a dTEC-peak immediately after the peak flare time is seen, although judging by eye it appears to last only a single data point. Determining the exact peak dTEC remains difficult even after subtraction of 2-day backgrounds, because the signal is embedded into similar intra-day fluctuations. This is particularly true for the subsolar average, because fewer values are averaged and regional fluctuations have a stronger impact.

Figure 6.11: Top: Average dTEC values globally, over the dayside and in a 45° region around the subsolar point during the flare of 2003-10-28. 2-day moving median backgrounds were subtracted from each curve. Bottom: GOES SXR-irradiance. The peak time of the flare is indicated by the dashed line.

Table 6.5 lists the estimates of the peak dTEC for the two events, comparing the values taken directly from Figures 6.11 and 6.12, i.e. as resulting from subtraction of 2-day backgrounds, as well as the values after pre-/post-event subtraction described in section 5.5. The bigger difference between the processing methods for 2003-11-04 flare can be explained by preceding geomagnetic activity. During a period of 24 h before the peak of the flare, the Kp-Index reached a value of $K_p = 7$. In comparison, before the 2003-10-28 flare it did not exceed $K_p = 5$. The results for the subsolar dTEC are below the dayside averages in all cases, which is not expected from equation 3.17 and indicates a strong error due to regional fluctuations in the TEC-maps.

Figure 6.12: Top: Average dTEC values globally, over the dayside and in a 45° region around the subsolar point during the flare of 2003-11-04. 2-day moving median backgrounds were subtracted from each curve. Bottom: GOES SXR-irradiance. The peak time of the flare is indicated by the dashed line.

Table 6.5: Peak dTEC values for the events of 2003-10-28 and -11-04 in three different regions and using 2-day median as well as pre-/post-event background subtraction.

Region	2003-10-28		2003-11-04	
	2-d median	pre-/post-event	2-d median	pre-/post-event
Global	4.7 TECU	3.8 TECU	0.7 TECU	1.9 TECU
Dayside	9.7 TECU	8.4 TECU	0.9 TECU	3.0 TECU
Subsolar	8.5 TECU	7.7 TECU	-2.0 TECU	0.7 TECU

Of the remaining events listed in Table 5.1, only the events of 2005-01-20, 2017-09-06 and 2017-09-10 showed a small peak coinciding with the flare time, but the dTEC values are even lower. For the other cases, no enhancement could be detected in both global and regional dTEC-averages.

Despite the uncertainties of the Nov-04 event it is clear that the event of Oct-28 caused a larger dTEC, which is in agreement with the findings of Tsurutani et al. (2006). Because the peak X-Ray flux was additionally an estimated factor of 2 lower for the Oct-28 event (Table 5.1), it can be considered as an example of a worst-case scenario. The result can thus be used to formulate a scaling law between mean dayside dTEC and SXR-irradiance, where I assume an error of 2 TECU to account for the variations between the different background subtraction methods:

$$dTEC_{\text{dayside, worst}}(X_{1-8\text{\AA}}) = \frac{(8.4 \pm 2) \text{ TECU}}{1.7 \cdot 10^{-3} \text{ W m}^{-2}} \cdot X_{1-8\text{\AA}} \quad (6.21)$$

$$= (5000 \pm 1200) \text{ TECU m}^2 \text{ W}^{-1} \cdot X_{1-8\text{\AA}} \quad (6.22)$$

Figures 6.13, 6.14 and 6.15 show three superposed epoch results for C-, M- and X-class flares in the period 2003-2014 and with filtering for $K_p \leq 6$ as described in section 5.5. All cases show a peak at the flare-time, although it is not larger than other variations in the ± 2 d covered by the plots. For the C-flares, there are two strong features around ± 24 h. However, all 7821 flares contributing to this superposed epoch are distributed evenly across time of day, so it is likely not a signature of periodic ionospheric processes. The superposed epoch of the events after 2014-11-01 do not show any peaks, despite the improved temporal resolution of 1 h.

Figure 6.13: Superposed epoch analysis for 7838 C-class flares between 2003-01-15 and 2014-10-05, showing the global average, average over the dayside and average in a 45° radius around the subsolar point. 2-day moving median backgrounds were subtracted from each curve.

Figure 6.14: Superposed epoch analysis for 752 M-class flares between 2003-01-15 and 2014-10-05, showing the global average, average over the dayside and average in a 45° radius around the subsolar point. 2-day moving median backgrounds were subtracted from each curve.

Figure 6.15: Superposed epoch analysis for 73 X-class flares between 2003-01-15 and 2014-10-05, showing the global average, average over the dayside and average in a 45° radius around the subsolar point. 2-day moving median backgrounds were subtracted from each curve.

Table 6.6 lists the computed pre-/post-event subtracted $dTEC$ -values, together with the mean flare intensity of each class. As can be seen, the SXR irradiance follows the same statistical distribution in each group so that they differ almost exactly by a factor of 10 between the classes. As the number of events in this period is large, this is the case for both Kp-filtered sets. The $dTEC$ -values, on the other hand, show a large variation with different Kp-filtering. Together with the fluctuations outside the superposed flare times, this suggests that the values have not statistically converged for this number of events. For $Kp \leq 30$, C- and M-flares show the same dayside averaged $dTEC$, while for $Kp \leq 60$ it is a factor of 2 larger for M-flares. The difference between M- and X-flares is a factor of 14 for $Kp \leq 30$ and a factor of 5.6 for $Kp \leq 60$, more consistent with the mean X-Ray irradiance. The values can also be compared to Equation 6.22, which for the X-class flares would predict a dayside $dTEC$ of

$$dTEC_{\text{dayside}} = 5000 \text{ TECU m}^2 \text{ W}^{-1} \cdot 2.78 \cdot 10^{-4} \text{ W m}^{-2} = 1.39 \text{ TECU} \quad (6.23)$$

which is a factor of 8 greater than the superposed result. In comparison with Figure 6.15, this value could have been clearly distinguished from the fluctuations outside the peak flare time. As the peak for the X-flares in Figure 6.15 shows the expected behaviour of stronger $dTEC$ going from global average to dayside average to subsolar average, an estimated scaling relation for a mean flare can be computed, similar to the worst-case scaling derived above:

$$dTEC_{\text{dayside,mean}}(X_{1-8\text{\AA}}) = \frac{(0.34 \pm 0.17) \text{ TECU}}{2.78 \cdot 10^{-4} \text{ W m}^{-2}} \cdot X_{1-8\text{\AA}} \quad (6.24)$$

$$= (1200 \pm 600) \text{ TECU m}^2 \text{ W}^{-1} \cdot X_{1-8\text{\AA}} \quad (6.25)$$

Table 6.6: Peak dayside $dTEC$ values for the superposed epoch analysis of flares between 2003 and 2014, compared with the mean irradiance $\bar{X}_{1-8\text{\AA}}$ of the corresponding flares. The $dTEC$ -values are computed with pre-/post-event background subtraction.

	Kp ≤ 30		Kp ≤ 60	
Flare Class	$dTEC_{\text{dayside}}$	$\bar{X}_{1-8\text{\AA}}$	$dTEC_{\text{dayside}}$	$\bar{X}_{1-8\text{\AA}}$
C	0.025 TECU	$2.67 \cdot 10^{-6} \text{ W m}^{-2}$	0.016 TECU	$2.68 \cdot 10^{-6} \text{ W m}^{-2}$
M	0.024 TECU	$2.44 \cdot 10^{-5} \text{ W m}^{-2}$	0.031 TECU	$2.51 \cdot 10^{-5} \text{ W m}^{-2}$
X	0.34 TECU	$2.32 \cdot 10^{-4} \text{ W m}^{-2}$	0.173 TECU	$2.78 \cdot 10^{-4} \text{ W m}^{-2}$

Figure 6.16 shows the result of the regional analysis of the 2003-10-28 event, together with a cosine-fit analogous to equation 3.17, as well as a linear fit. These fits were evaluated only on the data between $\chi = 60^\circ$ and $\chi = 110^\circ$, where a consistent trend as expected is visible. At lower zenith angles, the profile flattens out, which is in disagreement with the results from Zhang and Xiao (2005) and Qian et al. (2012). There is good agreement with Zhang and Xiao (2005) in the result that the $dTEC = 0$ TECU level is reached at 105° , but the dTEC levels observed in the TEC-maps are lower, peaking at about 10 TECU compared to 17.6 TECU, or even the 25 TECU found by Tsurutani et al. (2006) and Sahai et al. (2008). The extrapolation of the cosine fit would yield a similar subsolar dTEC of 19 TECU, but it can be seen that over the range of fitting it deviates only slightly from a linear trend, making the result found here inaccurate.

Figure 6.16: dTEC values caused by the flare on 2003-10-28 as a function of solar zenith angle, evaluated in bins of 10° . A linear and cosine fit to the values between 15° and 105° are overplotted.

6.3 Impacts of Coronal Mass Ejections

Figures 6.17, 6.18 and 6.19 show the mean global dTEC after subtraction of 27-day backgrounds (top panels) during the geomagnetic storms of 2003-10-29, 2015-03-17 and 2017-09-08, compared with the solar wind B_z - or $v \cdot B_z$ -values (middle panels) and the Kp-index (bottom panels). The OMNI data unfortunately showed a large data gap during the 2003-10-29 event. The ACE Level-2 data also has a data gap in the proton velocity, but B_z data is available, so it is shown in Figure 6.17. On the global scale, the three storms show very different behaviour. The 2003-event shows a dTEC-peak shortly after onset time of the strongest Kp-values, but it is not large compared to previous fluctuations. About 18 h after the arrival of the ICME, there is a sudden drop by about 10 TECU, which appears to recover and repeat over the following day. The 2015-event shows two very clear enhancements by about 5 TECU compared to the pre-event levels after the arrival of the ICME, and also a strong drop 18 h after the onset. The 2017-event only shows a single, initial enhancement by about 4 TECU and no minimum. One important difference between the 2015 and 2017 events is the morphology of $v \cdot B_z$. For the 2015-event, it alternates between positive, negative and positive in the sheath-phase, and then turns negative for a longer period of the ICME passage. For the 2017 event, there is an initial strong negative excursion, which slowly turns positive, followed by another, slightly weaker negative phase plus recovery. In each case, a peak follows after the southward-turning of the IMF.

Figure 6.17: Global average dTEC for the geomagnetic storm of 2003-10-28 (top), together with the ACE B_z (middle) and Kp-index (bottom). The dashed lines show identified timings of dTEC and the solar wind.

Figure 6.18: Global average dTEC for the geomagnetic storm of 2015-03-17 (top), together with the OMNI $v \cdot B_z$ (middle) and Kp-index (bottom). The dashed lines show identified timings of dTEC and the solar wind.

Figure 6.19: Global average dTEC for the geomagnetic storm of 2017-09-08 (top), together with the OMNI $v \cdot B_z$ (middle) and Kp-index (bottom). The dashed lines show identified timings of dTEC and the solar wind.

An overview of the dTEC values measured for the first peak of all events is shown in Figure 6.20. The values were computed by taking the difference between the dTEC values at the time of the peak and at the time of the onset of the rise phase. The vertical blue line indicates the separation between the events of the OPTIMAP time series (Table 5.3) and the additional events from outside this period (Table 5.5). The events of the OPTIMAP timeseries show peak values below 4 TECU (with the exception of event #4 at ≈ 4.5 TECU), while more than half of the additional events are above 4 TECU and only two values below 2 TECU.

Figure 6.20: Observed dTEC for the geomagnetic storm events, computed as the difference between the values at the event peak and rise times.

The identified times of TEC and solar wind features, as described in section 5.6, were compared to identify patterns. Figure 6.21 shows a plot of the time difference between the first peak of global mean dTEC (vtpeak1) and the first southward-turning of the IMF (swbz1). For the data points marked as “ambiguous”, the event either started with a strong southward-turning so that the two times are identical, or there was no distinct southward turning before the first dTEC-peak, and the event start-time was used instead. Of all parameter combinations, Figure 6.21 showed the best correlation. The mean and standard deviation indicated in the top left corner of the plots were computed without the ambiguous points.

A few potential outliers with over 10 h time difference can be seen, namely events #9, 24 and 31. In case of event #9, there is data gap in the OMNI-data shortly after the event start, so the B_z -time may have a large error. In case of event #24, the large time can be explained with the $v \cdot B_z$ -profile. The corresponding plot can be found in Appendix A, Figure A.2. The event begins with a shock towards positive $v \cdot B_z$, which then gradually turns negative, with the whole event extending over roughly two days. The global mean dTEC is also unique for this event in that it does not rise continuously up to the peak, but shows two fluctuations during

the rising phase. In case of event #31, shown in Figure A.3 of the appendix the beginning of the dTEC rise closely follows the identified B_z turning, which is followed by a long, smooth period of negative B_z . there is also a slight dent in the dTEC-profile during the rise phase similar to event #24.

An outlier in the negative direction is event #28, see Figure A.1 in Appendix A. Here, the start of the rising phase is closely related to the solar wind event start. $v \cdot B_z$ is fluctuating between this time and the identified first B_z -turning, but with a negative mean, so that for this event, the solar wind start time might be the better indicator as the first B_z -turning time. In turn, the identified $v \cdot B_z$ -turning, corresponds better to the second peak, which is not clearly distinct from the first peak for this event.

The mean time difference is slightly higher for the events of the OPTIMAP time series compared to the additional events, excluding the aforementioned outliers, with mean and standard-deviations of (5.2 ± 1.3) hours and (4.0 ± 1.3) hours. It is not clear whether this effect is real. While on one hand there is a systematic difference, as they were selected using different criteria, it must on the other hand be remembered that all events of the OPTIMAP timeseries have a TEC-resolution of 1 h, while the additional events mostly have a resolution of 2 h, and the difference of the mean values is only around 1 h.

Figure 6.21: Time differences between the identified first dTEC-peak ($vtpeak1$) and the first B_z southward-turning ($swbz1$). For the events marked as ambiguous, the identified B_z -time is identical to the identified solar wind start time. The mean and standard deviation were computed without the outliers with $\Delta t > 10$ h.

To compare with Figure 6.21, Figure 6.22 shows the time difference between the first peak and the beginning of the solar wind event, i.e. regardless of strong negative B_z . It shows a much larger fluctuation of the time differences, confirming that negative B_z is the better indicator for dTEC.

Another comparison of the identified times is shown in Figure 6.23, where the times of the second (vtpeak2) and first (vtpeak1) global dTEC-peak are compared. There are again a few outliers with very large time difference for both time series, which were excluded from the computation of the mean and standard deviation. There is no obvious difference here in the mean values of the two selections, but it can be seen by the large number of missing data points that fewer of the additional events showed a second global peak.

Figure 6.24 shows a plot of the time difference between the minima of global mean dTEC (vtmin1) and the first peak of global mean dTEC (vtpeak1). Here the numbers are scattered over a wide range between 10 hours and 55 hours. Only 13 events showed a global minimum, 9 of which were found in the OPTIMAP time series.

Figure 6.22: Time differences between the identified first dTEC-peak (vtpeak1) and the start of the event in the solar wind (swstart).

Figure 6.23: Time differences between the identified second (vtpeak2) and first (vtpeak1) global dTEC-peaks. The mean and standard deviation were computed without the outliers with $\Delta t > 15$ h.

Figure 6.24: Time differences between the identified dTEC minimum (vtmin1) and the first dTEC peak (vtpeak1).

The analysis of regional TEC behaviour during geomagnetic storms again shows the clearest differences between summer and winter seasons. Figure 6.25 and 6.26 show the mean dTEC in the northern (top) and southern (bottom) high latitudes (above $\pm 60^\circ$; additional Figures for spring and autumn can be found in Appendix A, Figures A.20 and A.21). All curves have been offset along the y-axis to a pre-event dTEC, computed as the mean dTEC in the interval between 36 and 12 hours before the global dTEC peak, and aligned along the x-axis to the time of the first global dTEC peak.

The biggest positive peaks at the time of the global peak is observed in the southern hemisphere in summer and in the northern hemisphere in winter, with no significant negative effects after the storms. In the opposite hemisphere, there are no positive peaks (with the exception of one event that already showed strong fluctuations before the start). Strong and long-lasting negative values can be seen for some but not all events, consistent with the observation described above that not all events show global minima.

In the spring and autumn seasons, both types of behaviour are observed in both hemispheres, but there are no additional features that are not observed for summer or winter.

Figure 6.25: Average dTEC values in the northern (top) and southern (bottom) high latitudes between $\pm 60^\circ$ and $\pm 90^\circ$ of the magnetic coordinate system for 13 geomagnetic storms in the summer season. All curves are offset by the mean value in the interval from -36 to -12 hours.

Figures 6.27 and 6.28 (as well as Figures A.22 and A.23 in the appendix), show the analogous plots for the midlatitudes between $\pm 30^\circ$ and $\pm 60^\circ$. The qualitative behaviour is identical to the high latitudes, and the same picture continues down to low latitudes, even when the band of the equatorial anomaly between $\pm 10^\circ$ and $\pm 20^\circ$ is considered (Figures not shown).

Figure 6.26: Average dTEC values in the northern (top) and southern (bottom) high latitudes between $\pm 60^\circ$ and $\pm 90^\circ$ of the magnetic coordinate system for 11 geomagnetic storms in the winter season. All curves are offset by the mean value in the interval from -36 to -12 hours.

Figure 6.27: Average dTEC values in the northern (top) and southern (bottom) high latitudes between $\pm 30^\circ$ and $\pm 60^\circ$ of the magnetic coordinate system for 13 geomagnetic storms in the summer season. All curves are offset by the mean value in the interval from -36 to -12 hours.

To study the longitudinal behaviour, Figures 6.29, 6.31 and 6.30 show the dTEC for the three strongest storm of the OPTIMAP-events along the north and south EIA between $\pm 10^\circ$ and $\pm 20^\circ$ magnetic latitude in longitudinal bins of 30° .

Figure 6.28: Average dTEC values in the northern (top) and southern (bottom) high latitudes between $\pm 30^\circ$ and $\pm 60^\circ$ of the magnetic coordinate system for 11 geomagnetic storms in the winter season. All curves are offset by the mean value in the interval from -36 to -12 hours.

In the 2015-03-17 event, the behaviour is nearly symmetric between the hemispheres, in line with the description above, since it lies in the spring season. The first positive dTEC peak is not very pronounced around the EIA. The second peak is stronger, and superseded by a third peak that precedes the negative storm phase but only appears at longitudes greater than 30° . The first and second positive peak appear roughly at equal times at all longitudes. The third peak and subsequent negative phase, however, show a pattern of both peak time and strength. The negative phase peaks later with increasing longitude, and is strongest between 30° and 90° .

The 2015-12-19 event shows only two positive peaks, where the first also corresponds to the first global peak. In both hemispheres, this event also shows a time-dependence of the first peak. The negative phase appears only in the south EIA, in accordance with the global scheme described above.

The 2015-06-22 event appears bit weaker overall, but again follows the same patterns, with the negative phase only appearing in the north. For positive longitudes, there appears to be a weak third positive peak, and there is again no time-dependence of the first peak in the south and only a slight dependence in the north. The negative peak

Figure 6.29: Average dTEC values for the 2015-03-17 geomagnetic storm in the northern (top) and southern (bottom) EIA-latitudes between $\pm 10^\circ$ and $\pm 20^\circ$ of the magnetic coordinate system for different longitudes from $\pm 30^\circ$ to $\pm 180^\circ$. All curves are offset by the mean value in the interval from -36 to -12 hours.

