Annual Report
Jahresbericht 2023

Front Cover: The Infrared Integrating Sphere Radiometer (IRIS) serves as a reference instrument for downwelling atmospheric longwave irradiance and is a candidate instrument for the planned redefinition of the atmospheric longwave irradiance scale, which is currently under review by the WMO expert team on radiation references. The picture shows the new upgraded IRIS radiometer and control box, both designed and built at PMOD/WRC.

Das PMOD/WRC ist eine Abteilung der Stiftung Schweizerisches Forschungsinstitut f. Hochgebirgsklima und Medizin in Davos, Schweiz.

The PMOD/WRC is a department of the Swiss Research Institute for High Altitude Climate and Medicine (SFI) in Davos/Switzerland.

Physikalisch-Meteorologisches Observatorium
Davos/ World Radiation Center (PMOD/WRC)
Dorfstrasse 33,
7260 Davos Dorf
Schweiz

Tel. +41 (0)81 417 51 11
www.pmodwrc.ch

pmod wrc

Annual Report
Jahresbericht 2023

Physikalisch-Meteorologisches Observatorium Davos und Weltstrahlungszentrum PMOD/WRC

Unsere Mission

Wir sind ein international anerkanntes Kalibrierzentrum für meteorologische Strahlungsinstrumente. Zu diesem Zweck entwickeln wir Strahlungsinstrumente, sowohl für den Einsatz am Boden, als auch satellitengetragen im Weltraum. Unsere Forschung konzentriert sich auf den Einfluss der solaren Strahlung und der Sonnenaktivität auf das Klima der Erde und deren Atmosphäre.

Geschichte des PMOD/WRC

Das Physikalisch-Meteorologische Observatorium Davos (PMOD) erforscht seit seiner Gründung im Jahr 1907 den Einfluss der solaren Strahlung auf das Klima der Erde. Im Jahr 1926 schloss sich das Observatorium dem Schweizerischen Forschungsinstitut für Höhenklima und Medizin Davos an und ist seither Teil dieser Stiftung. Auf Antrag der Weltorganisation für Meteorologie (WMO) beschloss der Bundesrat 1970 die Finanzierung eines Kalibrierzentrums für Strahlungsmessungen als Beitrag der Schweiz an das Weltwetterbeobachtungsprogramm der WMO. In der Folge wurde das PMOD mit der Errichtung und dem Betrieb des World Radiation Center (WRC) beauftragt.

Kernaktivitäten

Das World Radiation Center unterhält den Primärstandard für die solare Bestrahlungsstärke, der aus einer Gruppe von hochpräzisen Absolutradiometern besteht. Als Reaktion auf weitere Anfragen der WMO wurde 2004 ein Kalibrierzentrum für Instrumente zur Messung der langwelligen atmosphärischen Strahlung und 2008 ein Kalibrierzentrum für spektrale Strahlungsmessungen zur Bestimmung der atmosphärischen Trübung eingerichtet. Seit 2013 wird auch das Weltkalibrierzentrum für UV von unserem Welt-Strahlungszentrum betrieben.

Heute besteht das Welt-Strahlungszentrum aus vier Abteilungen: Solare Radiometrie (WRC-SRS), Infrarot-Radiometrie (WRC-IRS), atmosphärische Trübung (WRC-WORCC) und UV-Radiometrie (WRC-WCC-UV).

Das PMOD/WRC ist vollständig in den Europäischen Verband der nationalen Metrologieinstitute (EURAMET) und in den Rahmen des Bureau International des Poids et Mesures (BIPM) integriert. Das PMOD/WRC ist assoziiertes Mitglied von EURAMET und wurde im September 2002 durch METAS beim BIPM als designiertes Institut (DI) für die Grösse "Solare Bestrahlungsstärke" im Rahmen des CIPM-MRA gemeldet.

Wir entwickeln und bauen Radiometer, die zu den genauesten ihrer Art auf der Welt gehören und sowohl am Boden als auch im Weltraum eingesetzt werden. Diese Instrumente sind auch käuflich zu erwerben und werden seit langem von den Wetter-und Klimadiensten weltweit eingesetzt. Darüber hinaus haben wir ein globales Netz von Stationen zur Überwachung der atmosphärischen Trübung mit Präzisionsfilterradiometern ausgestattet, die vom PMOD/WRC entwickelt wurden.

Die im Weltraum gesammelten Daten (Radiometrie und Solar Imaging) sowie die Bodenmessungen werden in Forschungsprojekten zum Klimawandel und zur Sonnenaktivität ausgewertet. Zu diesem Zweck haben wir ein eigenes globales Chemie-Klimamodell entwickelt, mit dem wir die Beziehung zwischen Sonne und Erde unter besonderer Berücksichtigung der mittleren Erdatmosphäre und der Ozonschicht untersuchen. Diese Forschungsaktivitäten und unsere internationalen Kooperationen sind weltweit anerkannt.

Schliesslich unterrichten wir an der ETH Zürich sowohl auf Bachelor- als auch auf Masterstufe innerhalb des Departements Physik und des Departements für Umweltsystemwissenschaften.

Physikalisch-Meteorologisches Observatorium Davos and World Radiation Center PMOD/WRC

Mission

Our core mission is to serve as an international calibration center for meteorological radiation instruments. To this end, we develop radiation instruments for use on the ground and in space. Our research focuses on the influence of solar radiation and solar activity on Earth's climate and its impact on the Earth's atmosphere.

PMOD/WRC History

Since its establishment in 1907, the Physikalisch-Meteorologisches Observatorium Davos (PMOD) has been studying the influence of solar radiation on the Earth's climate. In 1926, the Observatory joined the Swiss Research Institute for High Altitude Climate and Medicine Davos and has since become part of this foundation. At the request of the World Meteorological Organization (WMO), the Federal Council decided in 1970 to finance a calibration center for radiation measurement as Switzerland's contribution to the World Weather Watch Programme of the WMO. Following this decision, PMOD was commissioned to establish and operate the World Radiation Center (WRC).

Core Activities

The World Radiation Center maintains the primary standard for solar irradiance, which consists of a group of high-precision absolute radiometers. In response to further requests from WMO, a calibration center for atmospheric longwave radiation instruments was established in 2004, and the calibration center for spectral radiance measurements to determine atmospheric turbidity was established in 2008. Since 2013, the World Calibration Center for UV has also been operated by the World Radiation Center.

Today, the World Radiation Center consists of four sections: Solar Radiometry (WRC-SRS), Infrared Radiometry (WRC-IRS), Atmospheric Turbidity (WRC-WORCC), and UV Radiometry (WRC-WCC-UV).

PMOD/WRC is fully integrated into the European Association of National Metrology Institutes (EURAMET) and into the framework of the Bureau International des Poids et Mesures (BIPM). PMOD/WRC is an associated member of EURAMET and was nominated in September 2002 by METAS at the BIPM as the designated institute (DI) for the quantity "solar irradiance" within the framework of CIPM-MRA.

We develop and build radiometers that are among the most accurate of their kind in the world and are used both on the ground and in space. These instruments are also available for purchase and have long been used by Meteorological Services worldwide. Furthermore, a global network of atmospheric turbidity monitoring stations is equipped with precision filter radiometers developed by PMOD/WRC.

Data collected in space (radiometry and solar imaging) and by means of ground measurements are analysed in research projects on climate change and solar activity. For this purpose, we have developed our own dedicated global chemistry-climate model, devoted to investigating the Sun-Earth relationship with particular focus on the Earth's middle atmosphere and ozone layer. These research activities and our international collaborations are recognised worldwide.

Last but not least, we carry out teaching at both, the bachelor and master level at ETH Zürich, hosted within the Department of Physics and the Department of Environmental Systems Science.

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PMOD/WRC Introduction

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In 1970, the Federal Council financed a calibration center for radiation measurement as Switzerland's contribution to the World Weather Watch Programme of the World Meteorological Organisation (WMO). Since 1970, PMOD has been operating the World Radiation Center (WRC).

"Our core mission is to serve as an international calibration center for meteorological radiation instruments. We develop radiation instruments for use on the ground and in space. We research the influence of solar radiation and activity on the Earth's climate and its impact on the Earth's atmosphere."

World Radiation Center

The World Radiation Center (WRC) maintains the primary standard for solar irradiance. In addition, a calibration center for longwave radiation instruments was established in 2004, and the calibration center for spectral radiance measurements to determine atmospheric turbidity was established in 2008. Since 2013, the World Calibration Center for UV has also been operated by the WRC.

Today, the WRC consists of four sections: Solar Radiometry (WRC-SRS), Infrared Radiometry (WRC-IRS), Atmospheric Turbidity (WRC-WORCC), and UV Radiometry (WRC-WCC-UV).

PMOD/WRC is integrated into the European Association of National Metrology Institutes and into the framework of the Bureau International des Poids et Mesures (BIPM).

Weltstrahlungszentrum

Das Weltstrahlungszentrum (WRC) unterhält den primären Standard für die Sonneneinstrahlung. Darüber hinaus wurde 2004 ein Kalibrierzentrum für langwellige Strahlungsinstrumente und 2008 das Kalibrierzentrum für spektrale Strahlungsmessungen zur Bestimmung der atmosphärischen Trübung eingerichtet. Seit 2013 wird auch das Weltkalibrierzentrum für Ultraviolettstrahlung (UV) durch das WRC betrieben.

Heute besteht das WRC aus vier Sektionen: Solar-Radiometrie (WRC-SRS), Infrarot-Radiometrie (WRC-IRS), Atmosphärische Trübung (WRC-WORCC) und UV-Radiometrie (WRC-WCC-UV).

Das PMOD/WRC ist in die European Association of National Metrology Institutes und in die Rahmenordnung des Bureau International des Poids et Mesures (BIPM) integriert.

Research

Climate change is one of the biggest risks to humankind. We hold the longest datasets in the world on irradiance and ozone measurements – key for understanding the climate. Data collected in space and on the ground are analysed to understand and predict climate change. For this purpose, we have developed our own dedicated global chemistry-climate model, to investigate the Sun-Earth relationship with particular focus on the Earth's middle atmosphere and ozone layer.

We research solar activity using high spatial and spectral resolution data. We are involved in the design, build and operations of these complex instruments. The key science questions are "what drives the solar wind?" and "What triggers solar flares?".

Forschung

Der Klimawandel ist eine der größten Risiken für die Menschheit. Wir verfügen über die weltweit längsten Datensätze zu Einstrahlungs- und Ozonmessungen – der Schlüssel zum Verständnis des Klimas. Im Weltraum und am Boden erhobene Daten werden in Forschungsprojekten zum Klimawandel ausgewertet. Zu diesem Zweck haben wir unser eigenes dediziertes globales Chemie-Klima-Modell entwickelt, um die Sonne-Erde-Beziehung mit besonderem Fokus auf die mittlere Atmosphäre und die Ozonschicht der Erde zu untersuchen.

Wir erforschen die Sonnenaktivität anhand von Daten mit hoher räumlicher und spektraler Auflösung. Wir sind an der Konstruktion, dem Bau und dem Betrieb dieser komplexen Instrumente beteiligt. Die wichtigsten wissenschaftlichen Fragen lauten "Was treibt den Sonnenwind an?" und "Was löst Sonneneruptionen aus?".

Technology

Technology is the key to building instruments for both ground and space-based applications.

We have world recognised skills in the design of electronics and structures for harsh environments (all weather and in space). This also provides an ideal environment for the training of apprentices. We have five instruments that are currently operational in space, including those that conduct irradiance, spectroscopic and imaging measurements of the Sun.

We are involved in the design and build of future space instruments and collaborate with industry, institutes, and space agencies around the world.

Technologie

Technologie ist der Schlüssel zum Bau von Instrumenten für boden- und weltraumgestützte Anwendungen. Wir verfügen über weltweit anerkannte Fähigkeiten im Design von Elektronik und Strukturen für raue Umgebungen (bei jedem Wetter und im Weltraum). Dies bietet auch ein ideales Umfeld für die Ausbildung von Lernenden. Wir verfügen derzeit über fünf Instrumente im Weltraum, darunter solche, welche die Bestrahlungsstärke sowie spektroskopische und bildgebende Messungen der Sonne durchführen.

Wir sind an der Konstruktion und dem Bau zukünftiger Weltrauminstrumente beteiligt und arbeiten mit der Industrie, Instituten und Raumfahrtagenturen auf der ganzen Welt zusammen.

ETH-Zurich

Since 2019, the director at PMOD/WRC is an affiliated professor located in D-PHYS in the Institute of Particle Physics and Astronomy at ETH-Zürich. This role provides strong collaboration in teaching (both lecture courses and projects), technology (complementary technologies are required for all research areas in IPA) and research.

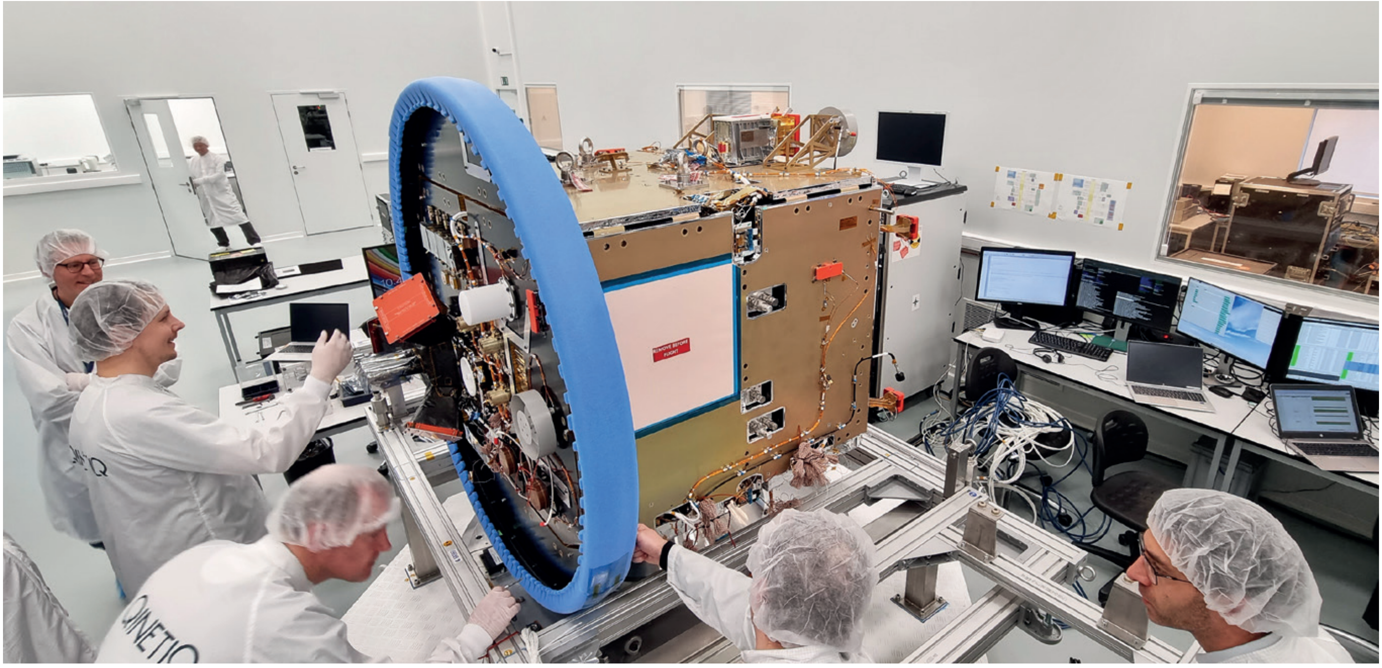
We also have strong links with the Department of Environmental Systems Science (D-USYS) through our climate modelling expertise and provide teaching there.

ETH-Zürich

Seit 2019 ist die Direktorin des PMOD/WRC als affiliierte Professorin im Departement Physik (D-PHYS) des Instituts für Teilchenphysik und Astronomie (IPA) angesiedelt. Diese Rolle bietet eine starke Zusammenarbeit in Lehre (sowohl Vorlesungen als auch Projektarbeiten), Technologie (komplementäre Technologien sind für alle Forschungsbereiche im IPA erforderlich) und Forschung.

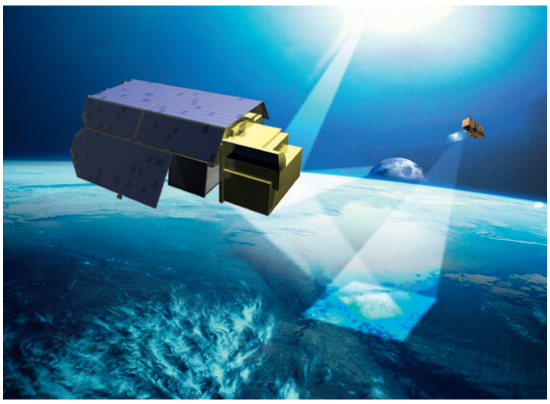
Auch mit dem Departement Umweltsystemwissenschaften (D-USYS) sind wir durch unsere Expertise in der Klimamodellierung und durch die dortige Lehre eng verbunden.

Highlights 2023



The year started with the integration of our DARA instrument to the ESA spacecraft, PROBA-3. This will be launched in 2024 from India.

Our WRC measurement campaigns were back fully in place in 2023 following the pandemic (above left), with campaigns taking place in Japan, US, Spain and Sweden. These accurate measurements are key inputs to climate models and are also used by solar energy companies. We even conducted measurements in Davos at the Thöny-Mode clothes shop (above right) to understand the impact of UV radiation on the fading of clothes!



During the World Economic Forum (WEF) in January 2023, Davos, we had a visit from the ESA Director General and the astronaut, Matthias Maurer. This was organised by the Swiss Space Office and ETH, and showcased Space projects at PMOD/WRC and ETH.

The year was very busy for the ESA space mission, TRUTHS – a future gold standard for climate measurements. The ESA contract was signed with Airbus during the COP-28 UN Climate Change Conference. Our role is related to the radiometer design and electronics, building on our experience with our existing ground-based Cryogenic Radiometer.




Our WRC instruments continue to be developed, with new infra-red instruments (IRIS) being built and tested (see right). These new IRIS radiometers were built to replace the current IRIS radiometers, which are more than 10 years old. They have more powerful shutter motors and an upgraded control box, and will maintain our long term-measurement datasets.

14 Wissensstadt

Dienstag, 28. März 2023
Davoser Zeitung

Publireportage

ETH-Studierende tüfteln in Davos

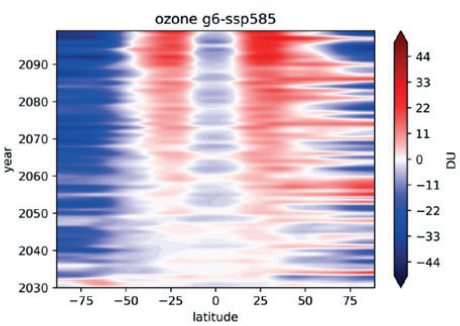
Finde einen Algorithmus, der Sonnenjets erkennt!

Das ETH Studio Davos wurde im Sommer 2022 gegründet und bietet Masterstudierenden der ETH die Möglichkeit, mit viel Ideenreichtum Lösungen für Unternehmen im Bereich der Digitalisierung zu erarbeiten. «Die ETH Studios befinden sich in einigen der dynamischsten Regionen der Welt. Sie sind thematisch fokussierte Aussenposten, die eng mit ihrer innovativen Umgebung verbunden sind», heisst es auf der Website der ETH Zürich. Die Partner des ETH Studio Davos sind das CERC/SLF, Davos BioSciences, Lab42, das Schweizerische Institut für Allergie- und Asthmaforschung SIAF und das Physikalisch-Meteorologische Observatorium Davos/Weltstrahlungszentrum (PMOD/

Luka Skolc, Student ETH Zürich, forscht im Rahmen des ETH Studio Davos am PMOD/WRC. Foto: Academia Raetica

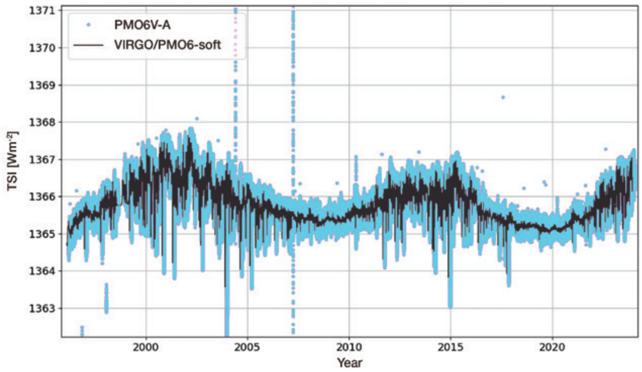
We had 18 MSc and BSc students carrying out projects across all areas of research and technology. This also included our first ETH Studio Davos student, Luka Skolc (see left), who did excellent work on hunting fast speed streams of plasma known as "jets", reaching speeds of 700,000 km/hr on the Sun. These are small-scale and ubiquitous, and can feed into the solar wind that flows past us here on Earth. ETH Studio Davos is a new cooperation between ETH Zurich and Canton Grisons with the thematic cornerstone of Artificial Intelligence and Data Science.

Our tours and public talks are now back in full swing after the pandemic with regular visits (>40 organised tours) and local events (see right). We also had interactions with the media including local and regional newspapers, Swiss Info, SRF and Blick.



Our research continued to be successful with over 60 refereed research papers published and over 40 talks given at international conferences – including a strong presence at the European Geophysical meeting in Vienna in April with seven presentations from PMOD/WRC. The research covered aspects of climate change such as future ozone layer evolution (see left) and how the Sun's solar wind is formed. The research was recognised through several SNSF awards and the IoP Cecilia Payne Gaposhkin medal.

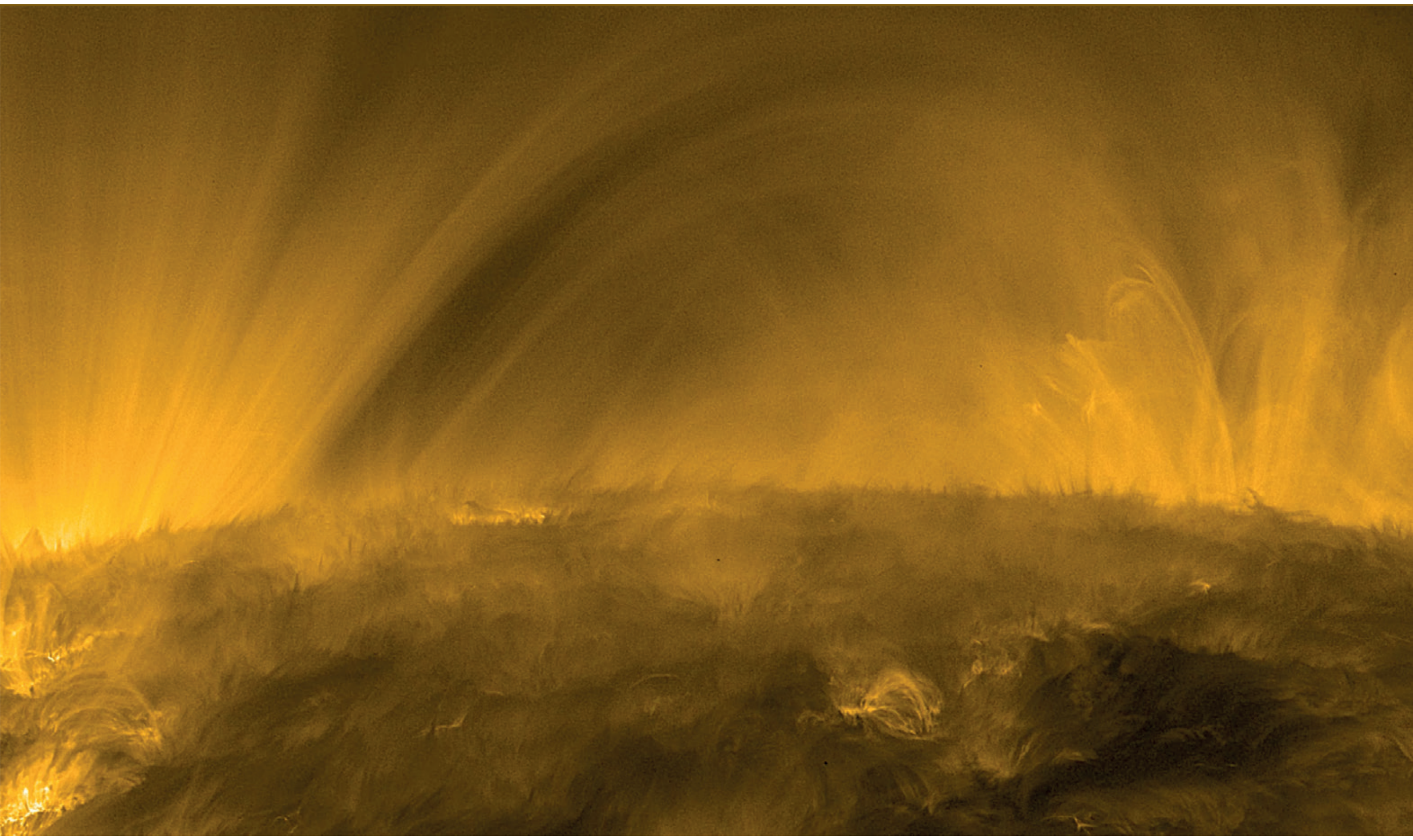
The ESA Solar and Heliospheric Observatory (SOHO) space mission celebrated the 10,000th day in space in April with PMOD/WRC's instrument, Virgo, still operational. Beginning in early 1996, VIRGO now has the longest space-based measurement record for Total Solar Irradiance (see right) – a key measurement for climate models.



The international network for Harmonisation of Atmospheric Aerosol Retrievals from ground based photometers (HARMONIA) is led by PMOD/WRC, and held its first meeting here in May with 55 people from 35 countries attending (see left). Aerosols are particles in the Earth's atmosphere that are linked to the largest uncertainty on estimates of the Earth's complex and changing energy budget.

Our first face-to-face meetings, post pandemic, took place with our colleagues from the Japanese Solar-C mission (see right). Our instrument, the solar spectral irradiance monitor, has made great progress this year, resulting in a successful preliminary design review held by ESA and JAXA in October. Our instrument will provide the full Sun irradiance at a sub-second time cadence to understand what drives solar flares, and to measure solar irradiance that impacts the Earth's thermosphere and the mesosphere.

Two PhD student successfully defended their theses: Alberto Remesal on improvements on the Cavity Absorptance for Space TSI Radiometers; and Conrad Schwanitz (see left), completing one of the first PhD theses worldwide using data from the Solar Orbiter mission on sources of the slow solar wind. Congratulations!



We have six instruments, operational in space, which we continue to operate, and plan coordinated science campaigns with other missions and telescopes on the ground. Solar Orbiter had two successful close encounters with the Sun last year, and we are looking forward to the first views of the solar poles, occurring in 2025.

Our Quality Management System is key for the work of our World Radiation Center, along with audits – this occurs every five years and was successfully evaluated last year.

"With a role to play in research that is recognised internationally and as the holder of an International Standard, PMOD/WRC seeks to maintain and increase the position and reputation of Switzerland for world-class research and technology. I would like to thank the staff at PMOD/WRC for their dedication and the Board of Trustees and the Advisory Commission for their constant support and advice. My ETH colleagues continue to provide excellent collaboration in teaching, space and technology. Thank you."

Louise Harra, Director
PMOD/WRC and ETH Professor

Number of papers in non-reviewed papers or technical documents (e.g. space project documents for the agencies, white papers, conference papers)

152

Number of peer-reviewed research publications

52

Presentations (oral or poster) given at international meetings and conferences

50

Number of PhD students with PMOD/WRC supervisor

10

Industry collaborations (e.g. collaborations on hardware)

34

Public events (local, cantonal, national e.g. open door events, school talks, public talks)

28

Number of lecture courses PMOD/WRC staff are involved in

4

Interaction with media (interviews or articles in newspapers, TV)

12

International collaborations (users, research and government organisations)

106

Participation in national and international commissions, editorial boards

82

Number of calibrations (number of Instruments)

219

Number of employees

44

Number of student projects supervised by PMOD/WRC staff (MSc and BSc)

15

World Radiation Center / Operational Services

Introduction

The World Radiation Centre (WRC) is a service centre which PMOD operates on behalf of the World Meteorological Organisation (WMO). The WRC was established in 1971 and was originally tasked with the standardisation of solar irradiance measurements and the world-wide dissemination of the standard. Toward this goal, the World Radiometric Reference (WRR) was defined in 1977 and has been maintained ever since by the WRC. Over the years, additional tasks have been added to the WRC mandate, including the standardisation of terrestrial (infrared) radiation, spectral UV, and aerosol optical depth measurements. Therefore, the WRC today consists of four sections: i) the Solar Radiation Section (SRS), ii) the Infra-Red Section (IRS), iii) the World Calibration Centre for UV (WCCUV), and iv) the World Optical Depth and Research Calibration Centre (WORCC).

Each section defines, maintains and disseminates the standards for their respective type of radiation measurements and data products. To this end, the WRC sections offer radiometric calibrations and engage in or organise instrument inter-comparisons, such as the quinquennial (five-yearly) International Pyrheliometer Comparison (IPC), the International Pyrgeometer Comparison (IPgC), the Filter Radiometer Comparison (FRC) and the international solar UV Calibration campaign (UVC).

In 2010, the WMO decided that its reference and calibration laboratories (such as the WRC) would adapt the concept of SI-traceability for all meteorological data products. As a result, the WRC became a so-called Designated Institute for solar irradiance. A quality management system according to ISO/IEC 17025 (General requirements for the competence of testing and calibration laboratories) had to be implemented to formally allow the WRC to file its “Calibration and Measurement Capabilities” in the BIPM key comparison database. The latter database is where all reference laboratories throughout the world, list their standards and achievable measurement uncertainties.

The WRC sections also run fundamental and applied research projects to develop, improve and maintain their radiometric standards, providing and benefitting from synergies with the solar physics, climate science, and space hardware groups at PMOD.

Quality Management System, Calibration Services, Instrument Sales

Ricco Soder, Wolfgang Finsterle, Julian Gröbner and Administration Department

Quality Management System (QMS)

i) Activities

The most important activity for the PMOD/WRC Quality Management System in 2023 was the successful reassessment by the Technical Committee for Quality (TC-Q) of EURAMET. In March, PMOD/WRC presented its QMS and summarised its activities over the last five years to the committee. National Metrology Institutes (NMI) and Designated Institutes (DI) are re-evaluated every five years by the TC-Q to verify conformity of the applied QMS against the standard ISO 17025 and to prove the QMS functionality in daily life. The outcome of this assessment was very positive, and we passed the re-evaluation without any major issues.

Continuous improvement is mandatory to achieve the requirements given by EURAMET TC-Q. Strengthening the communication throughout the different sections of our QMS and keeping track of their feedback is an important tool to further develop our QMS. Figure 1 shows the increasing response since the feedback system was revised five years ago.

Additional activities conducted in 2023 included two internal audits. The WRC-SRS section and IT Department were assessed, and the audits were concluded with very positive outcomes.

Our calibration sections participated in eight different inter-laboratory comparisons and international measurement campaigns throughout 2023.

According to the specific specifications of our WRC sections, staff-training took place. In addition, the QM-related documentation of all WRC sections was updated and kept current throughout the year.

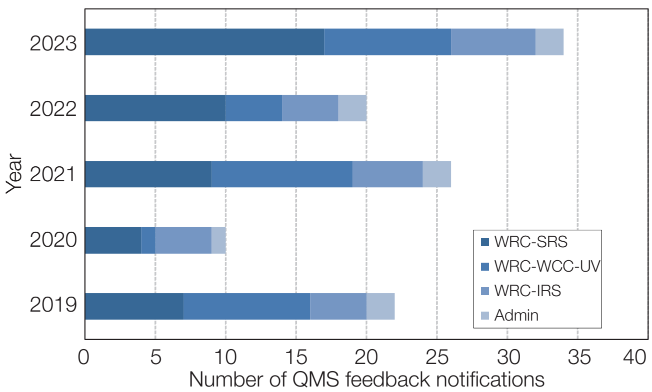


Figure 1. PMOD/WRC Quality Management System: The number of feedback notifications per section/department is shown.

ii) Infrastructure

In 2023, another major effort was made to push the implementation of the recently initiated revision of the data backup and archive solution one step further. A solution for the technical implementation was selected and the financing arranged. We are looking forward to commissioning at the beginning of 2024.

iii) Calibration and Measurement Capabilities (CMCs)

As there was no change regarding CMCs, PMOD/WRC still has eight different CMCs, which are listed in the Key Comparison Database (KCDB) of Bureau International de Poids et Mesure (BIPM).

iv) Organisation and Human Resources

No changes occurred in personnel regarding functions or responsibilities within the QMS.

Calibration Services

After two years of growth, the total amount of instruments sent to PMOD/WRC for calibration purposes, decreased by about 13% to a total of 219 instruments.

Solar Radiometry Section (WRC-SRS)

The WRC-SRS section calibrated a total of 101 instruments in 2023. Both the number of pyranometer and pyrheliometer calibrations decreased slightly to 81 and 20 instruments, respectively.

Infrared Radiometry Section (WRC-IRS)

The WRC-IRS section performed 30 pyrgeometer calibrations. This is a decrease of nine instruments compared to the previous year.

World Calibration Center for UV Section (WRC-WCC-UV)

Compared to the previous year, only 34 UVB broadband radiometers were calibrated in the WCC-UV section. This reduction by 44 instruments can be explained by the International UV Comparison (UVC-III) that took place last year and caused such a high demand.

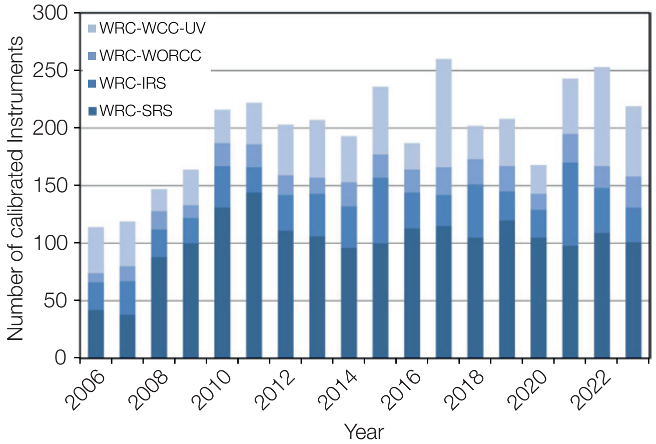


Figure 2. Statistics of instrument calibrations at PMOD/WRC for the 2006 - 2023 period.

