pmod wrc

Annual Report
Jahresbericht 2024

**Front Cover**: The PROBA-3 mission of the European Space Agency (ESA) was successfully launched on 5 December 2024 from India. Our instrument, the Digital Absolute Radiometer (DARA), is onboard, and will measure the Total Solar Irradiance (TSI). See pages 25 and 36 for further details. Image courtesy of the Indian Space Research Organisation (ISRO).

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.

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# 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.

# Table of Contents


# PMOD/WRC Introduction

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.

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 global primary standard for solar irradiance, on behalf of the World Meteorological Organization (WMO) and with financial contributions from the Swiss Federation, the Canton of the Grisons and the Commune of Davos. In addition, calibration centers for longwave radiation instruments, for spectral radiance measurements to determine the impact of particles and droplets in the atmosphere, and the World Calibration Center for UV have also been operated by the WRC.

Today, the WRC consists of four sections: Solar Radiometry (WRC-SRS), Infrared Radiometry (WRC-IRS), Aerosols (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 World Radiation Center (WRC) verwaltet im Auftrag der Weltorganisation für Meteorologie (WMO) und mit finanziellen Beiträgen des Bundes, des Kantons Graubünden und der Gemeinde Davos den globalen Primärstandard für die Sonneneinstrahlung. Darüber hinaus betreibt das WRC Kalibrierzentren für langwellige Strahlungsinstrumente, für spektrale Strahlungsmessungen zur Bestimmung des Einflusses von Partikeln und Tröpfchen in der Atmosphäre sowie das Weltkalibrierungszentrum für UV-Strahlung.

Heute besteht das Weltstrahlungszentrum aus vier Sektionen: Solar-Radiometrie (WRC-SRS), Infrarot-Radiometrie (WRC-IRS), Aerosole (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?".

**Ozone instruments are operated on behalf of MeteoSwiss and exploited together with MeteoSwiss as part of the Swiss contribution to the WMO Global Atmosphere Watch programme.*

## 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?".

**Ozonmessgeräte werden im Auftrag von MeteoSchweiz betrieben und gemeinsam mit MeteoSchweiz im Rahmen des Schweizer Beitrags zum WMO Global Atmosphere Watch-Programm genutzt.*

## 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 seven 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 sieben 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 has an affiliated professorship located in the Department of Physics (D-PHYS) in the Institute of Particle Physics and Astronomy at ETH Zurich. 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.

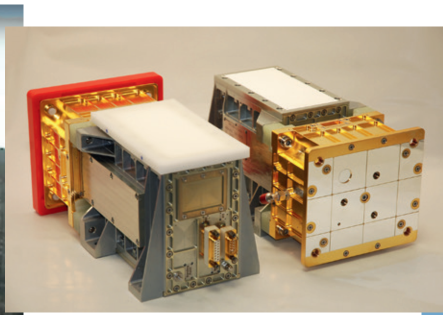
We also have strong links with the Department of Environmental Systems Science (D-USYS) through our climate modelling expertise and provide teaching there.

## ETH-Zürich

Seit 2019 ist die Direktorin des PMOD/WRC eine affiliierte Professorin im Departement Physik (D-PHYS) des Instituts für Teilchenphysik und Astronomie (IPA) der ETH Zürich. 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 2024

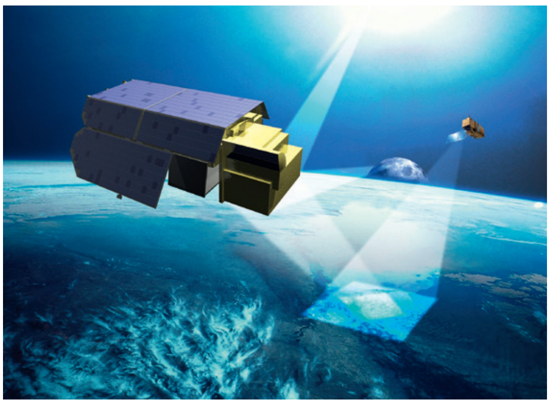


Left: ESA's Proba-3 was launched on 5 Dec. 2024 from India (Image courtesy of ISRO). Our DARA instrument (above: Flight Spare on left and Flight Model on right) is onboard.

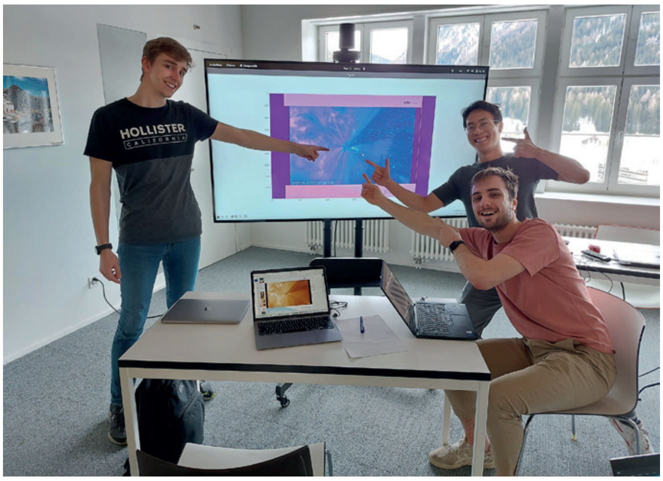
Right: Part of the PMOD/WRC crew who worked on DARA, with the rocket plume in the background just after launch.

Our WRC measurement campaigns were successful this year. More than 100 pyranometers were calibrated. We took part in the National Renewable Energy Laboratory Pyrheliometer calibration campaign in Colorado (USA; Ricco Soder in image on the left) and verified the stability of the World Radiometric Reference. During the same campaign, we also provided traceability to the World Infrared Standard Group with one of our pyrgeometers. Five UV calibration campaigns took place across Europe. A successful Brewer and Dobson campaign took place in Davos for the first time (right image).

During the World Economic Forum, we hosted an ETH event on 'rethinking observations'. We had a visit from the British Ambassador at this time.

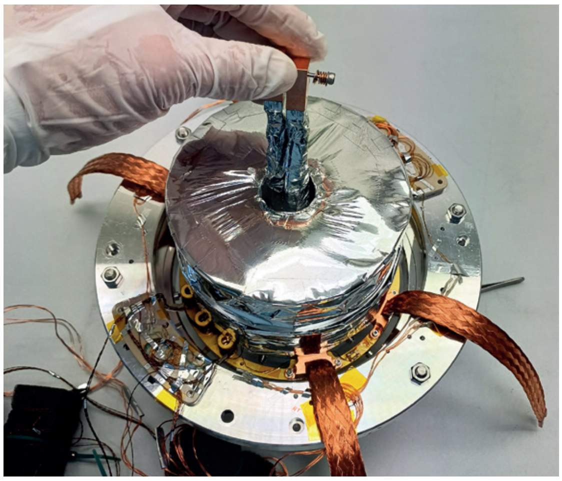


The year was very busy for the ESA space mission, TRUTHS. Our role is related to the radiometer design and electronics, building on experience with our existing ground-based Cryogenic Radiometer, CSAR.