Figure 6.30: Average dTEC values for the 2015-12-19 geomagnetic storm in the northern (top) and southern (bottom) EIA-latitudes between $\pm 10^\circ$ and $\pm 20^\circ$ of the magnetic coordinate system for different longitudes from $\pm 30^\circ$ to $\pm 180^\circ$. All curves are offset by the mean value in the interval from -36 to -12 hours.

Figure 6.31: Average dTEC values for the 2015-06-22 geomagnetic storm in the northern (top) and southern (bottom) EIA-latitudes between $\pm 10^\circ$ and $\pm 20^\circ$ of the magnetic coordinate system for different longitudes from $\pm 30^\circ$ to $\pm 180^\circ$. All curves are offset by the mean value in the interval from -36 to -12 hours.

6.4 Correlations with the Solar Wind During Quiet Conditions

In this section, I present the results of the correlation between fluctuations of TEC and the solar wind during periods of low geomagnetic activity. Table 6.7 lists the correlation coefficients between different parametrisations of solar wind $v \cdot B_z$ and global mean dTEC for days with $K_p \leq 30$, as described in section 5.7. The correlation coefficients in the top half are computed with 2-day moving median backgrounds subtracted from dTEC, while the coefficients in the bottom half are computed after all dTEC-values were additionally normalized with 2-day smoothed global mean VTEC to investigate if the solar-cycle variation of TEC are masking any correlation.

The results show that there is generally very low correlation between $v \cdot B_z$ and global mean dTEC during low geomagnetic activity. The highest value lies around $r = 0.2$, and is found between the standard deviation or minimum of $v \cdot B_z$ and the maximum and mean of dTEC. The mean dTEC, as noted in section 5.7, was not expected to show any correlation because of the 2-day background subtraction. Normalisation of the dTEC-fluctuations made them more even across the time series, but it did not improve any of the observed correlations.

Table 6.7: Correlation coefficients between daily solar wind $v \cdot B_z$ and dTEC-parametrisations for days with $K_p \leq 30$.

2-day median subtraction				
$v \cdot B_z \backslash$ dTEC	std-dev	min	max	mean
std-dev	0.135	-0.018	0.236	0.199
min	-0.120	-0.003	-0.224	-0.214
max	0.103	-0.021	0.173	0.121
mean	0.008	-0.047	-0.017	-0.080
normalized				
$v \cdot B_z \backslash$ dTEC	std-dev	min	max	mean
std-dev	0.022	0.092	0.160	0.212
min	-0.015	-0.107	-0.156	-0.227
max	-0.001	0.073	0.095	0.133
mean	-0.061	0.009	-0.077	-0.076

Chapter 7

Discussion of Ionospheric Space Weather Impacts

In this chapter, I discuss the results of the analysis of ionospheric impacts of space weather phenomena. Following the order of the previous chapters, begin with the results of the EUV correlations in section 7.1, followed by the solar flare impacts in section 7.2 and finally the impacts of geomagnetic storms and the solar wind in section 7.3. The findings are also discussed in the context of their application in forecasting of the global ionosphere.

7.1 Correlations with EUV Radiation

To analyse the relationship between EUV and TEC, a correlation between global mean TEC and EUV was made, using the full temporal resolution of the GIMs. The correlations were made both across the full time series between 2010-05-01 and 2018-12-31, for which EUV-data from SDO was available, and additionally separated into the four seasons. The time series covers both the last solar maximum, as well as the current minimum, meaning that the full dynamic range of the solar EUV output is covered - where it should be noted that the last cycle was weaker than previous cycles.

All data is fitted well by a linear relationship. For the dTEC values after subtraction of 27-day median background values, quadratic fits showed almost exactly the same linear and constant coefficients. For the absolute VTEC data, the quadratic fit shows a significant quadratic term, although by eye it seems to affect mainly the extrapolated values. The same was observed not only for the data over the full time series, but also for each season. With the exception of the data over the full time series, all fits of the absolute VTEC predict a negative VTEC when EUV goes to zero, which would be unphysical. While the errors of up to 20% for EUV (Didkovsky et al., 2012) and 10% for VTEC (Roma-Dollase et al., 2018) might be quite large, these values would be for a relative error and not explain any offset for either data set.

The correlation coefficient between global mean VTEC and EUV is very high at around $r = 0.87$ for all three EUV-bands considered in this work. For dTEC and dEUV, it is slightly lower between $r = 0.70$ to $r = 0.75$. In comparison, Jacobi et al. (2016), found a correlation of $r = 0.86$ between daily global mean dTEC, with 3-month high pass filtering as background subtraction, and integrated EUV-fluxes between 6 nm and 106 nm, for the period between 2011-03 and 2014-02. This suggests that narrow-band EUV measurements can be used as input for ionospheric models when spectra are not available without a general loss of accuracy.

Using the dayside-average instead of the global average, I did not observe significantly different correlation coefficients. This might be because the dayside contributes most of the integrated TEC and thus dominates the correlation coefficient. However, evaluating the correlations at a finer regional scale yielded a better picture. In the sun-fixed coordinate system (Figure 6.5), the day-night boundary at a longitude of -90° is clearly pronounced by the highest correlation coefficients, which gradually decrease with increasing longitude. This behaviour is explained by the fact that here the ionosphere has mostly depleted over the nightside due to recombination, and now the EUV radiation emerging over the horizon produces new ionisation.

In the sunfixed-magnetic coordinate system (Figure 6.7), the day-night boundary is not visible in the same way because the day-night terminator is not located at constant coordinates. Instead, high correlation immediately around the magnetic equator is observed. This could be explained by the fountain effect, by which ions are transported away from the equator towards higher latitudes. It is thus a similar effect to the sunrise terminator in that older electrons are removed and the measured electrons have only recently been ionised.

The delayed response of VTEC to EUV was found to be 20 hours for the global mean (Figure 6.4), and is thus slightly lower than the 1-2 days reported by Jacobi et al. (2016). The regional map of delays shows large differences, with negative delays as well as delays around 6 days, and the picture is not consistent between the individual seasons. Likewise, there is only a weak pattern visible at the sunrise terminator and no effect at the magnetic equator.

These results demonstrate that EUV irradiance measurements can be used in ionospheric forecasting to improve the predicted ground state. Currently, this is limited by the availability of dedicated EUV-forecasts. For example, the 27-day forecast provided by the NOAA Space Weather Prediction Center¹ only gives a forecast of the F10.7 index, which correlates much less with TEC. The delayed response can be used to further improve forecasts, but the difference would be relatively small. It is thus necessary to develop new forecasting products for EUV. A future space weather mission at the L5-Lagrange point can provide valuable input for this, as it is located ahead of the solar rotation and observes the face of the Sun that will be seen by the Earth in 4.5 days.

¹<https://www.swpc.noaa.gov/products/27-day-outlook-107-cm-radio-flux-and-geomagnetic-indices>, 27.04.2020

7.2 Impacts of Solar Flares

The effects of flares, even of very strong events, were only weakly visible in the GIMs. A clear enhancement of global, dayside or even more regional values was only seen for the two strongest flares of 2003-10-28 and 2003-11-04, with respective GOES-classes of X17 and an estimated X28. For the 2003-10-28 event, a mean dayside dTEC = 8.4 TECU was found, and a worst-case scaling law was formulated based this value (equation 6.22).

The regional peak dTEC of the 2003-10-28 event was found to be only slightly higher than the dayside average, at approximately dTEC = 10 TECU (Figure 6.16), showing a flat profile near the zenith. This is much lower than the values of 25 TECU reported by Tsurutani et al. (2006) and Sahai et al. (2008) for stations in Africa and Brazil, and also lower than the peak of 17.6 TECU observed by Zhang and Xiao (2005). While these studies also relied on GNSS-derived TEC, they used single-station data at high temporal resolution. According to Tsurutani et al. (2006), dTEC decays to pre-event levels in about 3 hours. It could therefore be expected that higher resolution VTEC-maps would show larger dTEC, although the time of this flare (11:00 UT) does not suggest a worst-case timing with respect to the temporal bins of the maps, making a difference by more than a factor of 2 seem unreasonable to explain with only this aspect. In future works, the analysis could be updated with GIM products such as the DGFI-TUM solution (Goss et al., 2019) as part of OPTIMAP, when it becomes operationally available. Furthermore in 2003, the number of GNSS-stations used to compute the TEC maps was lowest of the time series (Figure 4.4), and only few stations in Africa and South America, the regions closest to the subsolar point for this flare, were included. Most stations for these events were located beyond $\chi = 50^\circ$. A gradient in the regional dTEC values was only observed here beyond $\chi = 70^\circ$. A linear as well as cosine extrapolation from this region yields values compatible with the aforementioned studies.

The superposed-epoch analysis of 7838 C-, 752 M- and 73 X-flares between 2003 and 2014 could not reveal a trend between the individual classes as the impacts of weaker flares are too small in VTEC. A difference is observed between M- and X-flares, and the result of the X-flares was used to formulate a scaling relation for mean flare (equation 6.25). Comparison between the two derived scaling relations shows that there is a wide range of impact strengths even for flares of similar GOES-class. VTEC data, as used here, does not resolve the electron density as a function of height, so that it can not be quantified what the impacts on the different layers of the ionosphere are.

For space weather forecasting applications, these results provide relations that can be used to include solar flare forecasts. Like with EUV irradiance, the current situation of forecast products must be considered. Exact predictions of the time or the strength of a flare are not possible, because the complex physical processes in the lower solar corona are not yet fully understood (Nishizuka et al., 2017). Existing forecasting services, e.g. an automated machine-learning approach developed within the EU Horizon2020-project *Flare Likelihood And Region Eruption fore-*

CASTing (FLARECAST²), predict the likelihood of flares of a given GOES-class within a certain period of time (Murray et al., 2017). In combination with the scaling laws presented here, this can be translated to warn users of critical systems about potential ionospheric disturbances.

7.3 Impacts of Geomagnetic Storms and the Solar Wind

The study of geomagnetic storms was performed with two sets of events selected using different criteria. First, the OPTIMAP-events were compiled by manual inspection of solar wind data at L1 for signatures of ICMEs, and are thus composed of events of very different strength. Second, a list of “additional events” between 2003 and 2018, but outside the OPTIMAP-period, was compiled by applying criteria to the solar wind Bz , global mean dTEC and the Kp-index. This list only features events that had strong geomagnetic impact at Earth. For each event, key times were identified by manual inspection in global mean dTEC and solar wind data to determine arrival times, strong southward turnings of the IMF, as well as peaks and minima in dTEC. At least one positive global peak could be identified for all events, with the exception of event #2 from the OPTIMAP series as it occurred closely after another strong event and could not be separated from its effects.

For each event, global mean dTEC of the first peak was computed by taking the difference between the peak dTEC and the value at the beginning of the associated rising phase (Figure 6.20). The additional events showed typically higher dTEC than the events of the OPTIMAP time series, consistent with the different selection criteria. Two of the additional events (#30 and #40) showed very low dTEC below 2 TECU, which appears inconsistent with the selection criteria of the events, showing that a simple subtraction of moving-mean backgrounds (in this case with a window of 2 days) is not ideal to quantify the effects of geomagnetic storms.

The time difference between the first dTEC peak and the first strong southward turning of the IMF also shows a good correlation with a mean of 4.6 hours (Figure 6.21). There appears to be a systematic difference between the two event selections of about an hour, which is equivalent to the different temporal resolutions of the maps. A good correlation was also found for those events showing a second peak, with a difference of 8.2 ± 2.4 hours. The strong outliers could be a result of misidentification, as there can be a third positive peak phase. Only 13 of the events showed a strong global minimum. For these events, their delay from the first global peak is widely scattered between just over 10 hours to over 30 hours, and one outlier with over 50 hours.

The analysis of seasonal and regional dTEC revealed a systematic hemispherical pattern of the positive and negative phases. In the summer season, the negative phase appears to be constrained entirely to the northern hemisphere at all latitudes. In winter, the behaviour is opposite, while both hemispheres are affected

²<http://flarecast.eu/>, 27.04.2020

in spring and autumn seasons. The negative phase is most strongly pronounced at high latitudes above $\pm 60^\circ$, especially in a relative sense because VTEC is generally lowest here. Additionally in this region, the positive phase appears to be short without long-term effects, while the negative phase lasts for several days. Generally, the negative phases, if they are present, are stronger than the positive phases. In the analysis of longitudinal behaviour, three positive peaks can be seen for the studied events. The relative strength of the individual events varies, with the second and third peak being almost indistinguishable on 205-12-19. For 2015-06-22, the second peak shows the strongest regional dTEC, while for 2015-03-17 it is shown by the third peak. The negative storm phase is found to be localised around the evening sector, while the morning sector shows little or only delayed effects.

The correlation between different parametrisations of solar wind $v \cdot B_z$ and dTEC did not show any significant correlations beyond $r = 2$ (Table 6.7). While quiet times are arguably not of greatest interest for space weather forecasting, a relationship could have been used to compare with the results of the study of strong events presented above and provide an extrapolation for medium and weak events. It is most likely that the observed fluctuations are artefacts of the VTEC maps and do not represent space weather activity.

The picture of regional TEC behaviour during geomagnetic storms remains complicated due to the variety of storm morphologies observed. Multiple parameters are observed to have, or can not be excluded to have, an influence on the observed dTEC:

1. The structure, polarity and strength of the solar wind arriving at Earth.
2. Geomagnetic activity preceding the event.
3. The phase of the solar cycle, i.e. the ionospheric ground state.
4. The season.
5. The time of day of the beginning of the event.

Items 1 and 2 on this list are directly related to space weather forecasting capabilities. Some of the structure of ICME parameters can be predicted from the geometric properties of the impact at Earth, i.e. if the Earth crosses the apex of the CME's flux tube, one of its limbs or receives a glancing blow, as well as predicting if there will be a shock and associated sheath phase (Liu et al., 2010). The polarity or strength of the magnetic field are difficult to predict, as they are not directly observable with white light coronagraphs. MHD-based simulations such as WSA-ENLIL already attempt to provide a prediction for such values (Parsons et al., 2011). The possibility of using radio-observations to infer the CME magnetic field strength from gyrosynchrotron emission is also being investigated (Carley et al., 2017). The same input is required to predict the preceding activity at the time of a predicted ICME-arrival. In the context of transitioning research into operational capabilities, items 3 and 4 are the easiest to consider as both are known at any time, but the forecast model must consider seasonal differences. In a scientific analysis as presented here, it adds further variability, so that a larger

dataset has to be considered. While item 5 may seem least important regarding the analyses presented in this thesis, as the ionosphere has been “stabilised” by the use of appropriate coordinate systems, it is certainly important for practical applications. Most providers of services affected by ionospheric activity will issue warnings for specific regions on Earth. Here the accuracy will be determined by the arrival time accuracy of CMEs, as longitudinal patterns for geomagnetic storms were found.

For the OPTIMAP project, where the analysis was based mainly on the events between 2014-11-01 and 2016-04-30, I implemented an approach of using prototypic events. The geomagnetic storms of 2015-03-17, 2015-06-22 and 201-12-19 were selected as prototypes for the spring/autumn, summer and winter seasons respectively. The observed minimum solar wind $v \cdot B_z$ for each event was additionally recorded as a reference values. A forecast in this approach requires an arrival time prediction, as well as an estimate for the magnetic field strength and polarity. Generally speaking, it is important to not only perform case studies, but to develop and implement forecasting services and validate the models, as well as their applicability, in daily operations. In such future developments of forecasting services, the described approach can then be refined by including a wider range of prototypic events based on the influencing factors listed above.

Chapter 8

Design of the SCOPE Coronagraph

SCOPE belongs to the class of externally occulted coronagraphs, but follows an improved design, often labelled the *compact coronagraph*, which is currently also under development by other groups around the world (e.g. Cho et al. (2017)). The classical design presented in section 2.3.2 is fairly long due to the combination of multiple lens groups paired with baffles placed in various intermediate image planes. With the compact coronagraph, the aim is to improve the performance of the external occulter and entrance aperture to a degree that further stray light rejection mechanisms like the internal occulter and Lyot-stop are no longer required and a compact lens system without intermediate focal planes can be used.

In this chapter, the most important (optical) design requirements of SCOPE, and the specifications derived from them, are presented, followed by a detailed description of the *optics breadboard* (OBB) prototype.

8.1 Requirements and Specifications

A key difference between SCOPE and existing coronagraphs is reflected in its name: SCOPE is designed with operational space weather forecasting purposes in mind, while previous missions were defined to fulfil scientific objectives. This leads to different requirements and subsequent technical specifications, which were defined during the project in a trade study (internal communications), where a number of design iterations were considered as many specifications are connected. For some specifications, both a goal- and a threshold-value were defined to analyse the performance impact in the theoretical design study. The OBB is built to represent the goal values in order to test for the full potential.

Some assumptions and are first required to define technical specifications:

- Spec*₁ CME velocity: 3500 km s⁻¹ (goal); 3000 km s⁻¹ (threshold)
- Spec*₂ CME brightness: 1% of the total K+F-corona brightness
- Spec*₃ Optics transmission $T > 0.8$
- Spec*₄ Detector quantum efficiency $QE > 0.65$
- Spec*₅ Number of exposures: 3
- Spec*₆ Image sensor model: Teledyne e2v CCD230-42 CCD
- Spec*₇ Image sensor readout time: 1.0 s

The assumption of CME velocity is based on observed and estimated velocities of extreme events (e.g. Webb and Howard 2012), which cause the biggest space weather effects. It must be possible to observe such events with high image quality. The assumption of CME brightness is based on typical observed values and is needed for the calculation of the stray light budget (section 8.2). The optics transmission T and detector quantum efficiency QE are conservative estimates to account for possible changes of the optics design. Finally, the scheme of 3 exposures is selected for the purpose of so called cosmic ray scrubbing, a procedure to remove artefacts from cosmic ray and SEP impacts as shown in Figure 3.10. In STEREO/HI, this was implemented by comparing each pixel value to the previous exposures and removing all pixels above a certain threshold (Eyles et al., 2009). In each single, short exposure, fewer pixels will be affected. The total exposure time is reduced by this method, as some time is lost for the individual readouts, which is assumed here as 1 s. This is based on the assumption of a baseline detector, which is constrained to available models. A Teledyne e2v CCD230-42 CCD-sensor¹ was subsequently selected as a baseline. It features 2048 px $\times$ 2048 px with 15 μ m pitch, yielding a sensor area of 30.7 $\times$ 30.7 mm, and has backside-illuminated pixels to reach a peak QE of approximately 95% at a wavelength of 550 nm. Note that this QE is higher than the conservative estimate defined in assumption *Spec*₄.

The derived specifications relevant to the optical design are:

- Spec*₈ Instrument volume: $V \leq 0.15 \text{ m}^3$
- Spec*₉ Inner FOV limit: 2.5 R_☉ (goal); 3.0 R_☉ (threshold)
- Spec*₁₀ Outer FOV limit: 30 R_☉ (goal); 22 R_☉ (threshold)
- Spec*₁₁ Plate scale: 60'' px⁻¹ (goal); 120'' px⁻¹ (threshold)
- Spec*₁₂ Signal-to-noise ratio: 4 (goal); 2 (threshold)
- Spec*₁₃ $t_{\text{exp,max}} = 11.7 \text{ s}$
- Spec*₁₄ Single exposure time: $t_{\text{exp,max}} = 3.2 \text{ s}$
- Spec*₁₅ Effective exposure time: $t_{\text{exp,eff}} = 9.6 \text{ s}$

¹<https://www.e2v.com/resources/account/download-datasheet/3828>, 27.04.2020

*Spec*₁₆ Focal length $f = 110$ mm

*Spec*₁₇ Spectral band: 500 nm - 900 nm

*Spec*₁₈ Lens aperture diameter $d_{A1} = 25$ mm

*Spec*₁₉ The OBB needs to be cleanroom-compatible to ISO5 standard.