Note: One instrument can result in more than one calibration certificate.

The WRC WCC-UV section slightly increased their lamp, diode and spectroradiometer calibrations to a total of five. The increase in terms of spectroradiometer calibrations was quite substantial. Twenty-two spectroradiometer instruments were calibrated against the PMOD/WRC QASUME reference (portable World reference for UV radiation), which is an increase of 17 instruments.

Furthermore, the WCC-UV section also underwent some staff changes. Jakob Föller left the institute at the end of February, while Salim Ferhat started as a new scientific member of staff in September.

Atmospheric Turbidity Section (WRC-WORCC)

The WRC-WORCC section calibrated 24 sun-photometer instruments, which also includes Precision Filter Radiometers (PFR). Whereas only one Precision Spectro-Radiometer (PSR) was sent for calibration in 2022, the WRC-WORCC section calibrated three instruments in 2023. Calibrations were conducted against a reference standard, traceable to the German National Metrology Institute (PTB; Braunschweig, Germany).

Instrument Sales

In 2023, customers continued to buy new-generation Precision Filter Radiometers (PFR19) for long-term measurements of the aerosol optical depth (AOD; Figure 3). Five PFR19, one spectral Irradiance Calibration System (ICS) and one Ventilation Heating Unit (VHS) were sold. These are all designed and manufactured by PMOD/WRC.

The five PFR19 sunphotometers are part of a general overhaul of the MeteoSwiss network for long-term AOD monitoring to replace their current sunphotometers, which were designed and manufactured more than 20 years ago by PMOD/WRC. The spectral ICS was purchased by a customer in order to improve the quality of solar UV measurements.

When examining Figure 3, we draw attention to the fact that the production and sale of PMO6-cc absolute cavity pyrheliometers were outsourced to Davos Instruments (https://www.davos-instruments.ch/) in 2020. These type of radiometers have therefore not appeared in the sales statistics since then. Several years ago, Davos Instruments developed a new generation of radiometer, the PMO8 series. However, PMOD/WRC will continue to be responsible for the calibration of absolute cavity pyrheliometers against the World Standard Group (WSG) of pyrheliometers.

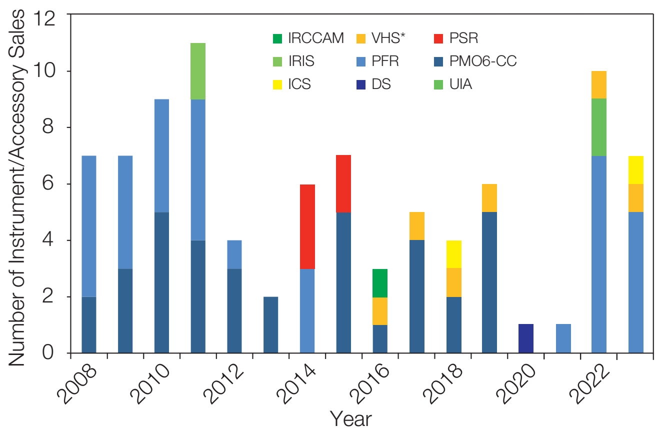


Figure 3. Number of PMOD/WRC instrument sales from 2008 up to and including 2023: i) IRCCAM = Infrared Cloud Camera, ii) VHS = Ventilation Heating System, iii) PSR = Precision Spectroradiometer, iv) IRIS = Infrared Integrating Sphere Radiometer, v) PFR = Precision Filter Radiometer, vi) PMO6-CC = absolute cavity pyrheliometer, vii) ICS = Irradiance Calibration System, viii) DS = Diffuser System for UV spectroradiometers, and ix) UIA = Universal Instrument Adapter.

**Note: VHS sales/year shown as a single unit for ease of interpretation. Actual VHS units sold: 2016 = 7; 2017 = 2; 2018 = 36; 2019 = 5; 2022 = 2; 2023 = 1.*

Solar Radiometry Section (WRC-SRS)

Wolfgang Finsterle and Ricco Soder

The Solar Radiometry Section (SRS) of the WRC maintains and operates the World Standard Group (WSG) of pyrheliometers which represents the World Radiometric Reference (WRR) for ground-based total solar irradiance measurements. In 2023, the SRS participated in three pyrheliometer comparison campaigns in Japan, Sweden, and the United States. The regional and sub-regional comparisons in Japan and Sweden were necessary to renew the traceability of solar irradiance measurements in countries that were unable to participate in IPC-XIII (2021) due to the pandemic. The SRS also operates the ISO 17025 certified calibration laboratory for solar radiometers (pyrheliometers and pyranometers).

In 2023, the SRS calibrated 101 solar radiometers: These consisted of six absolute pyrheliometers, 81 pyranometers, and 14 field pyrheliometers. The WSG was operated on 77 days. The Cryogenic Solar Absolute Radiometer (CSAR) underwent extensive long-term functional testing and was continuously operated from 9 June to 28 August. The year 2023 was unusually busy with three pyrheliometer comparisons in Japan, Sweden, and the US. The comparisons were necessary to renew the traceability of solar irradiance measurements in countries that could not participate in the IPC-XIII due to the pandemic.

The fifth WMO Regional Pyrheliometer Comparisons (RPC-V) of Regional Association RA-II was held jointly with RA-V at Mount Tsukuba (Japan) from 16 - 27 January. The event was jointly organised by the Japan Meteorological Agency (JMA) and Australia's Bureau of Meteorology (BoM; Sasaki et al., 2023).

The third Baltic Region Pyrheliometer Comparison was organised by the Swedish Meteorological and Hydrological Institute (SMHI) in Norrköping from 22 May - 2 June.

The National Pyrheliometer Comparison (NPC) was organised by the National Renewable Energy Laboratory (NREL) in Golden (USA) from 23 - 28 September (Carlund, 2023).

The SRS participated in all three comparisons with its travelling standard group, which consists of four absolute pyrheliometers. Traceability to the WRR was renewed for eight countries while the stability of the WSG was validated against the US standard group during the NREL NPC (Reda et al., 2023).

On 28 February, a dead insect was removed from the cavity of the WSG pyrheliometer, HF18748 (Figure 1). This instrument had been excluded from the WSG since its sensitivity dropped in spring 2022. After removal of the insect, the sensitivity returned to its nominal value and the pyrheliometer is again part of the WSG.

As part of the regular maintenance and to ensure flawless operations, several improvements were implemented to the hardware and software of the SRS calibration laboratory. These include:

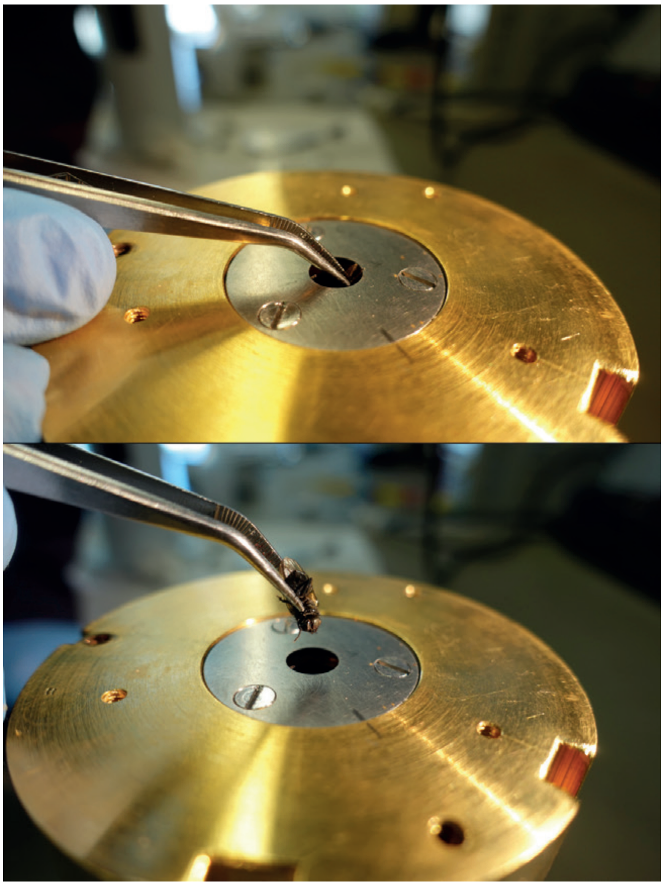


Figure 1. A dead insect was removed from the sensor cavity of the WSG pyrheliometer, HF18748, restoring its original sensitivity on 28 February. The procedure required extreme care to avoid scratching the delicate edge of the radiometric aperture.

1. New shading devices for pyrheliometers on the solar tracker. The old system was in use for several decades.

2. Transport container for the travelling standard group and associated data acquisition equipment. The new box will provide increased protection during transport and easier installation at the comparison sites as well as at PMOD/WRC.

3. CUI Software in Python. The electrical characterisation (CUI) of pyrheliometer control units is part of the calibration procedure for absolute pyrheliometers. The existing LabView software was migrated to Python.

References:

Carlund, T.: 2023, BRPC-2023, WMO IOP Report (in press).

Reda, I., Andreas, A., Stoddard M., Kepple A., Jaker S., Habte A.: 2023, NREL Pyrheliometer Comparisons: September 23 - September 28, 2023 (NPC-2023), NREL/TP-1900-87825.

Sasaki, S., Milner, M., Ohtake, J., Saito, A., Usuda, T., Yagi, K., Ohkawara, N.: 2023, Fifth WMO Pyrheliometer Comp. of RA II, Jointly Held with RA V, IOM Report (in press).

Infrared Radiometry Section (WRC-IRS)

Julian Gröbner and Christian Thomann

The Infrared Radiometry Section of the WRC maintains and operates the World Infrared Standard Group of pyrgeometers (WISG) that represents the world-wide reference for atmospheric longwave irradiance measurements.

The WISG serves as atmospheric longwave irradiance reference for the calibration of pyrgeometers operated by institutes around the world. The WISG has been in continuous operation since 2004, and consists of four pyrgeometers which are installed on the roof platform of PMOD/WRC. The measurements of the individual WISG pyrgeometers with respect to their average are shown in Figure 1 for the period 2004 to the end of 2023. As can be seen in the figure, the long-term stability of the WISG is very satisfactory, with measurements of the four pyrgeometers within ±1 Wm^{-2} over the whole time period.

A workshop on the operation and evaluation of the Absolute Cavity Pyrgeometer (ACP) took place at PMOD/WRC on 18 April 2023, with the participation of international experts. The workshop drafted guidelines on how measurement data and ancillary information should be combined in view of supporting post-analysis of future comparisons. Specifically the workshop addressed the required steps towards the establishment of the ACP as a future absolute reference for atmospheric downwelling longwave irradiance, in support of the ongoing activities of the WMO expert team on radiation references (ET-RR). In this context, an alternative ACP measurement equation was formulated and published, which takes into account the impact of convection on the signal measured by the thermopile of the ACP, see Forgan et al., 2023.

The EMPIR METEOC-4 project was successfully finished in August 2023. One of the outcomes for PMOD/WRC was the comparison of the BB2007 blackbody with the hemispherical blackbody developed by the German National Metrology Institute (PTB) with an excellent agreement between the irradiances of both blackbodies to within 0.5 Wm^{-2}, using an IRIS and a pyrgeometer as transfer standard instruments (Feierabend et al., 2023).

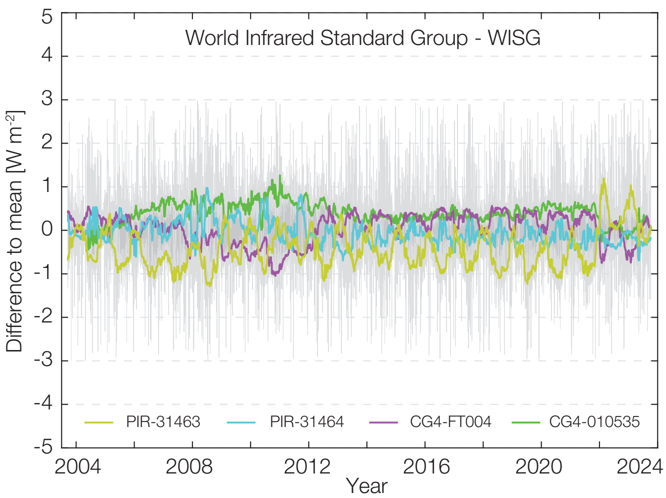


Figure 1. Night-time atmospheric longwave measurements of the WISG pyrgeometers relative to their average. The coloured lines represent a 30-day running mean of each WISG pyrgeometer, while the grey-shaded area represents daily averages.

Figure 2. Absolute Cavity Pyrgeometers (ACPs) and an Infra-Red Integrating Sphere (IRIS; in the foreground) on the roof of a measurement platform during the NREL Comparison of ACPs, IRIS, and pyrgeometers traceable to the World Infrared Standard Group. The campaign ran from 25 September - 6 October, 2023, in Golden (Colorado, USA).

PMOD/WRC took part in a field campaign held at NREL (Golden, Colorado, USA) from 25 September to 6 October to compare atmospheric downwelling longwave irradiance measurements between ACP, IRIS and pyrgeometers traceable to the WISG (see Figure 2).

A new contract between the PMOD/WRC and METAS was signed to extend the designation of PMOD/WRC to also cover the atmospheric downwelling longwave irradiance, and therefore allow the submission of Calibration and Measurement Capabilities (CMC) to the Key Comparison Database of the BIPM, as is already the case for total solar irradiance (WRC-SRS) and spectral solar irradiance (WRC-WCC-UV). This will underpin the redefinition of the WISG and its traceability to SI, which is one of the goals of the ET-RR.

References:

Feierabend, M., Gröbner, J., Müller, I., Reiniger, M., Monte, C.: 2023, Bilateral comparison of irradiance scales between PMOD/WRC and PTB for longwave downward radiation measurements, Metrologia, 60, 025010 (14pp), https://doi.org/10.1088/1681-7575/acbd51

Forgan, B. W., Gröbner, J., Reda, I.: 2023, New absolute cavity pyrgeometer equation by application of Kirchhoff's law and adding a convection term, Atmos. Meas. Tech., 16, 727–743, https://doi.org/10.5194/amt-16-727-2023

Atmospheric Turbidity Section (WRC-WORCC)

Stelios Kazadzis, Natalia Kouremeti and Julian Gröbner

The Atmospheric Turbidity Section of the WRC maintains a standard group of three Precision Filter Radiometers (PFRs) that serve as the reference for Aerosol Optical Depth (AOD) measurements within WMO. WORCC also operates the global GAW-PFR AOD network and collaborates with other global aerosol networks. WORCC has participated in a number of projects and activities related to the homogenisation of global aerosol networks, SI-traceable AOD retrievals, aerosol measurement analysis and capacity building activities based on WMO-GAW goals.

The World Optical depth Research and Calibration Center (WORCC) calibration hierarchy consists of the use of the WORCC reference. This reference is based on the average of three (triad) well-maintained Precision Filter Radiometers that are located in Davos (Switzerland; see Figure 1, next page). In addition, instruments operating at high mountain stations such as Mauna Loa (USA) and Izaña (Canary Islands, Spain) perform Langley calibrations, and are transported (one instrument every six months) to WORCC to check the PFR-Triad stability with an independent instrument. No changes were introduced to the triad data in 2023 after analysing the Langley transfer-related measurements.

Annual quality assured data from GAW-PFR stations were updated and submitted to the World Data Center for Aerosols (WDCA). In 2023, four instruments from the GAW-PFR network and 14 customer instruments, part of the extended GAW-PFR and MeteoSwiss networks, were calibrated against the reference PFR-Triad. WORCC calibration documentation was prepared for inclusion in the ISO 17025 Quality Management System at PMOD/WRC.

WORCC is participating in the Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS) of the Center for Aerosol Remote Sensing (CARS) through the ACTRIS-CH project (https://www.actris.ch/) by providing a permanent traceability link between the ACTRIS AOD measurements and the WMO primary AOD reference. During 2023, three PFR instruments were operated at Valladolid (Spain), OHP (France) and Izaña (Spain), and 14 certificates for the master AERONET instruments were issued for the 2022 - 2023 period. In the November 2023 ACTRIS general assembly, PMOD/WRC was defined as a new official CARS unit.

Within the QA4EO/ESA project, WORCC scientists have been collaborating with Serco, CNR (Italy), and the national observatory of Athens (Greece). Main results deal with the investigation of a correction algorithm for real time measurements of NO_2 when calculating AOD. In addition, a new project on synergistic cloud flagging algorithms and retrievals of PFR and Pandora instruments started in November 2023.

WORCC is involved in the activities of the Metrology of Aerosol Optical Properties (MAPP) project, coordinated by PMOD/WRC. An outcome of the project was that the WORCC PFR-triad will become SI-traceable through regular calibrations at the TULIP facility at the PTB (Germany). Furthermore, this traceability will also be extended to the ACTRIS/CARS reference radiometers.

The Lunar activities of WORCC, supported by the QA4EO/ESA and MAPP projects, have led to a benchmark dataset for Top-of-Atmosphere lunar irradiance presented at the GSICS/IVOS Lunar Calibration Workshop at EUMETSAT in December. A lunar campaign for optimising and testing the existing and newly-developed lunar PFRs was organised in summer 2023 in Rethymno (Crete).

WORCC has started operating the GAW-PFR website (https://gawpfr.pmodwrc.ch) including real-time station data.

WORCC participated in a publication related to an overview paper on aerosol mineral dust observations (Mona et al., 2023). Other studies included: spectral AOD retrievals (Gröbner et al., 2023), aerosol polarisation (Daskalopoulou et al., 2023) and aerosol retrieval from FTIR measurements (Alvarez et al., 2023).

WORCC results and an overview were presented in various workshops and meetings. Such meetings included the Scientific Aerosol group for Aerosols and the Expert team of Atmospheric Composition Measurement Quality. Also WORCC scientists have contributed to the new aerosol statement of guidance for the WMO Expert team of Atmospheric Composition and Network Evolution and also GAW/GCOS-CH.

WORCC is leading the COST action Harmonia – “International network for harmonisation of atmospheric aerosol retrievals from ground-based photometers” (https://harmonia-cost.eu).

PhD students X. Hu, A. Karanikolas (ETHZ), D. Kouklaki (NKUA, Greece) and A. Moustaka (AUTH, Greece) are being supervised, and are collaborating with WORCC. PhD student K. Papachristopoulou successfully defended her thesis in September 2023. There was one Master Thesis and one semester project related to aerosol research as a collaboration between WORCC and ETHZ.

References:

Alvárez, Ó., et al.: 2023, Aerosol properties derived from ground-based Fourier transform spectra within the Collaborative Carbon Column Observing Network, Atmos. Meas. Tech., https://doi.org/10.5194/amt-16-4861-2023

Daskalopoulou, V., et al.: 2023, Linear polarization signatures of atmospheric dust with the SolPol direct-sun polarimeter, Atmos. Meas. Tech., https://doi.org/10.5194/amt-16-4529-2023

Gröbner, J., et al.: 2023, Spectral aerosol optical depth from SI-traceable spectral solar irradiance measurements, https://doi.org/10.5194/amt-16-4667-2023

Mona, L., et al.: 2023, Observing mineral dust in Northern Africa, the Middle East and Europe: current capabilities and challenges ahead for the development of dust services, https://doi.org/10.1175/BAMS-D-23-0005.1

Figure 1. The triad of three Precision Filter Radiometers (white housings) and new PFRs (blue housings) are shown at PMOD/WRC against the backdrop.of the Seehorn mountain at Davos.

World Calibration Centre for UV (WRC-WCC-UV)

Julian Gröbner and Gregor Hülsen

The objective of the World Calibration Center for UV (WCC-UV) of the WMO Global Atmosphere Watch (GAW) is to assess the data quality of the Global GAW UV network and to harmonise the results from monitoring stations in order to ensure representative and consistent solar UV radiation measurements on a global scale.

The main activity during 2023 was to handle the increasing number of requests for QASUME site audits. Currently 4 - 5 visits are performed each year. Booking requests have so far been received up to 2026.

In 2023, five quality assurance site visits were conducted with the QASUME transportable reference spectroradiometer. This began in May with the 10th audit at the Agenzia Regionale Protezione Ambiente (ARPA) in Aosta (Italy). In May to June, we organised the 7th audit at the Sodankylä Arctic station, followed by the 3rd audit in Helsinki. Both stations are located in Finland, and are operated by the Finnish Meteorological Institute (FMI). In September, QASUME travelled to Spain to perform two site visits, one at the Spanish Meteorological Agency (AEMET) headquarters in Madrid, and the second at El Arenosillo.

During the 18th RBCCE inter-comparison at El Arenosillo, QASUME provided the global solar UV irradiance reference for the participating 16 Brewer spectrophotometers. Total column ozone values were provided by the Brewer #185 reference, operated by the Izaña Atmospheric Research Center of AEMET.

Results of all the QASUME site audits and reports of the campaigns can be found on the WCC-UV website: https://www.pmodwrc.ch/en/world-radiation-center-2/wcc-uv/qasume-site-audits/

The final report of the third UV inter-comparison campaign (UVC-III) was prepared and forwarded to the WMO publishing department. The report was published in December 2023 (Hülsen and Gröbner, 2023). The UV data acquisition system on the roof platform at PMOD/WRC will be upgraded in 2024, allowing the installation of additional radiometers. Specifically, the new digital interface (modbus) type radiometers have become popular, and the number we receive for calibration have been continuously increasing.

Figure 1. The QASUME site audit was conducted at the Sodankylä Arctic station in Lapland (Finland), operated by the Finnish Meteorological Institute. The inter-comparison campaign lasted from 29 May to 2 June 2023. The measurement platform is seen in the centre of the picture.

Figure 2. The 18th RBCCE inter-comparison at El Arenosillo (Spain) was conducted with 16 Brewer spectroradiometers and the QASUME reference spectroradiometer, mounted on the tripod seen in the lower left corner.

Three new projects in the frame of the European Partnership in Metrology (EPM) began in June 2023, each with a duration of three years:

- NEWSTAND: New calibration standards and methods for radiometry and photometry after phaseout of incandescent lamps,
- MeLiDos: Metrology for wearable light loggers and optical radiation dosimeters,
- S-Cale Up: Self-calibrating photodiodes for UV and exploitation of induced junction technology.

The interaction with the consortium partners will maintain and strengthen our close ties to the metrology community and will extend and improve the traceability of our UV radiometer calibrations to SI units.

References: Hülsen, G., Gröbner, J.: 2023, Report of the Third International Solar UV Radiometer Calibration Campaign (UVC-III), GAW Report No. 284, https://library.wmo.int/idurl/4/68642

Section Ozone: Total Column Ozone and Umkehr Measurements

Luca Egli, Franz Zeilinger and Julian Gröbner

Operational total column ozone (TCO) and Umkehr measurements are operationally performed at PMOD/WRC with three Dobson and four Brewer spectrophotometers. The objective of these instruments is to monitor the stratospheric ozone layer and to extend the world's longest continuous total ozone time-series from Arosa-Davos in Switzerland, which has been operational since 1926. In addition to the Dobson and Brewer instruments, one array spectroradiometer-based system (Koherent) and the portable world reference for ultraviolet radiation, QASUME, are operated at PMOD/WRC. The two supplementing instruments measure TCO with modern technology, which are compared with the performance of the traditional instruments. In total, nine instruments are located at PMOD/WRC to monitor the TCO at Davos.

The long-term Arosa-Davos time-series consists of measurements from three Brewer instruments (B040, B072 and B156) and three Dobsons (D051, D062 and D101) from Meteoswiss. These instruments perform TCO measurements (Figure 1) and vertical ozone profile measurements (Umkehr). Dobson D051 is mainly dedicated to Umkehr measurements. Occasionally, D051 is used for direct sun observations to compare with D101 and D062, forming a triad to monitor the stability across the three instruments. Once a month, all three Dobsons measure TCO from sunrise to sunset to detect airmass dependent biases. Once a week, the Dobson D051, D062 and D101 conduct Umkehr measurements for cross-validation of ozone profiles to form an Umkehr triad as well.

The afore-mentioned six instruments, forming the official Arosa-Davos time-series, are continuously operated at PMOD/WRC and agree to within ±1% in TCO. In addition to these instruments, PMOD/WRC operates its own Brewer double monochromator B163 since 2007. This instrument is also used for comparison with the instruments from MeteoSwiss, and is calibrated, operated and maintained as the official Brewer triad. In addition, B163 performs UV scans to measure global solar ultraviolet radiation.

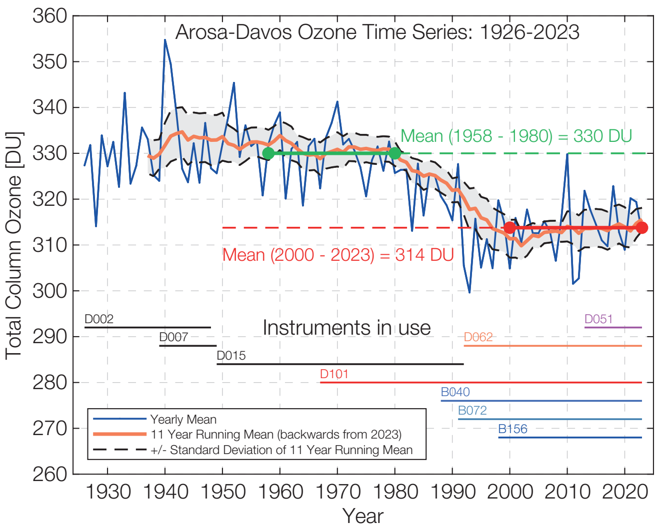


Figure 1. Total column ozone time-series from 1926 to 2023. Since 2010, the 11-year running mean seems to have stabilised within a limit of 2% (dashed line).

Figure 2. Housings of the two LuxMeters on the roof of the Dobson container.

As in previous years the World portable reference for UV radiation, QASUME, was occasionally retrieving traceable TCO, based on spectral direct sun measurements (Egli et al., 2022). These measurements are used to monitor and diagnose potential biases of the Arosa-Davos instruments relative to an independent instrument.

The array spectroradiometer-based system, Koherent (see page 50 of this report) has been continuously measuring TCO, and was able to retrieve effective ozone temperatures using a novel retrieval technique.

In order to perform Umkehr ozone profile retrievals during cloudy days, a cloud correction is implemented in the Umkehr data post-processing procedure. The cloud thickness is given as an index, and is measured with Luxmeters (Figure 2). In 2023, a second temperature stabilised housing was constructed and installed on the roof of the Dobson container to perform redundant Luxmeter measurements.

In summer 2023, the ground ozone instruments at PMOD/WRC (1540 m a.s.l.) and the SLF experimental site at Weissfluhjoch (2350 m a.s.l.) were calibrated in-situ with a reference instrument from the Amt für Natur und Umwelt (ANU) Graubünden.

For technical support of the MeteoSwiss Dobson and Brewer instruments in Nairobi, Franz Zeillinger successfully travelled to Kenya in July 2023.

References: Egli, L., Gröbner, J., Hülsen, G., Schill, H., Stübi, R.: 2022, Traceable total ozone column retrievals from direct solar spectral irradiance measurements in the ultraviolet, Atmos. Meas. Tech., 15, 1917-1930, https://doi.org/10.5194/amt-15-1917-2022

Instrument Development

Space Missions in the Build Phase

Andrea Alberti, Valeria Büchel, Matthias Gander, Louise Harra, Silvio Koller, Patrik Langer, Leandro Meier, Andri Morandi, Daniel Pffifner, Florian Reinhard, Pascal Schlatter, Werner Schmutz, Marcel Spescha and Jonas Weber

PMOD/WRC is involved in four Space missions at different design and development stages up to finalisation. DARA (onboard the ESA PROBA-3 mission) is a 3-channel absolute radiometer, designed for the long-term stable and highly accurate measurement of Total Solar Irradiance (TSI), which is fully traceable to SI units. VIGIL (previously called Lagrange) is ESA's space weather mission at the L5 Lagrange point. An EUV coronal imager is a potential remote sensing instrument, where PMOD/WRC may provide the camera electronics. CSAR, part of the ESA TRUTHS (Traceable Radiometry Underpinning Terrestrial and Helio-Studies) mission, is a cryogenic absolute radiometer to be launched in 2029. SoSpIM, an extreme UV Solar Spectral Irradiance Monitor for the Japanese Solar-C mission, is in its prototype phase, and is due to be launched in 2028.

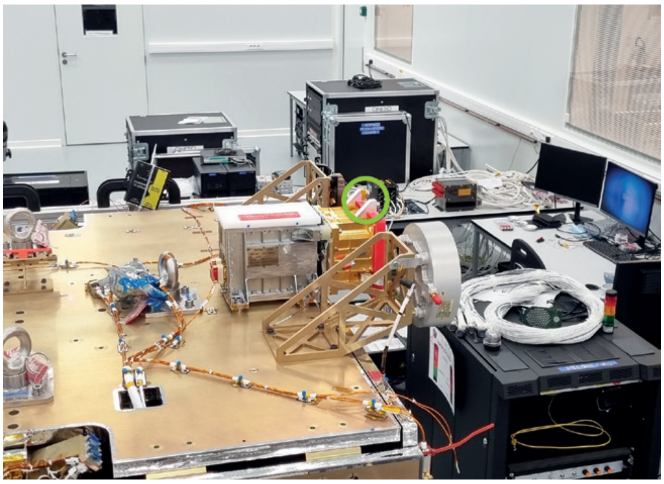


Figure 1. DARA mounted on the PROBA-3 occulter spacecraft. The green circle highlights the laser trackers for instrument alignment.

DARA Onboard PROBA-3

After delivery of the DARA (Digital Absolute Radiometer) Flight Model at the end of 2021, the instrument was mounted on the ESA PROBA-3 Occulter Spacecraft in January 2023 (Figure 1). PMOD/WRC employees took part in the integration and alignment campaign at REDWIRE Space (Belgium). Using temporary mounted laser marker trackers, the instrument was perfectly co-aligned with the optical axis of the Occulter Spacecraft.

During the year, both components (Occulter and Coronagraph) of the PROBA-3 satellite were sent to IABG (Germany) for satellite level environmental tests (Figure 2). PMOD/WRC occasionally received instrument data for analysis. All these tests were successful, and PROBA-3 is due to be launched from India on a PSLV rocket, most probably in the second half of 2024.

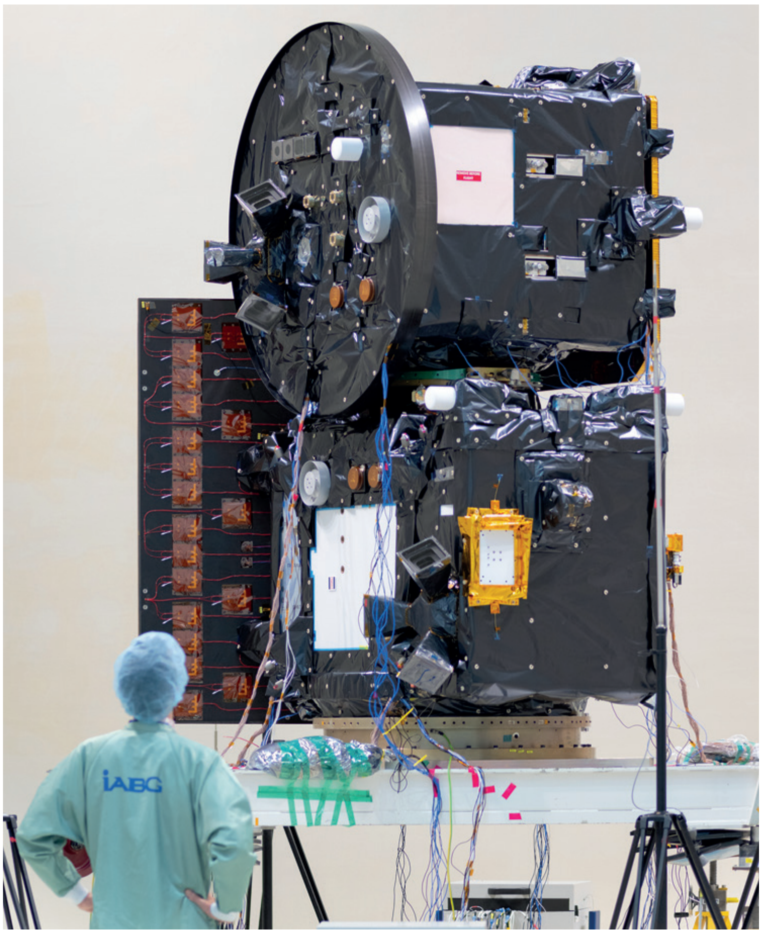


Figure 2. The combined PROBA-3 stack, with the Occulter satellite on top of the Coronagraph satellite, seen during environmental testing at IABG in Germany. (Image: courtesy of ESA)

VIGIL EUV Imager - Front-End Electronics (FEE)

NASA released a focussed mission of opportunity for a remote sensing extreme ultraviolet (EUV) imager instrument to be hosted on the European Space Agency (ESA) Vigil mission. Vigil is an ESA Space Safety Programme space weather mission to observe the Sun from the Sun–Earth Lagrange point L5. The American prime consortium for the instrument will be selected in early 2024, and the chosen institution will provide the Principal Investigator (PI) for the instrument. PMOD/WRC was requested to design the Front-End Electronics (FEE) for the imager, due to our successful collaboration on the EUI instrument onboard Solar Orbiter. Further collaboration partners include: i) the Centre Spatial de Liège (CSL), contributing extensive detector experience and the detectors, and ii) the Royal Observatory of Belgium (ROB), responsible for the selection of the Solar Orbiter/EUI spare detectors.

The goal of the Vigil mission is to understand and predict space weather. The uniqueness of the mission is that the spacecraft will be located at L5, which allows an early warning of disruptive activity from the Sun. A key aspect of understanding solar activity is to observe in the extreme UV range. EUV Imagers have observed the Sun extensively in Earth orbit, and the analysis methods are robust to track filament eruptions, flares and coronal waves as they propagate into the solar system.

The imager will allow us to study extreme space weather events (Figure 3), and answer fundamental questions about the Ground State of Space Weather as well – this includes solar wind formation, coronal mass ejection acceleration and propagation. The EUV imager will coordinate with the magnetic field measurements and coronagraphic images to provide a full view of solar activity that has an impact on the Earth's atmosphere.