We had 21 MSc and BSc students carrying out projects across all areas of research and technology. A new project was developed this year to develop a Cubesat with the students from the new MSc in Space Systems. We had three ETH Studio Davos students (see image) who also collaborated with Lab 42 to use machine-learning to identify solar jets. 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 cooperation between ETH Zurich and the Canton of Grisons with the thematic cornerstone of Artificial Intelligence and Data Science.

Our WRC instruments continue to be developed with the Cryogenic radiometer undergoing upgrades and tests.

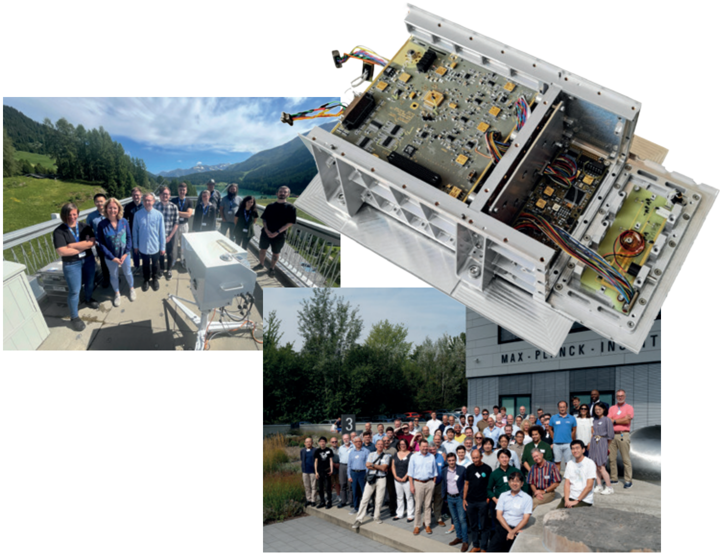



Our research continued to be successful, with over 60 refereed research papers published and over 40 talks given at international conferences. The research covered aspects of climate change, such as the future evolution of the ozone layer, and how the Sun's solar wind is formed. The research was recognised through the successful award of third-party funds: Eugene Rozanov was awarded a SCOSTEP fellow award for his contribution to solar-terrestrial sciences and Krzyzstof Barczynski was awarded a Forderungspreis from Canton Grison. One of Timofei Sukhodolov's papers was the most cited – a huge accolade!

Our tours and public talks continue to develop. The start of the year began with the 'Sonnensturm' theatre show in Chur, featuring Solar Orbiter. We were involved in the Davoser Mäss, Mittags der Forschungs, and a first time for us was to host the Davos Musik festival – mixing science and music. We also had interactions with media including local and regional newspapers, and SRF.

In May 2024, our instrument team was selected for the NASA contribution to the first ESA space weather mission, Vigil. Our instrument, the Joint EUV coronal Diagnostic Investigation, or JEDI (led by Don Hassler, SWRI), will capture images of the Sun in extreme ultraviolet light to understand and predict solar eruptions on the Sun. The launch of Vigil is due in 2031. In addition, we are part of the competitive phase A study for a mission to Mars – we are developing our spectral irradiance concept for understanding space weather at Mars.

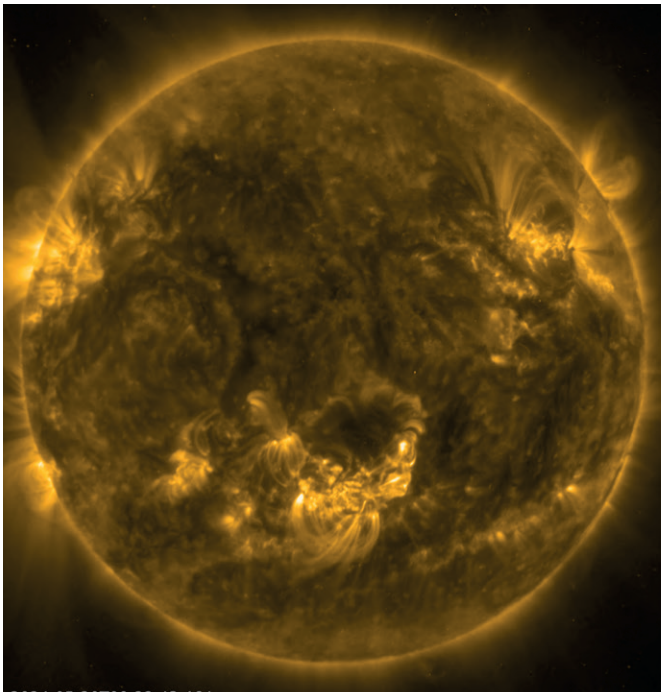
The International network for harmonisation of atmospheric aerosol retrievals from ground-based photometers (Harmonia) is led by PMOD/WRC. We organised a sun photometry school in Berlin in April 2024, and a Harmonia session at the European Meteorological Society conference. Aerosols are particles in the Earth's atmosphere that are linked with the largest uncertainty in estimates of the Earth's complex and changing energy budget.



We had a Solar-C team meeting at MPS (Göttingen, Germany) in September 2024 and an instrument science team meeting in the summer. Our instrument – the solar spectral irradiance monitor – has made great progress this year. The engineering model is shown on the right. Our instrument will provide the full Sun irradiance at a sub-second time cadence to understand what drives solar flares and measure solar irradiance that impacts the Earth's thermosphere and the mesosphere.


One PhD student successfully defended their theses: Andrea Battaglia on 'The rising STIX era: new insights on microflares and early flare emission'.

Congratulations!



We have 7 instruments operational in space – we continue to operate them and plan coordinated science campaigns with other missions and telescopes on the ground. Solar Orbiter observed the largest solar flare of the current cycle on 21 May 2024 when it was behind the Sun. The active region was the source of the aurora seen across Switzerland, as nicely captured by the PMOD/WRC cloud camera (on the right).