First, the instrument volume is a constraint from a baselined mission concept, where a certain volume is assigned to each instrument.

The specifications for the FOV and plate scale were defined based on experience with existing coronagraphs and to provide the required observations for forecasting applications. The plate scale, i.e. image resolution, is limited by the low expected telemetry rates of a deep space mission. For the goal specifications, this is equivalent to an image width of 1024 pixels. SCOPE is thus similar to LASCO/C3, which has a FOV of $3.2 R_{\odot}$ to $30 R_{\odot}$, and also an image resolution of 1024 pixels (Brueckner et al., 1995). The latter is lower than the resolution of the baseline CCD sensor, and so binning will be applied to the images. This binning is performed off-chip to provide another mechanism to improve cosmic ray scrubbing.

The specification signal-to-noise ratio (SNR) was defined after an analysis of a set of LASCO/C3 observations, complemented independently by a simulation using artificially generated coronagraph images (Hinrichs et al., 2020).

The maximum exposure time $t_{\text{exp,max}}$ is a consequence of assumption *Spec*₁ and specification *Spec*₁₁ to avoid motion blur, defined here as the time required to cross one pixel:

$$t_{\text{exp,max}} = \frac{2 \cdot \text{FOV}}{N_{\text{px}} \cdot v} = \frac{2 \cdot 30 R_{\odot}}{1024 \cdot 3500 \text{ km s}^{-1}} \approx 11.7 \text{ s} \quad (8.1)$$

In combination with the assumptions *Spec*₅ and *Spec*₇, the single exposure time and effective exposure time are derived.

The lens focal length is the result of the goal FOV and the size of the baselined detector. The spectral band and aperture diameter are again trade parameters and depend on e.g. the instrument volume, FOV limits, plate scale and SNR goal. The image resolution specified is not very demanding in terms of the required lens imaging quality, so chromatic aberrations are not critical, supporting the wide spectral band. However, broadband antireflective (AR) coatings are more difficult to achieve, which in turn can lead to stronger image ghosts.

Finally, the specification on clean room compatibility is based on the very high contrast that needs to be achieved, and manifests in two aspects: The first is to prevent dust particles from getting stuck on any of the components, as they would act as additional scattering sources. As the OBB can not be handled continuously inside an ISO5 environment (e.g. during the initial manufacture), this means that the surface coatings must allow for the required cleaning procedures. The second aspect is that the test setup to verify the stray light performance must provide

a sufficiently dark background. Dust particles suspended in air cause more stray light by the strongly forward-directed Mie-scattering than Rayleigh-scattering of the air-molecules (Born and Wolf, 1999), so a non-cleanroom laboratory could not provide the required conditions. Both issues can be seen in the test results presented in chapter 10.

In addition to the specifications presented here, the OBB is relaxed from some other requirements that are linked to compliance with spaceflight-conditions, and do not directly affect the stray light performance. This specifically includes a mass-budget, mechanical and thermal performance and the use of radiation-resistant materials, providing additional flexibility in the design, and facilitates the use of more cost-efficient components. Furthermore, it was not foreseen to conduct tests under vacuum, as the stray light background created from ISO5-quality air is expected to be low enough for the test.

8.2 Stray Light Budget

Before the detailed instrument design is presented, a stray light budget must be calculated to establish the performance requirement, which I will derive in this section.

For the computation of SNR, the signal and noise sources must be defined. In the following calculations, I denote the number of photoelectrons by the variable n . The total noise is a combination of the (uncorrelated) shot noise and sensor noise:

$$SNR = \frac{\text{signal}}{\text{noise}} = \frac{n_{\text{sig}}}{\sqrt{n_{\text{shot}}^2 + n_{\text{sens}}^2}} \quad (8.2)$$

The signal n_{sig} is assumed to be a CME with 1% of the brightness of the corona as per assumption *Spec*₂:

$$n_{\text{sig}}(R) = 0.01 \cdot n_{\text{K+F}}(R) \quad (8.3)$$

Shot noise is a statistical noise, calculated by the square root of the number of photoelectrons collected (Burke et al., 2005). This, in turn, is composed of the background, signal and stray light:

$$n_{\text{shot}} = \sqrt{n_{\text{K+F}}(R) + n_{\text{sig}}(R) + n_{\text{stray}}(R)} \approx \sqrt{n_{\text{K+F}}(R) + n_{\text{stray}}(R)} \quad (8.4)$$

where the signal was neglected relative to the background as by the assumption above. The sensor noise is composed of dark current noise, readout noise, and quantisation noise.

$$n_{\text{sens}}^2 = n_{\text{dark}}^2 + n_{\text{read}}^2 + n_{\text{quant}}^2 \quad (8.5)$$

Combining the equations above yields expression for SNR:

$$SNR = \frac{n_{\text{sig}}}{\sqrt{n_{\text{shot}}^2 + n_{\text{sens}}^2}} = \frac{0.01 \cdot n_{\text{K+F}}(R)}{\sqrt{n_{\text{K+F}}(R) + n_{\text{stray}}(R) + n_{\text{sens}}^2}} \quad (8.6)$$

which can be solved for $n_{\text{stray}}(R)$:

$$n_{\text{stray}}(R) = \left(\frac{0.01 \cdot n_{\text{K+F}}(R)}{SNR} \right)^2 - n_{\text{K+F}}(R) - n_{\text{sens}}^2 \quad (8.7)$$

Over the spectral band (specification *Spec*₁₇) defined, the solar irradiance is roughly $I = 570 \text{ W m}^{-2}$, and thus the radiance at 1 AU is $B = 8.4 \cdot 10^6 \text{ W m}^{-2} \text{ sr}^{-1}$.

For the purpose of this calculation, I assume that the incident irradiation is monochromatic at a wavelength of $\lambda = 650 \text{ nm}$, which lets us use a photon energy of $E_{\text{phot}} = \frac{hc}{\lambda} \approx 3 \cdot 10^{-19} \text{ J}$. The number of photons incident on the aperture with area $A = \pi(25 \text{ mm})^2$ (specification *Spec*₁₈) is then computed by:

$$n_{\text{phot}} = \frac{IA}{E_{\text{phot}}} = 3.7 \cdot 10^{18} \text{ s}^{-1} \quad (8.8)$$

As the performance at $30 R_{\odot}$ is of interest, the relative brightness of the corona at this point can be read from Figure 2.5, which is approximately $B(30 R_{\odot}) = 1.0 \cdot 10^{-11} B_{\odot}$. Furthermore, the number of photons detected is reduced by the optics transmission and detector quantum efficiency (assumptions *Spec*₃ and *Spec*₄), and proportional to the exposure time $t_{\text{exp,eff}}$ (specification *Spec*₁₅). This results in the number of photoelectrons detected from a patch of corona as large as the solar disc image:

$$n_{\text{det}} = n_{\text{phot}} \cdot \frac{B(30 R_{\odot})}{B_{\odot}} \cdot T \cdot QE \cdot t_{\text{exp,eff}} = 1.85 \cdot 10^8 \quad (8.9)$$

With a lens focal length of $f = 110 \text{ mm}$ and a binned detector pixel pitch of $30 \mu\text{m}$, the solar disc image would cover 915 px. The number of photoelectrons per pixel detected from the background corona at $30 R_{\odot}$ is thus:

$$n_{\text{K+F}}(30 R_{\odot}) = \frac{1.85 \cdot 10^8}{915} = 2.0 \cdot 10^5 \quad (8.10)$$

For the sensor noise, assumptions have to be made as the exact, final values will depend on the readout electronics and readout scheme. Taking the specifications from the data sheet², I assume a read noise of $n_{\text{read}} = 14$ for a $15 \mu\text{m}$ pixel. With the specified readout scheme of 2x2 binning and 3 exposures, this has to be multiplied by $2 \cdot \sqrt{3}$ to get $n_{\text{read}} = 48$. The quantisation noise, assuming a 16-bit ADC, is assumed at $n_{\text{quant}} = 8$. The operating temperature of a CCD in space

²<https://www.e2v.com/resources/account/download-datasheet/3828>, 27.04.2020

is typically around -80°C to reduce damage from energetic particles (Burke et al., 2005), which additionally ensures a low dark current noise.

The formula given in the data sheet is not specified for such low temperatures, but a typical dark current of $0.2\text{ e}^{-}\text{s}^{-1}\text{ px}^{-1}$ is quoted even at -25° , so the dark current will be negligible. Plugging all the numbers into equation 8.7, together with the goal $SNR = 4$, results in the acceptable stray light level:

$$n_{\text{stray}}(30\text{ R}_{\odot}) = \left(\frac{0.01 \cdot 2.0 \cdot 10^5}{4}\right)^2 - 2.0 \cdot 10^5 - 48^2 - 8^2 \approx 50000 \quad (8.11)$$

Equivalently, this is about 25% of the K+F-corona signal. For SCOPE, the definition was set slightly below this value:

*Spec*₂₀ The instrument stray light must be below 20% of the K+F-corona signal (at $30\text{ R}_{\odot}$)

With a budget in the region below the background, this calculation is very sensitive to the individual parameters. As it is based on preliminary, conservative specifications, the numbers will likely change. Most notably, this concerns the detector QE and lens transmission T , which are expected to be higher, as well as the spectral band, which can vary with AR-coating options.

8.3 Detailed Instrument Design

In this section, I present the design of the SCOPE Optics BreadBoard (OBB) based on the specifications described in the previous section. Figure 8.1 shows a *Computer Aided Design* (CAD) model of the OBB. Following the compact coronagraph idea, the instrument is structured into three components: the *baffle tube*, the *lens tube* and the *detector*. The cross section of these three components are outlined in green, blue and red, respectively, in Figure 8.2. The detector box is only indicated for reference, as different cameras were used throughout the tests.

Figure 8.1: Front view of the SCOPE OBB baffle tube (left) together with a cross section view (right).

Figure 8.2: Cross section view of the SCOPE OBB. The baffle structure is emphasized in green, including the labelling of the baffles. The lens barrel is indicated in blue, with a cross section of the individual lenses also shown. The detector box is indicated in red.

The initial optical and mechanical design of SCOPE was developed at RAL Space, with input and review provided by the project partners. The design was adapted together with the team at the University of Göttingen into the final OBB design for the purpose of manufacturing, and in collaboration with CSL to define the required interfaces with the test facilities.

Baffle Tube

The baffle tube itself is structured into 5 segments, with a circular baffle vane at the end of each segment (labelled V1 to V5 from front to back). The segments are made from aluminium, and each segment is machined together with the corresponding baffle from a single block.

The two defining, and hence most important baffles are V1 and V3. In this case, V3 defines the outer FOV limit (equivalent to the A0 aperture of the classical design), and V1 is oversized so that it is not visible to the lens aperture. V2, V4 and V5 each have a slightly larger opening diameter than their respective previous vane, so that they are not directly illuminated. Their purpose is to provide additional reduction of light scattered diffusely inside the baffle tube.

The rear-wall of the baffle tube additionally supports 3 conical baffles (labelled C1 to C3, from large to small), and also includes the aperture for the lens system. The conical baffles replace the HRM described in section 2.3.2, as a measure to further simplify manufacturing.

A sketch of the two most important proportions of the baffles is shown in Figure 8.3. The edges of the conical baffles and baffle V3 connect in line with the edge of the lens aperture (that is on the same side of the central axis), as indicated by the red line in the figure. Their diameters are chosen so that the image is free of vignetting out to the goal FOV of $30 R_{\odot}$ of the instrument (specification *Spec*₁₀ and equation 2.4). The edges of V1 and V3 connect to the opposite side of the aperture (orange line), i.e. V1 is fully shadowed from the aperture and so lies outside the OFOV limit (equation 2.5)).

Figure 8.3: Schematic of the two most important proportions of the baffles, shown on a section of Figure 8.2. The red dashed line indicates the outer FOV limit, which is defined by the third baffle, V3. The orange dashed line indicates the connection between baffles V1 and V3.

The detailed design of the conical baffles requires some further explanation. Originally, a larger number of cones was foreseen, following the principle shown in Figure 8.4. The V3 baffle casts a shadow onto the rear wall (upper orange line). This shadow marks the beginning of the first cone, which is drawn towards the edge of the final occulter disc (red dotted line). It ends at the unvignetted OFOV radius according to equation 2.4, as described previously. This way, the rear side of the occulter does not see the outside of the cone, and thus no light reflected off it, preventing a 2-scatter process into the lens aperture. The same principle is then applied to successively construct further cones: Draw the shadow line of the

cone to the rear wall, and make a new cone towards the occulter, stopping at the unvignetted OFOV radius. Diffuse light is mostly trapped between the cones, and between cone C1 and vane V5, so that only 3-scatter light off of black surfaces reaches the lens aperture.

Figure 8.4: Sketch of the geometry of the conical baffles. The dashed lines indicate the connections between the start- end endpoints of the various components.

However, if this design is to fully shadow the aperture from 2-scattered light, an infinite number of cones is required. Quite naturally, this is impossible to build, and becomes impractical even after a few cones. On the other hand, it can be sufficient to use only a limited number, if it means a large enough fraction of the 2-scattered light is suppressed. For SCOPE, 3 cones (as in Figure 8.4) were initially foreseen. The two inner cones were later combined into one that slightly deviates from this principle. Ray-tracing simulations indicated that this would still produce acceptable stray light levels. To minimize the scattered light hitting the aperture via the inside of the cone C2, another small baffle (C3) was placed around the aperture. It is also designed conical, but is not part of the series described above, with its opening diameter being smaller than the occulter.

All elements of the baffle tube are coated with matte black paint. In the flight model design, Aeroglaze Z306³ was assumed, which is space flight compatible and has heritage e.g. on the STEREO-HI instruments (Eyles et al., 2009). For the OBB, this coating was substituted with Nextel 811-21 Velvet Black⁴ for reasons of simplifying the manufacturing process. Compared to Aeroglaze, Nextel is slightly darker (5% vs 3.5% total hemispherical reflectance as quoted by the manufacturers), but it was shown by ray-tracing simulations that the stray light levels caused by either paint would be well below the requirement (specification $Spec_{20}$), so no adverse impact on the interpretation of the test results was expected.

³<https://www.socomore.com/shop/coatings/anti-erosion-coating/aeroglaze-z306/>, 27.04.2020

⁴<https://www.nextel-coating.com/products/>, 27.04.2020

Occulter

The occulter is a 5-discs design to achieve an improved rejection of diffracted light compared to LASCO-C3 or SECCHI-COR2, which feature 3-disc occulters (Brueckner et al., 1995; Howard et al., 2008). The spacing between the discs is 50 mm, leading to a total stack length of 200 mm. The baffle tube is 600 mm long, so that the distance between the lens aperture, which is incorporated into the back wall of the baffle tube, and the final occulter disc is 400 mm.

The individual disc diameters are derived from the same formula that was used to define the baffles of STEREO-HI, see Halain (2012), and lie between 37.8 mm and 34.4 mm. The profile of the disc edges was also based on the tests described therein, which demonstrated that a razor-sharp edge is not required, but a flat top gives the same performance. A 0.1 mm flat top was then chosen for the SCOPE occulter. Flat edged are easier to manufacture accurately and consistently, as well as less susceptible to damage.

The diffraction around the occulter was simulated using GLAD⁵, a commercial software, as well as PROPER (Krist, 2007)⁶, an open source library available for various programming languages. Figure 8.5 shows the simulated diffraction pattern at 530 nm and 800 nm, together with the specified stray light budget (specification $Spec_{20}$). All simulated diffraction data shown in this thesis was provided courtesy by James Tappin (RAL Space). Near the OFOV limit, the diffracted light is about three orders of magnitude below the stray light limit. The drop at ± 8 mm is at the location of the unvignetted IFOV limit.

Figure 8.5: Simulated diffraction performance of the occulter at 530 nm and 800 nm (courtesy J. Tappin). The specified stray light budget is indicated by the green line, using 20% of the coronal brightness from Baumbach (1937).

⁵<https://www.aor.com/>, 27.04.2020

⁶Note that the PROPER library website has moved to <http://proper-library.sourceforge.net>

The simulations were performed also with a random variation in the disc sizes, from which a tolerance of $40\text{ }\mu\text{m}$ for the disc radii and co-alignment was specified. The entire occulter stack was manufactured from a single piece of aluminium on a computer controlled turning machine, which gives the most accurate co-alignment. Metrology on the disc diameters was performed using a micrometer. The readings were taken only very carefully in order not to squeeze and damage the final disc edges, but they showed an accuracy better than $15\text{ }\mu\text{m}$. A less careful measurement performed on an earlier manufacturing sample even showed an accuracy of better than $5\text{ }\mu\text{m}$.

This tolerance for the radius is smaller than the typical thickness of a layer of matte paint, so the disc edges had to be left uncoated to ensure uniformity. For this reason, the occulter was first anodised black. The disc edges were then masked and only the remaining part of the occulter painted with Nextel Velvet Black. Figure 8.6 shows a close-up image of the finished occulter taken after painting.

Figure 8.6: Close-up view of one occulter disc edge after black anodizing and subsequent painting with the edge masked.

Spider-arms

The occulter is held in place at the centre of the baffle tube by 4 *spider-arms* (also often called *pylon*), 2 on each side at the front and back, with the two sides separated by 120 degrees. The configuration can be seen in Figure 8.1. They mount to the occulter at the side of its central section, which means that they are offset radially from the central optical axis by about 9 mm.

The design and manufacture of the spider-arms turned out to be a very important aspect during the tests. As a consequence, five different models have been produced between the three test phases, labelled S1 to S5, listed in Table 8.1. Figure 8.7 shows a photograph of all versions side-by-side. The first version, S1, was procured from an external supplier to realise a specific shape using metal 3D-printing, and was coated with Nextel at IAG. The second version, S2, was manufactured at IAG. Versions S3 and S5 were manufactured at RAL Space, and version S4 was 3D printed by myself using a consumer-grade 3D-printer. During the initial tests at IAG, the spiders S1 were used in all four positions. The second version (S2) was made as a replacement for the front spiders ahead of the tests at CSL, where they were used with versions S1 for the rear spider-arms. Versions S3 to S5 were produced later and used during the tests at RAL Space.

Table 8.1: Specifications of the different spider-arm versions.

#	Manufacturing technique	rms roughness	Position
S1	3D-print, steel, painted	18.1	Front & Rear (IAG) Rear Only (with S2)
S2	Al, wire-cut, partially painted	2.1	Front Only (with S1)
S3	Al, wire-cut and milled	1.2	Front & Rear
S4	3D-print, black PLA, polished	N.A.	Front & Rear
S5	Al, polished and lapped	N.A.	Front & Rear

Figure 8.7: Side-by-side picture of the spider versions used during the tests at RAL Space. from left to right: S1 to S5.

From S1 to S2, both the geometry and the manufacturing technique was changed, which is shown in Figure 8.8. The original design had rounded front and rear-edges that were coated with Nextel Velvet Black, which was then dropped in favour of sharp, unpainted edges, as the roughness of paint was identified as a cause for diffracted stray light (see section 10.1). The width of the front spider-arm was also increased to fully shadow the rear spider-arm. A shadowed rear spider-arm can still re-scatter light that is diffracted around the front spider-arm, but it minimises the overall amount. In the first version, S1, this was not yet considered necessary because no significant stray light was expected. For versions S2 to S5, the geometry remained the same, and only the manufacturing technique and post-processing differed.⁷

Figure 8.8: Cross section profile of the different spider-arm geometries.