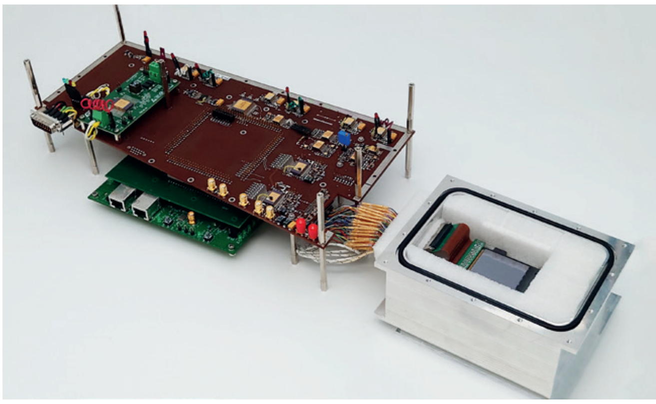


Figure 4. Front-End Electronics during characterisation.

Due to the tight schedule (FEE EM delivery in Q1/2025), PMOD/WRC and its subcontractor dlab GmbH initiated a pre-development effort to pro-actively mitigate risks and to demonstrate the FEE performance. This is a technology collaboration in the domain of control and read-out electronics for an EUV imager. The ESA-funded de-risking activity results in a functional breadboard with

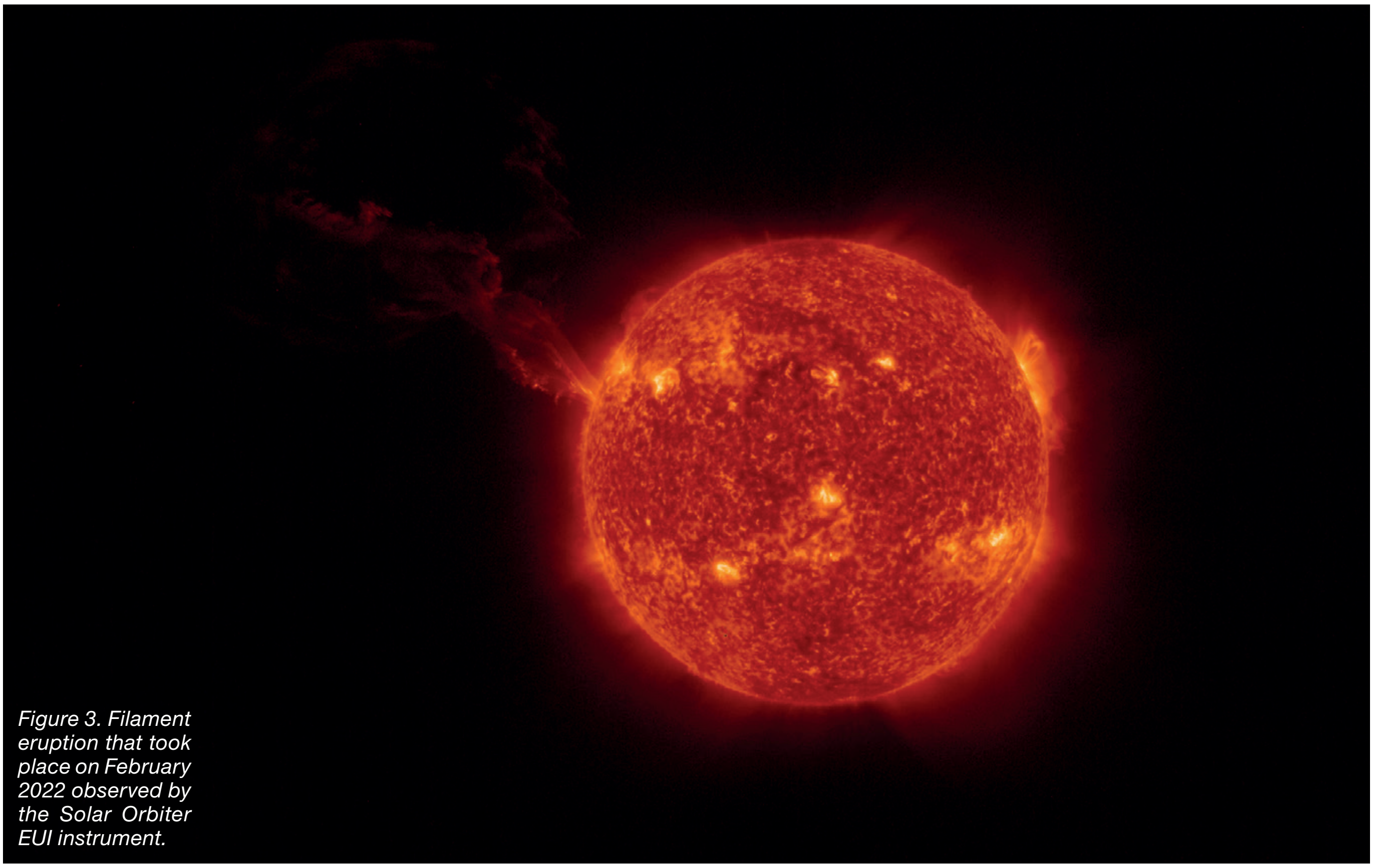


Figure 3. Filament eruption that took place on February 2022 observed by the Solar Orbiter EUI instrument.

Figure 5. First successful readout of the CMOS image detector.

Field Programmable Gate Array (FPGA) code and ground support equipment, which will be made available to the potential Swiss industry partner. The FEE consists of both, analogue and digital electronics (Figure 4). During the development phase of the LUCI project, an analogue Electrical & Functional Model (EFM) was designed and built. In the current de-risking phase of the VIGIL mission, this analogue EFM is intended to be controlled by a suitable FPGA development board, and the pixel sensor is to be read out on a laboratory setup (Figure 5).

The focus here is on the functionality of the various modules and their communication. It should highlight the difficulties, as well as the limitations of the entire camera electronics. Furthermore, it provides an indication of the extent to which the specifications can be achieved, and which optimisations should be considered in the next phase of building the engineering model (EM).

CSAR (Cryogenic Solar Absolute Radiometer) Onboard TRUTHS

After the pre-development study in 2022, the mission moved on to Phase B - the prototyping phase - with Airbus Defense and Space UK as the prime contractor. PMOD/WRC continued

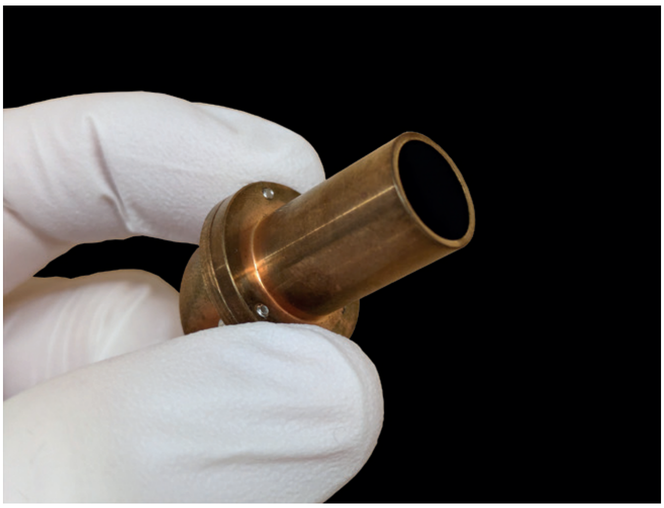


Figure 6. A 99.99% black CSAR cavity coupon with carbon nanotube coating.

Figure 7. Setup using liquid nitrogen for thermal cycling of adhesive samples to cryogenic temperatures.

with de-risking activities for the manufacture of the cavities and the electronics design. The goal of measuring the Total Solar Irradiance with an error of less than 100 ppm imposes tough requirements on the optical performance, thermal stability, and electronics.

The electronics concept of a lock-in amplifier to measure temperature and heating power accurately was tested on the ground-based CSAR at PMOD/WRC using laboratory equipment, and based on the results, the breadboard electronics were designed. The breadboard electronics will make use of every last bit of performance from off-the-shelf analog-to-digital and digital-to-analog converters with the help of the in-house developed Field Programmable Gate Array (FPGA) code in order to measure microwatt heating power and microkelvin temperature differences.

Coupons representing the material and geometry of the proposed cavity design were manufactured and coated with carbon nanotubes (Figure 6). Subsequent reflectivity tests showed that the cavity is absorbing 99.99 % of the incident radiation, as expected. Due to the slender shape of the cavities, the carbon nanotube coating must be applied to two separate parts, which then have to be joined. Joining methods that will withstand the thermal cycles to cryogenic temperatures and with a low enough process temperature for the black coating to survive, were evaluated. A setup was developed and manufactured, using liquid nitrogen and electrical heaters to allow controlled thermal cycling of joined samples between -190°C and +80°C (Figure 7).

In the coming project Phase B2, PMOD/WRC will produce Engineering Models of the CSAR instrument block and its proximity electronics.

SoSpIM (Solar Spectral Irradiance Monitor) Onboard Solar-C

Solar-C is the next Japanese solar physics mission to be developed with significant contributions from US and European countries. The mission carries an EUV imaging spectrometer with a slit-jaw imaging system called EUVST (EUV High-Throughput Spectroscopic Telescope) as the mission payload, to take a fundamental step towards answering how the plasma universe is created and evolves and how the Sun influences the Earth.

Solar-C is the fourth in the series of competitively chosen M-class missions by the Japan Aerospace Exploration Agency, and will be launched in 2028. A second instrument, led by PMOD/WRC, provides spectral irradiance capability through a Solar Spectral Irradiance Monitor (SoSpIM). This provides both scientific and calibration capabilities. SoSpIM and EUVST will work hand-in-hand. EUVST will provide consistent spectral observations from the chromosphere to the corona, tracking the energy flow on small spatial scales. SoSpIM will allow "Sun-as-a-star" measurements in two wavelength bands that overlap EUVST. This provides measurements of all solar flares visible from Earth, not just those within the EUVST field-of-view. The SoSpIM instrument provides the connectivity between the flare processes captured in detail on the Sun by EUVST and the impact of irradiance changes in different layers of the Earth's atmosphere.

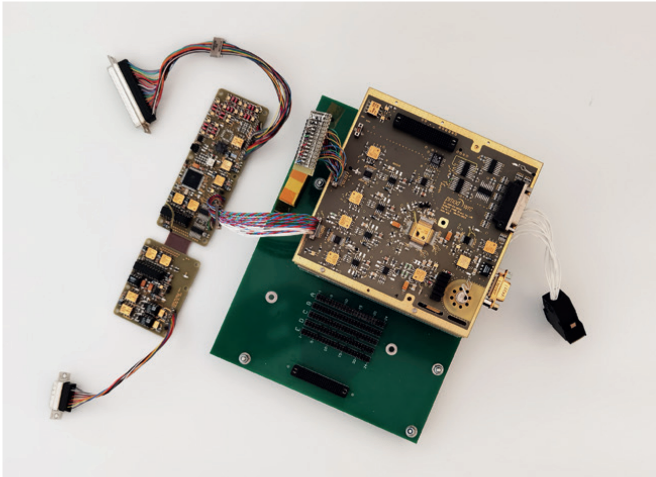


Figure 9. Electronics of the SoSpIM Engineering Model.

SoSpIM is being developed in a consortium with the Royal Observatory of Belgium (ROB), Swiss industry (Art of Technology, dlab, Micos) and PMOD/WRC. The consortium successfully passed the instrument Preliminary Design Review (PDR) in autumn 2023. The engineering model was assembled and is currently in the testing phase (Figures 8 and 9). The next major step is the manufacturing, assembly and testing of the structural model.

Figure 8. The SoSpIM Engineering Model.

Space Missions in the Operations Phase

Krzysztof Barczynski, Wolfgang Finsterle, Manfred Gyo, Margit Haberreiter, Louise Harra, Nils Janitzek, Silvio Koller, Jean-Philippe Montillet and Daniel Pfiffner

PMOD/WRC is involved in the operations of instruments onboard six operational spacecraft. The ESA SOHO mission was launched back in 1995, and the PMOD/WRC instrument, Variability of solar IRradiance and Gravity Oscillations (VIRGO) is still operational. The ESA PROBA-2 mission which was launched in 2001, hosts the LYRA instrument with PMOD/WRC involvement, measuring the solar spectral irradiance. The Compact Lightweight Absolute Radiometer (CLARA) is a payload onboard the Norwegian NorSat-1 micro-satellite and is a new generation of radiometer to measure the Total Solar Irradiance (launched in 2017). The ESA/NASA Solar Orbiter mission, which was launched in 2020, has ten instruments onboard, two which have PMOD/WRC involvement – these are an EUV Imager (EUI) and a spectrometer (SPICE). The Chinese JTSIM mission was launched in July 2021, and our Digital Absolute Radiometer (DARA) instrument is onboard.

PMOD/WRC have operational, calibration and scientific responsibilities for all the instruments we have developed. These include irradiance measurements (VIRGO, LYRA, CLARA, JTSIM-DARA, and PROBA-3 - DARA), and more recently imaging and spectroscopic measurements (Solar Orbiter). We have been funded through the Karbacher Funds, which have supported these efforts since the end of 2019 to the end of 2022. As of 2023, funding comes from the ESA Prodex programme.

VIRGO Onboard SOHO

The VIRGO experiment onboard the SOHO spacecraft has been providing total and spectral solar irradiance measurements almost continuously since February 1996. Over the years, the active sensor has degraded in terms of accuracy due to long exposure to UV/EUV light. The back-up sensor that operates at a much lower rate (once every 10 days) is used to monitor the alteration of the high recording rate sensor. A machine-learning based algorithm was developed in order to correct this degradation in the recorded measurements. Since then, the PMOD/WRC team have been regularly providing (every 4 months) the new PMO6v-v8 product (Finsterle et al., 2021).

The data pipeline for the VIRGO data on the SOHO archive is currently being updated at: https://soho.nascom.nasa.gov/data/archive

All information about the mission and new products are available on our website at: https://www.pmodwrc.ch/en/research-development/space/soho/

References: Finsterle, W., Montillet, J.-P., et al.: 2021, Scientific Reports, 11, https://doi.org/10.1038/s41598-021-87108-y

CLARA Onboard NorSat-1

Overview

The Compact Lightweight Absolute RAdiometer (CLARA) experiment (Finsterle et al., 2014; Walter et al., 2017) onboard the Norwegian micro satellite NorSat-1 was launched on 14 July 2017 and first light measurements were taken on 21 August 2017. CLARA's primary science goal is to measure total solar irradiance (TSI) in space and contribute to the long-term TSI record. CLARA is traceable to the National Institute of Standards and Technology (NIST) radiometric scale. Since November 2019, CLARA also measures the outgoing longwave radiation (OLR) when CLARA is on the night-side of Earth.

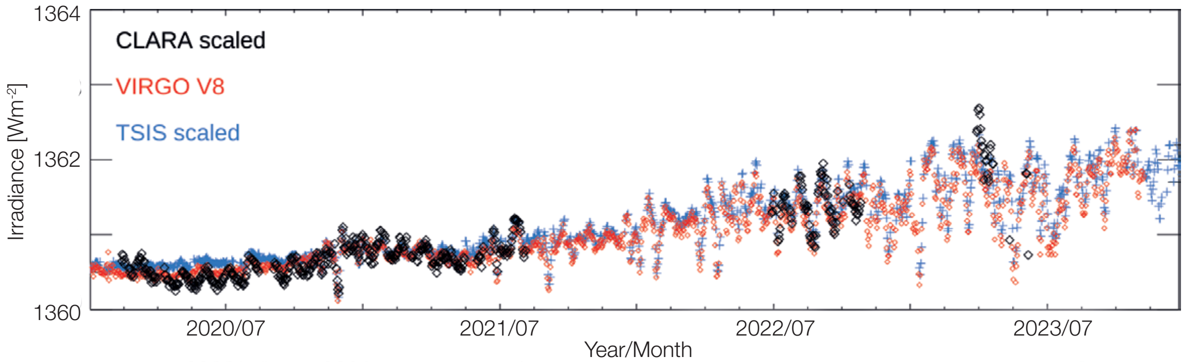


Figure 1. CLARA TSI time-series (black diamonds) compared to the VIRGO Level 2 PMOA TSI measurement (small red diamonds), and the TSIS time-series. All datasets are shown with daily resolution. Adapted from Haberreiter et al. (2023).

CLARA Operation
The CLARA instrument is currently healthy and operating well. However, as already reported last year, the solar pointing of the NorSat-1 platform was interrupted in November 2022. The Norwegian operation center investigated the issue, and solar pointing was established again on 4 January 2023. Solar measurements continued until April 2023, despite some intermittent short-term interruptions. However, in May and June 2023, additional issues of the platform hampered further solar measurements. It was only in September when some solar measurements were able to start again. However, due to recurring platform issues, no continuous solar measurements were possible for the rest of 2023.

The CLARA team has been continuously in contact with the Norwegian Space Operation Center (Statsat) to discuss the issues with the reaction wheels. In addition, the data exchange has been continuously monitored, and steps have been taken as required.

Re-visiting the TRF Calibration Analysis
As reported previously, the electronic temperature correction, based on the electronic calibration, had to be revised. For consistency, we also implemented this revised temperature correction, in the analysis of the pre-launch calibration at the Total Solar Irradiance (TSI) Transfer facility at LASP (Boulder, USA), and updated the respective calibration coefficients by Walter et al. (2017). Now that this has been implemented, we consider the calibration factors of the instrument as being consistent again.

The latest version of the CLARA TSI time-series is shown in Figure 1. Overall, CLARA tracks the solar variability quite well. However, during the solar minimum phase in 2020, CLARA showed a higher modulation, which neither exists in VIRGO nor in Total and Spectral Solar Irradiance Sensor (TSIS) data. The reason for this is currently being investigated. Despite the issues with the solar pointing in 2023, the CLARA Outgoing Longwave Radiation (OLR) measurements are still being conducted, see also the contribution “CLARA Earth Outgoing Radiation Measurements” on page 33.

References: Finsterle, W., Koller, S., Beck, I., et al.: 2014, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 9264, Earth Observing Missions and Sensors: Development, Implementation, and Characterization III, 92641S

Haberreiter, M., Finsterle, W., Montillet, J.-P., et al., 2023, Oral Presentation at the Sun Climate Symposium.

Walter, B., Levesque, P.-L., Kopp, G., et al.: 2017, The CLARA/NORSAT-1 solar absolute radiometer: Instrument design, characterization and calibration, Metrologia, 54, 674-682.

EUI and SPICE Onboard Solar Orbiter

Solar Orbiter is a spaceborne solar physics observatory, launched in February 2020. The spacecraft carries a suite of six remote-sensing (Sun and surroundings imaging, spectroscopy, photospheric magnetic field) and four in-situ instruments that measure plasma properties of the solar wind, the interplanetary magnetic field and energetic particles. We provide support for the operations, calibration and data analysis methodologies for two of these instruments: the Extreme Ultraviolet Imager (EUI; Rochus et al., 2020), and the Spectral Imager of the Coronal Environment (SPICE; Anderson et al., 2020) instrument. EUI and SPICE provide imaging and spectroscopy data, respectively. Solar Orbiter observations are divided into observation campaigns, which are periods where up to all ten Solar Orbiter instruments focus on the same scientific goal.

We provide assessment of the data return for EUI and SPICE. For EUI, we check that the campaign was carried out correctly. We use semi-automatic code to compare the EUI expected observations and the EUI obtained observations lists. A visual inspection of the EUI data is performed, which provides input for improvements in the next campaigns. For SPICE observations, feedback is provided about: data completeness, anomalies, and interesting features (e.g., solar flares, plasma upflow regions) based on the visual inspection.

Solar Orbiter provides simultaneous observation with Earth-orbiting and ground-based telescopes. In October, a coordinated campaign ran between Solar Orbiter and the Daniel K. Inouye Solar Telescope (DKIST). DKIST is the largest ground-based telescope observing the Sun. The aims of these coordinated observations were to track the evolution of the active region and to observe the polar magnetic field. DKIST is a new instrument, which made the first scientific observations in February 2022. We co-manage the first (October 2022) and second (October 2023) coordinated DKIST observation with Solar Orbiter.

To scientifically exploit overlapping observations between Solar Orbiter instruments and other observatories (in space and on ground), it is important to provide a systematic overview of Solar Orbiter observations to the scientific community. Toward this aim, we developed field-of-view (FOV) visualization tools for the EUI High Resolution Imager (EUI/HRI) as well as for the SPICE spectrometer. In contrast to the Full Sun Imager (EUI/FSI), these sensors only observe a small part of the Sun at a given time, but with very high resolution as well as providing spectral information. The FOV tools allow other researchers quick-look access to find out the pointing of these sensors at the time of scientific interest.

In Figure 2 (upper panel) we show an overview of EUI/HRI pointings at regions of interest during the Carrington Rotation 2255 in 2022.

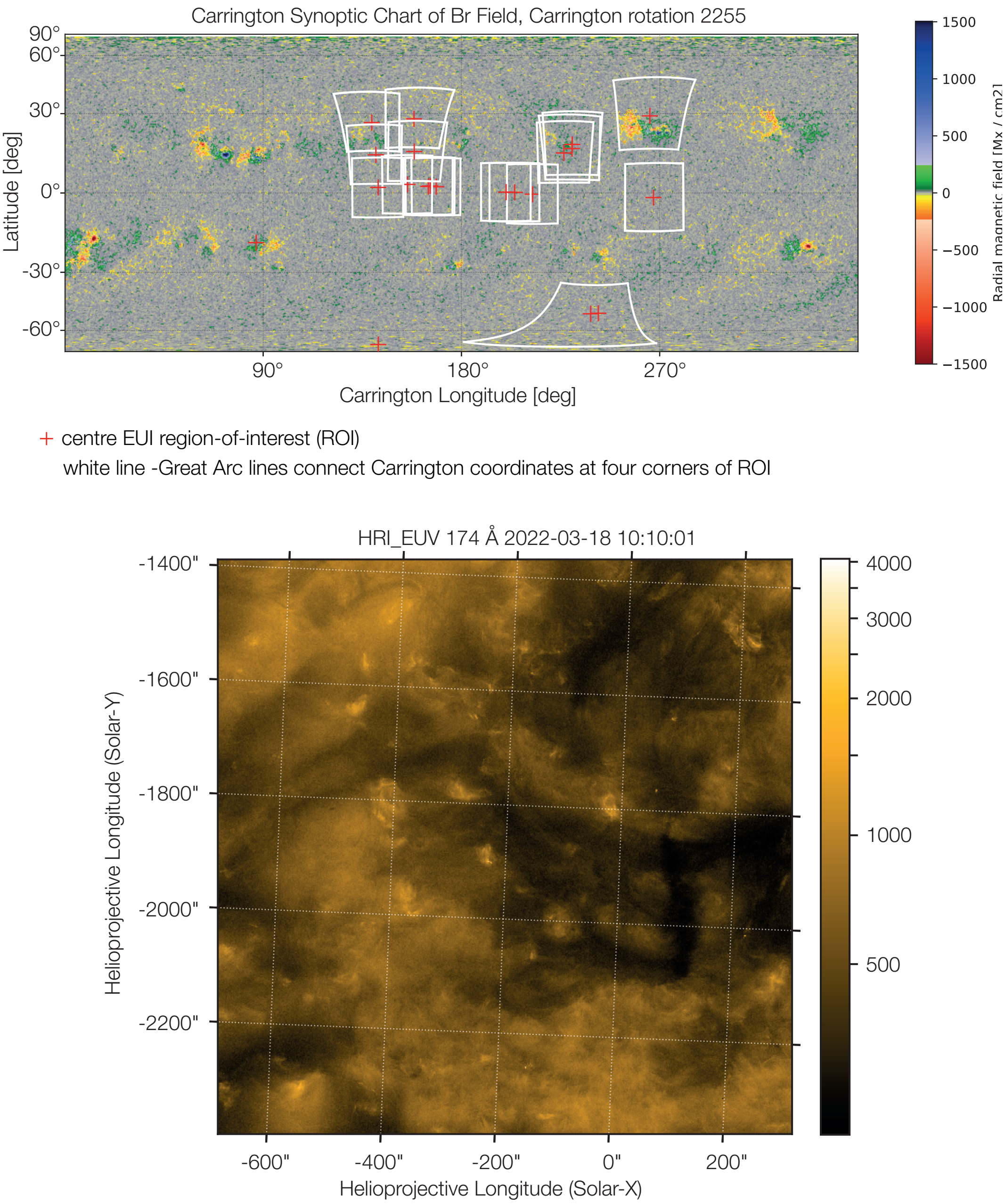


Figure 2. The position of the Solar Orbiter EUI/HRI field-of-view for one month of observations for the Carrington rotation 2255 (upper panel), and an example of EUI/HRI observations (bottom panel). The background image in the upper panel is a synoptic map of a photospheric magnetic field obtained from SDO/HMI in the cylindrical projection. The white boxes identify the field-of-view of EUI/HRI.

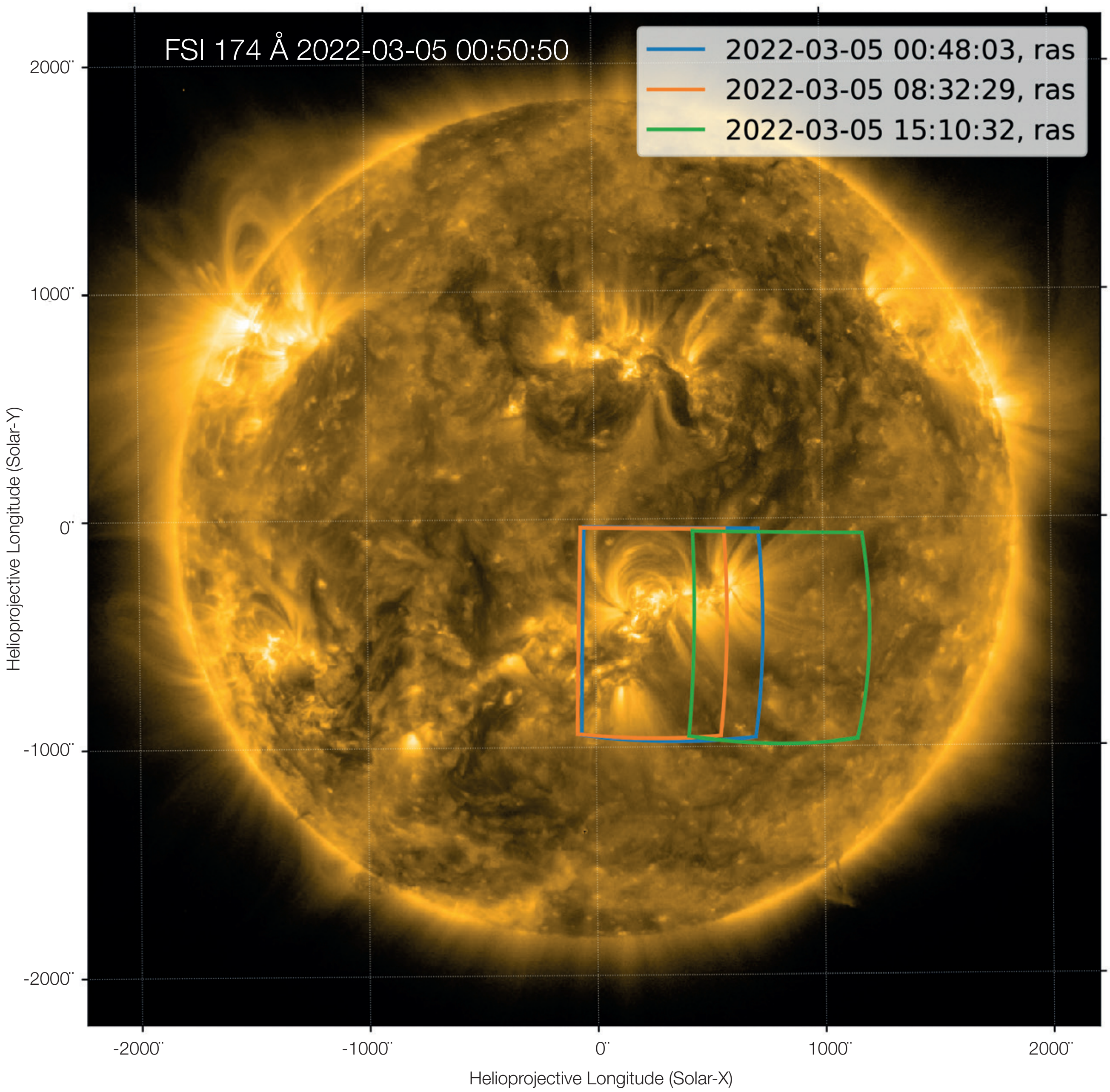


Figure 3. Example output of the SPICE FOV visualisation tool to coordinate remote-sensing observations with the Solar Orbiter spacecraft. The field-of-views (FOVs) of the SPICE spectrometer for several "raster"-observations on 5 March 2022 are overlaid over a full-sun image of the EUI-FSI instrument in the 174 Å channel.

As shown, these regions can be compared with photospheric magnetic field data that is observed with another spacecraft - in this case the Solar Dynamics Observatory (SDO). In the lower panel, we show an image obtained from the EUI/HRI 174Å channel.

In Figure 3 we show the FOVs of several raster spectrometer observations obtained from SPICE on 5 March 2022. The SPICE FOVs are overlaid over the EUI/FSI 174Å images. These show the upper transition region and lower solar corona where active regions are clearly seen as bright regions. The information from the developed FOV visualisation tools can also be used to optimise future observation campaigns by simulating the FOV beforehand.

The EUI and SPICE teams collaborate with other Solar Orbiter instrument teams. The Spectrometer/Telescope for Imaging X-rays (STIX) onboard Solar Orbiter provides information about X-ray flux, for instance from solar flares. Collaborating with the STIX team, we have fully automatised the process of presenting information about EUI observation time and data type in the STIX data browser: https://datacenter.stix.i4ds.net/.

The list of coordinated observations is necessary in order to investigate the same structures observed with different instruments onboard Solar Orbiter. We continuously update a flare list together with the Energetic Particle Detector (EPD) and STIX teams. We provide information about EUI data availability, observation time, image cadence, and the approximate position of the solar flares. The list currently contains (up to January 2024) more than 440 flare-associated events observed between November 2020 and October 2023 with EPD, STIX, and EUI.

As a new topic in 2023, we started to systematically investigate the sensitivity of the EUI sensors to high energy particles that are ejected by the Sun in solar eruptions. During strong eruptions, these particles are seen as so-called solar cosmic rays in the CMOS detectors of EUI as they mark distinct tracks in them. Since these particles are also directly measured by EPD onboard Solar Orbiter, the data from both instruments can be directly compared, and a first case study shows good agreement. Such studies can be used to investigate the high-energy particles themselves, and to derive conclusions about the sensitivity of the optical sensors to this radiation. The latter can be taken into account to understand the response of the Solar Orbiter instruments to the ambient particle radiation environment and to the design of future imaging instrumentation.

References: Anderson, M., Appourchaux, T., Auchère F., et al.: 2020, The Solar Orbiter SPICE instrument, A&A, 642, A14, https://doi.org/10.1051/0004-6361/201935574

Rochus, P., Auchère, F., Berghmans, D., Harra, L. et al.: 2020, The Solar Orbiter EUI instrument: The Extreme Ultraviolet Imager, A&A, 642, A8, https://doi.org/10.1051/0004-6361/201936663

JTSIM-DARA Onboard FY-3E

The satellite was launched on 4 July 2021 from the SLS-2 launch site at the China Jiuquan Satellite Launch Centre. After a short commissioning phase (until 17 August 2021), DARA began recording Total Solar Irradiance (TSI) observations (Montillet et al., 2022; Montillet et al., 2023; Zhu et al., 2023). Details of the mission can be found on our website at: https://www.pmodwrc.ch/en/research-development/space/fy-3e/

The associated TSI data product (JTSIM-DARAv1) is released on the PMOD/WRC ftp site (see above link) and the ASTROMAT repository at: https://repo.astromat.org/

References: Montillet, J.-P., Finsterle, W., Haberreiter, et al.: 2022, Total Solar Irradiance monitored by DARA/JTSIM: first light observations, EGU General Assembly 2022, Vienna, Austria, 23-27 May 2022, EGU22-616, https://doi.org/10.5194/egusphere-egu22-616

Montillet J.-P., Finsterle W., Zhu P., et al.: 2023, Assessment of solar variability through the analysis of TSI observations recorded by the FY3E/JTSIM/DARA radiometer, ESS Open Archive, https://doi.org/10.22541/essoar.170365223.34450405/v1

Zhu, P., Ye, X., Montillet, J.-P., Finsterle, W., Yang, D., Duo, W., et al.: 2023, The first light from the joint total solar irradiance measurement experiment onboard the FY3-E meteorological satellite, submitted to Earth and Space Science.

DARA Onboard PROBA-3

During 2023, final preparations for the "Build Phase" were completed (see page 23), and at the same time, initial preparations for the "Operations Phase" began. We finished the pre-flight calibration campaign within the facilities at PMOD/WRC and in Boulder (LASP, USA) (Montillet et al., 2023a; Montillet et al., 2023b). A specific part of the calibration campaign focuses on the noise analysis for each component of the radiometer and its reduction in order to obtain accurate total solar irradiance measurements. As mentioned previously, the launch date of the mission has been delayed the second half of 2024.

More information about the PROBA-3 mission is available at: https://www.pmodwrc.ch/en/research-development/space/proba-3/

References: Montillet, J., Schmutz, W., Finsterle, et al.: 2023a, The DARA/PROBA-3 radiometer: results from the preflight calibration campaign, EGU General Assembly 2023, Vienna, Austria, 24-28 Apr. 2023, EGU23-9007, https://doi.org/10.5194/egusphere-egu23-9007

Montillet, J.-P., Schmutz, W. K., Finsterle, et al.: 2023b, The DARA/PROBA-3 radiometer: results from the preflight calibration campaign, SWT PROBA3 meeting, Brussels, Belgium, 26-28 November.

Scientific Research Activities

Overview

Louise Harra

Projects at PMOD/WRC are related to solar radiation in which we address questions regarding the radiation energy budget in the terrestrial atmosphere, as well as problems in solar physics in order to understand the mechanisms concerning the variability of solar irradiance. Hardware projects at our institute are part of investigations into Sun-Earth interactions which involve measurements of solar irradiance.

There is strong synergy between the know-how obtained from the Operational Services of the World Radiation Center and other research activities. The same instruments are built for space-based experiments as are utilised for ground-based measurements. In addition, with the involvement in Solar Orbiter, the instrumentation extends to imaging and spectroscopy. The research activities can be grouped into four themes: chemistry-climate modelling, atmospheric physics, development of reference instruments for meteorological radiation measurements and solar physics.

The majority of research activities are financed through third-party funding. During 2023, there were a range of funding sources which included projects supported by the Swiss National Science Foundation, Karbacher Funds, European COST action, SBFI, Meteoswiss, European H2020, ESA, and EURAMET. These funding sources supported eight PhD thesis projects (six of these at ETH and two students based at other universities and jointly supervised), three post-doctoral positions, and four instrument scientists.