*"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. The students we teach are enthusiastic, smart and very engaged – thanks to them too."*

*Louise Harra*

*(PMOD/WRC Director 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

**63**

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

**86**

Number of PhD students with PMOD/WRC supervisor

**11**

Industry collaborations (e.g. collaborations on hardware)

**43**

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

**24**

Number of lecture courses PMOD/WRC staff are involved in

**5**

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

**15**

International collaborations (users, research and government organisations)

**105**

Participation in national and international commissions, editorial boards

**57**

Number of employees

**48**

Number of calibrations (number of Instruments)

**227**

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

**21**

# 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) Organisation

The former Quality Manager and long-time PMOD/WRC employee, Silvio Koller, retired on 31 July 2024. In his role as Quality Manager, Silvio made a significant contribution to the continuous development of the Quality Management System (QMS; Figure 1) at PMOD/WRC. Even after handing over the role of Quality Manager to Ricco Soder in 2019, he continued to support the QMS and provided advice and assistance as a deputy.

The integration of the WORCC section into the scope of ISO 17025 had been under consideration for some time and a gradual implementation began in 2024.

### ii) Activities

*Continuous Improvement* - Under the leadership of a review group, all QM-relevant feedback is processed in a structured manner at a monthly meeting and implementation progress is tracked. The feedback comes equally from internal employees and customers. This is an important pillar of the continuous development process.

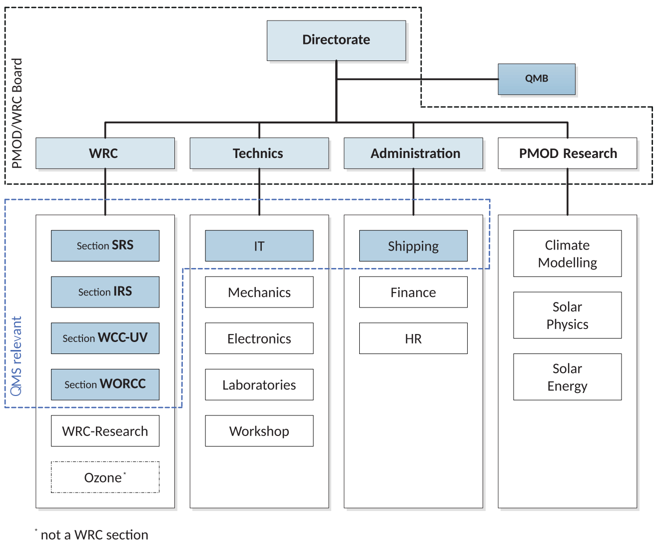



*Figure 1. Organisational chart of the PMOD/WRC Quality Management System (QMS). QMB = Qualitätsmanagementbeauftragte/r or Quality Management Officer. The WRC Solar Radiometry Section (SRS), the World Calibration Center for UV (WCC-UV), the Infrared Section (IRS) and the World Optical Research and Calibration Center (WORCC) perform calibrations according to the EN ISO/IEC 17025 standard (shown in blue).*

The existing QM documentation is also regularly checked to ensure that it is up-to-date and adapted if necessary.

*Auditing* - In addition, internal audits are systematically planned and carried out to ensure that the existing processes are validated and meet the requirements of the standard. In 2024, a technical audit was successfully carried out in the UV section and the suitability of the newly introduced data backup system was also reviewed.

*Intercomparison* - Participation in international measurement comparisons is another important requirement for the four calibration sections and serves, among other things, to validate their own measurement infrastructure. In 2024, the employees of the WRC sections successfully participated in eight international measurement campaigns.

*Education* - In order to maintain the quality of the services offered at the best possible level, training requirements are systematically identified and carried out in consultation with the respective employees.

### iii) Infrastructure

All calibration sections continued to work on the further development of their infrastructure in 2024, and implemented improvements through numerous projects.

After the new data backup system was adapted to the particular requirements of the calibration sections, planned and implemented by the IT department, this comprehensive project was successfully reviewed and completed in 2024.

### iv) Calibration and Measurement Capabilities (CMCs)

There have been no changes this year, either in terms of number or content. The two WRC sections, SRS and UV, still have eight individual CMCs in the database.

## Calibration Services

The number of calibrated items continues to show annual fluctuations in the individual sections, which is also reflected in the total number. As a result, demand for the calibration services offered by PMOD/WRC remains at a high level compared to the last 18 years and slightly increased to a total of 227 items for 2024 (Table 1 and Figure 2).

Looking at the development of the number of calibrated items per section (Table 1), it can be seen that both the IR and SRS sections recorded a slight increase last year. In contrast, the demand for calibrations in the other sections fell slightly.

*Table 1. Statistics of instrument calibrations at PMOD/WRC in 2024. WRC = World Radiation Center, SRS = Solar Radiometry Section, WCC-UV = World Calibration Center for UV, and WORCC = World Optical depth Research and Calibration Center .*

| Section | Type of instrument | Number of calibrated instruments | Change to previous year |
|---|---|---|---|
| WRC-SRS | Pyrheliometer | 25 | +5 |
| | Pyranometer | 102 | +21 |
| WRC-IR | Pyrgeometer | 37 | +7 |
| | IRIS | 1 | +1 |
| WCC-UV | UV broadband radiometer | 19 | -5 |
| | Spectroradiometer vs. QASUME | 1 | -2 |
| | UV lamps, diodes & spectroradiometer | 31 | -3 |
| WORCC | Sun-photometer (PFR & others) | 11 | -11 |
| | PSR | 0 | -5 |
| Total | | 227 | |

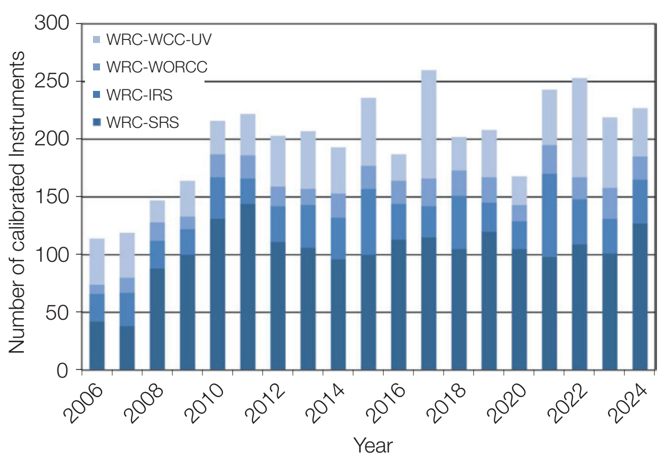



*Figure 2. Statistics of instrument calibrations at PMOD/WRC for the 2006 - 2024 period.*

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

## Instrument Sales

In 2024, customers continued to buy new-generation Precision Filter Radiometers (PFR19) for long-term measurements of the Aerosol Optical Depth. Five PFR19, one IRIS radiometer and two Ventilation Heating Unit (VHS) were sold (Figure 3). 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.