⁷With the slight exception of S4, where I elongated the central, triangular section to optimize the 3D-printing process. This had no impact on the results as the dominating factor were the edges and not the sides.

Because of the result that the roughness of the edge is very important, I attempted to measure the roughness of the edges for correlation with the stray light measurements. It was only possible to obtain a measurement for S1 to S3, as the edges of S4 and S5 were too smooth to be measured with optical techniques, and other measurement methods were not available or feasible for the specific geometry. The values obtained are included in Table 8.1. For S1, the roughness was measured using a DSLR with macro-photography lens, which achieved a pixel scale of $5.75\text{ }\mu\text{m}$ per pixel (not accounting for the actual resolution of the lens due to aberrations). For S3 to S5, an optical microscope with a pixel scale of $1.00\text{ }\mu\text{m}$ per pixel was used. The inspection of S1 under the microscope actually yielded worse results than using the DSLR due to the combination of the rounded edge and the depth of field of the microscope. The contour of the edge was then detected in each image using python, and the rms-deviation from a straight line computed over the imaged portion of the edge. The value computed for S3 is likely be too high, because the roughness is already close to the limit of the optical resolution. Figures 8.9 to 8.11 show an image of a portion of the edge of S1, S2 and S3, together with the extracted edge contour overplotted. Figure 8.12 shows the microscope image of S5 to demonstrate its much smoother edge.

Figure 8.9: A small section of the macro image of spider S1, with the detected edge overplotted.

Figure 8.10: A small section of the microscope image of spider S2, with the detected edge overplotted.

Figure 8.11: A small section of the microscope image of spider S3, with the detected edge overplotted.

Figure 8.12: Microscope image of a section of the edge of spider S5. The edge is so smooth that no roughness can be detected using optical microscopy.

Lens Barrel

The lens system consists of 5 lenses, has a focal length of 110 mm and an entrance aperture diameter of 25 mm. It is designed to be vignetting free out to the (fully vignettted) OFOV limit of the baffle tube at $40 R_{\odot}$. Figure 8.13 shows a full and cross section CAD model of the lens barrel. Figure 8.14 shows a cross section including ray-traced beam on-axis and at an angle of 8° (corresponding roughly to $30 R_{\odot}$).

Two slightly different versions of the lens barrel were designed and manufactured, implementing different methods of assembly. Figure 8.13 shows a cross section view of the first, “simple” version, where the lenses are directly inserted into a barrel and separated by spacer-rings. The barrel is machine-turned from aluminium, and black anodizing is used as the only surface finish to keep the dimensional accuracy as high as possible. The second version (not shown) uses a sub-cell mounting for the first two lens pairs. Consequently, the front section of this barrel is slightly larger in diameter to accommodate the cells. The sub-cell version was used for the initial tests at IAG, but had to be swapped for the single-barrel version before the tests at CSL and RAL Space due to a small crack appearing in one of the lenses.

Figure 8.13: CAD model of the SCOPE lens barrel (left), together with a cross section view (right). The first two lens pairs, consisting of a bi-convex and a bi-concave lens, are identical.

The lenses are made of N-LAK9⁸ and S-TIM8⁹ glass types. All surfaces are coated with a broadband AR-coating to reduce the formation of ghost images. Figure 8.15 shows a plot of the theoretical transmission of the lens as a function of wavelength, which was calculated from bulk glass absorption values taken from glass supplier data sheets and assuming the lens centre thickness, as well as AR-coating sample measurements from the lens manufacturer. The transmission is above 0.92 across the entire spectral band, as compared to the assumption 0.8 in specification *Spec₃*

⁸https://www.us.schott.com/d/advanced_optics/a2ca6c8d-ec8d-4886-9778-f6b188f54437/schott-datasheet-n-lak9-english.pdf, 27.04.2020

⁹<https://www.oharacorp.com/pdf/S-TIM8.pdf>, 27.04.2020

Figure 8.14: Side view of the SCOPE lens barrel. The ray paths shown indicate beams at 0° (red) and 8° (green) incidence.

Figure 8.15: Calculated transmission of the lens barrel (blue), with the contributions by bulk glass absorption (red) and antireflective coating (green).

Detector

The baselined flight model design assumes an e2v CCD230-42 CCD-sensor. It features 2048×2048 px with $15 \mu\text{m}$ pixel pitch, yielding a sensor area of 30.7×30.7 mm, and has backside-illuminated pixels to reach a peak quantum efficiency of approximately 95% at a wavelength of 550 nm. As usual in space-instrumentation, the sensor will be passively cooled by a radiator to a temperature of around -80°C .

As stated above, SCOPE will not make use full resolution, but use off-chip re-binning to 1024×1024 px. Reducing the image resolution is a trade parameter to increase the image cadence (at fixed telemetry data rates) and simplify the optical imaging requirements of the lens system. In this case, it will also be used as part of the SEP-scrubbing routine to reduce noise for extreme events. by using off-chip binning, the affected pixels can be ignored in the summation.

A second part of the SEP-scrubbing strategy is to readout multiple short exposures instead of a single long exposure (specification $Spec_5$). This is a trade with image SNR, as was shown in section 8.2, because some exposure time is lost during each sensor readout. One readout will take around 1 s with the assumed readout scheme. The third exposure has to end at the maximum total exposure time (specification $Spec_{13}$, so two readouts must happen within the maximum allowable exposure time of 11.7 s. (The final readout can take place afterwards). This reduces the effective exposure time to 9.6 s, i.e. by 18%. Details of the onboard image processing, as well as how the sensor will be read out, are, of course, still TBD, which is reflected in the assumptions of sensor noise in the stray light budget calculation.

This sensor was not yet available for the tests described in this thesis. Instead, a different detector available at each institution had to be used. Acquiring an equivalent large format camera was also not possible due to their large cost. Details of the cameras used are given in the following chapter, together with the description of the test setups.

Chapter 9

Laboratory Test Setups for SCOPE Performance Testing

Testing a coronagraph is a challenging task and requires dedicated testing equipment in large facilities. Because only a few space-borne coronagraphs have ever been built, and only by institutions in the USA, there are few facilities that can provide sufficient conditions. The most recent tests of similar instruments performed in Europe include those of the heliospheric imagers for STEREO and PSP (Defise et al., 2003; Thernisien et al., 2018), which also have a similar requirement on stray light rejection. However, as it turns out, the difference that the FOV of a coronagraph is centred on the Sun, and the FOV of a heliospheric imager is not, generates some additional requirements that are not easily met. In this chapter, general requirements for a coronagraph test setup are presented in section 9.1, followed by specific descriptions of the test setups used for testing SCOPE in sections 9.2 to 9.4.

9.1 Coronagraph Test Setup Design

The biggest potential source of stray light in a coronagraph is sunlight. In space, the irradiance of the Sun at 1 AU is 1367 W m^{-2} (Stix, 2004), most of which falls into the visible region, the wavelength range of the white-light coronagraph. In comparison, integration of the brightness of the corona relative to the Sun (using the model by Baumbach (1937)) between 2.5 and $30 R_{\odot}$ yields only a factor of $7 \cdot 10^{-8}$ of the direct sunlight, or equivalently $9.2 \cdot 10^{-5} \text{ W m}^{-2}$. Other sources, such as the stellar background, cause an even lower irradiance, although bright planets, such as Venus, can cause visible ghost images and saturate the image sensor locally, causing blooming (Eyles et al., 2009). A slightly different situation arises when the coronagraph is to be placed in a Low Earth Orbit (LEO). In this case, the Earth can present a significantly large out-of-field stray light source. This case will, however, not be covered in this thesis, since the main focus of the SCOPE development is targeted at a future mission in the Lagrange-point L5, and also because the development described here is focused on the rejection of solar stray light.

A coronagraph must hence be tested foremost for its stray light generation from sunlight, which will be incident along the optical axis for a coronagraph. The first question is now: how to simulate sunlight in a laboratory setup? There are three main requirements for an ideal (white light) solar simulator:

1. Sunlight is not perfectly collimated, but has a divergence of about $32'$.
2. Due to the effect of limb darkening, the brightness falls off with elongation from the visual centre, with the effect being strongest for blue light and weakest for red light.
3. The spectrum is approximately equal to a black body with a temperature of 5700K.

Obtaining an ideal black body source with 5700K is probably the most difficult. A $32'$ divergence alone could fairly easily be achieved, and even a limb darkening effect could be approximated with simple setups. However, these two aspects are also impractical for various reasons.

The limitations from the above list could in principle be overcome with the following setup and procedure, which might seem contradictory at first glance:

- A narrowly collimated light source is used.
- Different narrow-band-sources are used, e.g. lasers or LEDs.
- The test is repeated with the source being rotated by different angles in a $32'$ range.
- The test is repeated with different source wavelengths.

The result for sunlight can then be computed by adding the different results, taking into account the correct weighting factors for limb-darkening and the black body spectrum. If enough wavelengths and scanning angles are chosen, the result will be close to the real result. The drawback of this method is additional effort and time required to making multiple measurements. But, as an intermediate result, any collimator with a divergence well below $32'$ and a reasonably narrow-band light source can be used as a basis for a coronagraph test. Furthermore, the stray light performance of most optical systems is predicted nowadays by simulations, e.g. using ray tracing or Fourier-based Fresnel methods for diffraction. If the simulated results for a test setup that does not fully resemble the Sun can be confirmed, confidence is established in the simulations of the performance with real sunlight.

Further requirements for a test setup depend on the physical dimensions and observational characteristics of the instrument to be tested. I will use numbers for SCOPE in the following calculations.

First, this again concerns the light source, which must provide a sufficiently large beam diameter to illuminate all components of the instrument (all components are potential sources of stray light). In case of SCOPE, the first baffle (V1) has a diameter of 221.42 mm, meaning that a fairly large collimator is required.

The second requirement is set by the FOV of the instrument, in this case 2.5 to $30 R_{\odot}$, which defines the acceptable stray-light levels. As was explained in section 8.2, the budget for SCOPE was defined at 20% of the K+F-corona brightness at $30 R_{\odot}$, or roughly $2 \cdot 10^{-12} B_{\odot}$. The background of the test setup seen by the coronagraph must be darker than this level, or it will not be possible to distinguish background stray light from instrument stray light.

In combination with the beam diameter, the inner FOV limit sets a requirement on the minimal distance between the light source and the instrument. The reason is that, similarly to what was described in section 2.3.1 for the internally occulted coronagraph, the primary collimating optical element can (and will) diffusely scatter incident light. If seen by the instrument, this will again mask the instrument stray light. The illuminated area of the collimator (a mirror will be assumed from this point onward as the collimating primary) should thus not be visible to the camera lens. As will be shown later in sections 10.1 and 10.2, this was indeed observed during the tests and required workarounds to assess certain instrument performance aspects.

Using the beam diameter of approximately 221 mm given above and accounting for some margin, a diameter of 240 mm, or equivalently a radius of 120 mm, is assumed for SCOPE. The inner FOV limit, where the lens is fully occulted, is set at $2.5 R_{\odot} = 40'$. Figure 9.1 shows a sketch of this situation. The on- and off-axis beams are indicated by the red and blue lines, respectively, while the black dashed line indicates the inner FOV limit. The intersection points define the minimal distance, with the corresponding mirror locations marked in light blue. For SCOPE, the result is a minimal distance of 9.1 m between the collimator mirror and the coronagraph in the on-axis case. When accounting for a scan to $\pm 16'$, the facility length should be at least 16 m. Neither of these dimensions was given for any test setup presented in the later sections.

Figure 9.1: Schematic outline of the principle to determine the minimum required distance of the collimating mirror. The dashed black line indicates the inner FOV limit from the edge of the lens aperture over the edge of the occulter. The red and blue lines indicate an input beam filling the first baffle on- and off-axis, respectively. The minimum collimating mirror distances are the indicated in turquoise.

When the collimated beam hits the instrument, some light is reflected off of it. Even if it is coated black, there will be some reflection, as a good black paint still has a reflectance of a few percent. This illuminates the inside of the test chamber and thus contributes to the background stray light. To keep the background levels low, the test chamber must hence also be blackened and possibly be equipped with

additional baffles. The light source should be well baffled to avoid reflections into the instrument. Good closure of the test setup is also important so that no light sources can shine in from the outside. Even a dim light from a laboratory status light can cause a significant background illumination.

The issue of chamber illumination is particularly problematic in conjunction with an HRM. This is because, by design, it reflects all incoming light back out of the instrument, and thus into the test chamber. The chamber might then be illuminated so strongly that it exceeds the requirements and no longer allows a characterisation of the instrument stray light. This was already noted for the LASCO tests (Brueckner et al., 1995), where the HRM was covered by a black lid for some of the tests to avoid this issue. This aspect is another one that is much simpler to account for with heliospheric imagers. For the tests of HI (Halain, 2012), the function of the HRM was assumed by the first linear baffle, which was tilted down and away from the FOV. With a coronagraph, this can't be done so easily because it observes in all directions around the light source.

Furthermore, as was already described in the previous chapter with specification *Spec*₁₉, the test setup needs to be operated either in vacuum or under good cleanroom conditions, because forward-scattered light by Mie-scattering on dust-particles (Born and Wolf, 1999) is a source of strong background stray light. Additionally, large dust particles can settle on parts of the instrument and act as scattering centres. This in turn will require frequent cleaning, which can degrade coating performance, and should thus be avoided.

9.2 Tests at Centre Spatial de Liège

The tests at CSL were the primary tests for SCOPE, and the test setup also served as a blueprint for the simplified “fit-check”-test setup at IAG. For this reason, the CSL setup will be described first in this chapter, while the test results obtained at IAG are presented first in chapter 10. The tests themselves were conducted mainly by CSL staff, with some local support by P. Huke from IAG. I could unfortunately not attend myself, and only contributed in the planning stages.

CSL operates several vacuum-chambers with heritage in stray-light testing in their clean room facilities. For example, tests for the STEREO Heliospheric Imagers have been conducted there (Defise et al., 2003), as well as more recently test of the heliospheric imager of Solar Orbiter (SoloHI) and the Wide Field Imager for Parker Solar Probe (WISPR) (Howard et al., 2013; Thernisien et al., 2018). A dedicated setup was designed and built (Mazy et al., 2012) to provide a vacuum-compatible, extremely low background scattering test facility for small satellite instruments. In this setup, the Focal-3 chamber is used to house the instrument. The light source and collimator assembly are set up in an auxiliary chamber that is attached to Focal-3. Figure 9.2 shows a CAD model of the full test chamber.

Figure 9.2: CAD model of the Focal-3 chamber with black tent inside, and the auxiliary collimator chamber attached. Reproduced from Hellin et al. (2017) with permission.

The light source uses an optical fibre input. For the SCOPE tests, this is equipped with a 600 μm core fibre, and fed from a 20 W laser source with a wavelength of 808 nm. For stray light reduction, the fibre is inserted into a polished, black glass pyramid, and surrounded by a baffle structure. The light is then guided by a flat fold mirror, and finally collimated by an off-axis parabolic mirror with 2000 mm focal length and 400 mm diameter. Further baffling is placed around the mirror, and in the remaining section of the auxiliary chamber. These baffles are coated either with MAP PU-1¹ or Acktar coating². Additionally, Vantablack³ panels

¹<https://www.map-coatings.com/>, 27.04.2020

²<https://www.acktar.com/>, 27.04.2020

³<https://www.surreynanosystems.com/>, 27.04.2020

were installed on one side of the collimator baffles to provide a reference field where the background intensity is definitely below the instrument requirements, as simulations performed by CSL suggested the values with the regular setup could be slightly too high. Inside the Focal-3 chamber, SCOPE is placed on a precision hexapod stage for computer-controlled displacement and rotation. The setup is surrounded by a black tent coated with MAP-PU1 for stray light reduction.

As the test detector, a QSI⁴ 516-WS camera is used. The camera is water-cooled so that low sensor temperatures can be maintained (reducing dark current noise), and no fan is required that would cause additional air movement and stir up dust particles. The camera uses a KAF-1603 CCD sensor (ON Semiconductor, a). The active image area of this sensor is only 13.8×9.2 mm, considerably smaller than that of the design sensor with 30.7×30.7 mm. As a result, only part of the FOV can be observed, which needs to be carefully chosen. Figure 9.3 shows the selected location for the sensor during the test (the Figure also includes the locations of the sensors for the other test periods, which will be explained in their respective sections). The detector is mounted with an offset towards one side, covering a small margin beyond the centre of the occulter to include the location of the Poisson spot. The OFOV limit is just about covered by the image corners. The FOV was also chosen explicitly with one spider-arm in the FOV to observe any stray light generated by these.

A detailed test plan was written, including also the necessary calibration steps. This plan consists of the following steps:

1. The collimated light source is set up and aligned.
2. The OBB is inspected for dust upon delivery and cleaned before being placed in the clean room.
3. A detector flat field measurement is made to inspect for dust on the sensor.
4. The camera is assembled with the lens barrel and the focus is adjusted to infinity.
5. The camera and lens barrel are attached to the baffle tube.
6. The lateral position of the camera w.r.t. the external occulter is checked and, if necessary, corrected.
7. The camera and lens barrel are removed again from the baffles.
8. The camera is calibrated on a white calibration standard.
9. A flat-fielded of the lens and camera is taken.
10. The camera and lens barrel are re-attached to the baffle tube.
11. The whole OBB is installed on the hexapod.
12. The alignment of the OBB is calibrated w.r.t. the collimator beam.
13. The test chamber is closed and the main test conducted.

⁴<https://qsimaging.com/>, 27.04.2020

Figure 9.3: FOVs covered by the different test detectors. The limiting regions from the instrument baffles are indicated.

An issue occurred with steps 7 and 8 of the sequence above, concerning the radiometric calibration and flat-field of the lens barrel. In the SCOPE design, as was described in section 8.3, the defining lens aperture is built into the rear wall of the baffle tube, so that it needs to be substituted by an additional “aperture-plate” for the calibration steps without the baffle-tube. The lens-aperture has a diameter of 25 mm, while the opening of the lens barrel itself is 30 mm. This substitute aperture was, however, not attached, and the error not noticed during the calibration activity. This will be taken into account during the evaluation of the test results, since it introduces an error of a factor of $\frac{30^2}{25^2} = 1.44$ in the radiometric calibration. As will be seen from the results, however, this error is small compared to the general performance issues that are observed with the design described in section 8.3, and does not change the observations qualitatively.

For a physical interpretation of the results, and comparison with the stray light budget computed in section 8.2, it is necessary to convert the images from the CCD-camera, which are in units of Analog-to-Digital-Units (ADU), to solar brightness. The conversion factor can be calculated using the measurements from the calibration procedure as well as some additional technical specifications. Assuming that the collimator is directly observed without the external occulter, and has a divergence equivalent to the Sun ($32'$), the number of ADUs $^{-1}$ observed by the detector would then be equivalent to the mean solar brightness (MSB), where $1 \text{ MSB} \approx 0.8 B_{\odot}$ due to the limb darkening of the Sun (Livingston, 2002, pp.335-337).