Swiss participation in ESA's PRODEX programme (PROgramme de Développement d'Expériences scientifiques) funds the hardware development of science space experiments. The institute's PRODEX projects paid for the equivalent of 2.7 technical department positions. An additional two are funded from a contract with Airbus UK for the ESA TRUTHS project.

In the area of climate modelling, the research studies both long and short-term changes in the Earth's atmosphere. The ozone layer and climate responses to various anthropogenic and natural forcings are being modelled and analysed. The analysis is performed using our own simulations with the in-house SOCOLv4 model, as well as using data from multi-model campaigns. One of the main focuses is the modelling of different scenarios for the Sun from its current day state to theoretical highly active and quiet modes.

The solar physics focus is on Solar Orbiter, following the launch in 2020. These topics cover the creation of the slow and fast solar wind and the impact of flares, and are carried out in collaboration with an array of other space and ground-based missions including NASA's Parker Solar Probe, Solar Dynamics Observatory and JAXA's Hinode mission.

The institute's infrastructure and most of its overheads are paid for by the operational service of the World Radiation Center. We are proud of the fact that at the PMOD/WRC, the Center's services are based on research that is state-of-the-art in their respective fields. The WRC participated in several instrument inter-comparisons in 2023, acting as a reference for atmospheric longwave irradiance, total solar irradiance, spectral solar irradiance and aerosol optical depth. The swiss national metrology institute, METAS, enlarged our designation to cover not only solar irradiance and spectral solar irradiance but also the essential climate variable, surface radiation budget. Another important milestone was the inclusion of PMOD/WRC as a new unit of the Center for Aerosol Remote Sensing (CARS) of ACTRIS to provide traceability of aerosol optical depth measurements within ACTRIS to the WMO GAW-PFR reference.

In order to support the processing and analysis of increasingly large and complex data sets from our TSI space experiments, a new tool based on neural networks has been developed in collaboration with students from the Data Science Lab masters course at ETHZ. In addition, work is proceeding on understanding the top of the Earth's atmosphere outgoing radiation with the Norsat-1 CLARA mission.

The research carried out at PMOD/WRC is intertwined with the instrumentation, both ground and space-based. In addition, a transfer of knowledge on solar radiation is being carried out through the development of a short-term forecast model of solar energy.

PMOD/WRC's citations for refereed publications are shown below in Figure 1, reaching more than 25,000. There are now over 750 refereed publications.

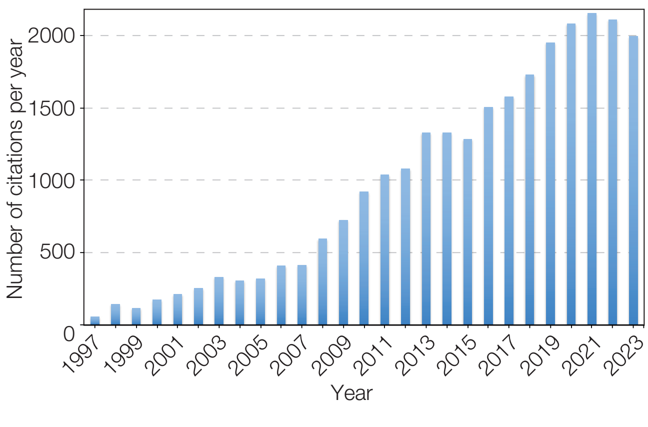


Figure 1. Number of annual citations to articles including an author with a PMOD/WRC affiliation. In December 2023, there were 25,245 citations to 752 articles included in Thomson Reuter's Web of Science. The articles were selected using the search criteria address = (World Rad* C*) OR (PMOD* NOT PMOD Technol* OR pmodak) OR (Phys* Met* Obs*).

Solar Wind Sources from the Quiet Sun

Louise Harra, Krzysztof Barczynski and Conrad Schwanitz

One of the key science questions of the Solar Orbiter mission is understanding the sources of the solar wind. There are two types of solar wind – the fast and slow solar wind. The fast wind emanates from open field lines in coronal holes. The slow wind sources are less well understood and have been a focus for our work. Solar Orbiter was launched in 2020 and now carries out two science perihelia per year when it reaches it closest point to the Sun and observes with all instruments. During this time we obtained observations that allow us to understand the small-scale sources that can feed into the solar wind.

The slow solar wind sources are a mystery. Progress in understanding these have been made through Parker Solar Probe mission data – that gets close to the Sun (within tens of solar radii) and has measured regular magnetic field reversals in the solar wind. These have been associated with network scales – the network outlines the location of the convective cells on the Sun's surface (Bale et al., 2021). Linking such large-scale behaviour in the solar wind to small-scale structures is a big step – and this is where the high resolution of the EUV Imagers (EUI) on Solar Orbiter are uncovering new phenomena. They have sizes of 400 - 5000 km, lifetimes of 10 - 200 s (Berghmans et al., 2021), many of which cannot be seen in other coronal imagers. Can these small-scale dynamical events be related to the solar wind? Schwanitz et al. (2021) discovered a new phenomena of upflow regions in the corona that did not show an intensity counterpart such as a jet of upflowing plasma – until the measurements from Solar Orbiter. Figure 1 shows an example of EUI data in a coronal upflowing region. Within the contour of the upflowing region, no strong plasma is seen. However, EUI reveals small complex loop structures that are dynamic in time and show a filament eruption, explaining the upflowing plasma in this case. This could not be seen with other instruments.

To understand whether these coronal upflows are associated with any magnetic phenomena or if they are seen in other parts of the atmosphere, a special observing campaign was set up. This was a two-week observing campaign led by Conrad Schwanitz and involved instruments from the ground-based GREGOR telescope along with two space missions – Hinode and IRIS (Schwanitz et al., 2023a). This provided datasets from the magnetic field on the Sun's surface through the atmosphere with spectroscopic measurements of the chromosphere and corona. We find a complex photospheric magnetic field with several small mixed polarities that are the footpoints of different loops (see Figure 2). Flux emergence and cancellation are observed at the constantly changing footpoints of the coronal loops. Reconnection of loops can be identified as the driver of the coronal upflow. Furthermore, the impact of the coronal activity triggers plasma flows in the underlying layers (Schwanitz et al., 2023b). This work highlights that frequent small coronal features can cause considerable atmospheric response and ubiquitously produce plasma upflows that potentially feed into the solar wind.

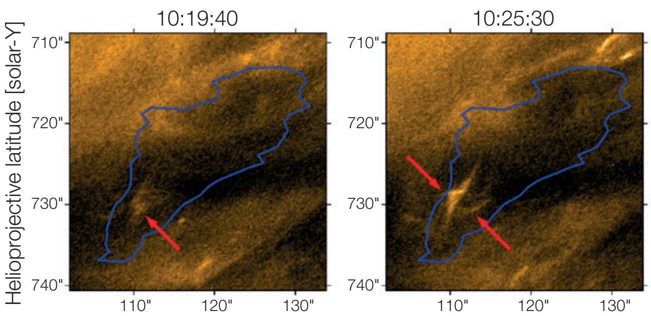


Figure 1. EUV high resolution imaging (HRI) data (orange) with blue contours highlighting the coronal upflow region as measured by Hinode EIS on 17 March 2022. The red arrows show the intensity features revealed by EUI that were not seen before. These are small-scale, multi-featured and have a small filament eruption associated with them. From Schwanitz et al., 2023a.

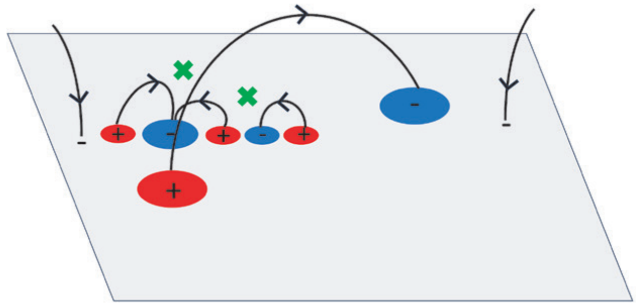


Figure 2. A schematic of the complex magnetic field seen in a small coronal upflow region. The red highlights a positive magnetic field and the blue a negative magnetic field. The small-scale fields cancel, allowing reconnection to take place (highlighted by green crosses).

References:

Bale, S., Horbury, T., Velli, M., et al.: 2021, A solar source of Alfvénic magnetic field switchbacks: In situ remnants of magnetic funnels on supergranulation scales, ApJ, 923, 174, https://doi.org/10.3847/1538-4357/ac2d8c

Berghmans, D., Auchère, F., Long, D., et al.: 2021, Extreme-UV quiet Sun brightenings observed by the Solar Orbiter/EUI, A&A, 656, L4, https://doi.org/10.1051/0004-6361/202140380

Schwanitz, C., Harra, L., Raouafi, N. E., Sterling, A. C., Moreno Vacas, A., del Toro Iniesta, J. C., Orozco Suárez, D., Hara, H.: 2021, Probing upflowing regions in the quiet sun and coronal holes, Solar Phys., 296, 1, https://doi.org/10.1007/s11207-021-01915-0

Schwanitz, C., Harra, L., Mandrini, C., et al.: 2023a, Small-scale EUV features as the drivers of coronal upflows in the quiet Sun, A&A, 674, 219, https://doi.org/10.1051/0004-6361/202346036

Schwanitz, C., Harra, L., Barczynski, K., et al.: 2023b, Small-scale upflows in a coronal hole - tracked from the photosphere to the corona, Solar Phys., 298, 11, https://doi.org/10.1007/s11207-023-02216-4

Active Region Upflows

Krzysztof Barczynski and Louise Harra

The solar wind has both fast and slow components with fast components originating in coronal holes and the slow component corresponding to closed structures at the activity belt. The origin of the slow solar wind is still an open question. The coronal upflows that are seen at the edges of active regions can contribute to the slow solar wind. The sources of the upflow have been challenging to determine. The high-resolution coordinated observations and observations obtained from two vantage points by Solar Orbiter and Earth orbiting spacecraft provide a new view of the upflow region properties as well as the exceptional spatial resolution now available.

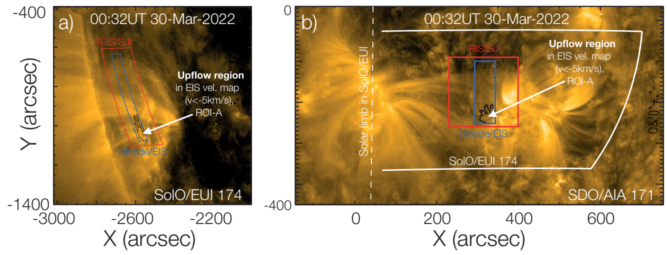


Figure 2. Overview of the active region observations from the Solar Orbiter EUI telescope at 174 Å (panel a) and SDO/AIA 171 Å (panel b). The boxes show IRIS/SJI (red), Hinode/EIS(blue) and Solar Orbiter EUI/HRI (white) field-of-views. The upflow region is highlighted as a black contour. After Barczynski et al. (2023).

The coordinated observations obtained by Solar Orbiter, Hinode/ EUV Imaging Spectrometer (EIS), and Solar Dynamics Observatory show an active region AR12960 with coronal upflows located unusually close to the sunspot umbra (Figure 1). Outflows are often seen at the edges of active regions or in the centre of the umbra. To determine whether this new source can feed into the solar wind, we measured the Doppler velocity, density, and plasma composition determinations, as well as conducting coronal magnetic field modelling.

We observed small magnetic fragments, called moving magnetic features (MMFs), moving away from the sunspot in the active region. Specifically, they moved towards the sunspot from the edge of the penumbra, where a small positive polarity connects to the umbra via small-scale and very dynamic coronal loops. At this location, small dark grains are evident, which flow along penumbral filaments in continuum images. The magnetic field modelling showed small low-lying loops anchored close to the umbral magnetic field.

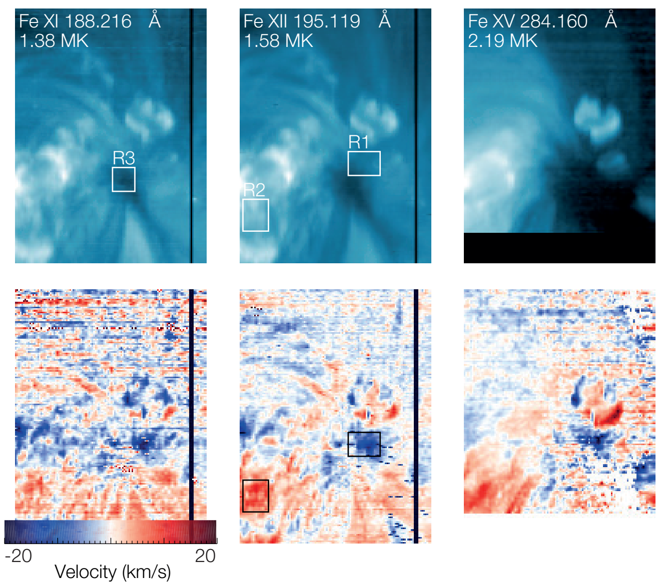


Figure 1. EIS intensity (top) and Doppler velocity (bottom) maps as a function of increasing temperature (from left to right) . The source R1 is where we see the strongest upflow and photospheric abundances. After Harra et al. (2023).

The high-resolution data of the Solar Orbiter EUV Imagers (EUI) showed the dynamics of these small loops, which last on time scales of only minutes. The edges of these small loops are the location of the coronal upflow that has photospheric abundance (Harra et al., 2023). This is in contrast to the frequently measured upflows at the edges of active regions that have coronal abundances.

To understand how the plasma upflows are generated, and which mechanisms are responsible for them, we analysed a coordinated observation of an active region upflow region. Barczynski et al. (2023) used data obtained with Hinode/EIS (FeXII), the Interface Region Imaging Spectrograph (IRIS), and Solar Orbiter EUI High Resolution Imager (HRI) at 174 Å (see Figure 2) obtained on 30 March 2022. For the first time, we were able to analyse the high-resolution quadrature view of the upflow region. We found extended loops rooted in a coronal upflow region. Plasma upflows at the footpoints of extended loops determined spectroscopically through the Doppler shift are similar to the apparent upward motions seen through imaging in quadrature.

The dynamics of small-scale structures in the upflow region can be used to identify two mechanisms of the plasma upflow: Mechanism I is the reconnection of the hot coronal loops with open magnetic field lines in the solar corona, and mechanism II is the reconnection of the small chromospheric loops with open magnetic field lines in the chromosphere or transition region. We identified the locations in which mechanisms I and II work.

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Harra, L. K., Mandrini, C. H., Brooks, D. H., et al.: 2023, The source of unusual coronal upflows with photospheric abundance in a solar active region, A&A, 675, A50, https://doi.org/10.1051/0004-6361/202245747

CLARA Earth Outgoing Radiation Measurements

Margit Haberreiter, Wolfgang Finsterle and Jean-Philippe Montillet in collaboration with ETHZ (Switzerland), RMI (Belgium), NPL (UK), CIOMP and Shenzhen University (China), JPL, LASP, NASA (USA) and LATMOS (France)

The energy budget of the Earth is governed by the balance between the energy entering and leaving the Earth's system. All components of the Earth Radiation Budget (ERB), i.e., Total Solar Irradiance (TSI), and outgoing shortwave and longwave radiation (OSR and OLR) are Essential Climate Variables (ECVs), identified by the WMO Global Climate System (GCOS). As such, the science community is mandated to continuously monitor these variables from space.

The Earth Radiation Budget (ERB) can be considered in terms of its sub-components. On the incoming side, there is the Total Solar Irradiance (TSI), ie the solar radiation reaching the top of the atmosphere (ToA). On the outgoing side, there is the outgoing shortwave radiation (OSR) i.e., the directly reflected solar radiation, as well as the outgoing longwave radiation (OLR), which is the thermal radiation of the Earth's surface and atmosphere. The CLARA instrument (Finsterle et al., 2014; Walter et al., 2017) onboard the NorSat-1 satellite has been measuring OLR since 2020. We have improved the data pipeline and analysis tools. One important element of the data analysis is the determination of the size of the CLARA footprint, which has a radius of approx. 40 km, corresponding to a diameter of about 0.7° on the Earth's surface for the case of nadir pointing. Figure 1 shows the latest CLARA outgoing radiances obtained for almost two years. The detailed co-temporal and co-spatial comparison with the CERES ToA is currently ongoing.

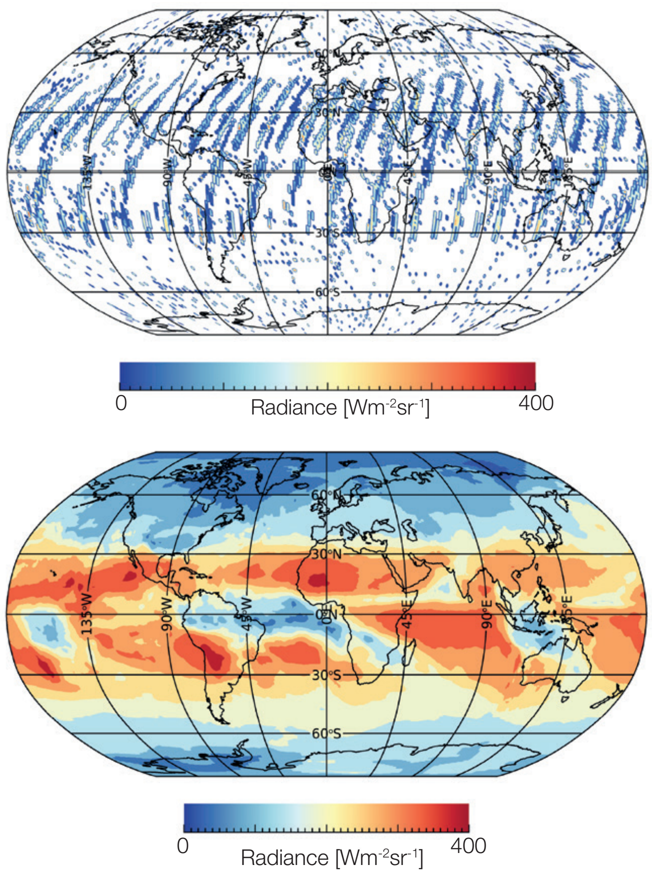

Figure 1. Upper panel: Individual measurements of CLARA ToA radiances ($Wm^{-2}sr^{-1}$) for almost two years of data, mostly obtained on the night-side of Earth. Lower panel: For general comparison, the monthly mean of CERES ToA OLR radiances including data for day and night.

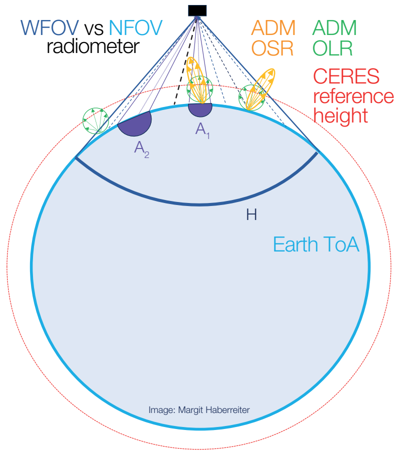

Figure 2. Schematic illustration (not to scale) of the different radiation fields of the terrestrial outgoing radiation as observed with a WFOV (dark blue lines) and NFOV (violet lines) radiometer (from Haberreiter et al., in preparation).

ISSI International - Towards Determining the Earth Energy Imbalance from Space

Within the ISSI International Team #500, we collect and compare, where possible, OLR and OSR data from various sources: RAVAN, GERB, CERES, CTIM, INSPIRE-Sat and the TARO and BOS/Picard. The challenge here is that the various instruments measure different radiation fields, which need to be transformed to the same quantity where possible. Figure 2 illustrates the radiation fields being measured with a narrow and wide field-of-view radiometer, NFOV and WFOV, respectively. Moreover, the OLR (green) has a spatial distribution, which is close to Lambertian, while the spatical distribution of the OSR (orange), strongly depends on the reflecting properties of the surface and the position of the Sun with respect to the observer. CLARA mainly measures the OLR on the night-side of Earth. Depending on the pointing of the satellite, footprints of varying size (A1 or A2) are observed with CLARA.

Acknowledgements: MH acknowledges support from the Karbacher Funds. We also thank the International Space Science Institute for supporting the International Team #500 and the great support during the team meetings.

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Total Solar Irradiance (TSI) Data Analysis

Jean-Philippe Montillet, Wolfgang Finsterle, Margit Haberreiter, Daniel Pfiffner and Silvio Koller

We have continued the development of several algorithms to: i) produce a new Total Solar Irradiance (TSI) composite time-series using all observations recorded by successive satellite missions launched since 1978 to the present, and ii) process new observations recorded by the DARA radiometer from the latest mission launched in space onboard the Chinese FY-3E satellite. It includes the study of the first light (with a revision of the values), comparison with other active missions and the release of the new TSI dataset, JTSIM-DARAv1. We also evaluated the pre-flight calibration of the DARA radiometer, which will fly on the next ESA mission, PROBA-3.

VIRGO onboard SOHO and the TSI composite time-series

The VIRGO/PMO6-v8 product

Following the development in 2020 - 2021 of the algorithm performing the degradation correction based on machine-learning, PMOD/WRC now releases the VIRGO/PMO6-v8 product every quarter on the PMOD/WRC ftp server (https://www.pmodwrc.ch/en/research-development/space/soho/).

The new 41-year TSI Composite produced and updated regularly by PMOD/WRC

Since the late 70's, successive satellite missions have been monitoring the sun's activity, and recording the total solar irradiance (TSI). To combine and concatenate all TSI measurements, we use the 3-step method based on data fusion developed in 2022 (Montillet et al., 2022; Montillet et al., 2023a). The time-series is now updated regularly (every quarter) on the public data repository (Montillet et al., 2023b) and the PMOD/WRC ftp server (links can be found here: https://www.pmodwrc.ch/en/research-development/solar-physics/tsi-composite/). The latest measurements are shown in Figure 1.

JTSIM-DARA / FY-3E Mission

Data Analysis of the Observations: The mission was successfully launched on 4 July 2021. After the commissioning phase, which lasted until mid-August 2021, PMOD/WRC has routinely analysed the observations from the DARA radiometer. The general processing focuses on converting the raw observations recorded by the instrument (Level-0) to irradiance measurements (Level-2). Level-2 observations are corrected for various factors (e.g., shutter aperture, reflectance, diffraction, the World Radiometric Reference factor, etc) (Song et al., 2021). Once all the corrections have been checked, the TSI time-series for the DARA-JTSIM instrument for the three cavities as shown in Figure 2 is available.

We estimate the first light value for DARA-JTSIM at about 1361.99 ±0.05 Wm^{-2} for the main cavity (cavity B), 1361.36 ±0.12 Wm^{-2} for the reference cavity (cavity A), and 1361.85 ±0.05 Wm^{-2} for the back-up cavity (cavity C) (Ye et al., 2023; Montillet et al., 2023c). The DARA-JTSIM data are at the moment being released on our ftp server (please see here: https://www.pmodwrc.ch/en/research-development/space/fy-3e/) and the public repository "ASTROMAT.org" (Montillet et al., 2023d). We are still working with the Chinese Meteorological Administration (CMA) on the publication of the DARA data on the CMA NSMC data portal in order to regularly update the TSI data product.

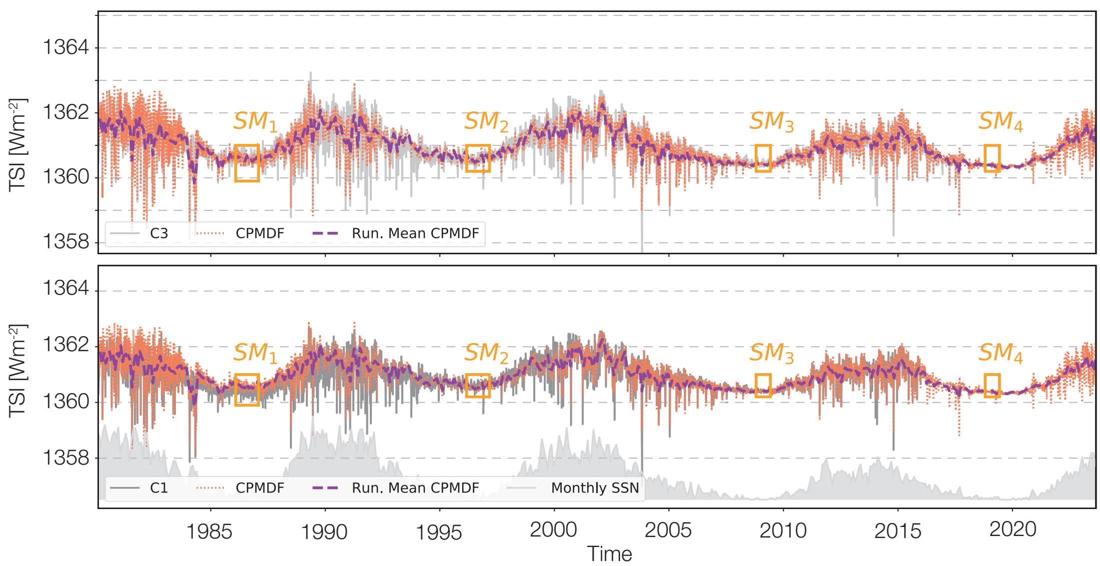

Figure 1. The new composite (CPMDF, orange), based on merging 41 years of TSI measurements, is illustrated. For comparison, the reference products, C3 and C1, are also shown (grey line; Montillet et al., 2022). A 30-day running mean of CPMDF is shown as a yellow/purple dashed line. The orange boxes are associated with the solar minima (SM) for each solar cycle. For context, the monthly sunspot number (SSN) is also displayed at the bottom of the lower panel.

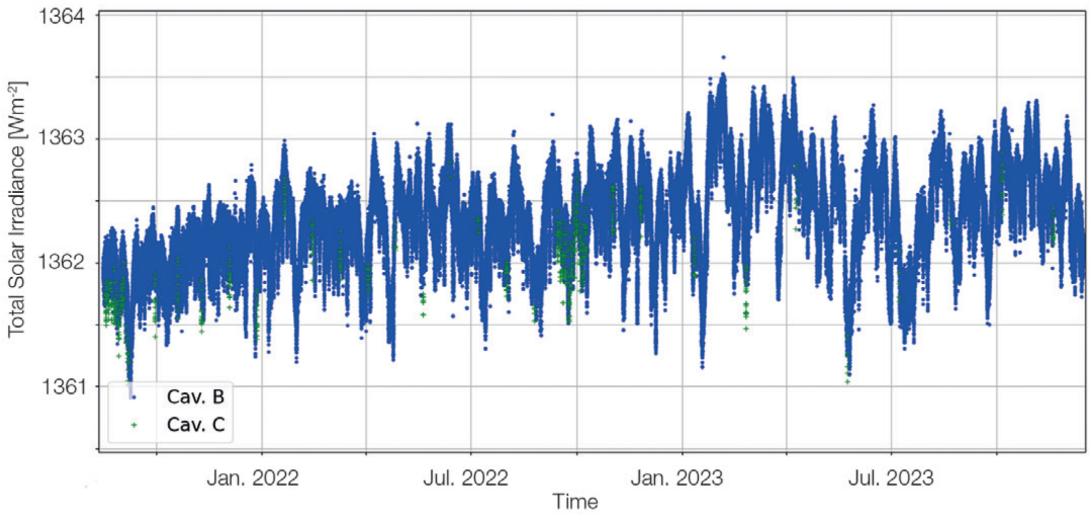

Figure 2. Shows the minute-rate TSI data recorded by the cavities B (nominal) and C (backup) of the JTSIM-DARA instrument from 18 Aug. 2021 to 14 Dec. 2023. It displays the overall behaviour of the time-series resulting from solar activity (e.g., faculae, sunspots).

PROBA-3 - DARA / ESA - PROBA-3 Mission

The Project for On-Board Autonomy-3 (PROBA-3) is the fourth satellite technology development and demonstration precursor mission within ESA's GSTP (General Support Technology Program) series. The PROBA-3 mission concept comprises two satellites in a highly-elliptical Earth orbit in precise formation, flying close to one another and with the ability to accurately control the attitude and separation of both satellites. The mission launch was scheduled for June 2024 but will probably be delayed by several months.

One of the satellites has a radiometer to record TSI observations. This is the Digital Absolute Radiometer (DARA) developed and manufactured by PMOD/WRC. We have finished the preflight calibration campaign within our own facilities and those at the Laboratory for Atmospheric and Space Physics (LASP, Boulder, USA). Several parameters (e.g., aperture, reflectance, lead heating) were calibrated, which are used to transform the raw measurements (e.g., voltage, current) into calibrated irradiance observations.

Acknowledgements: J-P. M., W. F., and M. H. gratefully acknowledge support from the Karbacher Funds. J.-P. M. also thanks the Swiss Space Office for support via the PRODEX funds.

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Flares, Solar Eruptions and Energetic Particles

Andrea Battaglia, Hannah Collier, Muriel Stiefel, Nils Janitzek, Krzysztof Barczynski and Louise Harra

In the current rising activity phase of Solar Cycle 25 we are observing an increasing number of solar flares and plasma eruptions on the Sun. These eruptions influence the plasma conditions in the inner heliosphere and can also lead to the release of high energy particles from the Sun that cause different kinds of space weather effects. By approaching the Sun as close as 0.3 AU, the Solar Orbiter spacecraft observes solar activity with unprecedented resolution. In close collaboration, scientists at PMOD, ETH Zurich and FHNW Windisch are investigating the solar flares and associated energetic particle acceleration on the Sun as well as their propagation in the heliosphere.

In their work, Battaglia et al. (2023) investigate the early onsets of solar flares and their underlying processes. The authors used X-ray emission measured with the Spectrometer/Telescope for Imaging X-rays (STIX) onboard Solar Orbiter together with emission data from the GOES X-ray Sensor (XRS). For both instruments, they found that in many flares, temperatures were significantly elevated before the non-thermal X-ray intensity increased, with the latter marking the onset of the flare in classical light curve analysis (Figure 1). In addition, during these "hot onsets" the emission measure in the flaring region typically increased about two orders of magnitude, indicating a series of increasing energy releases. It is possible that the onset conditions play an important role in the very early development of flares, which could be used as predictors for solar flares in the future.

Collier et al. (2023) researched the detection and characterisation of fast-time variations in the hard X-ray time profiles of solar flares. The research is based on larger flares of the GOES M and X-class as measured by STIX. In this study, it is shown that STIX is capable of resolving hard X-ray time variations on the order of a few seconds, and that these can be mathematically approximated by a series of Gaussian time profiles (Figure 2). Since the variations are often related to particle acceleration processes, their characterisation is key to understand the underlying physics of solar flares. Stiefel et al. (2023) used remote-sensing observations from several instruments to investigate solar flare hard X-rays from the anchor points of a solar filament. This emission is related to Bremsstrahlung from decelerated high-energy electrons within the corona. The study aims to understand an unusual flare geometry with four individual non-thermal sources, emitting hard X-rays instead of the usual two. It is found that the two outer sources are the anchor points of an erupting filament. The hard X-ray emission is interpreted as flare-accelerated electrons that are injected upward into the filament, and then precipitate along the filament towards the chromosphere, producing Bremsstrahlung. This work was undertaken by Muriel Stiefel during her MSc project.

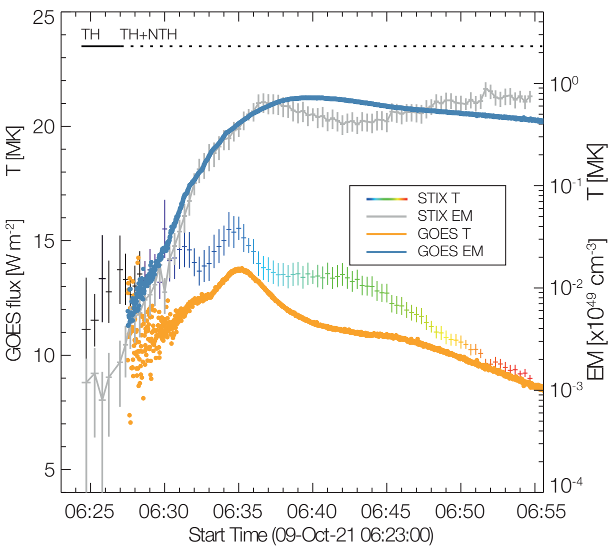

Figure 1. Evolution of temperature and emission measure (EM) for a flare on 9 Oct. 2021, which was measured by STIX on Solar Orbiter and XRS on GOES. The initial temperatures above 10 MK and the rapid EM increase, mark the "hot onsets".

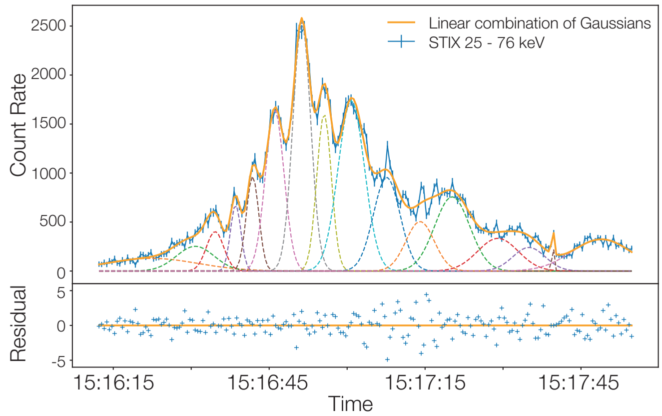

Figure 2. Fast time variations of X-ray intensity observed by STIX for a flare on 4 May 2022 in the 25 - 76 keV energy band. The decomposition of the signal time-series based on Gaussian functions with a width of several seconds is also shown.

Finally, a study co-authored by N. Janitzek (Wimmer-Schweingruber et al., 2023) discusses the propagation of flare-associated solar energetic particles (SEPs) throughout the heliosphere. In an exceptional event on 9 Apr. 2022 energetic electrons, protons, and heavy ions reached Solar Orbiter from a solar source along an exceptionally long path with a length >3 times the estimated magnetic connection line between the spacecraft and Sun. Both path length and release time of the particles were estimated from a velocity dispersion analysis of the SEPs. The particle source was identified with STIX and the Extreme Ultraviolet Imager (EUI) onboard Solar Orbiter as a flare-associated eruption on the Sun. The authors speculate that the unusually long travel path and thus late arrival time of the particles is related to an ambient coronal mass ejection (CME).