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.

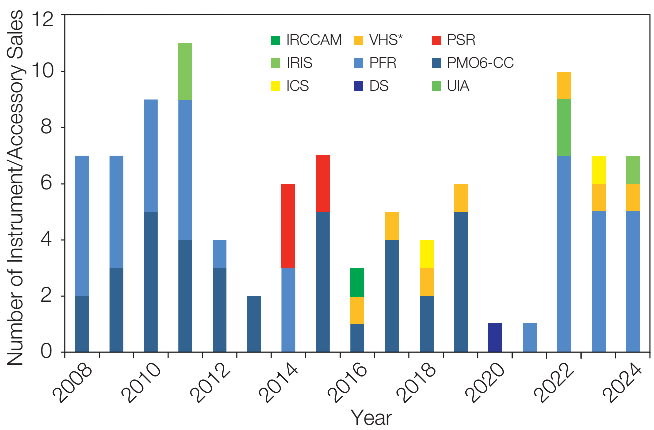



*Figure 3. Number of PMOD/WRC instrument sales from 2008 up to and including 2024: i) IRCCAM = Infrared Cloud Camera, ii) VHS = Ventilation Heating System, iii) PSR = Precision Spectroradiometer, iv) IRIS = Infrared Integrating Sphere Radiometer, v) PFR = Precision Filter Radiometer, vi) PMO6-CC = absolute 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; 2024 = 2.*

## 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 2024, the SRS participated in the National Pyrheliometer Comparison in the United States. The SRS also operates the ISO 17025 certified calibration laboratory for solar radiometers (pyrheliometers and pyranometers). The demand for calibration services has increased by 24 % compared to 2023.

In 2024, the SRS calibrated 127 solar radiometers: Theses consisted of six absolute pyrheliometers, 102 pyranometers, and 19 field pyrheliometers. This is a significant increase in the number of calibrated radiometers compared to the previous year.

The WSG was operated on 81 days. The Cryogenic Solar Absolute Radiometer (CSAR) was disassembled to re-determine the reflectivity of the cavity and to upgrade the thermo-mechanical design of the cooling chain and radiation shields.

In August, an insect had to be removed from the pyrheliometer F201-007A, which belongs to the travelling standard group. The insect not only affected the absorptivity of the sensor but also dislodged a soldering joint on the thermistor. The pyrheliometer was repaired by the technical department and then re-calibrated against the WRR. The WRR factor changed slightly by 160 ppm compared to IPC-XIII, which can be explained by the new soldering joint.

From 21 - 27 September, WRC-SRS participated in the National Pyrheliometer Comparison (NPC-2024), which was organised by the National Renewable Energy Laboratory (NREL) in Golden, USA. The newly-built travelling hardware was successfully used for the first time at the NPC-2024. This new setup consists of new universal mounting brackets for installing pyrheliometers on a mobile solar tracker and a shipping crate with built-in controllers for the travelling standard group, including power supply and data interface. The NPC-2024 report confirms the small shift of the pyrheliometer F201-007A and the stability of other members of the travelling standard group.

CSAR was disassembled to re-characterise the cavity reflectance and to install new heat links and thermistors. Functional tests of the re-assembled CSAR were successfully performed in December. The new heat links allow CSAR to be operated at lower temperatures than before. The temperature stability of the reference block was also improved by better damping of temperature fluctuations from the cryo-cooler (see separate article).

References: Reda, I., Andreas, A., Stoddard, M., Weyer, B., Jaker, S., Habte, A.: 2024, NREL Pyrheliometer Comparisons: September 21-27, 2024 (NPC-2024), NREL/TP-1900-91550, https://www.nrel.gov/docs/fy25osti/91550.pdf

*Figure 1. The WRC-SRS technician is installing the four travelling standard group pyrheliometers on the mobile solar tracker at NREL, using the new mounting brackets. The pyrheliometers on the left belong to the German Weather Service, DWD.*

## 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 an 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 PMOD/WRC roof platform. 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 2024. As can be seen, the long-term stability of the WISG is very satisfying, with measurements that are within ±1 $Wm^{-2}$ over more than 20 years.

The second workshop on the operation and evaluation of the Absolute Cavity Pyrgeometer (ACP) took place on 15 February 2024 at the Deutsche Wetterdienst (Lindenberg, Germany) with the participation of international experts. The workshop discussed current measurements, calibration procedures and the required steps towards the establishment of the ACP as a future absolute reference for atmospheric downwelling longwave irradiance, which is in support of the ongoing activities of the WMO expert team on radiation references (ET-RR). A sharepoint was created to host ACP datasets from the different groups operating these radiometers and to allow their analysis by interested experts.

A new series of IRIS radiometers was commissioned in 2023 and the first full year of operation in 2024 demonstrated good consistency between the IRIS radiometers (using the criteria defined in Gröbner and Wacker, 2015). As shown in Figure 2, the expanded uncertainty at the 95% confidence level of the weighted mean average of the IRIS radiometers for the year 2024 is 0.91 $Wm^{-2}$.

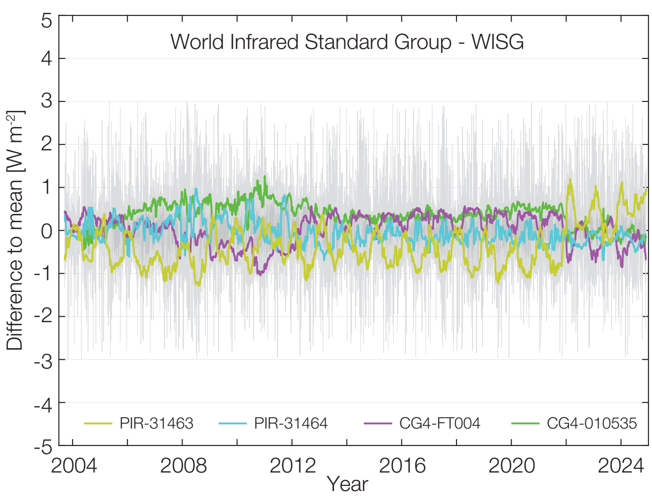



*Figure 1. Night-time atmospheric longwave measurements of the WISG pyrgeometers relative to their average. The coloured lines represent a 30-day running mean of each WISG pyrgeometer, while the grey-shaded area represents daily averages.*