First, I calculate the number of pixels n_{pix} covered by a $32'$ source via the focal length of the lens (using a value of $f = 109.3 \text{ mm}$ measured by CSL during calibration) and the pixel pitch of the test detector ($9.0 \mu\text{m}$):

$$p = \frac{206265''}{109.3 \text{ mm}} \approx 1875'' \text{ mm}^{-1} \quad (9.1)$$

$$d_{\text{Sun}} = \frac{32' \cdot 60}{p} \approx 1 \text{ mm} \quad (9.2)$$

$$n_{\text{pix}} = \frac{\pi \cdot d^2}{4 \cdot (9.0 \mu\text{m})^2} \approx 10036 \quad (9.3)$$

where, as intermediate steps, p is the plate scale of the lens and d_{Sun} the size of the Sun on the image sensor.

Next, I calculate the energy E entering the lens aperture per second and convert it to the number of photoelectrons detected ($N_{\text{det.}}$). For this step, the collimator irradiance ($I = 0.375 \text{ W m}^{-2}$, measured by CSL during calibration) is needed, as well as the lens transmission ($T = 0.95$, calculated, see Figure 8.15) and the detector quantum efficiency ($QE = 0.45$, taken from the CCD data sheet (ON Semiconductor, a)) at the test wavelength of $\lambda = 808 \text{ nm}$.

$$E = 0.375 \text{ W m}^{-2} \cdot \pi \cdot (25 \text{ mm}^2) \approx 736 \mu\text{W} \quad (9.4)$$

$$N = \frac{E \cdot \lambda}{h \cdot c} \approx 3.0 \cdot 10^{15} \text{ s}^{-1} \quad (9.5)$$

$$N_{\text{det.}} = N \cdot T \cdot QE \approx 1.3 \cdot 10^{15} \text{ s}^{-1} \quad (9.6)$$

Finally, I calculate the number of photoelectrons per pixel per second, $N'_{\text{det.}}$, as the ratio of the two previous results n_{pix} and $N_{\text{det.}}$, and then convert it to the desired image conversion factor F in units of ADU per seconds using the camera gain factor. The gain was measured as $G = 2.88 e^-/\text{ADU}$ during the calibration step at CSL (including the correction for the missing aperture plate), which is close to the value of $G = 2.6 e^-/\text{ADU}$ given by the camera data sheet.

$$N'_{\text{det.}} = \frac{N_{\text{det.}}}{n_{\text{pix}}} \approx 1.3 \cdot 10^{11} \text{ s}^{-1} \quad (9.7)$$

$$\rightarrow F = \frac{N'_{\text{det.}}}{G} \approx 4.43 \cdot 10^{10} \text{ ADU s}^{-1} \quad (9.8)$$

The calculation involves a number of different quantities, which can contribute to an error in the conversion factor. This is true even more for the tests at IAG and RAL Space, where not as much and not as accurate calibration were possible, and more values had thus been used directly from manufacturer data sheets. In any case, a conservative estimate should be made to know if the interpretation of the results could be significantly affected.

Table 9.1 list the errors assumed for the CSL test setup. The errors of the detector pixel pitch and aperture diameter are assumed to be negligible, as well as the test wavelength because a laser is used. An important source of error here is the beam intensity, because large offset tests were performed using the hexapod. The intensity was measured by CSL using a calibrated photodiode during one of the calibration steps, but only at a few positions closer to the centre of the beam, where a variation by $\pm 1\%$ was observed. The dominating value in this case is assumed for the sensor gain as a result of the difference between the calibrated and nominal value, because the former has been impacted by the missing aperture-plate. Applying error propagation yields a combined uncertainty of 14%, and thus $F = (4.43 \pm 0.61) \cdot 10^{10} \text{ ADU s}^{-1}$. As this test is only required to demonstrate the performance of the SCOPE design on an orders of magnitude scale of stray light rejection, this error would not lead to a qualitative misinterpretation of the results.

Table 9.1: Error assumptions for the CSL test setup.

Variable	Error	Justification
f	0.6%	Difference calibration vs. nominal
d_{Sun}	2%	Orbit variations
I	5%	Offset-tests
T	5%	Calculated curve
QE	5%	Conservative estimate
G	10%	Difference calibration vs. data sheet

9.3 Tests at the Institut für Astrophysik

For the fit check tests at IAG, a simplified version of the test setup used at CSL was designed and installed in one of the IAG laboratories. Figure 9.4 shows a simplified CAD model, and Figure 9.5 a photograph of the setup under construction. The frame is a quadratic tunnel of aluminium extrusion profile, with a quadratic cross section of 60 cm and a length of 5 m - the maximum possible in the laboratory. One end is supported by an optical bench, where the light source and collimator are installed. The SCOPE OBB is supported at the other end.

Figure 9.4: CAD Model of the IAG test setup, showing the location of the OBB and the collimator optics.

The collimator primary is a 12-inch parabolic mirror with a focal length of 1500 mm, large enough to illuminate the full OBB. It is not an off-axis mirror, but rotated by about 4 degrees to create an off-axis setup and keep the light source assembly out of the collimated beam. Using a non-off-axis parabolic mirror in an off-axis configuration will lead to some aberrations. However, these are not significant in this case because the beam divergence is large, but still far smaller than that of sunlight. Indeed, I observed no aberration in a direct observation of the light source using a DSLR camera with telephoto lens.

Figure 9.5: Picture of the IAG test setup under construction.

The light source is an Omicron⁵ LEDMOD V2 5600 K white-light LED. Like at CSL, it uses a fibre feed, here with a 910 μm core. Additionally, a small achromatic doublet lens is placed closely in front of the fibre output to collect as much light as possible. This also slightly shortens the effective focal length of the collimator. The resulting beam divergence was approximately $3'$, which is still small compared to sunlight. The source assembly is baffled with a few simple 3D-printed baffles. The entire source assembly is closed off with black aluminium foil to suppress any leakage. The optical fibre is also covered with black foil as too much light was initially observed leaked through its cladding and shell, and was visible in the test images as a bright stray light source.

The total length of the tunnel of 5 m does not fulfil the criterion presented in section 9.1, i.e. parts of the mirror are visible to the instrument. To minimize this effect, the baffling of the light source assembly was adjusted so that the final collimated beam only just illuminated the V1 baffle. Furthermore, an iris aperture was placed at the front of the light source assembly to further reduce the beam diameter for specific tests. For example, this allowed for a configuration where only the occulter was fully illuminated. In this way, no illuminated part of the collimator was visible, and the diffraction around the occulter could be observed.

⁵<https://www.omicron-laser.de/>, 27.04.2020

The beam irradiance was measured using a photodiode placed at the centre of the beam. The measurement yields a photocurrent i , which can be converted to the irradiance I using the technical specifications of the response R (measured in A W^{-1}) and the photodiode area A_{Diode} :

$$I = \frac{i}{R \cdot A_{\text{Diode}}} \quad (9.9)$$

This resulted in an estimate of $I = 0.1 \pm 0.02 \text{ W m}^{-2}$. The large error is a conservative estimate due to the white-light nature of the source, as an integrated value from the source spectrum and the (uncalibrated) photodiode QE had to be estimated from the respective graphs for the conversion. The beam profile was not measured accurately for this test, but appeared to vary only by a few percent, as would be expected.

The entire tunnel is blackened by wrapping black Molton cloth around. Covering the tunnel with a flexible material provides simple access to the entire setup. Molton also provides very good black levels and is inexpensive compared to black-out materials typically used in optical applications. The drawback is that cloth is never really clean and causes additional dust being generated, in turn causing elevated background stray light levels. A small air filter unit was placed inside the tunnel to help clear dust from the air. Using cloth despite this property was considered acceptable because the IAG laboratory was not operated as a clean room (at the time). Furthermore, the IAG test was only designed to catch coarse errors, and a performance similar to that at CSL was never expected. On the other hand, the additional dust finally required additional waiting time after adjusting the setup to allow dust to settle down, so that fewer optimisations could be tested.

As a detector, an SBIG STF8300 CCD-camera is used. It features a KAF8300 sensor (ON Semiconductor, b) with an image area of 17.96 mm x 13.52 mm and a 5.4 μm pixel pitch. This is larger than the KAF-1603 sensor used during the CSL tests, but still smaller than the flight design camera. The camera was off-centred by the the same amount as for CSL, thus observing a slightly larger FOV, as shown in Figure 9.3. It was placed on the other side of the occulter (for most of the time) to have the light source cage in the FOV. This provided visual confirmation of light leaking through insufficient baffling that could cause stray light and ghost images. Such leakages would otherwise have been difficult to trace back.

For diagnostic purposes, observations were not only made with the regular OBB configuration, but also with the SCOPE lens barrel plus CCD detector removed and replaced by a conventional DSLR camera (Canon EOS 70D) with a wide angle-lens that can focus at close distance (Canon EF 24-70mm f/4L IS USM). Such a test is possible due to the modular design of the compact coronagraph, and allows to take images while focussing onto the baffle edges instead of infinity only.⁶

The same prescription given for the CSL tests to convert measurements from ADU to MSB was applied to calculate a conversion factor between ADUs^{-1} and MSB. An average wavelength of $\lambda = 550\text{nm}$ is assumed, based on an estimate from the CCD and photodiode QEs and the spectrum of the white light source. This results in an average detector quantum efficiency of $QE = 0.45$ (taken from the data sheet) and an average optics transmission of $T = 0.95$ (taken from Figure 8.15). The technical specification of the camera gives a gain factor of $G = 0.38 \text{ e-ADU}^{-1}$.

The resulting conversion factor is $F = (2.17 \pm 0.65) \cdot 10^{10} \text{ ADU s}^{-1}$. The assumed uncertainties for this setup are shown in Table 9.2. In addition to the values presented for the CSL setup, the error of the wavelength must be taken into account. The dominating factor is the beam intensity, because it was measured without a calibrated photodiode, and an average wavelength had to be assumed due to its white-light nature. These numbers result in a net error of 30%. While this can be considered large, it is fine with respect to the goals of this test setup.

Table 9.2: Error assumptions for the IAG test setup.

Variable	Error	Justification
f	0.6%	(same as CSL)
d_{Sun}	2%	(same as CSL)
I	25%	uncalibrated + white light
T	5%	(same as CSL)
QE	5%	Conservative estimate
G	10%	(same as CSL)
λ	10%	white-light

⁶On a side note, LASCO/C2 on SOHO actually had a feature to focus onto the internal occulter. There, it was realised with an additional lens placed inside the filter wheel. Focusing on an arbitrary baffle was not possible, however.

9.4 Tests at RAL Space

The test setup used at RAL Space again follows the principle design of the CSL and IAG layouts. The dark tunnel is built the same way as the IAG tunnel (see Figures 9.4 and 9.5) using aluminium extrusion profiles, but with a slightly larger cross section of 90 cm and a length of 6 m. The light source is also set up at one end of the tunnel on an optical table, with the OBB mounted in the cage at its opposite end. Figures 9.6 and 9.7 show pictures of the setup and the OBB at one end of the tunnel, placed on two linear translation stages.

Figure 9.6: Picture of the test setup in the RAL laboratory.

Figure 9.7: Picture of the OBB in the RAL test setup, placed on two linear translation stages.

The light source for this test is a laser with a wavelength of $\lambda = 532 \text{ nm}$ and a power of $P = 1 \text{ mW}$. It is expanded to a beam diameter of 80 mm using a small doublet lens and a commercial, 30 degree off-axis parabolic mirror. This setup, in contrast to the IAG and CSL setups, does not fill the entire aperture of SCOPE, and is not visible over the occulter.

The beam irradiance was measured at approximately $(0.070 \pm 0.014) \text{ Wm}^{-2}$, again measured using an uncalibrated photodiode. The large uncertainty of 20% given in Table 9.3 is the result of large beam pointing fluctuations of the directly beam-expanded laser. I performed the measurement on three separate days, always after the laser had warmed up for at least 10 minutes. The results differed by over 10%, and I thus conservatively rounded up to 20% for the calculation. Also, without sufficient warm-up time, I observed a large gradient over the beam.

A large-format CCD-camera (Artemis 11002) was used as the detector. It features a KAI 11002 sensor (Kodak) with an active image area of $37.25 \text{ mm} \times 25.70 \text{ mm}$, so that almost the entire FOV can be observed. The quantum efficiency at the test wavelength is approximately $QE = 45\%$, the pixel pitch is $9 \mu\text{m}$ and the specifications report a gain value of $G = 0.92 \text{ e-/ADU}$. As shown in Figure 9.3, the camera is mounted at an angle compared to the other tests. This was done for mechanical reasons. The camera was modified at RAL Space for previous tests of other instruments and does not have a cover glass above the sensor. To avoid condensation, it must be flushed continuously with nitrogen gas. The pipe connectors for this flush favoured the specific camera orientation.

Following the prescription given in section 9.2, the conversion factor from ADU to MSB computes to:

$$F = (1.73 \pm 0.41) \cdot 10^{10} \text{ ADU s}^{-1} \quad (9.10)$$

The error is dominated by the uncertainty in beam intensity due to the laser beam pointing issue, resulting in a total error of 24%.

Table 9.3: Error assumptions for the RAL test setup.

Variable	Error	Justification
f	0.6%	(same as CSL)
d_{Sun}	2%	(same as CSL)
I	20%	beam pointing
T	5%	(same as CSL)
QE	5%	Conservative estimate
G	10%	(same as CSL)

As this test was devised following the results at IAG and CSL (see chapter 10), updated and more specific test objectives concerning the improvement of several design features were formulated:

1. Improve the edge quality of the spiders to reduce diffractive scattering.
2. Replace the conical baffles by a heat-rejection mirror (HRM).
3. Change the geometry of the FOV-defining third baffle (V3), and possibly all baffles, to a serrated design.

The work presented here covers the first task, i.e. to derive an appropriate spider-design with a quantification of its specifications. The other two tasks are not covered because the HRM and the serrated V3-baffle had not yet been manufactured at the time of this activity. The following steps were performed:

First, a few quick tests with the existing and newly produced spider-arms was made to establish the current status of both the instrument and the test setup. Some of the spiders were then reworked, until a few final sets of spiders was collected. The different versions of the spider-arms have already been described in section 8.3 and listed in Table 8.1.

Second, the two largest cones were removed from the OBB, even without the HRM ready as a replacement. The previous test phases had indicated that the background levels are limited by the diffraction from the cone edges, causing orders of magnitude more stray light at the lens aperture than the black painted baffle surfaces scatter. With the improved spider versions, a level was quickly reached that even the area around the spider-arms was dominated from stray light generated by the cones. In place of the cones, black tape and black flocked paper were applied to the rear wall of the OBB to mask the unpainted mounting flanges.

Figure 9.8 shows the rear wall of the OBB with the two largest conical baffles removed and instead covered with black flocked paper. A quick and simple test with light shining on the surface nearly on-axis suggests a reflectivity around 25% of Nextel paint. The rear wall was not covered fully because the collimator in the RAL setup does not illuminate the entire aperture. The area around the edge of the small cone was spared in order to not create another visible edge for the lens aperture.

The test setup was steadily improved by making adjustments as soon as the instrument sensitivity was improved enough to detect background features. These improvements include alignment of the collimator and placement of blackout materials in the test tunnel to lower the background brightness.

After these initial tests and improvements were done, further tests were made. One test was performed on the lens assembly (without the baffle tube) to assess its contribution to stray light. This was done by scanning the lens through the collimated laser beam and recording the stray light across the sensor. The procedure was repeated with both versions of the lens barrel that were described in section 8.3.

Figure 9.8: Rear wall off the baffle tube covered with black flocked paper after removing the two largest conical baffles.

A picture of the setup used to perform the lens barrel scan is shown in Figure 9.9. The lens and detector were placed on a rotary table to scan from an approximately central position out to an angle of 25° in steps of 1° . Beyond 25° , the scan was continued in steps of 5° out to an angle of 75° . At larger angles than 75° , the aperture-plate in front of the lens barrel already fully vignetted the lenses due to its non-negligible thickness. The scan is only performed in one direction due to the amount of time required to perform these measurements. Furthermore, the laser beam intensity had to be attenuated using a neutral density filter, with a different filter needed in the range below and above 25° .

Lastly, during the initial activities to finalise the different spider-arm versions, a systematic measurement plan was established to perform a final measurement with the different versions in one continuous test. Obtaining systematic measurements under equal conditions gives the most accurate results to derive a quantitative correlation between the measured surface characteristics and the measured scattered light. Table 9.4 lists the measurement plan, showing the front and rear spider version installed for each combination. The measurements are divided into three blocks: In the first block, the different sets of spiders were used. In the second block, the best rear-spider was kept and only the front spider varied. In the third block, the best front spider was kept and only the rear varied. The goal of the last two blocks, which are complemented by measurement M4, is to determine the relative importance of roughness of the front and rear spider.

Figure 9.9: SCOPE optics and CCD camera mounted on a rotary table for a scanning test to determine the lens barrel scatter contribution.

As the occulter is held by two spider-arms on two sides (4 in total), but not each version of the spiders was available as a full set of 4, the spiders under test were installed on the right side of the OBB (as seen from the lens barrel) for the systematic test. The other side is constantly equipped with a second set of S4-type spiders, which showed the lowest scattering levels besides the spider-arms used for the systematic test.

Table 9.4: Measurement plan for the spider-arm tests at RAL Space.

Measurement #	Front Spider	Rear Spider
M1	S2	S1
M2	S3	S3
M3	S4	S4
M4	S5	S5
M5	S2	S5
M6	S3	S5
M7	S4	S5
M8	S5	S1
M9	S5	S3
M10	S5	S4

Chapter 10

SCOPE Test Results

In this chapter, I show the results of the SCOPE OBB testing activities. They are presented in the order that the tests were conducted, which differs from the order of the test setups described in chapter 9. The first results obtained at IAG are presented in section 10.1, followed by the results obtained at CLS in section 10.2 and finally the results obtained at RAL Space in section 10.3.

10.1 Tests Results from Institut für Astrophysik

Figure 10.1 shows the first image obtained with the SCOPE coronagraph in the IAG test setup. The image colours show mean solar brightness, converted from raw data using the conversion factor $F = 2.17 \cdot 10^{10} \text{ADU s}^{-1}$ given in section 9.3. The beam diameter of the collimator was set to its maximum, so that the baffle tube was fully illuminated. Three strong stray light features are observed in the following image areas:

1. A circular ring around the occulter
2. A wide line along the locations of the spider-arms
3. In the left image corners

These three features were subsequently linked to the following components: The first feature is caused by scattering on the collimator primary, and was expected for this configuration due to the tunnel dimensions (compare Figure 9.1). The second feature is caused by the spider-arms, as the locations exactly coincide. The third feature is caused by the baffles and/or cones, as it lies in the vignetted portion of the outer FOV (compare Figure 9.3).

Figure 10.1: First image obtained with SCOPE in the IAG laboratory setup, converted to mean solar brightness (MSB).

To investigate the second and third features in detail, the lens barrel was replaced with the Canon DSLR camera. Figure 10.2 shows an image where the aperture of the camera lens had been stopped down to $f/22$ to bring all features inside the OBB close to focus simultaneously. Here, the stray light appears to originate from the edges of the spider-arms, the V3 baffle and the C1 and C2 cones. Strong colour patterns are visible, indicating the presence of diffractive effects.

Note two things about Figure 10.2: First, the bright ring around the occulter (i.e. feature 1 caused by scatter on the mirror surface) is not visible in this image

Figure 10.2: Image obtained by replacing the SCOPE lens barrel with a DSLR and 24mm camera lens, stopped down to $f/22$ to obtain an image with all features roughly in focus simultaneously.

because the camera aperture at $f/22$ is much smaller than the SCOPE aperture and hence shaded fully by the occulter. Second, the circular scattering features of the vanes appear decentred because the DSLR camera was not perfectly centred behind the OBB. This is not an indication of misalignment between the baffles.