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Atmospheric Chemical Response to Asymmetrical Spectral Solar Irradiance Changes

Tatiana Egorova and Eugene Rozanov in collaboration with Alexander Shapiro and Anna Shapiro MPI-S (Germany)

It has been suggested that the shift of the Sun to a high-activity regime leads to an increase in ultraviolet radiation (UV) accompanied by a drop in total solar irradiance (TSI). In this study, we applied the atmosphere-chemistry-ocean SOCOLv3-MPIOM model to simulate the response of the Earth's atmosphere to these changes. We show that the stratospheric ozone response is mostly positive and driven by solar UV. In the lower stratosphere, the ozone increase is enhanced by climate cooling and the deceleration of the Brewer-Dobson circulation due to the TSI decrease. The response of stratospheric H_2O is small due to competition between an enhanced photolytic production and a weaker influx from the colder and drier troposphere.

We applied the SOCOLv3-MPIOM model that was used in Egorova et al. (2023) to obtain the atmospheric response to the potential switch of the Sun to the high activity regime. This transition leads to the rise of UV and a simultaneous drop in longwave and total solar radiation irradiance (TSI). We calculated the impact of these changes in irradiance on surface climate, atmospheric temperature and chemical composition using different combinations of the solar irradiance changes to elucidate the contribution of chemical (UV-related, "chemical" case) and climate (TSI-related, "climate" case) processes on the total effect.

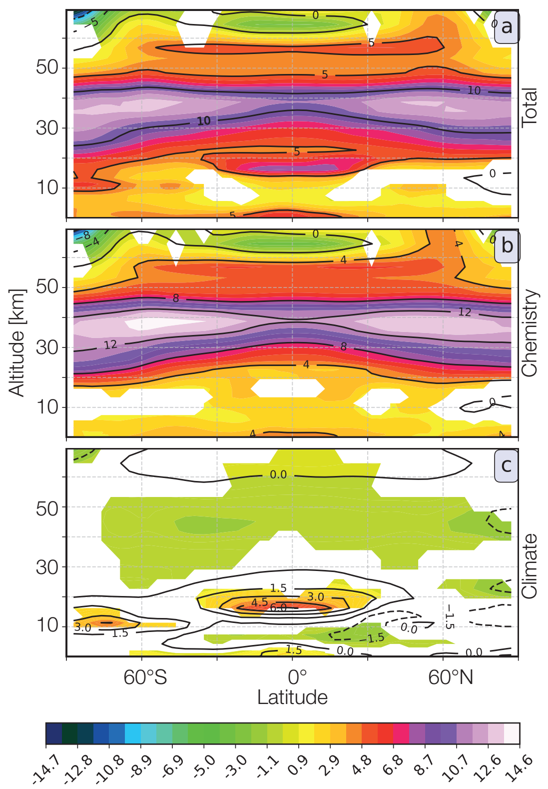

Figure 1. Zonal mean annual mean changes in O_3 mixing ratio (%) obtained for: a) the "total", b) "chemistry", and c) "climate" cases relative to the simulation with the present-day SSI. The coloured areas show the results, which are statistically significant at greater than the 95% level. The solid and dashed contour lines represent positive and negative responses, respectively.

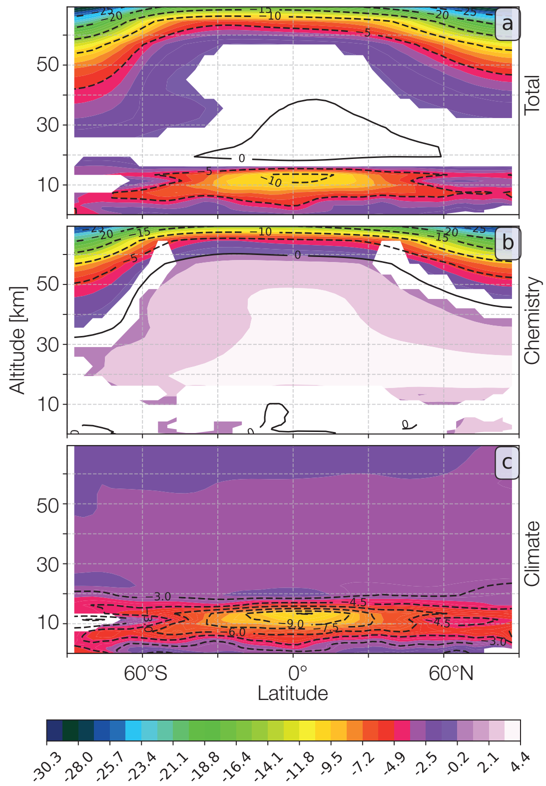

Figure 2. The same as in Figure 1 except for the H_2O mixing ratio (%).

Figure 1 illustrates zonal mean annual mean changes in O_3 mixing ratio for the "total", "chemical", and "climate" cases relative to the simulation with the present-day spectral solar irradiance (SSI). The strengthening of O_2 photolysis leads to an increase in stratospheric O_3 calculated for the "total" and "chemistry" cases. Above 40 km, a weaker efficiency in O_3 photolytic production and an increase in hydrogen oxides due to an enhanced H_2O photolysis, lead to a smaller O_3 response in the "total" and "chemistry" cases. Below 30 km, the O_3 response in the "chemical" case decreases, while for the "total" and "climate" cases the ozone mixing ratio increases at 20 km. This increase is caused by the tropospheric cooling due to the decrease of TSI followed by suppression of the Brewer-Dobson circulation and a decrease of the influx of O_3-poor air from the troposphere. Figure 2 illustrates the H_2O response. For the "total" case, we clearly see two areas with depleted H_2O. In the mesosphere and upper polar stratosphere, it is driven by chemical processes (increase of H_2O photolysis), while in the troposphere it is related to climate cooling and a decrease of H_2O flux to the stratosphere. More details of the study will be available in Shapiro et al. (2024, in review).

Acknowledgement: Project CISA was funded by the Swiss Karbacher Funds, Graubunden, Switzerland.

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Climate of the Maunder Minimum in Paleo-Reanalysis and Individual Proxy-Based Data

Tatiana Egorova, Jan Sedlacek, Timofei Sukhodolov and Eugene Rozanov

In the current Karbacher project (No. 11685), we focus on establishing the amplitude of long-term solar forcing variations from climate reconstructions and modelling. Before starting the modelling, it was important to collect and analyse the latest available temperature reconstructions covering the Maunder Minimum (17th-18th centuries). This analysis is crucial for the next stage of the project, which will include the detection and attribution of simulated climate changes.

The climate of the 17th - 18th centuries was influenced mainly by natural forcings such as solar and volcanic activity. Figure 1a shows total solar irradiance (TSI), calculated with the CHRONOS model (Egorova et al., 2018) and aerosol optical depth (AOD), which represents volcanic forcing (Toohey and Sigl., 2017). TSI variations over this period are characterised by a strong decrease (Maunder Minimum, 1645 - 1715) followed by sharp increases. Hence, for the surface air temperature in the absence of any other driving forces, one could expect cooling until about 1710 and warming thereafter. However, unless the evolution of TSI is relatively well-constrained, its amplitude remains very uncertain and the TSI decrease overlaps with intense volcanic activity, which complicates the attribution of reconstructed climate variations to the individual forcings.

Reconstructions themselves are also very uncertain. We have collected multiple reconstructions of surface temperature based on various proxy data such as the width and density of tree rings, ice cores, coral growth, borehole temperature profiles, speleothems, or historical documentary data. As an example, Figure 1b shows temperature reconstructions based on tree-rings (PAGE 2k database) for different parts of Europe. Even within such a small region and the same proxy type, the data shows very different behaviour, which indicates that local variations could be insensitive or nonlinear with respect to the global forced changes.

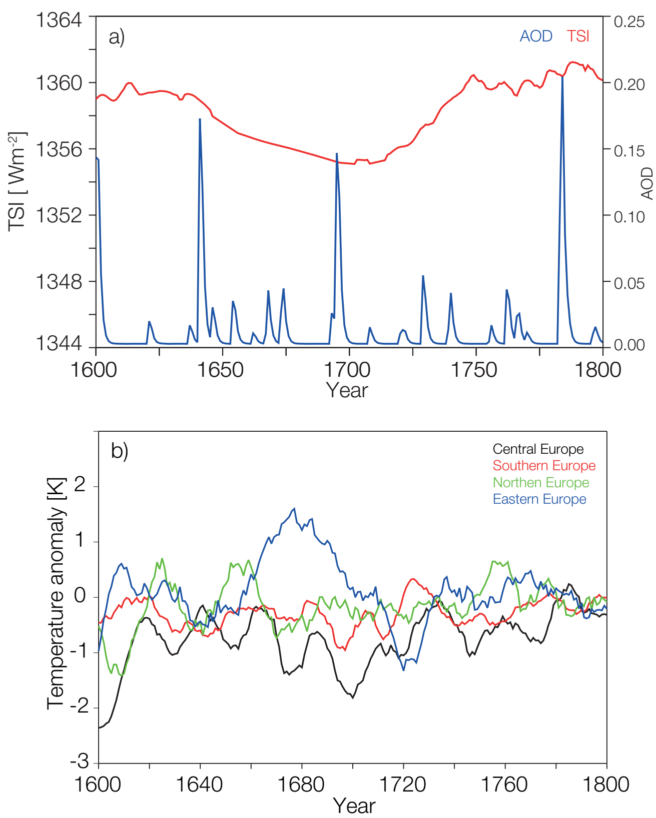

Figure 1. Panel a): Time evolution of TSI (Wm-2, red) and AOD (blue) from 1600 to 1800. Panel b): Summer-time temperature anomaly reconstructions (K) from tree-rings and various sources.

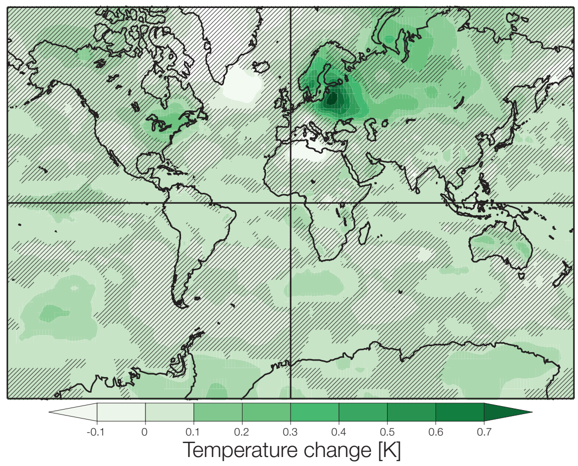

Figure 2. Warm temperature anomaly (K) over Europe during the winter season, obtained from ModE-RA data (Valler et al., 2024). Hatched areas show statistically insignificant changes.

To have a global view, we also used a state-of-the-art ModE-RA reanalysis product (Valler et al., 2024) that combines all available individual proxy-based reconstructions, and fills the missing areas and seasons by modelling and assimilation methods. Figure 2 shows the anomaly of the ModE-RA surface air temperature obtained as the difference between the globally cold (1660 - 1710) and warm (1715 - 1780) periods, coinciding with low and high TSI values, respectively. Interestingly, the strongest signal of up to 0.7K appears in Europe. This geographical inhomogeneity can be explained by either local amplification factors (e.g., modulation of the Arctic oscillation) or by the fact that Europe has the densest coverage of climate proxies. In the latter case, it could indicate that the external forcing (TSI and AOD), used in the modelling part of ModE-RA, might have been underestimated. This work allowed us to collect the data and define reliable regions of interest for the next part of our project, which will consist of a transient experiment with our Earth system model, SOCOLv4.

Acknowledgment: The project is funded by the Swiss Karbacher Funds, Graubünden, Switzerland.

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Sensitivity and Linearity of Surface Temperature Response to Solar Irradiance Changes

Jan Sedlacek, Timofei Sukhodolov, Tatiana Egorova and Eugene Rozanov

During the last millennia, prior to industrialisation, long-term climatic variations correlate with low-frequency Total Solar Irradiance (TSI) changes. An additional natural forcing is volcanic activity. The exact magnitudes of these two natural forcings are unknown as the reconstructions are subject to substantial uncertainty. There is still a debate about which forcing, i.e., solar vs. volcanic, has influenced the climate to what extent during that time. The amplitude of the TSI decrease is especially uncertain, and suggestions range from a few Wm^{-2} to a few tens of Wm^{-2} lower than today's value. In this project, we address the problem from an idealised perspective, analysing simulations with the SOCOL chemistry-climate model where different solar forcings ranging from +10 Wm^{-2} to -20 Wm^{-2} in TSI terms are applied.

On a global scale, our simulations suggest that changes in temperature are quasi-linear with changes in TSI (see Figure 1), and have a sensitivity of about 0.06 K/Wm^{-2}. However, on a regional scale, the changes in temperature are more heterogeneous. Figure 2a shows the sensitivity of the surface temperature in relation to changes in TSI. There is a difference between ocean and land area due to the different heat capacities. In the northern high latitudes, the temperature changes are larger per TSI change. This phenomenon is related to changes in sea ice and snow cover, modifying optical properties as well as modulating the insulation of heat exchange between the ocean and atmosphere. Over Antarctica, the changes are very small as an increase in snow would not lead to large changes in albedo. The Weddell Sea and Southern Ocean region is a special case showing a change in sign of the sensitivity. There are several factors which can lead to such behaviour. One is a change in sea ice cover, thus altering the heat transfer between the ocean and the atmosphere. A second possible factor is a strengthening of the polar vortex, which could modify the Ekman pumping around Antarctica. Another possible mechanism would be that the katabatic winds are getting stronger, pushing the water mass from the continent and allowing warmer deep water to get closer to the surface. Which factor or which interplay of factors is responsible for this signal has not been fully investigated yet.

Figure 2b shows the error to linearity, which is a measure of how linear the relation is between surface temperature and TSI. Most

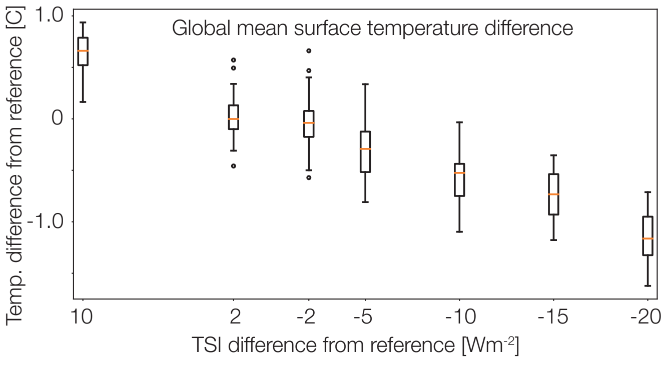

Figure 1. Global mean surface temperature change as a function of TSI change.

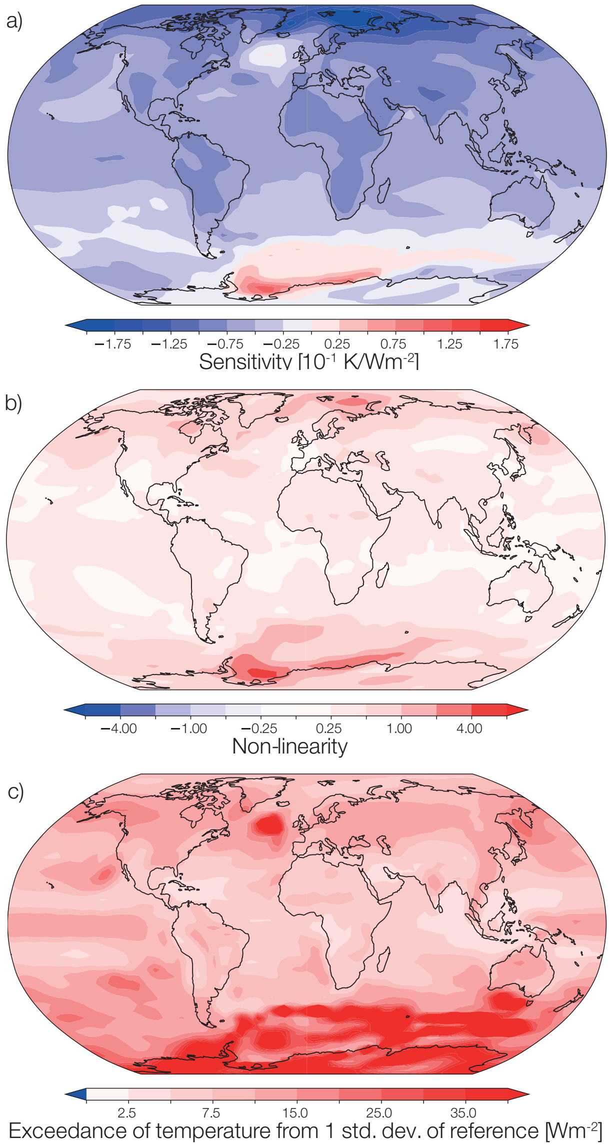

Figure 2. Panel a): The sensitivity of surface temperature per change in TSI (the values are multiplied by -1 for illustration purpose). Panel b): The standard error from the linear regression shown in panel a. The light colours denote areas close to linearity, while darker colours are those, which deviate more strongly from linearity. Panel c): Required TSI change to have a temperature signal larger than the natural variability.

of the globe behaves quite linearly with a few exceptions where the sensitivity is slightly larger. Finally, in Figure 2c the exceedance of the signal is shown, i.e., the TSI at which temperature is larger than one standard deviation from the reference. For example, over Europe and North-Western Canada/Alaska, the value is large. This means that the change in TSI has to be very large to attribute a clear signal to a change in TSI. On the other hand, it also means it is almost impossible to exclude that small temperature changes were not driven by TSI changes in that region. Understanding the physical processes leading to these differences in regional sensitivity will advance the attribution of the impact of solar irradiance on surface climate.

Acknowledgement: The project is funded by Swiss Karbacher Funds, Graubünden, Switzerland.

Stratospheric Ozone-Climate Interactions in Idealised DECK Experiments from CMIP6

Timofei Sukhodolov and Jingyu Wang in collaboration with IAC ETH Zurich

Rising greenhouse gases (GHG) and decreasing anthropogenic ozone-depleting substances (ODS) are the main drivers of stratospheric climate evolution in the 21st century. However, our understanding of the coupling between stratospheric composition, radiation and dynamics is still the subject of many uncertainties, partly because of the simplified representation of ozone in many current climate models, as well as a limited signal-to-noise ratio related to these processes over the satellite period. In this Master thesis project, we studied stratospheric ozone-climate interactions using idealised multi-model CMIP6 experiments.

Stratospheric ozone abundances are sensitive to temperature and circulation variations and, thus, respond to climatic changes. In turn, ozone variations can also affect temperature and the large-scale atmospheric circulation, since ozone is a radiatively active gas that absorbs solar and terrestrial radiation and radiatively heats the stratosphere. Therefore, under climate change, stratospheric ozone will respond and result in feedback on climate (Nowack et al., 2015). Understanding this response and its implications on climate is critical for future climate projections. However such investigations are complicated by a limited signal-to-noise ratio over the satellite period. Previous research was based on single models, and showed very uncertain results ranging from no impact to a 20% decrease in climate sensitivity to CO_2 due to ozone feedback.

CMIP6 (Coupled Model Intercomparison Project phase 6) DECK (Diagnostic, Evaluation and Characterization of Klima) timeslice experiments (pre-industrial control and abrupt quadrupling of CO_2) provide a unique opportunity to study such processes in more detail (Eyring et al., 2016). This set-up provides longer time-series and stronger GHG forcing than in the historical period, as well as the 6th CMIP now has a larger number of participating models with interactive chemistry ("chem") to be contrasted against the models where it is prescribed ("non-chem"). In total, we have processed data from 22 CMIP6 models, including our SOCOLv4 model, among which we selected six "chem/non-chem" pairs of models that share the same dynamical cores.

Our findings show that CMIP6 models broadly share a similar ozone response to CO_2 with an increase in the upper stratosphere

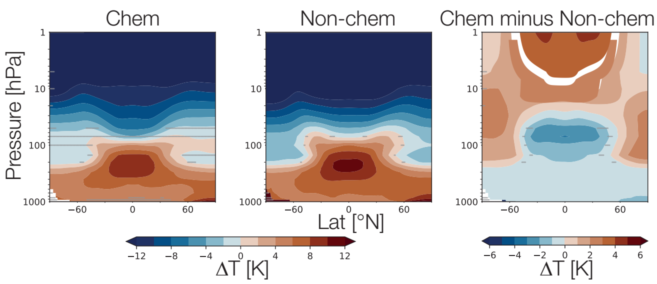

Figure 1. Comparison of the 100-year long yearly-mean air temperature response to 4 x CO_2 between six pairs of "chem and "non-chem" models. The left column shows the response from "chem" models, the middle column shows that from "non-chem" models, and the right column shows their difference.

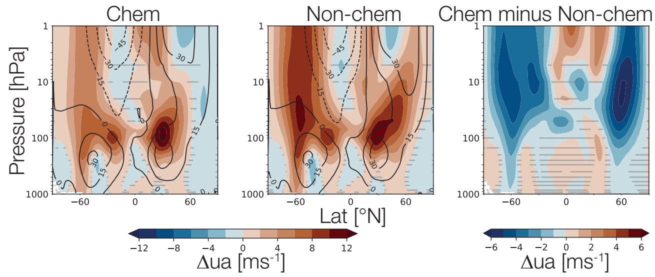

Figure 2. Same as in Figure 1, but for the December-January-February zonal wind. Black contours show climatology of the pre-industrial control experiment.

(US), driven mostly by fast chemistry adjustments, and with a slow transport-driven decrease in the tropical lower stratosphere (LS) and increase in the extra-tropical LS. The total column ozone response is around zero in the tropics and positive at high latitudes, with a large inter-model discrepancy, possibly arising from model biases in polar vortex dynamics. Stratospheric temperature responds to ozone changes with a cooling in the tropical LS and warming everywhere else in the stratosphere (Figure 1).

When comparing "chem" and "non-chem" models under abrupt 4 x CO_2, "chem" models exhibit weaker tropospheric warming than "non-chem" models, resulting in a multi-model estimate of a 15% decrease in climate sensitivity to CO_2. This effect cannot be explained by the radiative effect of the ozone response alone. Other feedbacks, such as the response of stratospheric water vapour transport to tropical cooling, as well as the bias of the elevated tropopause might play a part. Ozone effects on stratospheric temperature also induce large changes in stratospheric dynamics (Figure 2). "Chem" models have a smaller meridional temperature gradient in the stratosphere, resulting in a weakening of subtropical and polar night jets. Such changes in the stratosphere would induce further downward effects, and modulate the circulation patterns in the troposphere. Further research is needed to explain the details of the presented results, and to investigate the dynamical stratosphere-troposphere coupling effects.

A paper discussing these results is in preparation for the Atmospheric Chemistry and Physics journal.

Acklowledgement: This project received support from the Swiss Karbacher Fund, Graubünden, Switzerland.

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Eyring, V., et al.: 2016, Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geosci. Mod. Dev., 9, 1937–1958, https://doi.org/10.5194/gmd-9-1937-2016

Nowack, P. J., et al.: 2015, A large ozone-circulation feedback and its implications for global warming assessments, Nature Climate Change, 5, 41-45, https://doi.org/10.1038/nclimate2451

Analysis of the Global Atmospheric Background Sulphur Budget in a Multi-Model Framework

Timofei Sukhodolov, Christina Brodowsky and Eugene Rozanov in collaboration with IAC ETH Zurich and the ISA-MIP community

A growing number of general circulation models are adapting interactive sulphur and aerosol schemes to improve the representation of relevant physical and chemical processes and associated feedbacks. While the effects of volcanic eruptions have been studied in the framework of global model inter-comparisons, the background conditions of the sulphur cycle have not been addressed in such a way. Within this Master thesis project and the framework of the Interactive Sulphate Aerosol Multi-model Intercomparison Project (ISA-MIP, Timmreck et al., 2018), we filled this gap by analysing the distribution of the main sulphur species in nine global atmospheric aerosol models for a volcanically quiescent period.

In our analysis, we used 9 models (see legend in Figure 1), which performed a 20-year timeslice experiment with boundary conditions for the year 2000. This year was chosen as it was one of the volcanically quietest years. We used various available observational data to evaluate model results. Resulting burdens and fluxes, constituting the total atmospheric sulphur budget, are presented in Figure 1.

Overall, the models agree that the three dominant sulphur species in terms of burdens (sulphate aerosol, OCS, and SO_2) make up about 98% of stratospheric sulphur and 95% of tropospheric sulphur. However, models vary considerably in the partitioning between these species. Models agree that anthropogenic emission of SO_2 strongly affects the sulphate aerosol burden in the Northern Hemispheric troposphere, while its importance is very uncertain in other regions, where emissions are much lower. Sulphate aerosol is the main deposited species in all models, but the values deviate by a factor of two. In addition, the partitioning between wet and dry deposition fluxes is highly model-dependent. Inter-model variability of sulphur species is low in the tropics and increases towards the poles. Differences are largest in the dynamically active Northern Hemispheric extra-tropical region, and could be attributed to the representation of the stratospheric circulation. The differences in the atmospheric sulphur budget among the models arise from the representation of both chemical and dynamical processes, whose interplay complicates the bias attribution. Several problematic points identified for individual models are related to the specifics of the chemistry schemes, model resolution, and representation of cross-tropopause transport in the extra-tropics. Further details of this model inter-comparison activity can be found in Brodowsky et al. (2023).

References: Brodowsky, C. V., et al.: 2023, Analysis of the global atmospheric background sulfur budget in a multi-model framework, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-1655

Timmreck, C., et al.: 2018, The Interactive Stratospheric Aerosol Model Intercomparison Project (ISA-MIP): motivation and experimental design, Geosci. Model Dev., 11, 2581-2608, https://doi.org/10.5194/gmd-11-2581-2018

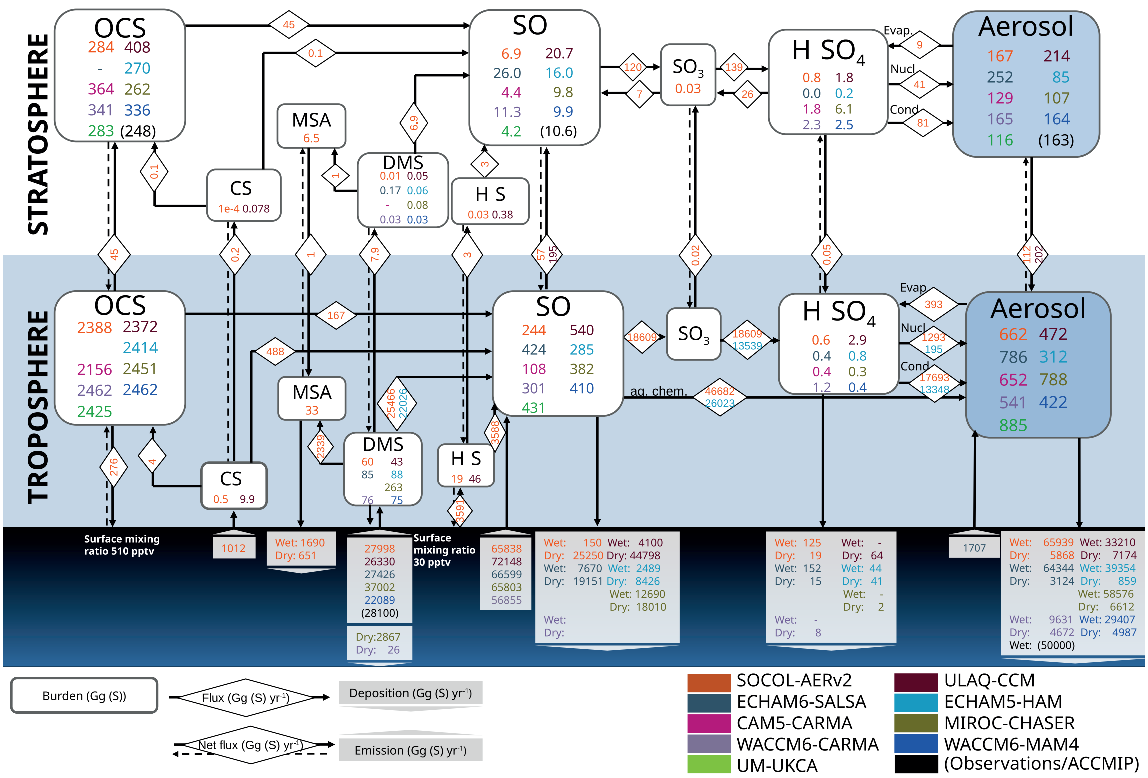

Figure 1. The atmospheric background sulphur cycle with burdens (in Gg (S)) and fluxes (Gg (S) yr^{-1}) for S-gases and sulphate aerosols. The figure includes all burdens as provided by the models involved. The observation-derived data are in parentheses. See Brodowsky et al. (2023) for more details.

Multi-Model Analysis of Stratospheric Aerosol Injection Impacts on the Ozone Layer

Timofei Sukhodolov, Andrin Jörimann and Eugene Rozanov in collaboration with IAC ETH Zurich and the CCMI community

Stratospheric Aerosol Injection (SAI) holds the potential to offset some of the future warming of the Earth's surface. However, it comes with many potentially dangerous side-effects, which are currently not well-understood and poorly constrained. A major concern is the effect on stratospheric ozone, which could be weakened and delayed in its recovery, given that ozone-depleting substances will take decades to be completely removed. In this Master thesis project, we analysed multi-model estimates of ozone depletion and recovery processes in a scenario, where SAI is employed to keep the global surface temperature constant.

Previous analyses of SAI impacts on ozone have been conducted with models that have widely different treatments of aerosol microphysics and chemistry. To isolate and estimate the uncertainty of the chemical and dynamical effects in a multi-model context, CCMI-2022 (Chemisty-Climate Model Initiative Phase 2) proposed a new senD2-sai experiment, where the ocean is kept fixed and the elevated stratospheric aerosol burden, thus, only affects the middle atmospheric composition and temperature (Plummer et al., 2021). Stratospheric aerosols are also uniformly prescribed for all participating models in order to minimise the uncertainty arising from the treatment of aerosol microphysics. In our work, we performed these experiments with our aerosol-chemistry-climate model SOCOLv4.0, and compared our results with three other CCMI-2022 models (WACCM, CMAM, and MIROC), with a focus on stratospheric chemistry and changes in dynamics. Our model analysis showed agreement with the fact that the considered SAI scenario can cause a delay in global ozone recovery by 3 - 4 decades. We found that polar regions in both hemispheres will be affected by chlorine activation on sulphate aerosol surfaces until the end of the century, which is more strongly pronounced in the Southern Hemisphere (Figure 1), deepen the ozone holes and increase their occurrence frequency. However, the polar regions were also found to have the largest multi-model discrepancies, mostly due to the differences in treatment of stratospheric dynamics.

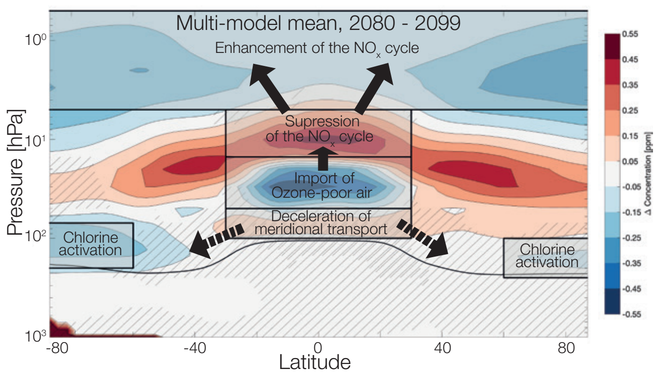

Figure 1. 2080 - 2099 zonal and annual mean multi-model estimates of ozone changes [ppmv] due to SAI. Boxes with text highlight the regions where dominant effects have been established. Solid arrows indicate strengthening of the transport, while dashed indicate weakening.

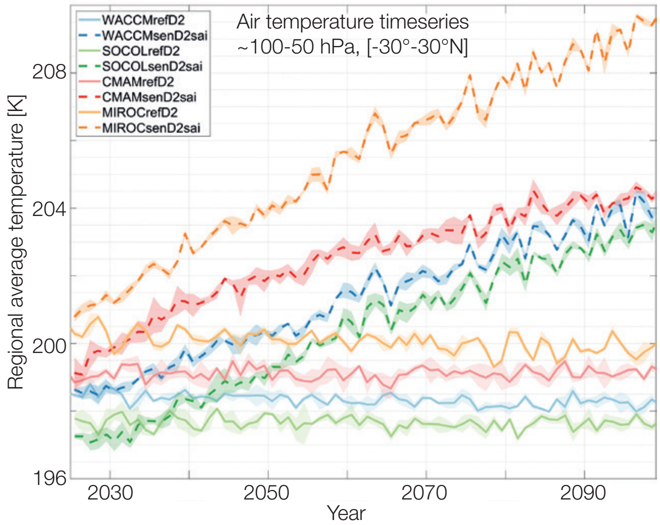

Figure 2. Tropical lower stratospheric temperature evolution in four models and two experiments. The term, senD2sai, stands for the SAI scenario, while reD2 is a reference mild climate change scenario.

While the models do not fully agree on the strength of polar ozone depletion, they robustly project a full global mean total ozone column recovery in senD2-sai towards the end of the century. This happens despite the elevated stratospheric aerosol levels - mainly as a result of the phase-out of anthropogenic ozone-destroying substances. However, it does not come without substantial spatial redistribution of ozone, which is driven by the temperature increase in the lower tropical/subtropical stratosphere. Such effects include a deceleration in meridional ozone transport in the lowermost stratosphere, and acceleration of the vertical transport in the tropics. Lower stratospheric heating is also a subject of multi-model uncertainties (Figure 2). However, the models agree that this effect is systematic and that besides modulating the stratospheric dynamics, it will also warm the cold point tropopause. Hence, this will increase the upward transport of tropospheric water vapour with important implications for climate. Other confirmed global effects are related to the modulation of the NO_x catalytic cycle of ozone destruction. In the middle atmosphere, this cycle is suppressed as a result of a N_2O_5 hydrolysis reaction on aerosol surfaces. However, in the upper atmosphere, the NO_x cycle intensifies, following a stronger influx of N_2O from below.

Overall, we conclude that the dynamical response to SAI controls the ozone changes to a larger extent than the chemical response. Further research is needed to more closely investigate the multi-model differences and individual model biases. A paper discussing our results is in preparation for submission to the Atmospheric Chemistry and Physics journal.

Acknowledgment: This project received support from the Swiss Karbacher Fund, Graubünden, Switzerland.

References: Plummer, D., et al.: 2021, in: SPARC Newsletter 57, pp. 22-30.