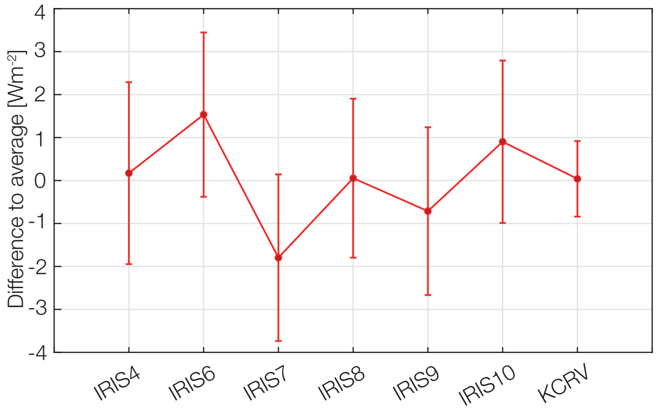



*Figure 2. Weighted average and expanded uncertainties (95% confidence interval) of the IRIS radiometers during 2024. The Key Comparison Reference Value (KCRV) represents the weighted average of the IRIS radiometers and its error bar, the expanded uncertainty.*

This uncertainty was obtained by taking into account the correlated and uncorrelated uncertainty components of the IRIS radiometers. These IRIS radiometers (of which one was sold to the Deutsche Wetterdienst) will be used to provide the atmospheric longwave irradiance reference for the planned redefinition of the WISG during the upcoming IPgC-IV, which is planned for September to October 2025. The comparison of the WISG with this weighted average IRIS reference on cloud-free nights during the year 2024, yielded a difference of -4.75 $Wm^{-2}$, the WISG measuring lower irradiances than the IRIS, with an expanded uncertainty of 1.1 $Wm^{-2}$.

PMOD/WRC took part in a field campaign held at NREL (Golden, Colorado, US) from 23 September to 4 October 2024 to compare atmospheric downwelling longwave irradiance measurements between the ACP, IRIS and pyrgeometers traceable to the WISG.

### Publications in 2024

Gröbner, J., Thomann, C., Reda, I., Turner, D. D., Feierabend, M., Monte, C., McComisky, A., Reiniger, M.: 2024, Traceability of surface longwave irradiance measurements to SI using the IRIS radiometers, AIP Conf. Proc., 18 Jan. 2024, 2988 (1), 070001, https://doi.org/10.1063/5.0183304

Nyeki, S., Gröbner, J., Vuilleumier, L., Lanconelli, C., Driemel, A., Knap, W., Maturilli, M., Ohkawara, N., Riihimaki, L., Schmithüsen, H.: 2024, Extending the calibration traceability of longwave radiation time-series (ExTrac), AIP Conf. Proc., 18 Jan. 2024, 2988 (1), 060011, https://doi.org/10.1063/5.0183543

Vuilleumier, L., Nyeki, S., Gröbner, J., Aebi, C., Collaud Coen, M.: 2024, Thermal infrared radiation trends in Switzerland, AIP Conf. Proc., 18 Jan. 2024, 2988 (1), 060003, https://doi.org/10.1063/5.0183492

References: Gröbner, J., Wacker, S.: 2015, Pyrgeometer Calibration Procedure at the PMOD/WRC-IRS, IOM 120, WMO, https://library.wmo.int/index.php?lvl=notice_display&id=18511#.Y4YSnBTMLe8

## 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 that serve as the reference for Aerosol Optical Depth (AOD) measurements within WMO. WORCC also operates the global Global Atmosphere Watch - Precision Filter Radiometer (GAW-PFR) AOD network and collaborates with other global aerosol networks. WORCC has participated in a number of projects and activities related to the homogenization of global aerosol networks, SI-traceable AOD retrievals, aerosol measurement and processes analysis, and capacity building activities based on WMO-GAW goals.

The World Optical depth Research and Calibration Center (WORCC) calibration hierarchy uses the WORCC reference. This reference is based on the average of three (triad) well-maintained Precision Filter Radiometers (PFRs) that are located at Davos, Switzerland. In addition, instruments operating at high mountain stations such as Mauna Loa (USA) and Izaña (Tenerife, Spain) are performing Langley calibrations, and are then sent (one instrument every six months) to WORCC/Davos to check the PFR-Triad stability using an independent instrument. No changes were introduced to the triad data in 2024 after using/comparing the Langley transfer-related measurements.

Annual quality assured data from GAW-PFR stations were updated and submitted to WDCA. In 2024, five instruments from the GAW-PFR network and 14 customer instruments, part of the extended GAW-PFR and MeteoSwiss networks, were calibrated against the GAW-PFR Triad reference. WORCC calibration documentation has been prepared and the WORCC calibration activities will be included in the ISO 17025 Quality Management system of PMOD/WRC as of 1 January 2025.

WORCC is participating in ACTRIS-CARS (Aerosols, Clouds, and Trace gases Research Infrastructure Network; Center for Aerosol Remote Sensing) through the ACTRIS-CH project (https://www.actris.ch). This provides a permanent traceability link between the ACTRIS AOD measurements and the WMO primary AOD reference. During 2024, three PFR instruments were operated at Valladolid (Spain), OHP (France) and Izaña (Spain). In May, the ACTRIS community met in Rennes (France) for the ACTRIS Science Conference 2024. Results on long-term aerosol comparisons, long-range transported aerosols from wildfire episodes reaching Switzerland and Greece, and Lunar PFR measurements were presented. The ACTRIS-Switzerland annual meeting was held at PMOD/WRC in Davos in August.

Within the Quality Assurance Framework for Earth Observation (QA4EO) ESA project, WORCC scientists have been collaborating with Serco (CNR, Italy), the University of Innsbruck (Austria) and the National Observatory of Athens (Greece). The aim was the investigation of algorithms for cloud detection and flagging for real-time AOD and $NO_2$ measurements when calculating AOD. The main results showed the potential of a synergy of different sun-photometers and spectroradiometers for improving the related algorithms.

The lunar activities of WORCC include the continuous monitoring of AOD during the polar winter with the Lunar-PFR (Mazzola et al., 2024). The traceability of the PFR irradiance is maintained through calibration at PTB (Germany) in August 2024 (EURAMET collaboration project), A synergetic use of the PFR and QASUME spectroradiometer lunar irradiance measurements, provides additional data for the evaluation of existing lunar irradiance models.