A second image, taken with a slightly wider aperture and focused on the rear spider-arm, was used to highlight the difference to a ray-tracing simulation that involved only scattering on matte black surfaces. This is shown in Figure 10.3, with the simulation at the top and the DSLR image at the bottom. The stray light from the spider-arm and baffle edges is not visible in the simulation, and also could not be reproduced by simple means like rounded edges and an angled input beam. The only identical feature, indicated by the red arrow, is a line along the centre of the spider-arm. This feature is due to lambertian scattering on the rounded rear edge of the S1 spider-arm (see Figure 8.8).

At this stage, the roughness of the black Nextel paint was suspected as the source of the unexpected stray light, as it was coated over the edges of the spider-arms, baffles and cones. To confirm that stray light could in fact be improved by smoother edges, sharp objects were used to mask the spider-arms. Figure 10.4 shows the

Figure 10.3: Comparison between a ray-tracing simulation (top) and a DSLR-image (bottom), showing a cropped region around the outer edge of one rear spider-arm. The red arrows indicate a bright line due to the rounded edge of the S1 spider-arm.

first, simple setup using a kitchen knife sharpened with a 10,000 grit whetstone. The knife was masked with black tape except near the cutting edge to avoid reflections on blank metal. The cutting edge was placed as close as possible to the upper edge of the front spider-arm, in order to not increase the diffraction angles. The result in Figure 10.5 shows a much reduced level of stray light. The two bright, quasi-circular features originate from two small scattering centres on the underside of the knife. Some residual stray light along the spider-arm location can be seen. It is most likely caused by reflections from the unmasked metal near the cutting edge.

Figure 10.4: First setup to test for improved spider-arm scattering by placing a sharp knife in front of the OBB. Except for the cutting-edge, the knife is masked with black tape.

Figure 10.5: Result from the test setup to block the spider-arm with a sharp knife (Figure 10.4).

After testing a few different setups, a 3D-printed mount was designed to hold a set of small carpet-knife blades. This provided the best result while not significantly increasing the size of the spider-arms, and could also be applied to the spider-arms on both sides of the occulter. (Unfortunately, no image of the setup installed on the OBB was taken.) This reduced the signal seen to a few scattering centres, either due to dust particles or small defects in the knife blades, which could not be removed by careful cleaning.

Additionally, a series of measurements was taken where the diameter of the collimated beam was successively reduced using the iris aperture in the light source assembly. The beam diameters were set so that it just covered the edges of V3, the cones C1 and C2, and finally only the occulter. Between each image, a reduction in the background level was observed, although the exact contributions of tunnel background illumination, scattering on air/dust and the stray light from the baffle edges could not be distinguished. Only one ghosting feature from either the edge of cone C1 or C2 was visible - which one exactly was not clear from this test as the beam diameter may have been reduced slightly too much for cone C2. The images obtained at RAL Space, where the background was lower overall, show the ghosts more clearly, see e.g. Figure 10.18.

Finally, the beam diameter was reduced so far that only the occulter remained fully illuminated. Figure 10.6 shows the image obtained with this configuration. The illuminated area of the collimating mirror is no longer visible, and the background levels are also much reduced. Diffraction rings around the occulter can now be observed. A magnified view, shown in Figure 10.7, reveals about 5 rings. Due to the reduced beam diameter, a comparison with Figure 10.1 in terms of the background stray light levels can not be made.

Figure 10.6: Result after blocking both spider-arms with carpet-knife blades, and the beam diameter reduced to just illuminate the occulter.

Figure 10.7: Magnification of Figure 10.6, showing the diffraction rings around the occulter.

Figure 10.8 shows a plot comparing the measured diffraction profile and simulated values at 530 nm and 800 nm wavelengths. The profile was extracted by fitting the centre of the diffraction rings, then interpolating the image and integrating along circular arcs. For this image, two 60° wide arcs at the top and bottom were used for the integration to avoid scattering features from the spider-arms. Figure 10.9 shows the fitted first diffraction ring (orange) together with the range for integration (red). The chosen angular range showed the best compromise between clear diffraction rings and including too many background features.

The extracted diffraction profile does not match either of the simulations in terms of intensity, location or shape. While the location of the first diffraction ring lies close to that of the simulation at 800 nm, the spacing of the further rings is too narrow. However, it is too wide compared to the 530 nm simulation. The measured intensity is approximately a factor of 30 below the simulation at 800 nm and a factor of 2.5 below the 530 nm simulation. Diffraction simulations for further wavelengths were not computed because the purpose and precision of the IAG tests did not justify the additional, large computation time required. The scaling factor of 12.0 in Figure 10.8 for the measured values was chosen in between for illustrative purposes only.

After these initial results had been evaluated, it was decided to manufacture a new set of front spider-arms (version S2) before delivery of the OBB to CSL. Figure 10.10 shows a stray light image obtained with the new configuration. The levels around the spider-arms are improved from the original configuration, although some scattering is still visible. The setup was not allowed enough time for the dust in the air to settle, which is why the background levels appear elevated compared to Figure 10.1. The excess brightness at the spider-arms over the background was estimated by averaging small sections on an just beside the spider-arm locations, resulting in a value of around $1.0 \cdot 10^{-8}$ MSB.

Figure 10.8: Comparison of the diffraction profile extracted from Figure 10.6 and simulated values for monochromatic, collimated light at 530 and 800 nm. The scaling factor of 12.0 of the measured data is chosen for illustrative purposes only.

Figure 10.9: Magnification of Figure 10.6, showing the fitted first diffraction ring (orange) and the selected range for integration (red).

Figure 10.10: Result obtained with the second spider-arm (S2). The background in this image is heavily dominated by dust in the air.

Mechanically measuring the co-alignment of components inside the fully assembled OBB was not possible, as the measurement probes of e.g. a coordinate measurement machine could not reach far inside the instrument. To get an indication of the alignment of the occulter w.r.t. the axis of the baffle tube, the OBB was aligned to the collimated beam so that the diffraction rings around the occulter appeared as symmetric as possible. (The same had been done to obtain Figure 10.6.) Afterwards, a photo was taken from the front to check the position of the shadow of the occulter around the A1 aperture. Figure 10.11 shows this photo. A decentration of the shadow is clearly visible. This decentration was forward-modelled by ray tracing, where the collimated beam and occulter were kept co-aligned as an assumption from the symmetric diffraction rings. The baffle tube was rotated and shifted in the simulation to match the observed shadow location. This is shown in Figure 10.12. When a shift or tilt only were considered, values of roughly (0.7 ± 0.2) mm and (4 ± 1) arcminutes, respectively, were obtained. Of course, the real value could be a combination of the two. It is also not fully clear how the alignment to symmetric diffraction rings is affected by such a displacement, adding a systematic error to these values. It is most likely, however, that the decentration of the shadow is dominated by the occulter tilt, as mechanical measurements that could be made constrained the shift of the first occulter disc to 0.2 mm. However, for a stack length of 200 mm, a tilt of $4'$ corresponds to a shift of only 0.25 mm of the rear end of the occulter relative to the front. Further results concerning the occulter alignment are presented in section 10.3.

Figure 10.11: Picture showing the shadow of the occulter around the aperture and smallest cone. The OBB was aligned for the diffraction rings to be as symmetric as possible. A second light source was placed close to the camera to make the surrounding structure visible.

Figure 10.12: Forward-modelled ray-tracing of Figure 10.11. The angle of the camera and the support light were approximated to match the photograph.

10.2 Tests Results from Centre Spatial de Liège

Figure 10.13 shows the on-axis image obtained in the test chamber at CSL. This test setup is also limited close to the occulter by scattering on the collimating mirror, again as expected. The mirror performs better than that at IAG, and the scatter does not extend as far into the image, but the brightness is slightly higher than predicted by simulations during an earlier planning phase of the project. The spider-arms also still show a large amount of scattered/diffracted light here, in agreement with the estimate of $1.0 \cdot 10^{-8}$ MSB derived from Figure 10.10. The background also remains limited to about the same level of 10^{-9} MSB, but with less structure from the tunnel being visible compared to IAG, which would indicate a limitation by the instrument rather than the test facility.

Figure 10.13: On-axis test result from CSL. The collimator mirror again shows strong scattering, limiting the test result close to the occulter.

As this setup does not include an iris aperture to reduce the beam diameter, the diffraction rings of the occulter could not be made visible by stopping down the beam. Instead, the hexapod was used to shift the entire OBB sideways inside the beam. Since the mirror scatter only extends slightly beyond the occulter, it was possible to observe the diffraction around the occulter in at least some area of the image. Figure 10.14 shows the resulting image for a lateral displacement of 125 mm. Diffraction rings can be seen, but they appear asymmetric. The alignment of this setup to the collimated beam was made by rotating the hexapod and observing the location of the light source on the detector, then rotating the hexapod back to position the light source on the optical centre of the lens. The observed asymmetry of the diffraction rings thus indicates a misalignment of the occulter with respect to the lens barrel. Due to the background stray light and the weak strength of the diffraction signal on the bottom side, the misalignment can not accurately be modelled from these results, however. Measurements taken at IAG and RAL Space, despite showing similar asymmetries in some measurements that were taken as part of the procedure in each case, can neither be taken as a reference, because those test setups did not allow accurate measurements of the

alignment of the collimated beam to the lens barrel. The value derived from Figure 10.11 does not apply either, because the spider-arms were changed between these measurements, and the results obtained at RAL Space show that this can have a strong impact on the occulter alignment.

Figure 10.14: Off-centre test result from CSL, where the OBB was shifted laterally by 125mm.

The diffraction-ring profile extracted from Figure 10.14, using the same algorithm as for Figure 10.8, is shown in Figure 10.15. A smaller angular range of 30° on both the top and bottom was used here, as the remaining part is either out of the FOV or affected too strongly by the collimating mirror. The value shown are the average of the top and bottom part of the rings, which is expected to be a good approximation of the on-axis intensity for tilts below $5'$, i.e. comparable to the value derived from Figure 10.11 at IAG.

The measured intensity of the first diffraction ring is a factor of 1.8 below the simulated value. Its location shows a significant mismatch between the theoretical and measured values. A small scaling of the x-axis is already applied to account for the measured focal length of the lens (109.3 mm compared to a nominal 110.0 mm assumed by the simulation), but its effect is much below what is observed here. The scaling required to match the first diffraction peak would imply a focal length of 120 mm, which is unreasonable. Instead, the profiles match very well when an additional shift of 0.148 mm, equivalent to about 16 px, is applied, as shown in Figure 10.16. However, the resulting circle centred at the shifted location would not match the observed diffraction ring. It is not clear what caused this effect, as it was not observed in simulations of off-axis beams.

Figure 10.15: Comparison of the diffraction profile extracted from Figure 10.14 and the simulated value for 800 nm.

Figure 10.16: Comparison of the diffraction profile extracted from Figure 10.14 and the simulated value for 800 nm. The measured profile is shifted by 0.148 mm to match the simulation.

10.3 Tests Results from RAL Space

Figure 10.17 shows the results of the lens barrel scatter measurements, where the “old” lens is the one that was used during the tests at IAG, and the “new” lens that used at CSL and RAL Space. The values are computed as the average value over the entire sensor, after subtraction of a dark image. For the images up to 10° , where the laser spot directly hit the image sensor and caused blooming, a 400-pixel wide column around the main spot was excluded before the computation. The new lens shows lower scattering levels over most of the FOV than the old lens. The strong peak around 15° in both lens barrels is explained by the light being focused onto the interior of the lens barrel, which is a glossy black anodized surface that re-scatters onto the detector. At RAL Space, part of this surface was subsequently blackened further using black flocked paper, resulting in the third curve shown in the Figure. The angular ranges subtended by the baffle and cone edges as seen from the aperture are marked. As the stray light from the cones is diffractive, the behaviour might not be as simple, but the Figure shows that particularly the two largest cones, which are fully illuminated by design, scatter into the angular range around 15° . The new lens also shows a second peak around 25° that is not eliminated by the flocked paper. This is due to the different diameter of the front section of the lens barrel, as described in section 8.3, causing a second reflection path in the new lens.

Figure 10.17: Comparison of the measured lens barrel scattering, averaged over the CCD sensor, for the different barrel versions. The angular ranges of the aperture seen by the baffle edges are indicated.

One of the initial images acquired with the test setup at RAL Space is shown in Figure 10.18. The spider-arms on the right side of the occulter were still in the same configuration as during the tests at CSL (S2 front, S1 rear). The spider-arms on the left side were replaced by the S3 version, which had been manufactured between these tests. The lens barrel was not yet blackened with black flocked paper as described above. Diffracted light from the conical baffle edges is strongly visible. The background appears to show several steps (in the form of concentric rings) as seen before in Figure 10.5, which might be a result of ghost images of the cone edges. Some features of the tunnel can be seen in the image as well, but only slightly over the strong stray light.

Figure 10.18: Initial image obtained with the RAL Space tests setup. The spider-arms on the left side of the occulter have been replaced with a remade version (S3), while the configuration on the right side is identical to CSL (S2 - S1).

Figures 10.19 and 10.20 show the final images using spider-arm versions S4 and S5, respectively, installed on the right side of the occulter. The left side is equipped with a second set of S4-type spiders, which was not quite as well polished but otherwise the best performing set. These images were furthermore taken with the lens barrel fitted with black flocked paper, as well as the conical baffles replaced by black flocked paper as described in section 9.4. The S4 and S5 set show similar low levels of scattered light. One notable difference about the S5-version is a bright stripe across the image, perpendicular to the spider-arm. It is caused by a reflection off the polished front of the spider-arm, which was applied in strokes along the spider-arm, and the residual grooves thus reflect (or possibly diffract) in the perpendicular direction. The S4-spider-arm lacks this feature, most likely due to a combination of their black base material and a different front surface finish.

Another notable aspect is the different asymmetry of the diffraction rings around the occulter. This indicates a change in the occulter alignment solely through swapping one side of the spider arms, as the OBB itself was fixed firmly inside the cage and not re-aligned for each individual measurement. The latter would not have been possible due to measurement time constraints.

Figure 10.19: Image obtained with the S4 spider-arms, installed on the right of the occulter, and the conical baffles replaced by black flocked paper. The dark spot near the top right corner is an artefact from the dark-image.

Figure 10.20: Image obtained with the S5 spider-arms, installed on the right of the occulter, and the conical baffles replaced by black flocked paper. The dark spot near the top right corner is an artefact from the dark-image.

For some further diagnostics of the residual diffraction of the S5 spider-arms, the lens barrel was again unmounted and replaced with the same DSLR and lens used at IAG in macro-imaging mode. Figure 10.21 shows the region around the front spider-arms, onto which it was also focused. On the top, a single strong scattering centre can be seen, probably corresponding to a point defect in the edge. Otherwise, the edge appears very dim. The bottom side additionally shows scattering off the side face of the spider-arm, indicating some roughness on these sides (which were not actively polished). Some scatter is still visible along the rear-facing edge, similar to what was shown in Figure 10.3, although also much reduced due to the thinner edge in this version.

Figure 10.21: Picture of the setup from Figure 10.20 taken with a DSLR, focused on the front spider-arm. Only the region cropped around the illuminated part of the right spider-arm (S5) is shown.

Table 10.1 lists the result derived from the systematic test sequence. The stray light levels were evaluated from an average of two small, rectangular regions of the scattering region and immediately next to it. The regions were chosen manually, and the procedure repeated for several locations. This was necessary particularly for the best results (involving spider-arms S4 and S5), as the stray light produced was not far above the background levels. Figure 10.22 shows an example of the choice of the regions from measurement # M4. The resulting images from measurements #M3 and #M4 are shown in Figures 10.19 and 10.20. The remaining images can be found in appendix B.

For measurement M10, the lowest value are observed in only a small part of the spider-arm region. For this reason, the value is put in brackets in the table. The other areas along this spider-arm appear to be dominated by the point defect on the front-S5 mentioned above, and possibly some residual particulate contamination present during this particular measurement. To put this value of $2 \cdot 10^{-12}$ MSB into perspective, it was only 8 ADU per pixel above the estimated background level in that location, for a 600 s exposure.

Measurements M4, M8, M9 and M10 show that the roughness of the rear spider is important in this design despite the fact that it is shadowed. Even with the S3-spider, which had a barely measurable roughness of around $1 \mu\text{m}$, the stray light is a factor of 10 higher than with S4 or S5 as the rear spider. This is also confirmed by the measurements M2 and M6, where the contribution by the front and rear spider is comparable.

Table 10.1: Measured stray light enhancements of the spider arms.

Measurement #	Spider-arms (front - rear)	Stray Light (MSB)
M1	S2 - S1	$4.3 \cdot 10^{-9}$
M2	S3 - S3	$1.4 \cdot 10^{-10}$
M3	S4 - S4	$2.3 \cdot 10^{-12}$
M4	S5 - S5	$4.1 \cdot 10^{-12}$
M5	S2 - S5	$4.3 \cdot 10^{-9}$
M6	S3 - S5	$8.4 \cdot 10^{-11}$
M7	S4 - S5	$3.0 \cdot 10^{-12}$
M8	S5 - S1	$7.8 \cdot 10^{-11}$
M9	S5 - S3	$3.2 \cdot 10^{-11}$
M10	S5 - S4	$(< 1.9 \cdot 10^{-12})$

Figure 10.22: Example illustrate how the stray light levels of the spider-arms were evaluated. The yellow rectangle indicates a position over the spider-arm, the blue rectangle over the background. The rectangles were moved to multiple positions to estimate the average value.

Figure 10.23 shows the profile of the diffraction rings around the occulter, extracted again by the same procedure used to generate Figure 10.8. The measurement from the S4-spider-configuration (Figure 10.19) was used for this image, as it showed the most symmetric diffraction rings. The clean background now also allowed to use a very wide angular range of a total of 320° to extract the profile.

In this case, the profile matches the theoretical computation very well. A shift of the profiles, as in the CSL test (Figures 10.15 and 10.16), was not required here. Instead, a very small scaling by a factor of $1.01 \approx$ was used, but this could be explained by a small error of the lens focal length. About 20 diffraction rings can be distinguished by eye. The amplitude of the outer peaks is not as large as in the simulations, but it has to be kept in mind that the detector pixel scale of $9\text{ }\mu\text{m}$ is below the design scale of the lens system at $30\text{ }\mu\text{m}$, so the resolution might be reduced due to aberrations. The simulation assumes an ideal lens.

Figure 10.23: Comparison of the diffraction profile extracted from Figure 10.19 and the simulated value for 530 nm. The x-axis values of the measured data are scaled by a factor of 1.01 to match the profiles.

Chapter 11

Discussion of the SCOPE Test Results

The three test phases at IAG, CSL, and finally RAL Space have revealed many important details about both the construction as well as the testing of a space-borne, externally occulted coronagraph. Due to the differences between the test setups, e.g. the light source wavelength or the collimator size, some of the results complement each other as independent experiments. In this chapter, the findings are discussed separately with respect to the different components of the coronagraph in section 11.1, and with respect to the test facility requirements in section 11.2.

11.1 Coronagraph Design Aspects

11.1.1 Occulter

In all three tests, it was possible to observe the diffraction pattern around the occulter, so that measurements are available for three different light sources. Unfortunately, some errors remained in each case due to different aspects of the setup and components involved.