Side-Effects of Sulphur-Based Geoengineering due to Absorptivity of Sulphate Aerosols

Timofei Sukhodolov and Elia Wunderlin in collaboration with IAC ETH Zurich

Sulphur-based stratospheric aerosol intervention (SAI) can cool Earth's climate, but can also heat the tropical lower stratosphere. Within this Master thesis project, we explored the role of this heating in the climate response to SAI, by using mechanistic experiments with our SOCOLv4 model that removes the effects of longwave (LW) absorption of sulphate aerosols above the tropopause.

One of three potential ways to mitigate the increasing negative effects of climate change is a modification of the incoming solar radiation through the injection of sulphur into the stratosphere (Crutzen, 2006). This would reduce global mean temperatures, similar to explosive volcanic eruptions. However, this type of SAI has several potential side-effects, one of which is the heating of the tropical lower stratosphere. It is related to the optical properties of sulphate aerosols, namely, that they not only scatter shortwave solar light, but also strongly absorb the longwave (LW) terrestrial radiation. It has been previously discussed that this stratospheric heating can lead to substantial circulation changes at the surface. In our study, we isolated such effects in a novel way by performing a set of mechanistic experiments with and without LW absorptivity of sulphuric aerosol particles in the stratosphere. We still maintained a fully interactive aerosol microphysics, thereby keeping every other feature of the climatic response intact, while concentrating on the direct down-stream impacts of the stratospheric heating. In our analysis, we focused on three experiment pairs:

- SSP5-8.5-SSP4.5 (Figure 1a and 1d), which indicates the climate change difference between two shared socio-economic pathways (extreme SSP5 and mild SSP2), that needs to be geoengineered.
- G6-SSP4.5 (Figure 1b and 1e), which indicates the side-effects of SAI, where G6 is an SAI scenario aimed at reducing global surface temperatures of the SSP5 scenario to the levels of the SSP2 scenario.
- G6-G6_nolw (Fig. 1c and 1f), which indicates side-effects of aerosol LW absorptivity, where G6_nolw is the same scenario as G6, but with aerosol absorptivity being switched off in the model.

We found that if LW absorption by stratospheric aerosols is disabled, the heating of the tropical tropopause and most of the related side-effects are strongly alleviated. In the stratosphere, such side-effects include acceleration of the stratospheric residual circulation, delay of Antarctic ozone recovery, and increase of the stratospheric water vapour. Modulation of the stratospheric dynamics then led to pronounced changes in the troposphere such as the poleward expansion of eddy-driven jets, modulation of the annular circulation modes in both hemispheres, and additional strong surface temperature anomalies, such as, residual continental warming over Siberia, which is dangerous for permafrosts. In Figure 1, this can be seen by comparing the middle column (full SAI side-effects) to the right column (LW absorptivity effects), which shows that most of the circulation effects (shown as pressure anomalies) and strong residual regional temperature anomalies are similar in both columns. Moreover, regionally such side-effects are even comparable to those produced by the CO_2 warming signal (left column). A paper discussing these results is currently in review in the Geophysical Research Letters journal (Wunderlin et al., in review).

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Crutzen, P. J.: 2006, Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma? Climatic Change, 77, 211-220, https://doi.org.10.1007/s10584-006-9101-y

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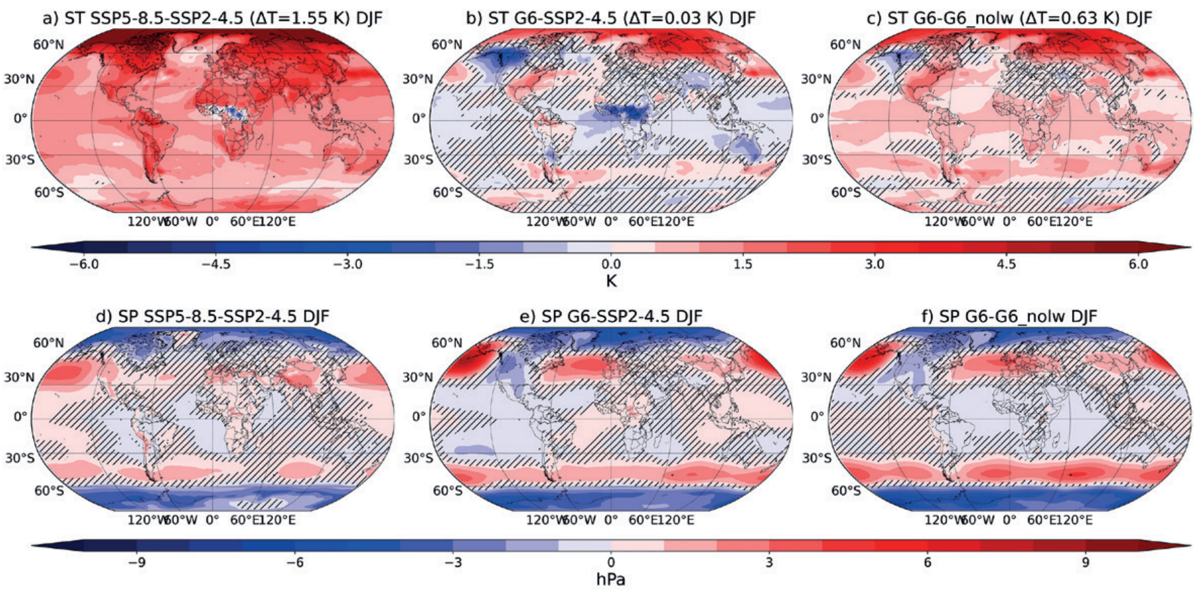

Figure 1. Mean 2080 - 2099 values for Dec - Feb (DJF): Panels a-c) surface temperature (ST) [K] changes for SSP5-8.5- SSP2-4.5, G6-SSP2-4.5 and G6-G6_nolw. Panels d-f): Same differences but for surface pressure (SP) [hPa]. Hatched areas indicate statistically insignificant changes.

Solid Particle SAI with a Fully-Coupled Atmosphere-Ocean-Aerosol-Chemistry-Climate Model SOCOLv4.0

Timofei Sukhodolov and Fabrice Stefanetti in collaboration with IAC ETH Zurich

Solid particles, such as alumina, calcite, and diamond, have been proposed as alternative materials for stratospheric aerosol injection (SAI) studies. The traditional SAI set-up based on sulphate aerosols was shown to have several limitations such as stratospheric heating and ozone depletion. Solid particles are thought to potentially overcome these limitations by having better optical properties and/or greater chemical inertness. In this semester project, we used, for the first time, a fully coupled atmosphere-ocean-aerosol-chemistry-climate model SOCOLv4.0, which incorporates a solid particle emission scheme, to assess the SAI effects of the alumina, calcite, and diamond species.

Dykema et al. (2016) proposed a list of potential species that have promising optical properties and can be used for SAI instead of sulphur. Among them, alumina, calcite and diamond appeared to be the most feasible, and we tested their impacts by introducing them into our SOCOLv4 model using the solid particle algorithm newly developed at IAC ETH. For each solid particle type, we followed the GeoMIP (Geoengineering Model Intercomparison Project) protocol and performed the G4 experiment, which assumes a constant emission of aerosols throughout the 21st century. In our case, the emitted amount was specified to introduce a 1 K cooling in the global mean surface temperature.

For all considered SAI substances, we found that the resulting burden is close to the yearly emission quantity, suggesting an average atmospheric particle lifetime of approximately one year. Diamond has the highest burden-per-emission ratio, suggesting a higher lifetime, which is explained by its small particle radius. Sulphur, alumina, and calcite provide very similar cooling per emission, while diamond has a cooling efficiency of about a factor three higher. Diamond also has the lowest absorption in the longwave, which allows it to show: i) the weakest heating of the lower stratosphere (Figure 1, upper row), ii) no increase in the stratospheric water vapour (Figure 1, lower row), and iii) the smallest dynamical effects on ozone. In terms of surface climate artifacts, those species that show the weakest heating in the stratosphere (calcite and diamond) also are expected to show the least side-effects in atmospheric and oceanic circulation patterns. Low or no increase in the stratospheric water vapour also increases the cooling efficiency, since water vapour is a greenhouse gas.

Information on the interaction between alumina, calcite and ozone-relevant chemical cycles is available, but has not been sufficient so far to implement their ozone chemistry with high confidence in the results. Additional laboratory studies are therefore required for further modelling research on this subject.

A paper discussing these results is in preparation for submission to the Geophysical Research Letters journal.

Acknowledgement: This project received support from the Swiss Karbacher Fund, Graubünden, Switzerland.

References: Dykema, J. A., et al.: 2016, Improved aerosol radiative properties as a foundation for solar geoengineering risk assessment, Geophys. Res. Lett., 43, 7758-7766, https://doi.org/https://doi.org/10.1002/2016GL069258

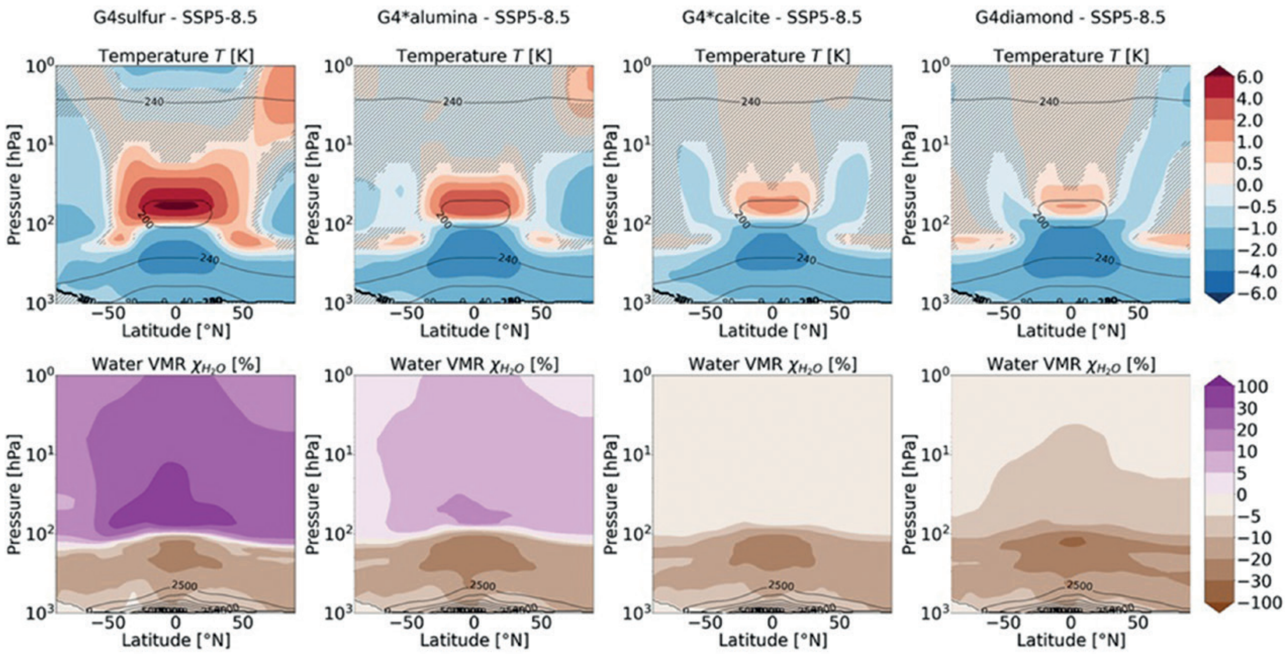

Figure 1. 2080-2099 anomalies of zonal and annual mean temperature (upper row) and water vapour volume mixing ratio (lower row) of SAI scenarios using four different species (columns) with respect to the base extreme climate change scenario (SSP5-8.5). Hatched areas denote statistically insignificant changes. Contours show climatology of the SSP5 scenario.

Reflectivity Measurements of the Solar Radiometer Cavity

Natalia Engler, Wolfgang Finsterle and Ricco Soder

The Solar Radiometry Section (SRS) at PMOD maintains and operates the Cryogenic Solar Absolute Radiometer (CSAR). This instrument was designed and built with the goal of replacing the World Standard Group, which currently represents the World Radiometric Reference (WRR) for ground-based total solar irradiance measurements. CSAR will also establish a new WRR, fully traceable to SI primary standards for optical power. To achieve this goal, the SRS group is conducting work to completely characterise the CSAR performance, and to demonstrate its metrological traceability to SI primary standards. This work includes reflectivity measurements of the CSAR cavity.

The CSAR cavity or detector is a key instrument component in measuring the incident solar radiation. It is made of copper, has a cylindrical shape with an inclined rear, and is covered by a field-of-view limiting aperture at the open end. The cavity is coated inside with a black paint, Aeroglaze Z302, to absorb the incoming radiation. Since the absorptance of the detector is not equal to unity, a small part of the radiation is reflected and leaves the cavity through the aperture, thus contributing to the uncertainty of the measured solar power. To correct the instrument reading for the reflectivity losses, the amount of escaped radiation should be experimentally determined as accurately as possible.

As a part of the CSAR characterisation project, the reflectivity measurements are performed using the experimental setup in the optical laboratory at PMOD/WRC. For the test experiment, CSAR has to be disassembled, and the detector-head, the central part of the instrument containing the cavity, has to be installed on the optical table so that the cavity axis is precisely aligned with the optical path of the experiment. The installation and testing must be conducted in a clean environment, which is required for operation of CSAR. Therefore, the whole detector head and an integrating sphere are mounted inside a flow box to avoid contamination of the detector head and cavity with dust particles (Figure 1).

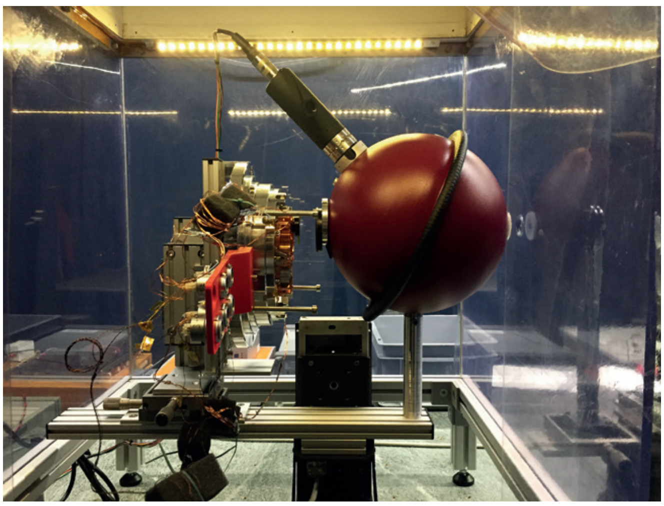

Figure 1. Installation of the CSAR detector head (on the left) together with the integrating sphere (on the right) inside the flow box in the optical laboratory at PMOD/WRC.

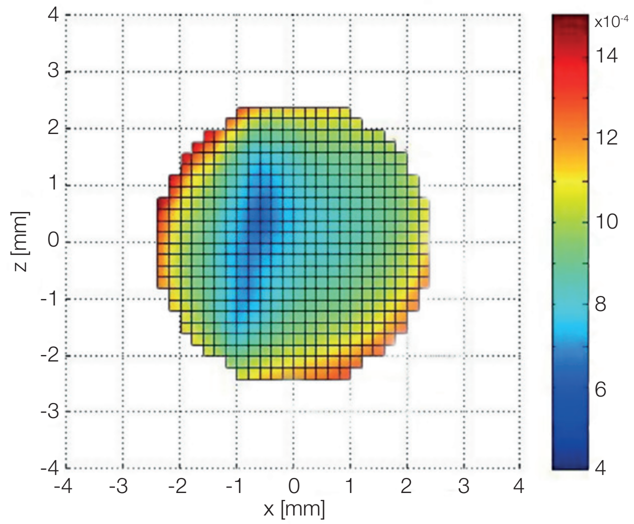

Figure 2. Reflectivity map of CSAR cavity at 532 nm showing the reflectivity distribution over the cavity area. The map was obtained during the test run using a Carbon Nanotubes reference sample S-VIS from Surrey Nano Systems Ltd., and shows preliminary results.

The test setup includes laser equipment, generating a light beam entering the cavity, which is attached to the rear port of the integrating sphere. The sphere collects all the radiation reflected by the cavity, and measures a signal proportional to its amount. This signal is compared to the signal from an externally calibrated reference sample with a known reflectance. In this way, the reflectance of the CSAR cavity is evaluated at four different laser wavelengths: 532, 808, 1063, and 1550 nm. During the measurement, the position of the cavity relative to the laser beam is shifted in small steps of 0.2 mm, allowing the complete surface of the sensor to be scanned, and to create a 2D reflectance map of the cavity at each laser wavelength. Figure 2 shows an example of such a test reflectance map scanned with the laser at λ = 532 nm. It visualises the reflectance homogeneity of the cavity bottom.

To obtain the final correction factor applicable to the measurements of direct solar irradiance with CSAR, the reflectance values derived for specific laser wavelengths are corrected for the sphere entrance losses and spectrally weighted with the terrestrial solar spectrum.

The CSAR characterisation project is sponsored by Karbacher funds and also benefits from synergies with the TRUTHS project.

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Spectral Aerosol Optical Depth from SI-Traceable Spectral Solar Irradiance Measurements

Julian Gröbner, Natalia Kouremeti, Gregor Hülsen and Stelios Kazadzis in collaboration with GigaHertz-Optik GmbH (Germany), PTB (Germany), AEMET (Spain) and NPL (Great Britain)

Spectral aerosol optical depth (AOD) is retrieved from spectral solar irradiance measurements traceable to SI via laboratory calibrations. The TSIS-1 HSRS solar spectrum was validated against Top-of-Atmosphere (ToA) solar spectra derived from ground-based measurements using zero airmass extrapolation over the spectral range from 300 nm to 1700 nm with an agreement of 1% in the unsaturated spectral bands. The spectral AOD derived from these measurements was in very good agreement with the AOD retrieved from reference sunphotometers belonging to the AERONET and GAW-PFR global networks.

SI-traceable spectral solar irradiance measurements were obtained with solar spectroradiometers at the high-altitude observatory in Izaña, Tenerife (Canary Islands, Spain; 28.309°N, 16.499°W) from 6 - 22 Sept. 2022 in the frame of the project, EMPIR 19ENV04 MAPP ("Metrology for aerosol optical properties", Gröbner et al., 2023). The ToA solar spectra derived from zero-airmass extrapolations were compared to the TSIS-1 Hybrid Solar Reference Spectrum (HSRS; Coddington et al., 2021) over the 300 - 2100 nm range. Furthermore, the spectral aerosol optical depths (AOD) retrieved from using the TSIS-1 HSRS ToA solar irradiances were compared with those from collocated measurements from reference filter radiometers from the GAW-PFR and AERONET global networks. The spectroradiometers used during the campaign are traceable to SI through transfer standards calibrated directly against the primary spectral irradiance standard of the German National Metrology Institute (PTB). The spectroradiometers used in this study were:

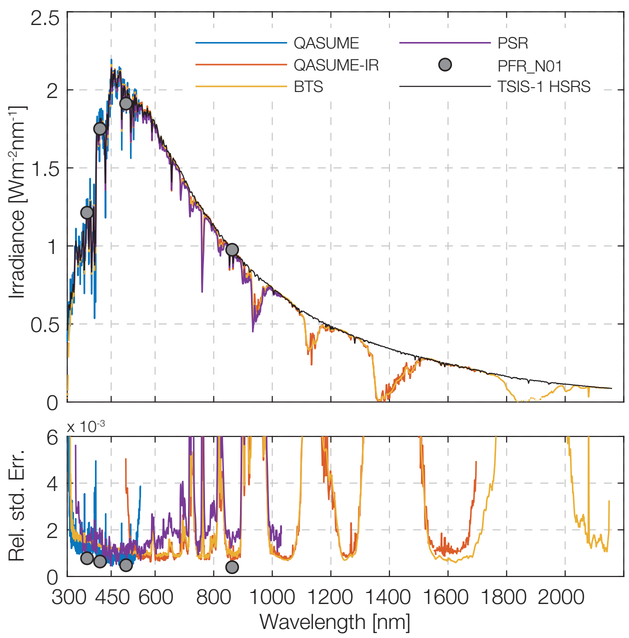

Figure 1. Upper panel: Top-of-atmosphere (ToA) solar spectra derived from zero air-mass extrapolations by QASUME (blue), QASUME-IR (red), the BTS (yellow), the PSR (violet), and the TSIS-1 HSRS (black) convolved with a 1 nm FWHM triangular line-spread function. The grey circles represent the ToA solar irradiances measured with PFR-N01. Lower panel: Relative standard error of the mean of the ToA solar spectra shown in the upper panel using the same colour scale.

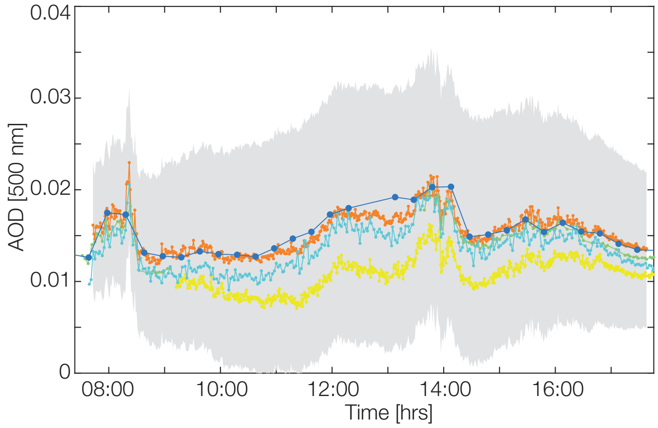

Figure 2. Diurnal variation in AOD on 13 Sep. 2022. The AOD from QASUME and QASUME-IR (blue dots), the BTS (light blue), and the PSR (yellow) are averaged over a 5 nm wide spectral band. AOD from the PFR (orange) and Cimel sun photometer (green) are also shown. The grey area represents the WMO limits.

- QASUME scanning double monochromator spectro-radiometer in the spectral range from 290 nm to 550 nm.
- QASUME-IR, scanning single monochromator in the spectral range from 500 nm to 1700 nm.
- BTS-UV/VIS/NIR and BTS-IR covering the spectral range from 300 nm to 2150 nm (types BTS2048-VL-TEC-WP and BTS2048-IR-WP).
- Precision Solar Spectroradiometer (PSR) in the spectral range from 316 nm to 1030 nm.

Measurements during this campaign were used to retrieve ToA solar spectra for selected half-day periods by zero-air-mass extrapolation. Subsequently, the mean ToA solar spectrum and the corresponding standard error were computed from these retrievals for each spectroradiometer. Figure 1 shows the extrapolated ToA solar spectra in the upper panel and the relative standard error of the mean in the bottom. The ToA solar spectrum from the TSIS-1 HSRS, convolved with a nominal 1 nm FWHM triangular line spread function, is also shown in the upper part of the figure. As shown in the figure, the agreement between the extrapolated ToA solar spectra and TSIS-1 HSRS in the spectral regions unaffected by strong gas absorptions is mostly within 1%, and thus within the measurement uncertainties. The spectral AOD from the cloud-free days of the campaign was retrieved from the QASUME/QASUME-IR, BTS, and PSR spectroradiometers and was compared to two sun photometers from the GAW-PFR and AERONET networks. Figure 2 shows the AOD at 500 nm from these instruments on 13 September 2022.

Acknowledgement: This work was supported by the European Metrology Program for Innovation and Research (EMPIR) within the joint research project, EMPIR 19ENV04 MAPP.

References: Coddington, O. M., Richard, E. C., Harber, D., et al.: 2021, Geophys. Res. Lett., 48, e2020GL091709, https://doi.org/10.1029/2020GL091709

Gröbner, J., Kouremeti, N., Hülsen, G., et al.: 2023, Atmos. Meas. Tech., 16, 4667-4680, https://doi.org/10.5194/amt-16-4667-2023

Average Angular and Spectral Correction Functions for UV Radiometers

Gregor Hülsen and Julian Gröbner

Average correction functions for broadband UV radiometers were calculated for five different radiometer types: Kipp & Zonen UV-S-AT and -ET, YES UVB-1 and Solar Light UVE/UVA. Both angular and spectral correction functions were derived using a large set of individual measurements acquired at the World Calibration Centre for UV (WCC-UV) during the last 15 years. The associated uncertainties were derived from the variability of the correction functions in each subset.

Global solar irradiance data derived from broadband UV radiometer measurements need to be corrected for the mismatch of the angular responsivity function (ARF) of the sensor to an ideal cosine receiver as well as the deviation of the spectral responsivity function (SRF) to a nominal weighting function (Hülsen and Gröbner, 2007). To calculate the correction functions, we measured the angular and spectral responsivities for each radiometer. As such measurements are not available for most radiometers deployed in the worldwide UV monitoring networks, an "average" correction function can serve as a tool to improve the data quality of those networks.

This study was initiated as a collaboration with the Servicio Meteorológico Nacional (SMN, Argentina) to enhance the measurement uncertainty of their regional UV network (Nollas et al., 2023). At the WCC-UV during the past 15 years, we have characterised 26, 22, 17, 40 and 9 of the radiometer types Kipp & Zonen (KZ) UV-S-ET and -AT, YES UVB-1, Solar Light 501-UVE and UVA, respectively. Figure 1 shows as an example of the resulting SRFs for the 26 KZ UV-S-ET erythemal weighing radiometers. Using our data we calculated the average, minimum and maximum SRF for the five radiometer types. Using the three spectral response functions, we proceeded by calculating the spectral mismatch correction functions, f_n_average, f_n_min and f_n_max. Figure 2 (top panel) shows f_n values, again for the UV-S-ET from KZ. The measurements of the ARFs were similarly used to derive the cosine correction functions: coscor_average, _min and _max.

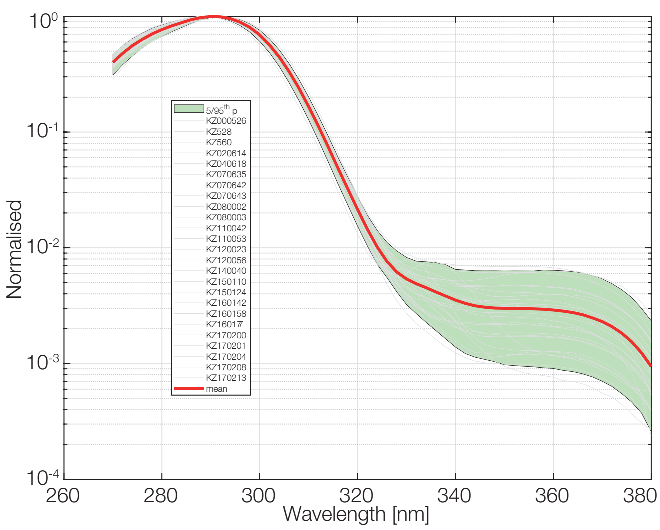

Figure 1. Spectral response function from 26 UV-S-ET radiometers (Kipp & Zonen).

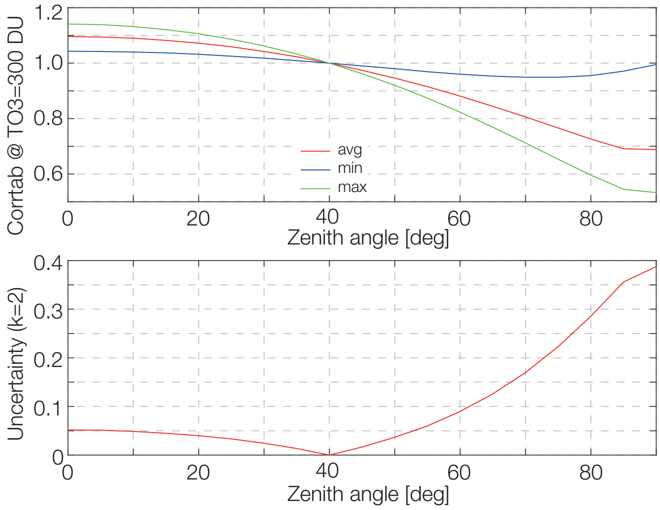

Figure 2. Average spectral mismatch correction function for UV-S-ET radiometers (Kipp & Zonen) as a function of the solar zenith angle (upper panel) and its associated uncertainty (lower panel).

The average, min, and max functions from the datasets were used to estimate the expanded uncertainty U of the average correction functions (k = 2, assuming a rectangular distribution, see Figure 2, lower panel). Table 1 summarises the uncertainty ranges, which differ significantly for the different radiometer types. The uncertainty increases for higher solar zenith angles for both the spectral and angular correction functions. The function f_n(SZA, TO3) is normalised at f_n(40, 300). Therefore, the uncertainty is zero at this point. The average correction functions were used by SMN during the calibration of the radiometers participating in the IC 2022 in Argentina to estimate the combined measurement uncertainty for the participating radiometers including the uncertainty of the average correction functions. These results are available in an open access publication by Hülsen and Gröbner (2024).

Table 1. Uncertainty range in percent of the corrections functions.

	UV-S-ET	UV-S-AT	YES UVB-1	SL UVE	SL UVA
coscor	2 - 6	1 - 5.5	2 - 5.5	6 - 15	1 - 3
f_n	0 - 4	0 - 2	0 - 11	0 - 45	0 - 1

References:

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Nollas, F., et al.: 2023, Intercomparación de radiómetros uva y eritémicos Argentina-2022, Nota Técnica SMN, 2023-156, https://repositorio.smn.gob.ar/handle/20.500.12160/2652

Total Column Ozone Retrieval from an Array Spectroradiometer by Applying a Custom Double-Ratio Technique

Luca Egli and Julian Gröbner in collaboration with MeteoSwiss

During the last five years, PMOD/WRC has developed and thoroughly tested a new system, Koherent, which is based on an array spectroradiometer for measuring total column ozone. The array spectroradiometer allows direct spectral solar irradiance in the UV band at hundreds of different channels to be measured within seconds. Furthermore, a new algorithm for retrieving total column ozone was developed. This allows the measurement of total column ozone (TCO), equivalent to a Brewer single monochromator. The instrument can be calibrated either in the laboratory, with a spectral ultraviolet reference instrument, or during an in-situ field campaign using total column ozone reference instruments. The instrument, including the new retrieval algorithm, is a promising system for a new generation of instruments for monitoring TCO.

Koherent is based on a small, cost effective, robust, low-maintenance and state-of-the-art commercial array spectroradiometer. The instrument has been operated for five years with a >99% data acquisition reliability. The system is based on a Bi-Tec Sensor (BTS-2048-UV-S-F) array spectroradiometer from Gigahertz-Optik GmbH. The spectroradiometer is coupled via an optical fiber to a lens-based telescope mounted on a sun tracker (Figure 1; blue instrument) to measure direct ultraviolet irradiance in the wavelength band from 305 nm to 345 nm (Egli et al., 2023).

Two different algorithms have been developed to retrieve TCO from these spectral measurements: First, a least-squares fit algorithm and second a Custom Double Ratio (CDR) technique using four specifically selected wavelengths from the spectral measurements.

The instrument can be calibrated in three different ways: absolute calibration of the solar spectra using the portable reference for ultraviolet radiation, QASUME, with laboratory calibration using standard lamps, or by the adjustment of the extraterrestrial constant (ETC) of the CDR retrieval. The calibration of the ETC allows the instrument to be calibrated with respect to an official TCO reference instrument during inter-comparison campaigns. Absolute TCO can be calibrated with a two-point calibration during such campaigns by also changing the absorption coefficient to achieve the best agreement to existing network instruments.

A comparison at PMOD/WRC in Davos between Koherent and the Brewer 156 (double monochromator) shows that TCO derived from Koherent and the Brewer 156 agree on average over the entire period within 0.05% +/- 0.88% in terms of the offset (Figure 2), when combining all retrievals. The performance in terms of slant -path is similar to a Brewer single monochromator. When applying a stray-light correction, the slant-path dependency is close to the performance of a Brewer double monochromator. The new algorithm further allows the determination of the effective ozone temperature within 3 K based on daily averages.

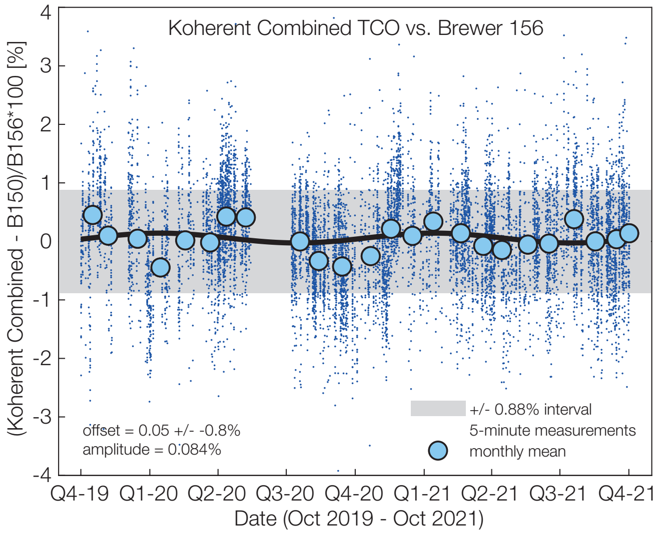

Figure 2. Relative difference between Koherent (LSF and CDR combined) and Brewer 156 double monochromator. The small blue points indicate the synchronised measurements with five minute intervals. The light blue circles are monthly means. The grey area indicates the standard deviation of the relative difference between the three retrievals used for the combined product. The seasonal amplitude is 0.084% with a long-term offset of 0.05%.

The BTS array spectroradiometer will be placed in the standard housing of the BTS Solar instrument (Figure 1, white instrument to the right of the blue instrument). In combination with the new retrieval algorithm and the different calibration possibilities, the system in the new housing, BTS Koherent, will form an improved new generation of TCO monitoring instruments. This modification will further allow a better comparison with BTS Solar instruments, which potentially can form a worldwide network for TCO observations.

Acknowledgment: This research has been supported by the ESA project QA4EO, grant no. QA4EO/SER/SUB/09) and by GAW-CH MeteoSwiss (project INFO3RS, grant no. 123001926).

References: Egli, L., Gröbner, J., Schill, H., Maillard Barras, E.: 2023, Total column ozone retrieval from a novel array spectroradiometer, Atmos. Meas. Techn, 16, 2889-2902, https://doi.org/10.5194/amt-16-2889-2023

Figure 1. The Koherent system in the temperature stabilised aluminium box (lower left) is shown along with the blue telescope entrance optics. Directly to the right, is the new BTS Koherent setup along with its white telescope optics. →

COST Action Harmonia: International Network for Harmonisation of Atmospheric Aerosol Retrievals from Ground-Based Photometers

Stelios Kazadzis, Natalia Kouremeti and Akriti Masoom

The Harmonia (International network for harmonisation of atmospheric aerosol retrievals from ground based photometers) COST Action is a European Cooperation in Science and Technology funded project. PMOD/WRC is a grant holder within Harmonia, which is led by S. Kazadzis. Harmonia began in November 2022 and will end in October 2026. The main aim is to establish a network involving institutions, instrument developers, scientific and commercial end-users, in order to improve, homogenise and establish aerosol columnar retrievals, using mainly solar and sky but also lunar and star photometers from different networks.