WORCC is participating in various projects on: i) aerosol-cloud-radiation interactions (CERTAINTY, https://certainty-aci.eu/), ii) validation of the Earth Care satellite mission products (Race ECV), iii) knowledge transfer (Excelsior and Atari), and iv) dust optical properties and effects on solar radiation (Marie Curie Dust Doctoral Network, https://dust-dn.cyi.ac.cy/). Also, WORCC members participated in several publications related to: i) the WORCC/SkyNet homogenisation of AOD measurements (Campanelli et al.; 2024; Karanikolas et al., 2024), ii) on a study of radiative effects of dust optical properties (Fountoulakis et al., 2024), and iii) on the impact of the $NO_2$ contribution to AOD measurements at several sites worldwide (Masoom et al., 2024).

WORCC results and overviews have been presented in various workshops and meetings. Such meetings included the Scientific Aerosol group for Aerosols and the Expert team of Atmospheric Composition Measurement Quality. These 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 also 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. There was one Master Thesis and one semester project related with aerosol research as a collaboration of WORCC and ETHZ.

References:

Campanelli, M., et al.: 2024, Evaluation of on-site calibration procedures for SKYNET Prede POM sun–sky photometers, Atmos. Meas. Tech., 17, 5029-5050, https://doi.org/10.5194/amt-17-5029-2024

Fountoulakis, I., et al.: 2024, A sensitivity study on radiative effects due to the parameterization of dust optical properties in models, Atmos. Chem. Phys., 24, 4915-4948, https://doi.org/10.5194/acp-24-4915-2024

Karanikolas, A., et al.: 2024, Intercomparison of aerosol optical depth retrievals from GAW-PFR and SKYNET sun photometer networks and the effect of calibration, Atmos. Meas. Tech., 17, 6085-6105, https://doi.org/10.5194/amt-17-6085-2024

Masoom, A., et al.: 2024, Assessment of the impact of $NO_2$ contribution on aerosol-optical-depth measurements at several sites worldwide, Atmos. Meas. Tech., 17, 5525-5549, https://doi.org/10.5194/amt-17-5525-2024

Mazzola, M., et al.: 2024, Atmos. Res., https://doi.org/10.1016/j.atmosres.2024.107667

## 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.

In 2024, our transportable reference spectroradiometer QASUME was used for four site audits in Europe. Between May and June, we travelled to three stations in Germany and Austria. Starting with the audit at the Universität für Bodenkultur (BOKU) in Vienna, we continued with a visit to the Meteorologisches Observatorium (DWD) in Lindenberg and finished with the audit at Bundesamt für Strahlungsschutz (BFS) in Munich. In August, the last visit in 2024 was to Kirchbichl in Austria. This station is operated by the Institute of Biomedical Physics of the Medical University Innsbruck.

During the 19th Regional Brewer Calibration Campaign-Europe (RBCCE), which was held at PMOD/WRC, QASUME provided the global solar UV irradiance reference for the participating six Brewer spectrophotometers. Results from all the QASUME site audits and campaign reports can be found at the WCC-UV website, https://www.pmodwrc.ch/en/world-radiation-center-2/wcc-uv/qasume-site-audits.

The upgrade of the UV data acquisition system on the PMOD/WRC roof platform was finished in Nov. 2024. Two new dataloggers allow the logging of up to 55 radiometers. In addition, digital interface (modbus) type radiometers can be connected directly on the roof panels.

The three European Partnership in Metrology (EPM) projects continued in 2024:

• **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.

*Figure 1. The QASUME site audit to BFS (Munich, Germany). The intercomparison campaign lasted from 3 May to 7 June 2024. The data from three of the four BTS spectroradiometers (left) were compared to Qasume. It's entrance optic can be seen on the right of the picture.*

*Figure 2. Site visit to the UV monitoring station in BOKU near Vienna (Grossenzersdorf, Austria).*

*Figure 3. The 19th RBCCE at Davos (Switzerland) with the participating six Brewer spectroradiometers.*

• **S-Cale Up**: Self-calibrating photodiodes for UV and exploitation of induced junction technology.

The interaction with the consortium partners maintains and strengthens our close ties to the metrology community and will extend and improve the traceability of our UV radiometer and spectroradiometer calibrations to SI.

The QASUME spectroradiometer also measured direct spectral solar irradiance using a collimating tube during cloud-free conditions at PMOD/WRC. These measurements were used to retrieve the total ozone column and spectral aerosol optical depth following the procedures described in Egli et al. (2022) and Gröbner et al. (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

Gröbner, J., Kouremeti, N., Hülsen, et al.: 2023: Spectral aerosol optical depth from SI-traceable spectral solar irradiance measurements, Atmos. Meas. Tech., 16, 4667-4680, https://doi.org/10.5194/amt-16-4667-2023

## Section Ozone: Total Column Ozone and Umkehr Measurements

*Luca Egli, Franz Zeilinger and Julian Gröbner*

Operational total column ozone and Umkehr measurements are conducted at PMOD/WRC using three Dobson and four Brewer spectrophotometers to monitor the stratospheric ozone content and extend the Arosa-Davos ozone time-series, measuring since 1926. These instruments are operated on behalf of MeteoSwiss and exploited together with MeteoSwiss as part of the Swiss contribution to the WMO Global Atmosphere Watch programme. In 2024, the Brewers and the Dobsons were calibrated by the Dobson reference instrument (D064) from the regional Dobson calibration center Europe (Hohenpeissenberg, Germany) as well as the reference Brewer (B185) from the World Brewer calibration center (Izaña, Tenerife, Spain). In addition, the intercomparison of Brewer and Dobson instruments, and four BiTec Sensor (BTS) - Solar units from Gigahertz GmbH were tested against Brewer 185.

The Arosa-Davos time-series stems from three Brewers (B040, B072, B156) and three Dobsons (D051, D062, D101), which measure total column ozone (TCO) and vertical ozone profiles (Umkehr). Dobson D051 primarily performs Umkehr measurements but is used occasionally for direct sun observations to compare with D101 and D062, forming a triad for stability checks. On a monthly basis, all Dobsons measure total column ozone from sunrise to sunset to identify airmass biases, while weekly, they perform Umkehr measurements for ozone profile cross-validation. The six instruments, forming the official Arosa-Davos time-series, are operated continuously at PMOD/WRC and have a ±1 % agreement in TCO, ensuring a high-quality continuation of the long-term times-series starting in 1926. Remarkably, the annual mean TCO of 2024 shows a value which is about +4 % higher (~13 DU) than the 11-year running mean up to 2024 or the average TCO between 2000 and 2024 (Figure 1).