For the IAG tests, the white-light nature of the light source made it difficult to characterise and calibrate the test setup, as well as to compute accurate simulations for comparison. The CSL-tests were affected by the necessary workaround for the collimator mirror scatter in the background, giving rise to an unaccounted factor in the beam intensity drop off, the missing aperture-plate, as well as the unknown misalignment between the occulter and the collimated beam. Lastly, the test setup at RAL Space suffered from pointing instability of the laser light source, and also lacked the precise alignment features for some characterisation.

A first lesson from this for future coronagraph designs is to incorporate specific features to precisely align the occulter with respect to the lens system. The large size of SCOPE made measurements on the assembled system nearly impossible. This is particularly important in experimental work when different setups are

compared, exemplified by the test of different spider-arm versions at RAL Space, where the diffraction pattern changed visibly due to slight alignment changes. The forward-modelling done with the images at IAG (Figures 10.11 and 10.12) revealed a significant misalignment of, effectively, 4 arcminutes. This value assumes the entire error in the occulter tilt, but could be a combination of occulter tilt and occulter shift. It might also have been a result of accumulated tilt and shift of the smallest conical baffle, which was the image reference for the shadow position, via the 5 baffle tube segments and the rear wall. However, from the test sequence at RAL Space, I will conclude that this is realistic for the SCOPE mounting scheme.

In the test sequence at RAL Space, the centre of the diffraction rings moved with a peak-to-peak variation of 11.6 pixels between the two most extreme images, or $3.3'$ at the plate scale of the camera. Since the visible diffraction originates from the final disc, the rings are assumed to represent the location of the final disc. With a distance of 400 mm, this corresponds to a displacement of $d = \tan(3.3') \cdot 400 \text{ mm} = (0.38) \text{ mm}$. For the “best” measurements at IAG and RAL Space, the instrument was aligned in such a way with the light source that the diffraction rings appeared most symmetric. While it is expected that the pattern is mostly unchanged if the aperture is only shifted inside the shadow of a well aligned occulter, it is not clear how this misalignment affects the measurements. In any case, a misalignment should lead to an increased diffraction signal compared to simulated values.

Ultimately, the final result obtained at RAL Space (Figure 10.23) shows the best agreement with the simulations. About 20 diffraction rings fit very well with the theoretical profile. The intensity is slightly below the theoretical value with a factor of 1.49 ± 0.36 , but close when the large uncertainty of 24% for this set setup is considered.

The result obtained at CSL is also below the theoretical intensity, with a slightly larger margin of 1.82 ± 0.25 (Figure 10.16), at an estimated uncertainty of 14%. The beam calibration in this case is better than at RAL Space, assuming that the correction for the missing aperture is accurate near the image centre. The source stability is also better, leading to a smaller uncertainty estimate. On the other hand, due to the different pointing calibration, the diffraction profile is asymmetric. The exact impact can't be estimated due to the missing information of occulter misalignment. The profile also only matched the simulations when shifting the entire curve. The amount of shift required is far greater than could result from an inaccurate fitting of the diffraction rings. The reason for this effect is not clear. It could be a result of the misalignment. The same lens system was used as for the RAL tests, hence differences in the lens focal length can not explain any deviation. The axial position of the occulter could also not have shifted by the amount required for this error.

The measurement at IAG (Figure 10.8) remains difficult to interpret quantitatively. The incoherent, white-light source causes a different diffraction profile with a lower identified number of peaks. Determining a correct “average” wavelength for comparison with simulations would require a more elaborate calibration procedure in this case. The comparison with the available simulations shows a similar intensity relative to the 530 nm simulations as the other tests, but a profile closer

to that at 800 nm. Despite this, I see it as a result from the IAG test that it is possible to test an occulter down to the required performance in a simple, non-clean room laboratory through the means of a reduced beam diameter. A final coronagraph test should also use a broadband light source to characterise the diffraction for a non-coherent source like the Sun.

As far as the mechanical design of the occulter is concerned, the total stack length of 200 mm is fairly large, both in comparison with existing instruments as well as other recent studies (e.g. Yang et al. 2018). The metrology results after manufacture support the possibility to manufacture a more compact occulter, also with a larger number of discs, without significant challenges in manufacturing or a loss of accuracy. One drawback of this, which must be taken into account, may be a more difficult mounting scheme, as the area between the discs will not be as accessible with a shorter spacing. It is also unclear if there would be a greater impact of mechanical imperfections of the discs and - particularly - contamination by dust particles, as noted already by Bout et al. (2000), Thernisien et al. (2005) and recently Yang et al. (2018). With a larger number of discs and shorter disc spacing, the difference in consecutive disc radii is lowered, and thus an individual scattering centre might be visible above one or more discs. This is supported even by experience with the current occulter in the RAL Space tests, as a particle had to be cleaned off on a few occasions. It is thus imperative that an explicit cleanliness plan is devised, including a procedure to clean the occulter before launch, and keep it clean during launch vibrations.

In terms of the occulter disc shape, it appears that the multi-disc circular occulter will be able to provide sufficient stray light suppression. More complicated shapes might thus not provide a significant merit for near-future compact coronagraphs, compared with the simplicity of manufacture of circular discs, although other studies (Bout et al., 2000; Yang et al., 2018) suggest the conical occulter to also work. This aspect was already mentioned by Newkirk and Bohlin (1963). Their comment on the requirement that the discs need to be very precisely aligned appears achievable, as the occulter can be machined as a single part on a CNC turning machine. Depending on the exact requirements for disc edge roughness, some additional error in the individual disc radii might be introduced if each disc needs to be polished individually. An additional, systematic test campaign would be required to investigate these aspects of further advanced occulter designs.

11.1.2 Spider-Arms

The spider-arms have proven to be a critical component for the compact coronagraph design. As they stretch over the entire FOV at a certain position angle of the image, their stray light contribution must be low enough to not adversely affect this region.

The first versions of spider-arms produced for the tests at IAG and CSL showed high stray light levels in excess of $1 \cdot 10^{-9}$ MSB (Figure 10.1 and Figure 10.13). Another, less rough version (S3), manufactured again by wire-cutting, showed improved levels, however still in excess of $1 \cdot 10^{-10}$ MSB (Table 10.1). Matte black

painting and wire-cutting should thus be ruled out as suitable manufacturing and finishing techniques for this component.

Promising results were achieved using polished spiders made from both simple PLA-plastic (S4), as well as aluminium (S5). The levels observed in the darkest parts for the best combination of front and rear-spider was below $2 \cdot 10^{-12}$ MSB. This would mean that the stray light budget described in section 8.2 is almost already met. Close to the occulter, where this value was measured, this is already below the requirement. Full illumination over the entire FOV could not yet be tested at RAL Space, but it can be expected from the general behaviour of the diffractive scattering that the level should be slightly lower further out, as seen for example in Figure 10.1 with the original rough spiders (S1) at IAG. The images acquired using a DSLR camera with macro lens furthermore suggest that the residual stray light is dominated by small defects and insufficient polish of the side-faces for the aluminium spiders, which would be unrelated to the diffractive performance. In these spider-arm versions, it was attempted to polish a sharp edge. It could be beneficial to polish a round edge, as sharp edges are always more susceptible to damage. The resulting curvature could be kept small enough that no significant amount of light is scattered (instead of diffracted) into the aperture by the visible portion of the round edge. It is not clear from existing literature how the problem of spider-arm scattering is handled by other groups studying the compact coronagraph. In the test results shown in Yang et al. (2018), scatter from the spiders is visible as well, but little mention of this is made.

At certain times during the tests, dust particles got caught on the edges of the spider-arms, causing additional scattering centres. This lead me to conclude that cleanliness will be even more important for the spider-arms than for the occulter. The spider-arms can not be hidden from the aperture by consecutive shadowing as for the occulter discs, so that dust particles stuck on the front spider will directly scatter light into the lens aperture. The only way to achieve this would be to increase the width of the spider-arms to the width of the occulter discs, but this would introduce full vignetting into a portion of the FOV, which is also undesirable for observational purposes. During the frequent handling of the OBB at the RAL Space tests, the polished spiders had to be cleaned on several occasions. However, because this procedure actively generated debris from paint, and there were also some particulates stuck to the black sheeting of the tunnel, it can not yet be concluded in general if well maintained ISO 5 levels would present an issue. Ideally, this would be investigated in combination with vibration testing, to check if debris generated during launch can present an issue.

As Figure 10.20 showed, polished spiders can show a feedback into the test chamber by reflecting the light incident on their front surface into a visible part of the test chamber, thus contaminating the background. It requires further design iterations to check if this would be solved by a better polish of the front surface, thus directing the light back close to the source where it is blocked by the occulter.

11.1.3 Baffles

Like the spider-arms, the baffle vanes of the main tube also produced a large amount of diffracted stray light in the original SCOPE design. In this case, though, the reason is not only the rough edge. For a circular baffle, there is always diffraction into the centre. Existing instruments such as LASCO and SECCHI had used star-shaped baffles to reduce the diffracted light into the objective lens. For SCOPE, the amount was initially expected to be lower due to the larger overall size of the instrument, a relation that is also mentioned on the topic in literature (Bout et al., 2000). Together with the fact that it was impractical to simulate large baffles due to computational constraints, this led to the decision to manufacture simple, circular baffles. Furthermore, the attempt to replace the classical heat rejection mirror with a number of conical baffles further amplified the issue, as now multiple circular apertures were illuminated and scattered into the lens system.

With the limited FOV and background stray light issues at IAG and CSL, the exact impact on background stray light could not be quantified in those tests. With the larger CCD sensor available at RAL Space, together with clean room conditions and a dark background, it became obvious that the diffraction plus subsequent scattering in the lens system presented a major limitation. In this specific case, the background levels seen in Figure 10.18 showed a background limitation to around $1 \cdot 10^{-9}$ MSB when only the two largest cones were illuminated. This value should not be seen as an absolute limit for circular baffles, though. In Figure 10.17, a large specular reflection inside the lens barrel is shown, which can be expected to generate stray light on the sensor from mainly the middle conical baffle. Reverting to a classical heat-rejection-mirror design (more details are given in the following section) would reduce the issue to one baffle edge, and the lens system can be improved to cause less re-scattering.

Presently, work on SCOPE continues at RAL Space to fix and further investigate the baffle design. A star-shaped baffle and heat rejection mirror was manufactured in parallel to the activities reported here and will be tested in detail after the collimator was upgraded to a wider beam diameter, which will be required to illuminate the new baffle. Experimental tests with a star-shaped baffle will also have to confirm the requirements on edge roughness, similar to the spider-arms. Manufacturing is expected to be a bit more time-consuming due to the larger circumference. To achieve good polish everywhere and sharp interior corners, it is foreseen to manufacture the baffle from two halves that stack with half a wedge of rotation. The inner corners are then produced as the overlap of two wedge faces.

11.1.4 Heat Rejection Mirror

As noted in the previous section, the conical baffle design was found to be too problematic, and needs to be reverted to a classical HRM concept. Direct results were not presented here as the mirror for SCOPE had not yet been manufactured, but an aspect about its design is already evident from the tests.

it is evident from the tests that two aspects about its design will need to be considered.

A central bore is required in the HRM to allow coronal light to pass through the lens aperture. This bore obviously needs to lie in the shadow of the occulter, or there will be effects from both light leaking past it and light diffracted on the bore edge, as with the circular baffles. In Figure 10.19, some residual diffracted light is still visible even without any cone being directly illuminated. Note that the Figure shows a step in the diffracted light, as there was some stray illumination of baffle V3. This effect can probably not be avoided with the HRM bore, but the margins of its location must be considered. Ideally, the bore itself would form the defining lens aperture. With SCOPE, the HRM is manufactured as a replacement for the conical baffles, and will mount into the existing rear wall. This creates some space between the lens aperture and the mirror surface. The further away from the aperture the mirror is, the wider the central bore needs to be as per the OFOV angle. If it is placed too far away, the margin for misalignment before the bore edge becomes illuminated will be small. For SCOPE, the numbers still work out, but in the future, if attempts will be made to shorten the compact coronagraph even further, the occulter would shrink, too, and with it the size of its shadow. This leads to the same argument that bore should define the lens aperture.

11.1.5 Lens Barrel

The lessons learned from the various components in the baffle tube are valuable also to simplify the lens design as far as possible. Keeping the stray light that reaches the lens aperture to a minimum also lowers the requirements on glass quality and the barrel design, as more re-scattering could be accepted.

The lens barrel built for SCOPE consists of flat, black anodized surfaces without an internal baffle structure. The test results have shown that this poses a great risk for re-scatter of diffracted light from the baffles, as demonstrated in Figure 10.17 with the off-axis scattering test. Some slight baffling should hence be included, although it is not currently expected that this needs to be very complicated.

Having a separation between baffles and optics has also proven very valuable for testing the coronagraph, as the lens barrel could be swapped out for other lenses, allowing tests that focus inside the baffle tube for diagnostic purposes. In the development of SCOPE, this helped to confirm stray light sources, and could even be used to characterise the nature of stray light generation, e.g. as shown in Figures 10.2 and 10.21.

This also opens up the possibility to develop a fully modular coronagraph system, that could be configured easily for different mission requirements. For example, if a baffle tube is designed for a particular FOV, it can then be equipped with a simple, low resolution lens (e.g. for an operational satellite in L5 where the telemetry is low), or a more complex, high-resolution lens (e.g. a scientific mission in a near-Earth orbit.). If the baffle tube can indeed be manufactured to create less stray light than the coronal background, no alterations to its design or manufacture would be required.

11.2 Coronagraph Testing

As laid out first in section 9.1, testing a coronagraph is a challenging task due to the high stray light rejection ratios that need to be achieved, in combination with the specific FOV all around the light source. In this section, I want to discuss some further aspects for the design of a coronagraph test chamber.

The ambient conditions of the test with respect to cleanliness have also proven to be an important factor for different reasons. A comparison of Figures 10.5 and 10.10, both performed at IAG with the maximum beam diameter, demonstrates the need to let the setup settle for an appropriate amount of time after handling to allow dust in the air to settle. Even with a reduced beam diameter, this effect is visible in Figure 10.6. At IAG, where the tests were not performed in a clean-room environment, improvements could still be observed after an hour of settling time. Even in better conditions at RAL Space, meeting at least ISO6 specifications, dust particles were occasionally observed, e.g. visible in Figure 10.21, and settling for at least 10 minutes showed an improvement. As mentioned in the paragraphs above, the possibility of dust particles sticking to baffles, spider-arms or the occulter presents a potential source of unwanted stray light that could seriously impact the instrument performance in some areas of the image even after launch into space.

For SCOPE, an important aspect was the dimension of the test chamber, specifically the distance between the instrument and the collimating mirror of the light source. Even a high quality polished mirror in a clean room environment, as used in the tests at CSL, scattered so much light on its surface that the background level was dominated close to the occulter. For SCOPE, a chamber length of at least 16 m would be required for an unobstructed test, as computed in section 9.1. This number is not valid for coronagraph tests in general, as it is a combination of the inner FOV limit and the diameter of the first instrument aperture. A test chamber of over 16 m length is not readily available, especially if advanced requirements that were not yet needed for SCOPE are considered. This includes a test in vacuum, or better clean room conditions than the ISO5 levels used here.

When a sufficient chamber dimension is not available, the limitation imposed by scattering on the collimator primary needs to be overcome by other means. The tests at IAG have demonstrated that useful tests are possible at least for the occulter by reducing the beam diameter. However, this will not be a viable solution for testing every performance aspect, as the total stray light level can only be determined with full illumination.

The observations, in combination with modelling in case of the CSL test, confirm that the source of scattering was scratch/dig and dust on the mirror surface. The surface microroughness is of little importance here, as it causes strong forward-scattering but only weak diffuse scattering at the angles of interest. A discussion of this effect can be found in Nelson (2006), where internally occulted coronagraphs are investigated that observe very close to the solar limb. For a test setup where scattering from microroughness is important, their findings also suggest that a collimator would best be realised with a refractive rather than reflective primary. However, lenses of the required diameter are not available off the shelf. A refractive

design also does not fold to make the setup more compact (a mirror can be located at the very end of the tunnel), although a fold mirror can be used between the primary and its focal point, depending on the inner FOV limit. Together with the fact that a very long focal length lens will be desirable, this would add at least another metre to the total system length. The clean room conditions are also again important here, as some dust will be collected over time even under good conditions. It is thus imperative that the collimator receives good cleaning immediately before the test.

Another aspect of test chamber dimensions will come into play when a HRM is used. As already described in section 9.1, the function of the HRM is to redirect light out of the instrument, where it will inevitably end up on the test chamber walls. In turn this leads to strongly elevated background levels. A solution such as that described by Brueckner et al. (1995), i.e. coating the mirror black for the tests, must be found. The ray-tracing simulations performed for SCOPE (with conical baffles) showed stray light levels due to diffuse scattering well below the requirements. A rear wall covered with black flocked paper, as was done at RAL Space, might be a viable option. The HRM could be tested separately to confirm that it's polish is good enough and does not produce larger diffuse scattering. Instead of black flocked paper a carbon-nanotube based black coating such as Vantablack could be used instead to provide superior performance. Theoretically, a test chamber could be coated entirely with such a coating as well to allow a test with the HRM, but this would be a very costly solution that would also be very fragile and possibly susceptible to contamination.

If the requirements discussed above can not be fulfilled, most importantly a sufficiently long test chamber or a collimator with low enough scattering properties, it can still be considered how bad the test is affected and if it can be split into some “subtests”, probing different components at a time. The SCOPE tests at IAG and RAL Space used small beam diameters to successfully test the occulter and spider-arm diffraction - at least along a portion of their length. The use of a DSLR lens in place of the main optics, which featured an effectively smaller aperture, also meant that the collimator scatter was hidden from view and allowed to take test images without overexposing the sensor. This could be used to measure the diffuse brightness arriving at the lens aperture from the rear surfaces of the occulter and baffle tube during full illumination. Even with some collimator scatter visible near the inner FOV limit, if the lens system re-scatters only very little light, the outer FOV regions might not be adversely affected. This requires a separate characterisation of the lens system, similar to the measurements presented in section 10.3. It would then be feasible to split the test in two subtests: One with full input beam, testing the background stray light in the outer FOV region, and one with a slightly reduced input beam, testing the occulter diffraction and thus the background in the inner FOV region.

The final aspect of the test setup I want to discuss is the light source. The tests at RAL Space and CSL used a monochromatic laser, while the test at IAG used a broadband white light source. On one hand, the use of a monochromatic laser has the advantage that it is easier to compare test results with simulations

when diffractive effects are involved, e.g. the occulter diffraction profile shown in Figure 10.23. This has also helped to identify and understand the nature of the scattering seen from the spider-arms, which could not be distinguished from simple diffuse scattering in the IAG tests. Secondary effects in the diffracted light can furthermore reveal information about surface roughness or defects of individual edges beyond what can be seen in optical microscopy. On the other hand, it is exactly this different behaviour that can lead to thresholds being exceeded with incoherent white light, while they are met at a single wavelength. This is exemplified by the diffraction profile measured at IAG, shown in Figure 10.8, which deviated from the simulated values by a large amount and could not be matched accurately at all in terms of its profile or its intensity. It is thus advisable to perform a final test of any solar coronagraph also with a white light source. An intermediate solution that could be considered for future test is the use of a narrow-band LED source. This would provide light with a larger incoherence, while still being limited to a small wavelength range.

Chapter 12

Summary and Outlook

In this final chapter, I present a summary of the results obtained and give an outlook to future operations. The thesis covered two topics: First, an analysis of the impacts of space weather phenomena on the terrestrial ionosphere; and second, the design and testing of an optical breadboard model of a new, compact coronagraph to observe CMEs in white-light for operational space weather purposes.