Aerosols are particles floating in the Earth's atmosphere linked to the largest uncertainty on estimates and interpretations of the Earth's changing energy budget. Measurement principles differ, depending on the desired derived aerosol optical parameter and on the measurement platform (surface or space). The common retrieval techniques for aerosol columnar properties, consists of the direct measurement of a bright source of radiation (sun, star, moon, sky) with multi-wavelength photometers. Several global photometric aerosol networks exist. However, there are several instrumental, algorithm and hardware-based differences on their related aerosol products and global standardisation is needed. In addition, in order to improve and optimise sun and moon photometric aerosol measurements, a network of aerosol scientists and operators, aerosol measurement users and software, hardware developers is needed.

The objective of Harmonia is to establish a network involving institutions, instrument developers, scientific and commercial end-users, in order to improve and homogenise aerosol retrievals using mainly solar and sky but also lunar and star photometers from different networks. It aims to bridge user needs and the science and technology expertise residing in academia and industry, through:

• Increasing the interaction and exchange of knowledge between several atmospheric aerosol network measurement scientists and users.
• Standardisation and improvement of existing aerosol products and tools, towards a "harmonisation" in aerosol photometry.
• Stimulating the communication between operational agencies and academia, in order to increase the applicability of aerosol products.
• Encouraging and organising the dialogue between researchers and instrument manufacturers, towards innovation actions on current and future photometric aerosol instrumentation.

Harmonia deals with a number of challenges/scientific questions:

• How European and global-based sun-photometer users can use common standards?
• How can scientists improve the measurement quality of aerosol optical properties?
• How can the aerosol community increase the applicability of aerosol products?
• How can scientists improve aerosol measurement quality and future measurement capabilities, including low-cost sensors?

Figure 1. Participants of the Harmonia meeting at the Academy of Athens.

These questions are discussed through a network of scientists, students, aerosol users, instrument and algorithm manufacturers and developers to define the major objectives of Harmonia:

• Homogenisation and harmonisation of global aerosol measurements and retrievals.
• Improvement of aerosol measurements using solar, lunar and star photometry.
• Increase the applicability of aerosol optical properties in different scientific fields.
• Creation of innovation for hardware and software developers.
• Increase the dissemination of scientific, technical and innovation ideas in sun-photometry.

The current structure of Harmonia consists of: i) a leading core group of 16 people from nine countries, ii) the management committee with 56 members from 37 countries that act as country representatives for Harmonia management decisions, and iii) working group participants that in December 2023 number 118 people from 42 countries.

During the first year of Harmonia, 12 virtual mobility, four short scientific missions and four IT conference grants were funded. In addition, the management meeting in Davos (Switzerland) with 60 participants, the Harmonia sun-photometer day at the Sorbetto school at ESA ESRIN (Rome, Italy) and the workshop of end-users in Athens (Greece) were initiated (Figure 1).

The foreseen impacts of Harmonia are focused on the research community, which will enhance the procedures and decrease the uncertainty of the inter-compatibility of aerosol data-sets. In addition, improved and new results will directly affect satellite-based and modelling applications that include aerosols, that have a more direct impact on important; climate (Earth's radiative balance, solar energy potential and use), health (air quality) and weather (aerosol assimilation related) aspects.

Laser Versus Lamp-Based Calibration of a Precision Solar Spectroradiometer

Natalia Kouremeti and Julian Gröbner in collaboration with PTB (Germany)

A Precision Solar Spectroradiometer (PSR) was calibrated using the state-of-the-art tunable laser-based setup, TULIP, at the German National Metrology Institute (PTB). In addition, the PSR was also calibrated using an irradiance transfer standard lamp. The two calibration methodologies are analysed and compared with the aim of validating the standard PSR calibration procedure.

The Precision Solar Spectroradiometer (PSR) is a grating-type array spectroradiometer, developed as a reference instrument for spectral solar irradiance measurements in the spectral range from 300 nm to 1040 nm and for the determination of aerosol optical depth (Gröbner and Kouremeti, 2019). The uncertainty budget of the PSR spectral responsivity (Gröbner and Kouremeti, 2019) showed that a significant uncertainty source is the uncertainty of the irradiance standard used in the calibration. To improve this, a PSR was calibrated at the TUnable Lasers In Photometry (TULIP) setup at PTB, aiming at a low uncertainty and stray-light corrected spectral responsivity. The PSR used in this calibration, measures in the 315 - 1030 nm spectral range. There is no ordering sorting filter in front of the detector, instead relying on post-processing of measured spectra using a correction method based on Line-Spread-Functions (LSFs) to correct for internal stray-light, extending the method by Zong et al. (Kouremeti et al., 2021; and references therein).

Prior to the measurements at PTB, the PSR was calibrated at PMOD/WRC using transfer standard lamps for spectral irradiance (Gröbner and Kouremeti, 2019). However, in order to rule out any possible changes to the instrument during transport, it was recalibrated at PTB facilities. Irradiance responsivity, wavelength scale and stray-light were recalibrated following procedures similar to those used at PMOD/WRC. The LSFs were measured over the full spectral range of the spectroradiometer using a ns-pulsed OPO system at PTB. The mathematical suppression of the stray-light due to higher grating orders has been extensively investigated and optimised (Kouremeti et al., 2021), where it was estimated that it can be realised with an uncertainty of <1%. The pixel-to-wavelength function was determined from the LSF measurements using a Laser Spectrum Analyser (LSA) that was monitoring the laser beam. The irradiance responsivity was determined using a transfer standard lamp calibrated at PTB. Measurements at two distances were combined to reduce signal-to-noise in the low sensitivity range of the PSR (700 - 1030 nm) or at low irradiance levels (315 - 450 nm).

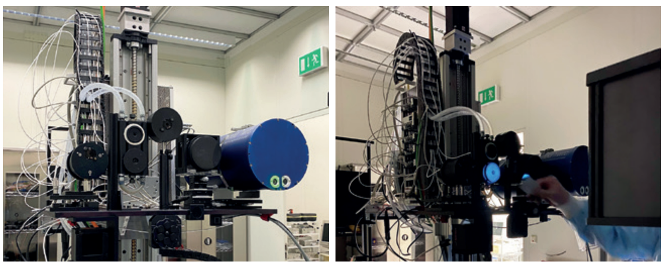

Figure 1. PSR#009 in the TULIP setup.

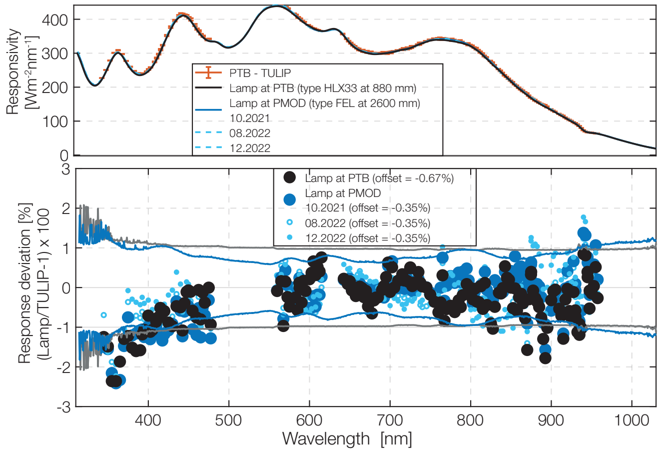

Figure 2. PSR#009 irradiance responsivity based on TULIP calibration and lamp-based calibrations at PTB and PMOD/WRC (upper panel). Normalised deviations of the lamp and laser-based calibrations (lower panel). The grey and blue lines represent the relative expanded uncertainty of the PTB and PMOD/WRC calibration setups, respectively.

The PSR responsivity derived from the TULIP calibration was based on: i) the integral ±10 nm from the centroid wavelength divided by the irradiance reference trap detector, and ii) the lamp-based calibrations at PTB and PMOD/WRC (before Oct. 2021 and after the PTB visits in Aug. and Dec. 2022). Their deviations from the TULIP calibration are shown in the upper panel of Figure 2. The deviations shown in the lower panel are normalised to the median value of the differences in the 550 - 800 nm region. The offset of 0.3% between the PTB lamp calibrations and PMOD/WRC seems to arise from the entrance plane definition. The remaining offset, especially in shape, resembles the results obtained with the QASUME spectroradiometer from a similar calibration test, which is under investigation. Moreover, the observed relative underestimation of the responsivity in the 315 - 450 nm range from the lamp calibration method is consistent with atmospheric observations, e.g. the PSR Langley top-of-atmosphere solar spectrum compared to TSIS-1 HSR (Gröbner et al., 2023). Further analysis will be performed to minimise uncertainties from interpolation of the LSFs and stray-light correction, and to assess the remaining discrepancies to form a correction factor for the lamp-based calibration.

Acknowledgement: We would like to thank the PTB team, S. Nevas, P. Schneider, and K. Schwind, for making this work possible. This work has been supported by the European Metrology Program for Innovation and Research (EMPIR) within the joint research project EMPIR 19ENV04 MAPP.

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Solar Radiation/Energy Research at PMOD/WRC

Stelios Kazadzis, Xinyuan Hou and Kyriaki Papachristopoulou

PMOD/WRC is participating in various EU funded projects related to solar radiation/energy research. Specifically, the effects of various atmospheric parameters such as aerosols and clouds on solar radiation are being investigated.

The E-Shape project (https://e-shape.eu; EuroGEO Showcases: Applications Powered by Europe) has received funding from the European Union's Horizon 2020 Research and Innovation Programme (April 2019 - May 2023) with the aim of bringing together Earth Observation and in-cloud capabilities into services for decision-makers, citizens, industry and researchers. PMOD/WRC is leading the pilot study on solar radiation and energy forecasting. The upgrade of the nextSENSE model that was developed by PMOD/WRC, was documented in a publication under review. The new system can be seen here: https://solar.beyond-eocenter.eu/#solar_short for short and long-term solar forecasts.

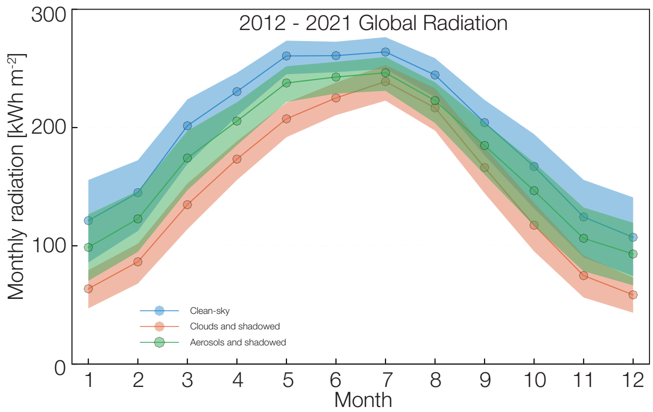

Figure 1. Monthly mean global radiation during the following conditions in Athens during 2012 - 2021: clear-sky (blue), clouds and shadows (pink), and aerosols and shadows (green).

PMOD/WRC is also participating in the EU-funded EIFFEL project (Revealing the role of GEOSS as the default digital portal for building climate change adaptation & mitigation applications, 2021 - 2024). The project aims to exploit existing GEOSS and external datasets contributing to Europe's efforts towards the implementation of the Paris Agreement for Climate Change. Solar radiation/energy research is included as a pilot study of photovoltaic (PV) penetration in an urban area with a demonstration study in the Attica region (Greece). Cadastral archives, inclination and orientation aspects and shadowing effects, are used to calculate the solar energy availability at a building and neighbourhood level. Results will include reporting the solar availability for a choice of PV orientations, available surface areas and PV materials for the region, and a building-scale database and interactive map (Figure 1). The PMOD/WRC research is part of the work of X. Hou, a PhD student.

PMOD/WRC participates as a partner in the EU Excelsior project (Excellence Research Centre for Earth Surveillance and Space-Based Monitoring of the Environment). PMOD/WRC aims to contribute towards the development of The Cyprus Solar Radiation Laboratory, which aims to establish an excellence hub for conducting basic and applied research and innovation related to solar radiation measurements and modelling, towards contributing to the thematic clusters of Environment and Climate, Resilient Society, and Big Earth Data Analytics (Fragkos et al., 2023). During the project, people from the solar radiation laboratory of the Eratosthenes Center of Excellence Cyprus, visited PMOD/WRC in order to gain experience on solar measurements and solar modelling.

PMOD/WRC was involved as an external unfunded partner in the advisory board of the Greek National Project, ASPIRE (Atmospheric parameters affecting SPectral solar IRradiance and solar Energy). The aim of this project is to investigate the spectral solar irradiance variability due to changes in various atmospheric parameters and to assess the effect of this variability to applications such as:

a) PV energy production (Kouklaki et al., 2023).

b) Health, agricultural, marine-related indices.

c) Real-time and short-term forecasting for solar energy calculations and related systems (Raptis et al., 2023).

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Traceability of Aerosol Optical Depth Measurements and Links With the Clouds and Trace Gases Research Infrastructure (ACTRIS) / Calibration of Aerosol Remote Sensing (CARS)

Stelios Kazadzis, Natalia Kouremeti, Akriti Masoom and Julian Gröbner

The World Optical Depth Research and Calibration Center (WORCC) is participating in the Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS-CH, 2021 - 2025), and collaborates with the Centre for Aerosol Remote Sensing (CARS) of ACTRIS. After receiving the approval of the ACTRIS General Assembly in November 2023, PMOD/WRC is now officially a new sun-photometric unit of ACTRIS/CARS.

The main task of the CARS-PMOD/WRC unit is to link the aerosol optical depth (AOD) calibrations from ACTRIS/CARS with the WMO scale and SI traceable measurements. This goal is being achieved through the continuous operation of PMOD/WRC reference Precision Filter Radiometers (PFRs) at the ACTRIS/CARS calibration sites: Izaña (IZO) in Spain, Observatoire de Haute Provence (OHP) in France and the University of Valladolid (VLD) in Spain. More on the Swiss participation in ACTRIS can be found at https://www.actris.ch/.

The aim of this collaboration is: i) to link CARS with the WMO-defined AOD scale maintained by WORCC, ii) the homogenisation of AOD retrievals, and iii) the provision of standard operating procedures and process documents on the comparison of PFR (WORCC) and CIMEL (ACTRIS/CARS) sun-photometers. In addition, WORCC aims to standardise and homogenise AOD reference scales and to improve the calibration and processing algorithms for consistent long-term measurements of AOD.

In addition, based on the results of SI-traceable AOD retrievals obtained within the MAPP (Metrology of Aerosol oPtical Properties) project (Kouremeti et. al., 2022), WORCC aims, in collaboration with the German National Metrology Institute (PTB), to form an SI-traceable pool of PFR reference and travelling standard instruments. This activity will lead in turn, in providing SI traceability to the ACTRIS/CARS reference CIMEL sun-photometers.

The traceability to the WMO AOD scale is checked via comparisons of co-located, synchronous AOD measurements between PFRs and AERONET-Europe Cimel CE318(-T) sun-photometers at the calibration sites. All Cimel channels in the UV NIR range are validated, extrapolating the PFR AOD data using the Ångström law for atmospheric conditions that lead to uncertainties less than 0.01 in AOD. A comparison protocol has been established and certificates for the performance of the reference Cimels are issued every four months. Since 2022, seven reference Cimel instruments have been certified. The overall performance for each calibration site is shown in Figure 1, while the comparison time-series at 500 nm for IZO is presented in Figure 2. For this site, all AOD differences are consistent with the WMO limits by more than 95%, while for VLD and OHP this level of agreement is achieved for wavelengths longer than 440 nm.

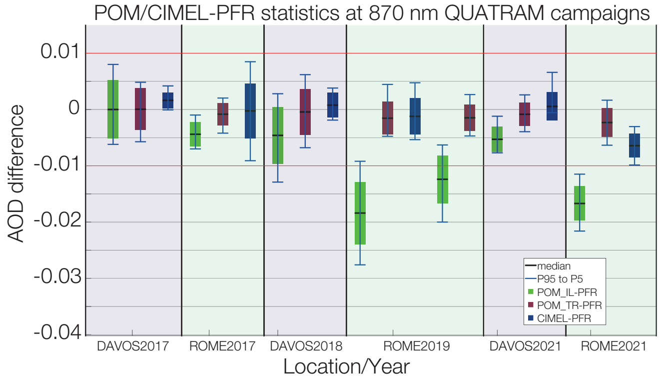

Figure 1. Median, 5th and 95th percentiles of AOD differences at seven nominal Cimel wavelengths for the three ACTRIS/CARs sites in the 2022 - 2023 period.

Results of this initiative have been presented at ACTRIS workshops and meetings and also at the European Meteorological Symposium (Bratislava, Slovakia) in September 2023.

Acknowledgement: This research has been funded by ACTRIS Switzerland.

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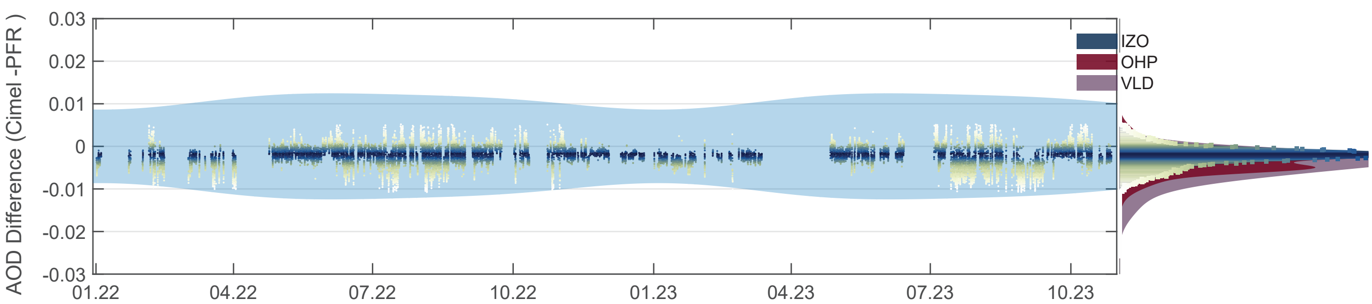

Figure 2. Left panel: Time-series of AOD comparison at 500 nm at the Izaña ACTRIS/CARS calibration site. The shaded area indicates the WMO limits for AOD traceability. The coloured points are based on the distribution probability function shown in the right panel for IZO as well as for VLD (purple) and OHP (red) at the same wavelength.

Traceability of Lunar Direct Irradiances Measured with a Precision Filter Radiometer

Natalia Kouremeti, Julian Gröbner and Stelios Kazadzis in collaboration with PTB (Germany) and USGS (USA)

A Precision Filter Radiometer (PFR), measuring Lunar direct irradiances for the retrieval of Aerosol Optical Depth (AOD), has been characterised and calibrated at PTB and PMOD/WRC. The spectral irradiance responsivities of the instruments are used in the Langley extrapolation method to assess the precision of the Top-of-Atmosphere (ToA) Lunar spectral irradiance provided by known lunar irradiance models.

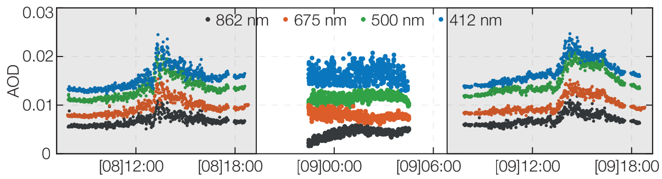

Figure 3. Daytime (PFR-N10, yellow areas) and nighttime (PFR-L02) AOD, based on Langley calibrations, during 8 and 9 September 2022. Daytime AOD at 675 nm has been interpolated, based on the Ångström law.

Atmospheric aerosols are known to impact the climate. They also represent one of the essential climatic variables with the largest uncertainties in climate change studies. Within the framework of Global Atmospheric Watch (GAW), AOD is monitored and is based on direct solar irradiance measurements performed by Precision Filter Radiometers (PFRs). The growing interest in nocturnal AOD observations, in an attempt to fill the gap in the annual cycle of the Arctic aerosol climatology, led to the development of the Lunar PFR in 2014. After the successful PFR SI-traceable AOD retrieval (Kouremeti et al., 2022), based on the TSIS-1 HSRS (Coddington et al., 2021) high resolution solar spectrum, the Lunar-PFR was calibrated at PTB following the same procedures as the sun-PFR, with the aim of providing a benchmark dataset for lunar model developers. The laser-based calibration at the PTB TULIP setup, led to calibration factors with combined expanded uncertainties of 0.26%, 0.27%, 0.18% and 0.25% at the four PFR channels with centroid wavelengths at 861.75 nm, 675.39 nm, 501.39 nm and 411.95 nm, respectively, at the minimum PFR gain. The determination of the maximum PFR gain (lunar gain) was achieved with an uncertainty of 0.3%, leading to a combined expanded uncertainty of lunar irradiance calibration factors at <0.4%.

Data used for retrieval of the top-of-the-atmosphere (ToA) lunar irradiance is from measurements at the Izaña observatory (28.3°N, 16.5° E, 2.4 km altitude, Spain) during the MAPP campaign from 3 - 23 Sept. 2022. Seven Langley-based ToA lunar irradiance (I_{L0}) retrievals were performed during one lunar cycle with lunar phases in the 6° - 58° range. The lunar irradiance models used include: the online available RIMO model (Barreto et al., 2019), and the customised ROLO model (Kieffer and Stone, 2005), accounting for the relative PFR responsivity and an adjustment for the initial ToA solar spectra (Wehrli, 1985) to TSIS-1 HSRS. A second preliminary adjustment offset factor, based on Air-LUCI preliminary results, was applied (ROLO*) and tested. A detailed uncertainty analysis of the ToA retrievals has investigated: i) Airmass calculation, time spacing of measurements using two Langley methods (airmass and 1/airmass), atmospheric refraction, uncertainty originating from the regression analysis and PFR irradiance measurements, and ii) phase relative variation of lunar irradiance over the measured cycle (Figure 1. Lunar cycle RIMO, ROLO).

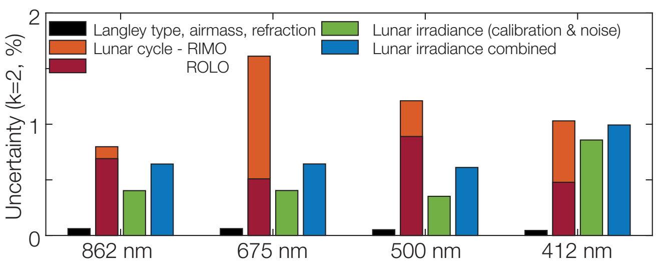

Figure 1. Uncertainty budget for the ToA lunar irradiance retrieved during the cycle from 3 - 23 September 2022 at the Izaña observatory.

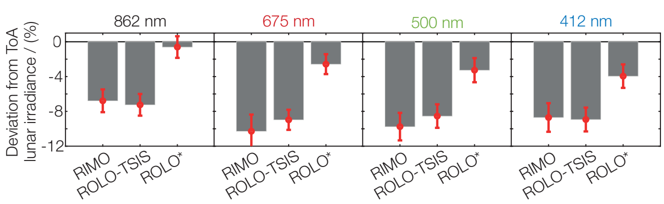

Figure 2. ToA lunar irradiance deviations (PFR-Model) at four PFR wavelengths. Grey bars show the deviation and the error-bars the combined expanded relative uncertainty of I_{L0}.

The results are presented in Figure 1. It is evident that sources of type 1 have a negligible contribution to I_{L0}. There is a substantial improvement in the representation of the lunar cycle with ROLO, leading to uncertainties comparable to the combined expanded uncertainty of the PFR ToA lunar irradiance (blue). The minimum uncertainty of I_{L0} is shown in green, excluding the estimated impact of the field-of-view inhomogeneity. In Figure 2, the mean over the cycle deviation of the ToA Lunar irradiance from the PFR and the models is presented. The ROLO* results show a substantial improvement of the deviations reaching the 0.5% agreement level at 862 nm, a limit that allows future SI-traceable AOD retrievals. An example of day and night-time AOD retrievals is shown in Figure 3, demonstrating the performance of the mean I_{L0}.

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Analysis of Greek Extreme Wildfires in August 2021 and its Effects on Air Quality and Solar Irradiance

Akriti Masoom and Stelios Kazadzis in collaboration with NOA and NKUA (Greece)

This analysis deals with the Greek wildfires of August 2021 that severely impacted the air quality in Athens leading to exceptionally higher levels of AOD (aerosol optical depth). Some high AOD days were characterised by smoke with spectrally decreasing single scattering albedo (SSA), while some had only Saharan dust events with spectrally increasing SSA, and others had both smoke and dust activities. Smoke from Greek fires was also transported to the nearby island of Antikythera. In Athens, solar irradiance was attenuated by dust in the ultraviolet region as compared to smoke with not much difference in near-infrared and visible regions. This study highlights the wider impacts of wildfires whose frequency is predicted to increase due to increasing summer heatwaves.

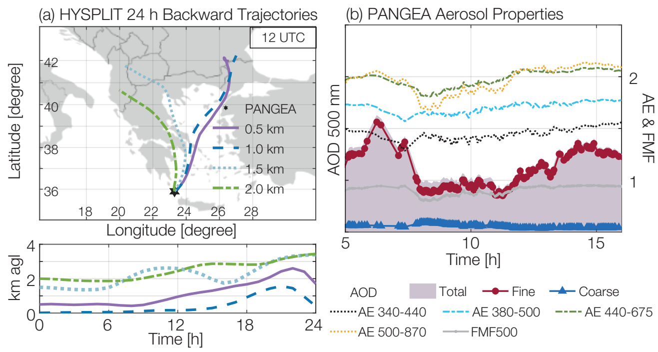

Figure 2. A): HYSPLIT 24-hr backward trajectories at PANGEA, b): variation of AOD (fine, coarse and total), AE and FMF at PANGEA on 7 August 2021.

The historic heatwave of 2021 in Greece led to severe wildfire events in August, deteriorating the air quality over Athens (Founda et al., 2022). During this period, Saharan dust was also transferred over Greece on certain days. This study investigated the impact of these events on air quality and surface solar radiation (Masoom et al., 2023). Event characterisation was performed using active and passive remote sensing instruments and modelling.

Significantly increased levels of aerosol optical depth (AOD) were recorded during 1 - 20 August. The presence of smoke led to high AOD values (~3.6 at 500 nm), a high Ångström exponent (AE) (~2.4 at 440 - 870 nm), and a strong and negative spectral dependence of the single-scattering albedo (SSA) that decreased from 0.93 at 440 nm to 0.86 at 1020 nm. The dust event led to high AOD (~0.7 at 500 nm), low AE (~0.9 at 440 - 870 nm), and a positive dependence of SSA on wavelength that increased from 0.89 at 440 nm to 0.95 at 1020 nm.

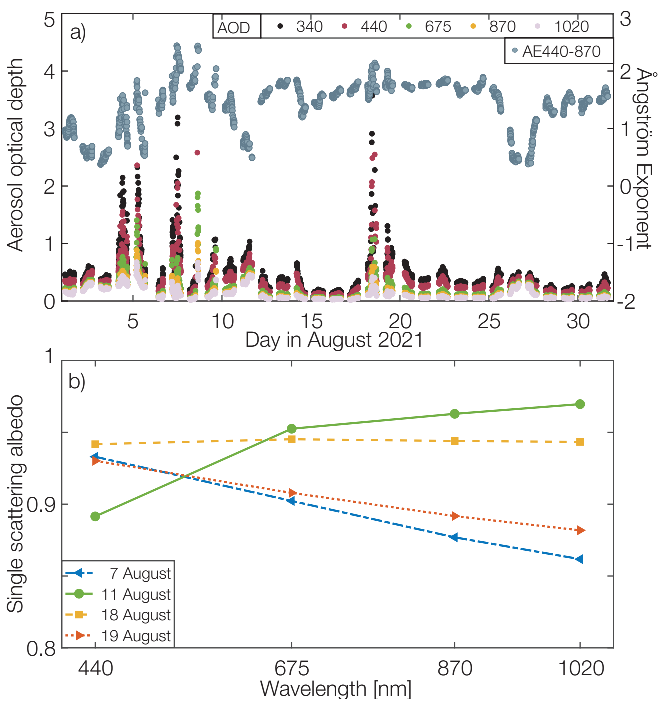

Figure 1. Variation in: a) aerosol optical depth (AOD) and Ångström exponent (AE), b) single scattering albedo (SSA) in Athens during the wildfires of August 2021.

On 7 August, smoke plumes were detected over the PANhellenic GEophysical observatory of Antikythera (PANGEA) located ~240 km away from Athens. Relatively higher AOD values (reaching ~0.90 at 500 nm) along with high fine-mode AOD (~0.85 at 500 nm) indicated the presence of fine biomass burning aerosols in the aerosol mixture. The two different aerosol types i.e., dust and smoke were found to have significant differences in the spectral dependence of the attenuation on solar irradiance based on libRadtran simulations performed for Athens (Masoom et al., 2023). The ultraviolet (UV-B) spectrum had lower attenuation with respect to dust as compared to smoke for a similar value of AOD at 500 nm, while the differences were not very prominent in the near-infrared and visible spectral regions.

Higher AOD levels also led to a decrease in the midday UV index (up to 53 %), as well as in the daily effective doses for the production of vitamin D (up to 50 %), in the daily photosynthetically active radiation (up to 21 %), and in the daily global horizontal irradiance (up to 17 %). This has serious implications for health, agriculture, and energy.

This study highlighted the wider impacts of wildfires that are part of the overall problem for Mediterranean countries, whose frequency is predicted to increase in view of the projected increasing occurrence of summer heatwaves.

Acknowledgement: This research was funded by ACTRIS Switzerland.

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FIve Years of AOD Inter-Calibration Experiments Between WORCC/PMOD-WRC and SKYNET

Angelos Karanikolas, Natalia Kouremeti and Stelios Kazadzis in collaboration with CNR (Italy), Univ. Valencia (Spain) and GRASP SAS (France)

Different sun photometer networks use different instruments, post-processing algorithms and calibration protocols for aerosol optical depth (AOD) retrievals. These differences can affect the homogeneity and comparability of the measurements between different networks. In this study, we evaluate the method used by the SKYNET network for sun photometer calibrations by analysing common measurements since 2017.

Aerosols are an atmospheric component with significant effects on weather, climate and air quality. One of most important parameters related to aerosols is the aerosol optical depth (AOD), which describes their overall direct effect on solar radiation attenuation. AOD is measured by sun photometers. There are several networks of sun photometers worldwide using different instruments and methodologies.

In this study, we evaluate the Improved Langley Plot (ILP) method used by the Sky Radiometer Network (SKYNET) that uses POM (Prede Co.) instruments. To achieve this, we used data from three inter-comparison campaigns (QUATRAM I, II, III) each including two phases, one in Davos and another in Rome during the 2017 - 2021 period. All campaigns included instruments from at least two additional networks. To evaluate ILP, we use the raw synchronous signal ratios from a Precision Filter Radiometer (PFR; belonging to the Global Atmospheric Watch PFR or GAW-PFR network) and a co-located POM to retrieve a new calibration for it. Then we compare this calibration with that calculated using the ILP method. In addition, we re-calculate the POM AOD with this new calibration and perform a comparison between the PFR AOD and both datasets of POM AOD corresponding to the two calibration methods. In order to achieve better quality assurance, we also compare the PFR AOD with the CIMEL (belonging to the Aerosol Robotic Network or AERONET) AOD. These three instruments have two wavelengths that are directly comparable, nominally 500 nm and 870 nm, which we used for the comparison.

The AOD comparisons in Figure 1 show that the POM AOD using the ILP calibration is significantly lower with the difference being larger in Rome. The CIMEL-PFR comparison shows a better agreement, which agrees with previous findings, while the calibration transfer-based AOD differences become significantly smaller and no longer systematically biased. This shows that the processing algorithm and instrument technical differences between GAW-PFR, AERONET and SKYNET have a minor effect on AOD. The main source of differences is the calibration method. According to WMO, at least 95% of the AOD differences should be within specific limits that depend on the air mass. For the case of the CIMEL-PFR comparison, this is true in all cases except for Rome 2019 at 500 nm. For the POM-PFR comparison, it is true only for Davos 2017 at 500 nm. At 870 nm, it is true for Davos 2017, 2021 and Rome 2017. Median differences vary from 0 to -0.034/-0.017 at 500/870 nm.

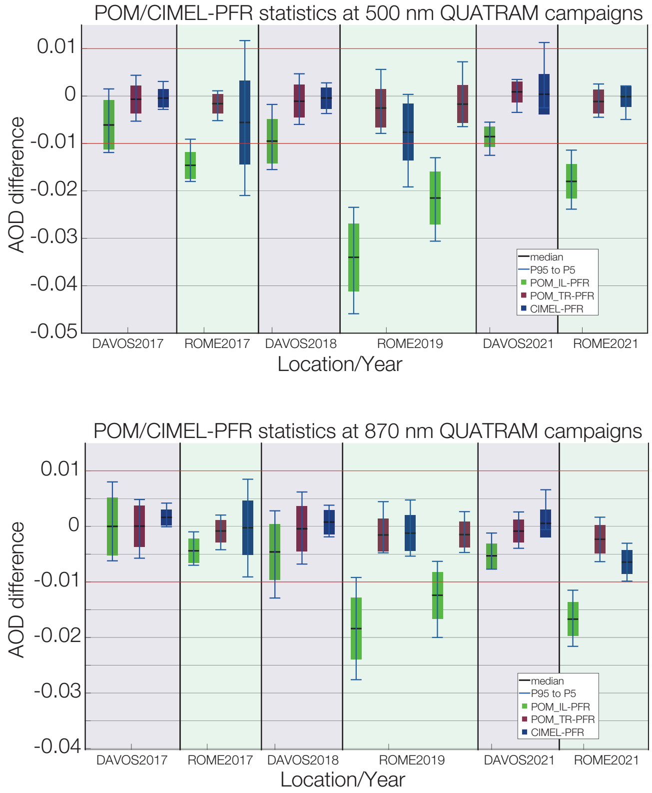

Figure 1. AOD differences during the three QUATRAM campaigns at 500 and 870 nm (upper and lower panels, resp. The black line is the median difference, the box size denotes the standard deviation, while error bars show the 5th and 95th percentiles. In all cases, the PFR AOD is the reference instrument. Green boxes correspond to the differences with the original AOD from POMs and the PFR. Red boxes are the calibration transfer-based POM AOD, and the blue to CIMEL. For the Rome 2019 campaign, a 2nd POM was added.