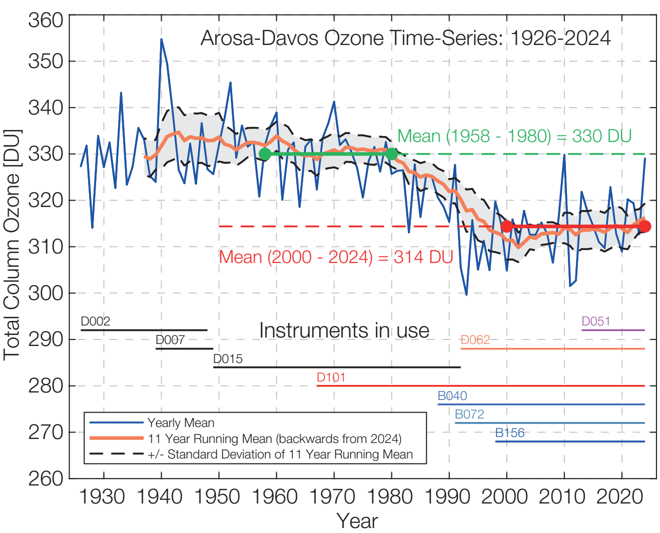



*Figure 1. Total column ozone (TCO) time-series from 1926 to 2024. In 2024, TCO of about 13 DU (~4 %) higher than the long-term average TCO between 2000 and 2024 was recorded.*

*Figure 2. Two operators of the manual reference Dobsons, from the Regional Dobson Calibration Center Europe (RDCC-E), are performing measurements in the PMOD/WRC measurement garden. In the background are the Brewers participating in the regional Brewer intercomparison, held at the same time as the Dobson intercomparison.*

From 19 - 29 Aug. 2024, the Regional Dobson Calibration Center for Europe (RDCC-E) visited PMOD/WRC for the first time. The regional Dobson reference instrument (D064) from DWD (Deutscher Wetterdienst, Hohenpeissenberg, Germany) was shipped to Davos to perform manual TCO measurements for comparison with the three automated Dobsons from the Arosa/Davos triad. The DWD operators (Figure 2) also performed hardware quality checks, and technical maintenance recalibration of optical parts of all three Arosa/Davos Dobsons. The results of the comparison revealed that a recalibration of the past data is not required and that all three Dobsons are in good agreement with the reference (D064) (relative difference in TCO smaller than 1 %). The intercomparison confirmed the long-term stability of the Arosa-Davos Dobson triad.

In conjunction with the RDCC-E, the Regional Brewer Calibration Center for Europe (RBCC-E) campaign was held at PMOD/WRC. As in 2022, the RBCC-E travelling reference instrument (B185) from the Izaña Atmos. Research Center (Tenerife, Spain) provided reference measurements for TCO. Alongside B185 and the four Davos Brewers (including B163 from PMOD/WRC), participants included one Brewer from DWD (Hohenpeissenberg), two Brewers from Ott HydroMet (Delft, Netherlands) and one from BOKU-Met (Austria). The Arosa-Davos Brewer instruments performed excellently, requiring no maintenance. Comparisons with the European Brewer reference (B185) showed that all instruments measured TCO within ±1%. In addition to the intercomparison of Brewer and Dobson instruments, four BTS-Solar instruments (from Gigahertz GmbH) were compared with the reference Brewer 185. TCO derived from the BTS by a custom-made algorithm (Egli et al., 2023) agreed well with B185. A task team was established by the WMO scientific advisory group for ozone and UV (SAG O3UV) to investigate the performance of such a BTS system and the new algorithm, in view of validating it as a potential network instrument for TCO monitoring.

References: Egli, L., et al.: 2023, Total column ozone retrieval from a novel array spectroradiometer, AMT, 16, 2889-2902, https://doi.org/10.5194/amt-16-2889-2023

# Instrument Development

## 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 seven 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. The latest launch of PROBA-3 in December 2024 brings the number of operational instruments up to seven.

The Total Solar Irradiance (TSI) is an essential climate variable and PMOD/WRC has been measuring TSI from various space missions since the early 1990s (Figure 1). We currently operate four TSI radiometers in space, of which two actively produce data. Because of degraded attitude control of the NorSat-1 spacecraft the CLARA can no longer point at the Sun accurately but still measures Outgoing Longwave Radiation (OLR) on the night side of the Earth. The recently launched DARA on PROBA-3 is still in commissioning phase and will start to measure TSI soon.

### VIRGO Onboard SOHO

The VIRGO experiment onboard the SOHO spacecraft has been providing total and spectral solar irradiance measurements almost continuously since February 1996. Degradation of the radiometric sensors is regularly assessed and corrected to update the VIRGO and composite TSI data products (eg Figure 1) on the Astromat open archive at: https://doi.org/10.60520/IEDA/113532

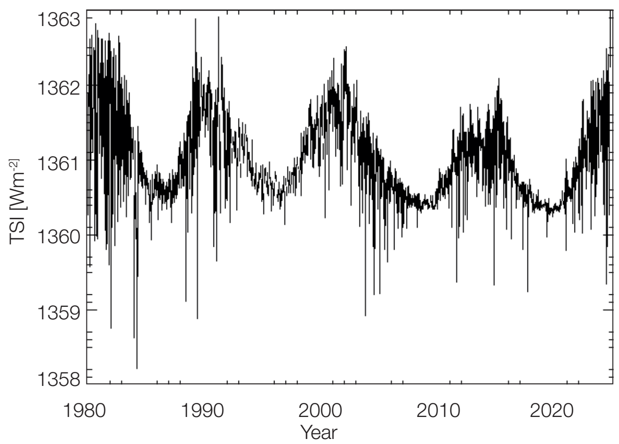



*Figure 1. This TSI composite uses data fusion to combine the measurements from various space missions.*

### CLARA Onboard NorSat-1

Due to the degraded attitude control of the NorSat-1 spacecraft, CLARA was not able to continue TSI measurements in September 2023, although the radiometer was and still is healthy and operating well. Despite this issue, the terrestrial OLR measurements continue with CLARA. Over the year, the CLARA team has been continuously in contact with the Norwegian Space Operation Center (Statsat) to discuss the issues with the gyration wheels. Also, the data exchange was continuously monitored, and steps were taken as needed.

*The TSI data pipeline*

The quality of the CLARA TSI data was further improved. We implemented a modified degradation correction by Finsterle et al. (2021). The latest version of the CLARA TSI is shown in Figure 2 in comparison with the TSIS-1 and VIRGO data. The absolute level of CLARA TSI is in very good with the TSIS-1 measurements. Generally, CLARA shows a slightly higher variability from the beginning of 2020 to mid 2021.