The work of the first part was motivated through the German project OPTIMAP, aimed at the development of a new automatic forecasting system of global VTEC maps that can make use of space weather forecasts as an input to improve the quality of the predictions. For this, I analysed the impacts of different phenomena in such maps to determine the importance of including the respective parameters and to find strategies to implement them. A long time series between 2003 and 2018 of high resolution data was compiled, consisting of:

- GNSS-based VTEC-maps from CODE with a temporal resolution of 2 hours (before 2014-11-01) and 1 hour (starting 2014-11-01). The maps are computed with an underlying spherical harmonic expansion and provided in the IONEX format with a spatial sampling of 5° in longitude and 2.5° in latitude.
- Solar EUV data from SDO/EVE/ESP, providing long-term calibrated EUV irradiance at high temporal resolution of 0.25 seconds. Three spectral bands at 18 nm, 26 nm and 30 nm were used. SDO data was only available starting 2010-05-01, but still covered the full dynamics of the last solar cycle.
- Solar X-Ray irradiance measured by GOES satellites to provide data of solar flares. The time series contained 11229 C-, 1117 M- and 104 X-class flares that were used for a superposed epoch analysis.
- Measurements of the Solar wind from the OMNI data set, which provides comprehensive and calibrated data including a correction of the arrival time at Earth from the measurement at the Lagrange point L1. A total of 46 events was compiled using two different sets of selection criteria.
- The Kp-index to classify the geomagnetic impact of events and apply corresponding filtering to the other data sets.

GNSS-based global maps of TEC provide the opportunity to study effects in sun-fixed and magnetic coordinate systems, as opposed to the study of single-station data that is still often used and requires to compile global patterns from many individual case studies (Mendillo, 2006; Cander, 2019). Nevertheless, identifying global patterns remains a challenging task due to the overlapping effects of different phenomena, as well as their different temporal characteristics and dependencies on ground states, e.g. through the phase of the solar cycle and seasonal processes. The following results were obtained in this work:

- The correlation between the EUV bands of SDO/ESP over the solar cycle showed global and dayside correlations around $r = 0.88$ for all three spectral bands. A strong seasonal pattern is visible, with the lowest relative VTEC measured in summer and highest during spring and autumn. When data in each season is considered separately, the correlation becomes as high as $r = 0.95$. After subtraction of 27-day median backgrounds to remove the solar cycle trend, i.e. computing the correlation over mid-term variations due to the solar rotation, the correlation lies between $r = 0.7$ and $r = 0.75$.
- A predominantly linear relationship between global mean TEC and EUV was found, with the correlation of absolute data also suggesting a slightly quadratic relationship. In all but one case, both types of fitting extrapolate to the unphysical case of negative VTEC when the EUV irradiance goes to zero. An explanation of this behaviour would require numerical simulations of the ionosphere, as this study already includes the lowest naturally occurring values during solar minimum.
- The delayed response of global mean dTEC to EUV was found to be 20 hours, consistent with the value of 1-2 days reported by Jacobi et al. (2016) using daily-averaged data. Consistent regional patterns could not be observed, with regional delays up to several days.
- Regional structures were also analysed for the correlation coefficients with EUV. In the sun-fixed coordinate system, the sunrise terminator forms a boundary across which the correlation coefficients increase. In the magnetic coordinate system, the strongest correlations are observed at the dayside magnetic equator.
- Solar flares have a strong impact on dayside VTEC, but only in the most extreme cases can these be measured in GIMs. For the strongest event of 2003-10-28, I find a peak of 10 TECU across large parts of the dayside. In comparison, values of up to 25 TECU are reported by studies using single-site GNSS measurements (Zhang and Xiao, 2005; Tsurutani et al., 2006; Sahai et al., 2008). The result was used to define a formula to compute a worst-case estimate of dayside dTEC from the GOES SXR-irradiance.
- The superposed epoch analysis of flares before 2013-11-01 could not reveal measurable effects over the background fluctuations for the M- and C-flares. The case of X-flares showed a larger dTEC with the expected relationship between global, dayside and subsolar averages. The result was used to define a formula for mean dayside dTEC from the GOES SXR-irradiance.

- The strongest impacts are caused by CMEs, as well as CIRs, and effects can be seen in events of different magnitudes. A total of 46 events was analysed, which were compiled using two different criteria - the OPTIMAP time series and a list of additional, strong events - covering two different periods of the time series. On average, higher global mean dTEC of around 5 TECU was observed for the additional events, compared to around 2.5 TECU for the OPTIMAP events.
- Almost all geomagnetic storms show an enhancement of the global mean TEC that is correlated well with the first strong southward turning of the IMF, which it follows with a delay around 5 hours.
- A second positive peak in global mean TEC was identified for 29 events, and a global minimum for 13 events. The latter is difficult to determine unambiguously, because negative phases can be of long duration and may thus be confused with the trend of the 27-day solar rotation.
- A clear seasonal pattern is seen for the geomagnetic storms. In the summer season, negative phase appears to be constrained entirely to the northern hemisphere in all latitude bands, with the opposite behaviour in winter, and symmetric behaviour in spring and autumn.
- Some of the strongest events show three positive peaks in the longitudinal analysis. I could not observe a consistent picture regarding their spatio-temporal appearance. In some cases, the peaks appear and vanish at all longitudes simultaneously, while in some cases there is a strong time-dependence.
- For the weaker geomagnetic storms, regional patterns are masked mostly by fluctuations in the GIMs.
- Fluctuations of the solar wind during geomagnetically quiet conditions showed no significant correlation to the observed fluctuations in the TEC maps ($r \lesssim 0.2$).

The second part of this thesis addressed the development of an optical breadboard model of the SCOPE coronagraph, which follows an advanced design of externally occulted coronagraphs with specifications aimed at forecasting purposes. Externally occulted coronagraphs are a highly specialised class of instruments that have only been built and used in space on eight missions to date. SCOPE is also the first instrument of this type developed by a fully European consortium. I have presented the optical and mechanical design of the OBB, as well as the three test phases used to investigate and verify its optical performance. Testing of a coronagraph is a challenging task due to the large stray light rejection ratio, and faces challenges in the design and construction of a test facility. The main results obtained here are:

- In all three tests, it was possible to observe the diffraction pattern of the 5-disc occulter. A very good agreement with computed values was obtained at RAL Space using a laser light source with $\lambda = 532$ nm. The observed intensity profile was a factor of 1.5 below the theoretically predicted value, and matched it in shape out to about 20 diffraction rings. At CSL, the

intensity matched similarly at a wavelength of $\lambda = 800 \text{ nm}$, but the profile could only be matched by applying a significant shift to the measurements. This might be the result of misalignment with the light source.

- The results obtained at IAG for the occulter diffraction, using a white-light source, showed very different profile, but it is not surprising due to the white-light nature of the source. Numerical computations were not performed for this case. A final test of a coronagraph should thus be made using a broad-band light source.
- The circular baffles of the baffle tube, as well as conical baffles intended to provide an alternative to an HRM design, led to strong diffractive stray light, limiting the instrument performance to around 10^{-9} MSB. A serrated edge should be used for all illuminated baffles, and the number of such edges be kept small.
- During the tests at RAL Space, background levels below 10^{-11} MSB could be observed, suggesting that tests can be successful with the back wall coated with a good matte black coating. This will be important for future tests with a HRM that would reflect large amounts of stray light onto the test chamber background.
- Strong diffracted stray light was furthermore observed originating on the edges of the spider-arms used to mount the occulter. Fine control of their surface roughness is needed, as they would affect the entire FOV range at their locations. Initial wire-cut and painted spiders resulted in stray light levels $> 10^{-10}$ MSB.
- Polished spider-arms made from both PLA plastic and aluminium provided a performance below 10^{-11} MSB in the tests at RAL Space. As these values were measured near the inner FOV boundary, a performance below the requirements has been demonstrated for this component. Further test will be required to establish the performance near the outer FOV boundary and using white-light. The surface roughness of the polished versions was too low to be measured with an optical microscope.
- Good control of dust contamination is necessary for the compact coronagraph, as individual grains on the spider-arms or the occulter can present strong scattering centres. In the classical Lyot-design, this stray light would be eliminated on the internal occulter or Lyot-stop.
- Realising a test chamber for the given FOV of SCOPE is challenging due to large distance from a collimating mirror that is needed to hide scattering on its surface behind the occulter. Provided that the scattering inside the lens system is low, as well as on the collimator, a test could be performed in two stages, where a small collimator is used first to probe the performance of the occulter and the inner part of the spider-arms, and a second test with full instrument illumination to confirm the performance in the outer FOV regions.

Many modern technological systems, as well as human health, are affected by space weather effects, and disturbances in the ionosphere can disrupt critical systems (Cannon et al., 2013; Cabinet Office, 2017). There is thus a demand to develop and improve forecasting products to ensure good mitigation of these effects (Talaat, 2019; Bingham et al., 2019). The results of the ionospheric impact analysis were discussed with respect to their applications in prediction models of global ionospheric maps. Currently, such endeavours are limited partly by the availability of forecasts of the input parameters. The EUV irradiance is well suited to predict the ground state of the ionosphere as a result of the high correlation, and could replace traditionally used proxy-parameters like F10.7. Improved EUV-forecasts could be developed in conjunction with a future L5- space weather mission that observes the face of the Sun rotating into view of Earth 4.5 days in advance. For solar flares, exact forecasting of individual events in terms of the strength and time is not yet possible due to the the complex physical relationships and unsolved questions in solar physics (Nishizuka et al., 2017). Recent projects like FLARE-CAST instead predict the probability of different flare classes over a certain time window. Such a service can nevertheless be used to drive space weather warning scales and predict the magnitude of possible SIDs. The largest improvements of TEC maps is expected from including the effects of CMEs. Not only are they responsible for the strongest impacts, but, due to the relatively low propagations speed compared to electromagnetic radiation, their arrival can be forecasted with warning times of 12 hours to 4 days. This provides an excellent opportunity to improve forecast models of TEC while providing a large advance warning time to users. The prediction of regional effects remains difficult due to the complex behaviour of geomagnetic storms, and must be verified and optimised in operational use. Forecasting services of the solar wind based on magnetohydrodynamical simulations, for example the WSA-ENLIL model (Parsons et al., 2011) have been implemented and are used operationally to predict the solar wind conditions at Earth. These can also be used to provide estimates of the magnetic field strength and morphology of CMEs, which can not be directly observed using coronagraphs.

The current CME forecasting capabilities rely mainly on the data provided by the coronagraphs on board SOHO and STEREO. Both missions have been very successful and advanced our understand of the geometry and interplanetary propagation of CMEs, but have now obtained a high age. One of the STEREO satellites, STEREO-B, has been lost in 2014 and the innermost coronagraph of SOHO, C1, has not been operational since 1998. A suitable replacement, ideally tailored towards providing data for consistent operational forecasting, must be developed for launch in the near future. The design and tests of the SCOPE OBB have furthered our understanding of the construction of solar coronagraphs and brought us closer to deploying an operational mission in the near future. The compact coronagraph design furthermore has the potential to provide a platform for easy adaptation to different mission profiles. As the lens system is not part of the baffle system, a lightweight low resolution lens for operational purposes at low telemetry can be used as well as a high-resolution lens for scientific goals, without requiring further design changes. System studies for space weather missions have been performed by ESA since 2015 to define preliminary mission concepts and goals

(Kraft et al., 2017). Missions to the Lagrange points L1 and L5 are particularly investigated as the ideal and stable orbits for continuous solar observations that provide a stereoscopic view. There is also close cooperation with NASA to coordinate the development of missions and achieve an optimal configuration (Hapgood, 2017). The current goal is that the next generation L1-mission will be developed by NASA, and the first ever L5-mission by ESA. NASA and NOAA are developing a compact coronagraph (CCOR) for the use on an L1-mission as well as the next generation GOES-satellite (Talaat, 2019). Further scientific missions are also under development. The Indian L1-mission Aditya-L1, expected to be launched later in 2020, features a coronagraph, VELC, to observe the inner corona in different emission lines (Prasad et al., 2017). The Proba-3 mission is scheduled for launch in mid 2021 to test the feasibility of fine formation flight and will provide further, high quality white-light images of the inner corona.

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Appendix A

Additional Figures of Ionospheric Results

This appendix includes additional plots from the analysis of ionospheric effects in chapter 6 that were moved here to improve readability of the text.

Figure A.1: Global average dTEC (top) for the geomagnetic storm of 2003-11-20 (event #28), together with the OMNI $v \cdot B_z$ (middle) and Kp-index (bottom).

Figure A.2: Global average dTEC (top) for the geomagnetic storm of 2003-08-18 (event #24), together with the OMNI $v \cdot B_z$ (middle) and Kp-index (bottom).

Figure A.3: Global average dTEC (top) for the geomagnetic storm of 2004-07-24 (event #31), together with the OMNI $v \cdot B_z$ (middle) and Kp-index (bottom).

Figure A.4: Regional correlation coefficients during spring between the SDO/ESP 30 nm band and dTEC with 27-day background values subtracted. The values were computed in the sun-fixed coordinate system and in $5^\circ \times 5^\circ$ patches.

Figure A.5: Regional correlation coefficients during summer between the SDO/ESP 30 nm band and dTEC with 27-day background values subtracted. The values were computed in the sun-fixed coordinate system and in $5^\circ \times 5^\circ$ patches.

Figure A.6: Regional correlation coefficients during autumn between the SDO/ESP 30 nm band and dTEC with 27-day background values subtracted. The values were computed in the sun-fixed coordinate system and in $5^\circ \times 5^\circ$ patches.

Figure A.7: Regional correlation coefficients during winter between the SDO/ESP 30 nm band and dTEC with 27-day background values subtracted. The values were computed in the sun-fixed coordinate system and in $5^\circ \times 5^\circ$ patches.

Figure A.8: Regional correlation coefficients during spring between the SDO/ESP 30 nm band and VTEC over the entire time series. The values were computed in the sun-fixed coordinate system and in $5^\circ \times 5^\circ$ patches.

Figure A.9: Regional correlation coefficients during summer between the SDO/ESP 30 nm band and VTEC over the entire time series. The values were computed in the sun-fixed coordinate system and in $5^\circ \times 5^\circ$ patches.

Figure A.10: Regional correlation coefficients during autumn between the SDO/ESP 30 nm band and VTEC over the entire time series. The values were computed in the sun-fixed coordinate system and in $5^\circ \times 5^\circ$ patches.

Figure A.11: Regional correlation coefficients during winter between the SDO/ESP 30 nm band and VTEC over the entire time series. The values were computed in the sun-fixed coordinate system and in $5^\circ \times 5^\circ$ patches.

Figure A.12: Regional correlation coefficients during spring between the SDO/ESP 30 nm band and dTEC, with 27-day background values subtracted, over the entire time series. The values were computed in the magnetic coordinate system and in $5^\circ \times 5^\circ$ patches.

Figure A.13: Regional correlation coefficients during summer between the SDO/ESP 30 nm band and dTEC, with 27-day background values subtracted, over the entire time series. The values were computed in the magnetic coordinate system and in $5^\circ \times 5^\circ$ patches.

Figure A.14: Regional correlation coefficients during autumn between the SDO/ESP 30 nm band and dTEC, with 27-day background values subtracted, over the entire time series. The values were computed in the magnetic coordinate system and in $5^\circ \times 5^\circ$ patches.

Figure A.15: Regional correlation coefficients during winter between the SDO/ESP 30 nm band and dTEC, with 27-day background values subtracted, over the entire time series. The values were computed in the magnetic coordinate system and in $5^\circ \times 5^\circ$ patches.

Figure A.16: Regional time delays of the correlation coefficients between the SDO/ESP 30 nm band and dTEC during spring, with 27-day background values subtracted, over the entire time series. The values were computed in the sun-fixed coordinate system and in $5^\circ \times 5^\circ$ patches.

Figure A.17: Regional time delays of the correlation coefficients between the SDO/ESP 30 nm band and dTEC during summer, with 27-day background values subtracted, over the entire time series. The values were computed in the sun-fixed coordinate system and in $5^\circ \times 5^\circ$ patches.

Figure A.18: Regional time delays of the correlation coefficients between the SDO/ESP 30 nm band and dTEC during autumn, with 27-day background values subtracted, over the entire time series. The values were computed in the sun-fixed coordinate system and in $5^\circ \times 5^\circ$ patches.

Figure A.19: Regional time delays of the correlation coefficients between the SDO/ESP 30 nm band and dTEC during winter, with 27-day background values subtracted, over the entire time series. The values were computed in the sun-fixed coordinate system and in $5^\circ \times 5^\circ$ patches.

Figure A.20: Average dTEC values in the northern (top) and southern (bottom) high latitudes between $\pm 60^\circ$ and $\pm 90^\circ$ of the magnetic coordinate system for 13 geomagnetic storms in the spring season. All curves are offset by the mean value in the interval from -36 to -12 hours.

Figure A.21: Average dTEC values in the northern (top) and southern (bottom) high latitudes between $\pm 60^\circ$ and $\pm 90^\circ$ of the magnetic coordinate system for 11 geomagnetic storms in the autumn season. All curves are offset by the mean value in the interval from -36 to -12 hours.

Figure A.22: Average dTEC values in the northern (top) and southern (bottom) high latitudes between $\pm 30^\circ$ and $\pm 60^\circ$ of the magnetic coordinate system for 13 geomagnetic storms in the spring season. All curves are offset by the mean value in the interval from -36 to -12 hours.

Figure A.23: Average dTEC values in the northern (top) and southern (bottom) high latitudes between $\pm 30^\circ$ and $\pm 60^\circ$ of the magnetic coordinate system for 11 geomagnetic storms in the autumn season. All curves are offset by the mean value in the interval from -36 to -12 hours.

Appendix B

Additional Figures of the Spider-Arm Test at RAL Space

This appendix includes all images from the spider-arm test sequence performed at RAL Space, see section 10.3. The images are ordered according to the measurement numbers defined in table 9.4.

Figures B.3 and B.4 are duplicates of figures 10.19 and 10.20 in section 10.3, respectively, included here for easier comparison with the other measurements.

Figure B.1: Result from spider-arm measurement # M1, using the configuration of S2 as the front- and S1 as the rear-spider-arms on the right side of the occulter.

Figure B.2: Result from spider-arm measurement # M2, using the configuration of S3 as the front- and S3 as the rear-spider-arms on the right side of the occulter.

Figure B.3: Result from spider-arm measurement # M3, using the configuration of S4 as the front- and S4 as the rear-spider-arms on the right side of the occulter.

Figure B.4: Result from spider-arm measurement # M4, using the configuration of S5 as the front- and S5 as the rear-spider-arms on the right side of the occulter.

Figure B.5: Result from spider-arm measurement # M5, using the configuration of S2 as the front- and S5 as the rear-spider-arms on the right side of the occulter.

Figure B.6: Result from spider-arm measurement # M6, using the configuration of S3 as the front- and S5 as the rear-spider-arms on the right side of the occulter.

Figure B.7: Result from spider-arm measurement # M7, using the configuration of S4 as the front- and S5 as the rear-spider-arms on the right side of the occulter.

Figure B.8: Result from spider-arm measurement # M8, using the configuration of S5 as the front- and S1 as the rear-spider-arms on the right side of the occulter.

Figure B.9: Result from spider-arm measurement # M9, using the configuration of S5 as the front- and S3 as the rear-spider-arms on the right side of the occulter.

Figure B.10: Result from spider-arm measurement # M10, using the configuration of S5 as the front- and S4 as the rear-spider-arms on the right side of the occulter.

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