In an attempt to investigate the causes of the reported differences, we used the AOD and Angström exponent from the PFR and the Single Scattering Albedo (SSA) from the CIMEL, but found no correlation or systematic differences between datasets from Davos and Rome during the campaigns. Secondly, we performed a sensitivity study of the ILP pre-assigned values for the total ozone column, atmospheric pressure, surface albedo (SA), instrument solid view-angle (SVA) and aerosol complex refractive index. The study showed that part of the differences can be explained by related uncertainties, mainly by SA and SVA. The current data limitations (mainly the sparse and low quality observations of SSA) do not allow us to fully understand the behaviour of the calibration underestimate or to suggest improvements. Other studies (e.g. Campanelli et al., 2023) showed that improvements can be accomplished with alternative methods, such as the Cross-Improved Langley plot (XIL) or the standard calibration protocols adopted by GAW-PFR and AERONET.

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Sudip, M., ... Barczynski, K., et al.: 2023, Evolution of dynamic fibrils from the cooler chromosphere to the hotter corona, Astron. Astrophys., 678L, 5, https://doi.org/10.1051/0004-6361/202347343

Vargin, P., Kostrykin, S., Koval, A., Rozanov, E., Egorova, T., Smyshlyaev, S., Tsvetkova, N.: 2023, Arctic stratosphere changes in the 21st century in the Earth system model SOCOLv4, Frontiers in Earth Science, 11, 1214418, https://doi.org/10.3389/feart.2023.1214418

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Zilker, F., Sukhodolov, T., Chiodo, G., Friedel, M., Egorova, T., Rozanov, E., Sedlacek, J., Seeber, S., Peter, T.: 2023, Stratospherically induced circulation changes under the extreme conditions of the no-Montreal-Protocol scenario, Atmos. Chem. Phys., 23, 13387-13411, https://doi.org/10.5194/acp-23-13387-2023

Zubov, V., Mironov, A., Egorova, T., Rozanov, E.: 2023, Annual cycle of total ozone content in the Southern Hemisphere using the Chemistry-Climate Model SOCOLv3, Preprints 2023, 2023091348, https://doi.org/10.20944/preprints202309.1348.v1

Media - Selected Highlights

21 Jan. 2023
• High-ranking ESA visit at PMOD/WRC during the World Economic Forum (WEF)
• Amongst the visitors were Josef Aschbacher (ESA Director General) and Matthias Maurer (ESA Astronaut) (see page 8)
• Davoser Zeitung newspaper, Switzerland
• https://www.pmodwrc.ch/wp-content/uploads/2023/01/PressArticle_20230124_DZ.pdf

9 Mar. 2023
• Interview and short video
• "Sonnenforschung am PMOD/WRC"
• ORF Austrian television
• https://www.pmodwrc.ch/wp-content/uploads/2024/02/Video_20230309_Sonnenforschungsinstitut_Davos.mp4

22 Feb. 2023
• Interview and short video
• "Modelling the Sun's influence on the Earth's climate"
• SwissInfo.ch
• https://www.swissinfo.ch/eng/modelling-the-sun-s-influence-on-the-earth-s-climate/48302692

28 Mar. 2023
• Newspaper article
• "ETH-Studierende tüfteln in Davos"
• Davoser Zeitung, Switzerland
• https://www.pmodwrc.ch/wp-content/uploads/2023/03/PressArticle_20230328b_DZ.pdf

2 Apr. 2023
• Public talk by Nils Janitzek (PMOD/WRC)
• "Mit Solar Orbiter zur Sonne"
• ETH Zurich within the framework of "Treffpunkt Science City"
• https://ethz.ch/staffnet/de/news-und-veranstaltungen/veranstaltungen/details.mit-solar-orbiter-zur-sonne.67670.html
and
https://www.youtube.com/watch?v=u7UG_ymxePU

16 May 2023
• Newspaper article
• "Finanzielle Unterstützung fürs WRC verlängert"
• Davoser Zeitung, Switzerland
• https://www.pmodwrc.ch/wp-content/uploads/2023/11/PressArticle_20230516_DZ.pdf

17 Jul. 2023
• Newspaper article
• "Japanische Weltraummission mit Davoser Hightech"
• Südostschweiz Zeitung, Switzerland
• https://www.pmodwrc.ch/wp-content/uploads/2023/11/PressArticle_20230717_SOS.pdf

1 Sep. 2023
• Interview and audio blog
• "Das Geheimnis des Sonnenwinds"
• SRF Wissenschafts-Magazin, Switzerland
• https://www.srf.ch/audio/wissenschaftsmagazin/das-geheimnis-des-sonnenwinds?id=12448056

12 Sep. 2023
• Newpaper article and short video
• "Wie sagt man das Wetter im All voraus, Frau Harra?"
• Blick newspaper, Switzerland
• https://www.blick.ch/wirtschaft/davoser-forscher-liefern-know-how-fuer-japanische-mission-wie-sagt-man-das-wetter-im-all-voraus-frau-harra-id18931426.html

16 Oct. 2023
• Cecilia Payne-Gaposchkin Medal and Prize
• Awarded to Prof. Louise Harra by Inst. of Physics (Great Britain)
• https://www.iop.org/about/awards/2023-cecilia-payne-gaposchkin-medal-and-prize
• https://www.pmodwrc.ch/wp-content/uploads/2024/02/PressArticle_20231120_SOS.pdf

Autumn 2023
• Online article
• "Das Urkilogram der Klimaforschung"
• ProClim Flash Magazine, 78, SCNAT, Switzerland
• https://proclim.scnat.ch/de

31 Oct. 2023
• Newspaper article
• "Internationales Messnetz für Aerosole"
• Davozer Zeitung newspaper, Switzerland
• https://www.pmodwrc.ch/wp-content/uploads/2023/11/PressArticle_20231031_DZ.pdf

8 Nov. 2023
• Interview and short video
• "L'aurora boreale vista con occhi esperti"
• RSI Swiss television
• https://www.rsi.ch/info/ticino-grigioni-e-insubria/L%E2%80%99aurora-boreale-vista-con-occhi-esperti--1983833.html

Administration

Personnel Department

Eliane Tobler and Kathrin Anhorn

External Outreach

This year we provided many guided tours for public schools, public offices, private groups and interested families (see Figure 1). In addition, we took part in different events and presented our work to the public. Some examples include:

• “Mittag der Forschung” in Klosters, where we had the opportunity to present our research activities to interested members of the cantonal parliament of Graubünden.

• “Spielplatzfest” in the Davos Kurpark, where we tried to bring space-related topics closer to children. We offered the opportunity to launch their first spacecrafts and look at the Sun, as they had never seen it before.

• “Fiutscher” cantonal job exhibition in Chur, where some of our apprentices presented their professions.

• “Zukunftstag”, held nation-wide, where we offered children an insight into our working routine.

• “Department Day” of the Department of Education, Culture and Environmental Protection Graubünden, where we welcomed over 70 people to PMOD/WRC.

Figure 1. Visit of the Davos District Council in March.

Internal

There were some changes in 2023 from the perspective of the personnel department, as well as reasons to celebrate:

In February, we said goodbye to Jakob Föller, followed by Lloyd Beeler who left us in June. Thanks to Lloyd and Jakob for all your work and commitment.

In July, we were again able to celebrate the successes of our apprentices. The following staff members passed their apprenticeships with flying colours:

• Linus Luzi (Way-Up Apprenticeship: Electronics EFZ)

• Nic Matthes (Polymechanic EFZ)

• Dario Tannò (Sports apprenticeship: Commercial employee EFZ)

Dario left us for a new job and for a sports opportunity in hockey. Nic Matthes stayed another two months to support us in the manufacturing of parts for space-related projects, while Linus stayed until the end of the year. Thank you for your extra time and your support. We wish you all the best for your future.

In September, Andrea Alberti our project manager left the institute. Thanks for your work.

Not only did we have to say goodbye to employees, but we also had the pleasure of welcoming new employees:

• At the beginning of July, Andri Morandi, our former electronics Apprentice (2012 - 2016), joined our team again - welcome back!

• On 1 August, we welcomed Nina Mark, who started her apprenticeship as a Commercial Clerk in the administration department.

• On 1 September, we welcomed Salim Ferhat as an Optical Radiometry scientist.

• Our latest team member started on 1 October, when we welcomed Florian Reinhard as a Project Manager of Space Projects.

Our doctoral students also achieved outstanding results. In Autumn, we had the pleasure of celebrating Conrad Schwanitz's success with his doctoral thesis, “Small-scale structures in the solar corona – appearance, development and impact“, and at the same time had to say goodbye to him. We wish him the best for his future.

Work Anniversaries

During our Christmas Dinner in Monstein (Figure 2), we celebrated three anniversaries of our long-standing employees:

• Dany Pfiffner: 25 years

• Tatiana Egorova: 20 years

• Silvio Koller: 10 Years

Many thanks for your loyalty and commitment to the institute.

Commission on Diversity and Equality

PMOD/WRC strives to be a safe, diverse and inclusive working environment for all staff, students and visitors. For that purpose, a Committee on Diversity and Equality was formed in 2022. We are pleased to announce that the Committee has fully taken up its duties.

Already, two staff surveys have been conducted to evaluate and improve our working environment. In addition, we implemented an anonymous reporting system for whistleblowers.

To analyse development and monitor ongoing initiatives, data is collected and evaluated on an annual basis. These Key Performance Indicators (KPIs) are available on our website.

Thanks

Thanks to everyone for continuously delivering excellent work, publishing a significant number of publications, showing our work to the public, supporting digitalisation initiatives, and striving for efficiency improvements. Thanks to everyone for being a member of our staff.

Finally, we'd like to thank all our civil servants for their commitment: Pascal Gamma, Samuel Wechsler, Leo Loprieno, Raphael Burkhardt, Cedric Renda, Julian Piller, Kaya Buchli, and Benjamin Brack.

Figure 2. Celebrating our long-standing employees during our annual Christmas dinner.

Personnel

Scientific Personnel

Prof. Dr. Harra, Louise	Director, affiliated Prof. at ETH-Zurich, Head of Solar Physics Group, Solar Physicist
Prof. Dr. Schmutz, Werner	PI DARA/PROBA-3 Scientist, former Director, Physicist
Dr. Barczynski, Krzysztof	Postdoc, Solar Physics Group, Physicist
Dr. Janitzek, Nils	Postdoc, Solar Physics Group, Physicist
Dr. Gröbner, Julian	Co-Head WRC, Head WRC-Sections IR Radiometry, WORCC, WCC-UV and Ozone Section, Physicist
Dr. Egli, Luca	Scientist, Ozone Section, Physicist
Dr. Ferhat, Salim	Scientist, Optical Radiometry, WRC Section, Physicist, (since 09.2023)
Föller, Jakob	Technical Employee, (until 02.2023)
Dr. Hülsen, Gregor	Scientist, WCC-UV Section, Physicist
Dr. Kazantzis, Stylianos A.	Scientist, WORCC Section, Physicist
Dr. Kouremeti, Natalia	Scientist, WORCC Section, Physicist
Dr. Masoom, Akriti	Postdoc, WORCC Section, Physicist
Thomann, Christian	Technician
Zeilinger, Franz	Technical Engineer, BSc, Ozone Section
Dr. Finsterle, Wolfgang	Co-Head WRC, Head WRC-Section Solar Radiometry, Physicist
Dr. Engler, Natalia	Instrument Scientist, WRC-SRS Section, Physicist
Dr. Haberreiter, Margit	Project Manager/Scientist Space, Instrument Scientist, WRC-SRS Section
Soder, Ricco	Research Engineer, Quality Systems Manager
Dr. Montillet, Jean-Philippe	TSI Instrument Scientist, Geoscientist
Dr. Sukhodolov, Timofei	Head of Climate Group, Climate Scientist
Dr. Rozanov, Eugene	Scientist, Climate Group, Physicist, (former Head of Climate Group)
Dr. Egorova, Tatiana	Scientist, Climate Group, Climate Scientist
Dr. Sedlacek, Jan	Scientist, Climate Group, Climate Scientist

PhD and Project Students

Battaglia, Andrea	PhD student, ETH Zurich, FHNW
Collier, Hannah	PhD student, ETH Zurich, FHNW
Hou, Xinyuan	PhD student, 3rd year, ETH Zurich
Karanikolas, Angelos	PhD student, 4th year, WRC-WORCC Section
Kouklaki, Dimitra	PhD student, National and Kapodistrian Univ. Athens, Greece
Kult-Herdin, Jessica	PhD student, BOKU-met, Vienna, Austria
Moustaka, Anna	PhD student, Aristotle Univ. Thessaloniki, Greece
Papachristopoulou, Kyriakoula	PhD student, NKU Athens, Greece
Schwanitz, Conrad	PhD student, 4th year, ETH Zurich, (until 09.2023)
Stiefel, Muriel	PhD student, ETH Zurich, FHNW, (since 07.2023)
Aregger, Simone	MSc student, ETH Zurich, (until 06.2023)
Bajzath, Peter	MSc student, ETH Zurich, (since 10.2023)
Brodowsky, Christina	MSc student, ETH Zurich, (until 04.2023)
De Sassi, Adriana	MSc student, ETH Zurich, (until 02.2023)
Faessler, Benjamin	MSc student, ETH Zurich, (until 12.2023)
Jörimann, Andrin Nico	MSc student, ETH Zurich, (until 04.2023)
Kistler, Fabian	MSc student, ETH Zurich, (since 10.2023)
Rixen, Marius	MSc student, ETH Zurich, (until 06.2023)
Stefanetti, Fabrice	MSc student, ETH Zurich, (since 03.2023)
Wang, Jingyu	MSc student, ETH Zurich, (since 02.2023)
Wunderlin, Elia	MSc student, ETH Zurich, (until 04.2023)

Benz, Nora	BSc student, ETH Zurich, (until 02.2023)
Weber, Jonas	BSc student, FHGR, (until 08.2023)
Skolc, Luca	ETH Studio Davos student, (until 04.2023)

Technical Personnel

Koller, Silvio	Co-Head Technical Department, Project Manager Space
Alberti, Andrea	Project Manager Space, (until 09.2023)
Büchel, Valeria	Project Manager Space
Gyo, Manfred	Electronics Engineer, MSc
Langer, Patrik	Mechanics Engineer, MSc
Matthes, Nic	Poly-Mechanic Apprentice, 4th year, (until 09.2023)
Meier, Leandro	Electronics Engineer, BSc
Reinhard, Florian	Project Manager Space, (since 10.2023)
Schlatter, Pascal	Mechanic, Head of Workshop, Safety Officer
Spescha, Marcel	Technician / Mechanics Dept.
Pfiffner, Daniel	Co-Head Technical Department, Project Manager Space
Beeler, Lloyd	Electronics Engineer, MSc, (until 06.2023)
El Sammra, Karim	Electronics Apprentice, 2nd year
Gander, Matthias	Electronics Engineer, BSc
Luzi, Linus	Electronics Apprentice, 4th year, (until 12.2023)
Morandi, Andri	Electronics Engineer, BSc, (since 07.2023)
Senft, Marco	IT Systems Administrator
Vignali, Fabrizio	IT Systems Administrator

Administration

Tobler, Eliane	Head HR / Finances, Accountant, MSc
Anhorn, Kathrin	Administration, Book-Keeping
Keller, Irene	Administration, Import/Export
Dr. Nyeki, Stephan	Media Officer
Mark, Nina	Administration Apprentice, 1st year, (since 08.2023)
Tannò, Dario	Administration Apprentice, 4th year, (until 07.2023)

Caretaker

Ferreira Pinto, Maria Sofia	General caretaker, cleaning

Civilian Service Conscripts

Brack, Benjamin	06.11.2023 - 18.12.2023
Buchli, Kaya	18.09.2023 - 23.12.2023
Burkhardt, Raphael	01.06.2023 - 14.07.2023
Gamma, Pascal	01.10.2022 - 06.01.2023
Loprieno, Leo	01.04.2023 - 17.06.2023
Niethammer, Loris	06.02.2023 - 12.03.2023
Piller, Julian	17.07.2023 - 01.09.2023
Renda, Cedric	17.07.2023 - 18.08.2023
Vermeirssen, Jonathan	20.08.2023 - 14.02.2024
Wechsler, Noah	01.08.2022 - 03.02.2023

Lecture Courses, Participation in Commissions

Louise Harra	Member of the follow-up committee of the CLOSE_UP project, Belgium Member of the advisory board of the Solar Physics journal Secretary of the Swiss Committee of Space Research Board member of Davos Science City Chair of ESA Heliophysics User archive committee Member of Board of Reviewing Editors for Science journal Subject editor for Proceedings of the Royal Society A: Mathematical, Physical & Engineering Sciences Chair of ISSI Science Board Ministerial position on management committee of Armagh Observatory and Planetarium Risk and Audit committee of Armagh Observatory and Planetarium Co-chair of the Scientific Advisory Board of the MPS Member of the ESA Space Science Advisory Council Co-PI of EUV Imager, co-I on SPICE on Solar Orbiter Co-I on the NASA IRIS mission PI of SoSpIM instrument on the JAXA Solar-C mission Member of selection panel for editor for the Solar Physics journal Member of the ESA Athena Independent Science Review Team External member of the SNF evaluation commission Postdoc. Mobility in the area of Mathematics and engineering sciences Member of editorial board of the journal, RAS Techniques and Instruments Member of Congressi Stefano Franscini Science Committee Member of COSPAR Task Group on Establishing an International Geospace Systems Program (IGSP) PhD examiner (Vishal Upendran, 31 March 2023, Jawaharlal Nehru University, New Delhi, India), (Nicolas, Brehm, ETHZ, June 2023) Member of ISSI team "Novel Insights Into Bursts, Bombs, And Brightenings In The Solar Atmosphere From Solar Orbiter Research Domain"
Werner Schmutz	Honorary Member of the International Radiation Commission (IRC, IAMAS). PI of DARA on PROBA-3. Co-I of EUV and SPICE instruments on Solar Orbiter.
Wolfgang Finsterle	Member of the Swiss Society for Astronomy and Astrophysics Member of WMO Expert Team on Radiation References Board member of the Davos branch of the SCNAT NGD Member of the International Radiation Commission Solar Irradiance Working Group Member of the Schweizerische Normen-Vereinigung
Julian Gröbner	Member of the Dobson Ad-Hoc Committee, http://www.o3soft.eu/dobsonweb/committee.html since 2021 Member of the expert team on Atmospheric Composition Measurement Quality and QA-Central Facilities of the WMO, since 2020 Member of the Scientific Advisory Group for Ozone and UV in the Global Atmosphere Watch programme of the WMO, since 2016 Chair of the Scientific Committee of the Conference "New Developments and Applications in Optical Radiometry" (NEWRAD), since 2014 Member of the Swiss Global Atmosphere Watch Programme managed by Meteoswiss, since 2005 Member of the Expert Team on Radiation References of the Standing Committee on Measurements, Instrumentation and Traceability (SC-MINT) of the WMO, since 2014 Member of the WG-IR of the Baseline Surface Radiation Network (BSRN), since 2006 Member of the Regional Brewer Scientific Group - Europe (RBCC-E, 2005 - ongoing) Elected member of the International Radiation Commission, and Chair of the Working Group on Solar UV Radiation, IAMAS, since 2009 Member International Ozone Commission, IAMAS, since 2016

Margit Haberreiter	President Swiss Society for Astronomy and Astrophysics Member Swiss National SCOSTEP Committee SCOSTEP Science Discipline Representative Member of the Solar Irradiance Working Group in the International Radiation Commission (IRC) Member of ISSI Working Group on Solar Forcing for CMIP7 Swiss Delegate to WMO's ET-SpWx Co-I on EUI and SPICE on Solar Orbiter Lead ISSI International Team "Towards the determination of the Earth Energy Imbalance from Space" Topical Editor Annales Geophysicae Chair Jury Prix Schäfli Astronomy 2023 Chair EGU Hannes Alfvén Medal Committee
Stylianos Kazantzis	Member of the International Radiation Committee (IAMAS-IRC) Member of the Scientific Advisory Group for Aerosols of WMO (WMO-SAG) Member of the Expert Team on Atmospheric Composition Measurement Quality of the World Meteorological Organisation Member of the Expert Team on Atmospheric Composition and Network Evolution of the World Meteorological Organisation Member of the Global Atmospheric Watch – Swiss panel Member of Atmospheric Chemistry and Physics journal editorial board Chair on COST Action Harmonia Swiss representative COST Action Probe and NEXUSNET
Timofei Sukhodolov	Guest editor of the research topic "The evolution of the stratospheric ozone - Volume II" in the Frontiers in Earth, Science journal Member of the SPARC project "High Energy Particle Precipitation in the Atmosphere", HEPPA-3 Co-lead of the SPARC activity "Interactive Stratospheric Aerosol Model Intercomparison", ISA-MIP Co-PI of the SOCOLv4 model, SPARC activity "Chemistry-Climate Model Initiative Phase 2", CCMI-2022 Member of the PASC23 Minisymposia and Posters Program Committee
Krzysztof Barczynski	Member Solar-C Science Working Group (ESA representative) Co-I EUI instrument onboard Solar Orbiter Co-lead of Solar Orbiter – DKIST coordinated observations group Member EPD – STIX – EUI coordinated flare observations team Member of Program Committee of Academia Raetica Representative of Akademischer Mittelbau am Physikdepartement ETH Zurich (AMP, Scientific Staff Association) to Departementskonferenz (DK) at ETH Zurich
Jean-Philippe Montillet	Reviewer for the journals: Journal of Geophysical Research (JGR) Atmospheres (AGU), Earth Spaces Sciences (AGU), Remote Sensing (MDPI) Guest Editor for Earth & Space Sciences (AGU) :Analyzing Big Data for Understanding Climate Variability, Natural Phenomena and Rapid Environmental Changes
Natalia Kouremeti	Member of COST Action Harmonia (working group leader)
Luca Egli	Member of the International Radiation Commission (IAMAS-IRC)
Natalia Engler	Member of Expert committee of Swiss National Competition 2021 "Schweizer Jugend forscht!"
Andrea Alberti	Advisor for the Space4Impact non-profit initiative Expert Evaluator for the Bench2Biz international workshop for young and aspiring entrepreneurs Expert for Innosuisse
Akriti Masoom	Member of COST Action Harmonia (working group co-lead)

Public Seminars given at PMOD/WRC

13 Mar. 2023 Malcolm White (National Institute of Standards and Technology NIST, USA)
"Decadal validation of the LASP TRF radiometer by NIST and establishment of a replacement room temperature standard"
~20 attendees

9 May 2023 Peng Fei Chen (Nanjing Univ., China)
"EUV waves"
~20 attendees

15 Nov. 2023 Isabel Steiner (Lab42, Davos, Switzerland)
"Explore42"
~20 attendees

23 Nov. 2023 Philip Judge (High Altitude Observatory & Bern Univ., Switzerland)
"The Sun’s magnetic machine"
~20 attendees

Meetings, Symposia, Workshops, Public Events (selected highlights)

28 Feb. 2023	Louise Harra gave a talk at the "Rose in Science" event which is one of a series of activities launched by CIOMP (China) as part of the UN 2015 "International Year of Light".
23 Mar. 2023	Grosser und Kleiner Landrat, Davos, Switzerland, PMOD/WRC tour. https://www.pmodwrc.ch/wp-content/uploads/2023/03/PressArticle_20230328a_DZ.pdf
28 Mar. 2023	Lions Club Lenzerheide, Switzerland, PMOD/WRC tour.
17 May 2023	PMOD/WRC Advisory Commission (Aufsichts-Kommission) meeting.
8 Jun. 2023	Ethiopian National Meteorology Agency NMA / OTT HydroMet, PMOD/WRC tour.
24 Jul. 2023	Visit by Swiss former Nationalrat, Heiner Studer, PMOD/WRC tour.
9 Aug. 2023	PMOD/WRC Board of Trustees (Stiftungsrat) meeting.
29 Sep. 2023	Rotary Club Davos, Switzerland, PMOD/WRC tour.
3 Oct. 2023	Kantonsschule Glarus, Switzerland, PMOD/WRC tour.
3 Oct. 2023	Kantonsschule Zurich, Switzerland, PMOD/WRC tour.
4 Oct. 2023	ETH Zurich MSc students, Switzerland, PMOD/WRC tour.
20 Nov. 2023	PMOD/WRC The Advisory Commission (Aufsichts-Kommission) meeting.
5 Dec. 2023	Researchers Beer Talk by K.Barczynski about latest Solar Orbiter results, public talk in Kulturplatz Davos, organised by Academia Raetica.
13 Dec. 2023	PMOD/WRC Board of Trustees (Stiftungsrat) meeting.

Bilanz per 2023 (inklusive Drittmittel) mit Vorjahresvergleich

	31.12.2023	31.12.2022
Aktiven	CHF	CHF
Flüssige Mittel	3'035'880.59	2'223'046.07
Forderungen	59'260.85	48'416.50
Aktive Rechnungsabgrenzungen	332'297.05	147'685.38
Warenvorräte	1'000.00	1000.00
Total Aktiven	3'428'438.49	2'420'147.95

Passiven		
Verbindlichkeiten	102'744.75	80'356.45
Kontokorrent Stiftung	0.00	0.00
Passive Rechnungsabgrenzung	1'595'398.53	909'568.74
Rückstellungen	1'380'000.00	1'150'000.00
Eigenkapital	350'295.21	280'222.76
Total Passiven	3'428'438.49	2'420'147.95

Erfolgsrechnung 2023 (inklusive Drittmittel) mit Vorjahresvergleich

Ertrag	CHF	CHF
Beitrag Bund Betrieb WRC	1'489'200.00	1'489'200.00
Beitrag Bund (BBL), Unterhalt Gebäude	98'521.05	1'250'185.65
Beitrag Kanton Graubünden WRC	509'268.00	509'268.00
Beitrag Kanton Graubünden für ETH Prof.	240'000.00	240'000.00
Beitrag Gemeinde Davos	664'191.00	664'191.00
Beitrag Gemeinde Davos, Mieterlass	160'000.00	160'000.00
Dienstleistungsauftrag MeteoSchweiz OZON	279'986.55	257'587.80
Dienstleistungsauftrag WMO Genève	21'881.00	21'881.00
Overhead SNF	0.00	27'422.50
Overhead Projekte	190'655.30	219'186.46
Instrumentenverkäufe	175'214.50	196'296.00
Reparaturen und Kalibrationen	242'352.20	235'531.55
Ertrag Dienstleistungen	112'051.96	61'602.70
Übriger Ertrag	4'578.07	135'460.71
Finanzertrag	0.00	0.00
Ausserordentlicher Ertrag	8'880.19	0.00
Drittmittel	2'330'781.23	2'132'769.14
Total Ertrag	6'527'561.05	7'600'582.51

Aufwand		
Personalaufwand	4'620'459.50	4'557'109.00
Investitionen Observatorium	228'770.28	137'029.45
Investitionen Drittmittel	102'266.40	15'492.35
Unterhalt Gebäude (Beitrag Bund)	98'521.05	1'250'185.65
Unterhalt	93'747.95	86'075.17
Verbrauchsmaterial Observatorium	112'452.45	38'415.80
Verbrauchsmaterial Drittmittel	182'455.26	261'708.95
Verbrauch Commercial	74'066.35	111'013.57
Reisen, Kurse	134'264.10	81'698.37
Raumaufwand/Energieaufwand	219'122.75	260'054.40
Versicherungen, Verwaltungsaufwand	104'211.05	122'579.66
Finanzaufwand	6'491.57	4'283.05
Übriger Betriebsaufwand	236'405.26	264'486.44
Ausserordentlicher Aufwand	14'254.63	44'616.92
Total Aufwand	6'227'488.60	7'234'748.78
Jahresergebnis vor Bildung/Auflösung Rückstellungen	**300'072.45**	**365'833.73**
Auflösung Rückstellungen	0.00	0.00
Bildung Rückstellungen	230'000.00	310'000.00
Jahresergebnis	70'072.45	55'833.73
	6'527'561.05	7'600'582.51

Abbreviations

AERONET	Aerosol Robotic Network, GSFC, USA
AOD	Aerosol Optical Depth
AU	Astronomical Unit (1 AU = 149,597,870.7 km; used to measure distances within the Solar System or around other stars)
BIPM	Bureau International des Poids et Mesures, Paris, France
BSRN	Baseline Surface Radiation Network of the WCRP
CCM	Chemistry-Climate Model
CIMO	Commission for Instruments and Methods of Observation of WMO, Geneva, Switzerland
CIOMP	Changchun Institute of Optics, Fine Mechanics and Physics
CIPM	Comité International des Poids et Mesures
CLARA	Compact Light-weight Absolute Radiometer (PMOD/WRC instrument onboard the NorSat-1 micro-satellite mission)
CMA	Chinese Meteorological Administration
CMC	Calibration and Measurement Capabilities
CME	Coronal Mass Ejections
COSI	Code for Solar Irradiance (solar atmosphere radiation transport code developed at PMOD/WRC)
COST	European Cooperation in Science and Technology
CSAR	Cyrogenic Solar Absolute Radiometer (PMOD/WRC research instrument, ground-based)
DARA	Digital Absolute Radiometer (PMOD/WRC instrument onboard the ESA PROBA-3 formation flying mission)
EAGLE	Entire Atmosphere Global Model
ECV	Essential Climate Variable
EMRP	European Metrology Research Programme
ESA	European Space Agency
EUI	Extreme Ultraviolet Imager (PMOD/WRC participation in EUI instrument onboard the Solar Orbiter mission)
EUV	Extreme Ultraviolet region of the light spectrum
FM	Flight Model
FRC	Filter Radiometer Comparisons, held at PMOD/WRC every 5 years
FS	Flight Spare
FY-3E	Chinese weather satellite, Fengyun-3
GAW	Global Atmosphere Watch, a WMO Research Programme
GCM	General Circulation Model
GCR	Galactic Cosmic Rays
HEPPA	High Energy Particle Precipitation in the Atmosphere (SPARC activity)
IACETH Zurich	Institute for Climate Research, ETH Zurich, Switzerland
IPC	International Pyrheliometer Comparisons, held at PMOD/WRC every 5 years
IPgC	International Pyrgeometer Comparisons, held at PMOD/WRC every 5 years
IRCCAM	Infrared Cloud Camera (PMOD/WRC research instrument)
IRIS	Infrared Integrating Sphere Radiometer (PMOD/WRC research instrument)
IRS	Infrared Section of the WRC at PMOD/WRC
ISO/IEC	International Organisation for Standardisation/International Electrotechnical Commission
ISO 17025	General requirements for the competence of testing and calibration laboratories
JTSIM-DARA	Joint Total Solar Irradiance Monitor – DARA (experiment onboard the Chinese FY-3E mission)
METAS	Federal Office of Metrology, (Eidgenössisches Institut für Metrologie), Bern-Wabern, Switzerland
MITRA	Monitor to Determine the Integrated Transmittance (PMOD/WRC research instrument)

MRA	Mutual Recognition Arrangement
NASA	National Aeronautics and Space Administration, Washington DC, USA
NIST	National Institute of Standards and Technology, Gaithersburg, MD, USA
NorSat-1	Norwegian Satellite-1
NPL	National Physical Laboratory, Teddington, UK
NREL	National Renewable Energy Laboratory, Golden, CO, USA
PFR	Precision Filter Radiometer (manufactured by PMOD/WRC)
PMO6-cc	Type of absolute cavity radiometer (previously manufactured by PMOD/WRC)
PROBA	ESA Satellite Missions (PROBA-1 to 3)
PRODEX	PROgramme de Développement d'Expériences scientifiques, ESA
PSR	Precision Spectroradiometer (manufactured by PMOD/WRC)
PTB	Physikalisch-Technische Bundesanstalt, Germany; The German National Metrology Institute
QASUME	Quality Assurance of Spectral UV Meas. in Europe (portable World reference for UV radiation constructed by PMOD/WRC)
QMS	Quality Management System
SCNAT	Swiss Academy of Sciences
SFI	Schweiz. Forschungsinstitut für Hochgebirgsklima und Medizin, Davos, Switzerland
SIAF	Schweiz. Institut für Allergie- und Asthma-Forschung, Davos, Switzerland
SKYNET	Sky Radiometer Network
SNSF	Swiss National Science Foundation
SOCOL	Combined GCM and CTM Computer Model developed at PMOD/WRC
SOHO	Solar and Heliospheric Observatory (ESA/NASA space mission)
Solar Orbiter	SolO; An ESA mission to conduct solar research (PMOD/WRC are participating with the EUI and SPICE instruments)
SoSpIM	Solar Spectral Irradiance Monitor (PMOD/WRC co-experiment onboard the JAXA Solar-C mission)
SPARC	Stratosphere-troposphere Processes And their Role in Climate (a core project of the World Climate Research Programme)
SPE	Solar Proton Events
SPICE	Spectral Imaging of the Coronal Environment (PMOD/WRC co-experiment, onboard the Solar Orbiter mission)
SRS	Solar Radiometry Section of the WRC at PMOD/WRC
SSI	Solar Spectral Irradiance
TRF	The Total Solar Irradiance Radiometer Facility (TRF) at the Lab. for Atmospheric and Space Physics (LASP), Boulder, USA
TRUTHS	Traceable Radiometry Underpinning Terrestrial and Helio-Studies (ESA space mission)
TRUTHS/CSAR	Cyrogenic Solar Absolute Radiometer (CSAR; PMOD/WRC space-based instrument) onboard the TRUTHS mission
TSI	Total Solar Irradiance
VHS	Ventilation Heating System (manufactured at PMOD/WRC)
VIRGO	Variability of Solar Irradiance and Gravity Oscillations (PMOD/WRC instrument onboard the SOHO mission)
WCC-UV	World Calibration Center for UV in the WRC of the PMOD/WRC
WDCA	World Data Centre for Aerosols, NILU, Norway
WISG	World Infrared Standard Group of pyrgeometers (maintained by WRC-IRS at PMOD/WRC)
WMO	World Meteorological Organisation, a United Nations Specialised Agency, Geneva, Switzerland
WORCC	World Optical Depth Research and Calibration Center of the WRC at PMOD/WRC
WRC	World Radiation Center at PMOD/WRC, composed of the Sections: IRS, SRS, WCC-UV, and WORCC
WRR	World Radiometric Reference
WSG	World Standard Group of pyrheliometers (realises the WRR; maintained by WRC at PMOD/WRC)

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Dorfstrasse 33, 7260 Davos Dorf, Switzerland
Phone +41 81 417 51 11
www.pmodwrc.ch