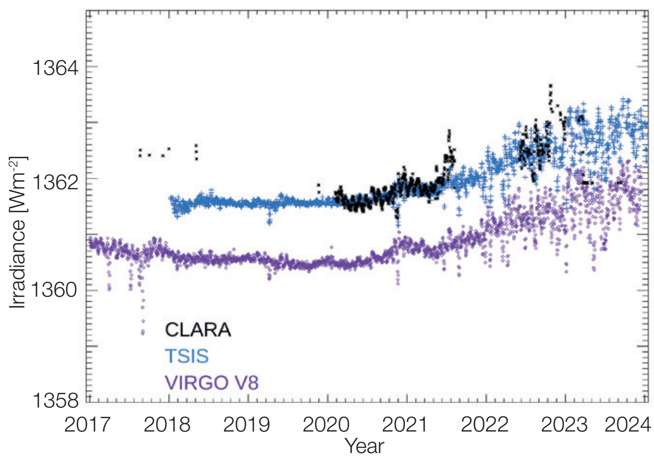



*Figure 2. Latest version of the CLARA TSI time-series (black) compared to the TSIS (blue) and VIRGO TSI (violet). All datasets are shown at the absolute scale and with daily resolution. Adapted from Haberreiter et al. (2025).*

*The OLR data pipeline*

Despite the issues with the solar pointing in 2023, the CLARA OLR measurements continue. We have been working on improving the data pipeline of the CLARA OLR data. Also, the latest update of the TSI degradation correction is being implemented in the OLR pipeline. The latest OLR data release is currently in progress.

## JTSIM-DARA Onboard FY-3E

The DARA on the Chinese FY-3E satellite has been providing regular TSI measurements since August 2021, although some operational challenges stlll had to be resolved in 2024. The normalisation of TSI to 1 astronomical unit (AU) required additional information to be transferred from the China Meteorological Administration (CMA), who operates the spacecraft.

The radiative losses of the cavity sensor to deep space have been re-modelled to further improve the TSI observations. The new models are currently being tested and validated against TSI measurements from other missions. The DARA/FY-3E TSI data product (JTSIM-DARAv1) is published on the:

PMOD/WRC website: https://www.pmodwrc.ch/en/research-development/space/fy-3e

ASTROMAT repository: https://repo.astromat.org

```
0:        0 --> Report ID :   9 --> RSR: 0x80
0:        0 --> Report ID :  19 --> DARA PROBA3 FM 4.10
0:        0 --> Report ID :  18 --> <Application Mode>
0: 2852124 --> Report ID :  56 --> [  OK  ] MRAMDRIVEMOUNT: mounting mram drive (a:) passed
0: 9563004 --> Report ID :  43 --> [  OK  ] FILESYSTEM: write/read test passed
0:10569636 --> Report ID :  75 --> [  OK  ] PARAMETERSETLOAD: loading parameter set file a:/default.prs passed
0:10569636 --> Report ID :  92 --> [  OK  ] PARAMETERSETCREATE: creating parameter set skipped as file a:/default.prs was found
1:16609428 --> Report ID :  24 --> [  OK  ] ROM: CRC passed
1:16609428 --> Report ID :  38 --> [  OK  ] SCLOCK: initialization passed
2:        0 --> Report ID :  45 --> [  OK  ] SHUTTERLOGGER: initialization passed
2: 5536476 --> Report ID :  67 --> [  OK  ] shutter: delay configuration loaded from file and verified
4:10905180 --> Report ID :  50 --> [  OK  ] SHUTTER: communication/motion test passed
4:12582900 --> Report ID :  60 --> [  OK  ] AD7710ERRORCOMMUNICATION: communication test passed
4:12582900 --> Report ID : 108 --> [  OK  ] AD7710ERRORCALIBRATION: loading calibration values skipped as file a:/ad7710Error.cal was not found
5: 3523212 --> Report ID :  68 --> [  OK  ] AD7710ERRORSELFCALIBRATIONCH0: self calibration ch=0 passed
5:11240724 --> Report ID :  68 --> [  OK  ] AD7710ERRORSELFCALIBRATIONCH1: self calibration ch=1 passed
5:13421760 --> Report ID :  62 --> [  OK  ] AD7710SCIENCECOMMUNICATION: communication test passed
5:13421760 --> Report ID : 112 --> [  OK  ] AD7710SCIENCECALIBRATION: loading calibration values skipped as file a:/ad7710Science.cal was not found
6: 4865388 --> Report ID :  70 --> [  OK  ] AD7710SCIENCESELFCALIBRATIONCH0: self calibration ch=0 passed
6:12918444 --> Report ID :  70 --> [  OK  ] AD7710SCIENCESELFCALIBRATIONCH1: self calibration ch=1 passed
6:13086216 --> Report ID :  39 --> [  OK  ] ADC128S: initialization passed
6:13086216 --> Report ID :  42 --> [  OK  ] AD5791: communication test passed
6:13253988 --> Report ID :  43 --> [  OK  ] DAC121S: communication test passed
6:13253988 --> Report ID :  35 --> [  OK  ] LUD: initialization passed
6:13253988 --> Report ID :  41 --> [  OK  ] SQUARE750: initialization passed
6:13421760 --> Report ID :  55 --> [  OK  ] BATCH: startup batch file a:/default.bat found
6:13421760 --> Report ID :  28 --> batch a:/default.bat started
```

*Figure 4. First data from DARA.*

Ten days later, we successfully powered-up DARA for the first time using a tele-command sent from the operations center in Belgium. DARA booted-up normally and completed all automatic tests without any issues. See Figure 4 for a read-out of the first data. DARA is currently being commissioned for TSI operations, and all mission and instrument parameters are nominal.

## DARA Onboard PROBA-3

The PROBA-3 mission consists of two spacecraft that will fly in close and precise formation (~150 m separation) to form an externally occulted coronograph. DARA is installed on the Occulter Spacecraft to measure Total Solar Irradiance (TSI) from this unique vantage point. 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 3; see next page). Employees from PMOD/WRC participated in the integration and alignment campaign at REDWIRE Space (Belgium).

From the time of integration to the delivery of the spacecraft to the launch site in India, all necessary environmental tests were successfully completed. These tests included vibration tests, thermal balance tests, shock tests, and thermal cycle tests. After each test, technical health checks were conducted on DARA, all of which confirmed that the instrument remained undamaged.

On 4 November 2025, PROBA-3 and its payloads departed from Liège (Belgium), bound for Chennai (India). Several additional tests were conducted in Chennai, including verifying that the satellite fitted correctly within the payload fairing of the launch vehicle. By mid-November, the satellite's hydrazine tanks were refilled. In the final week of November, after completing further tests, the two satellites were stacked and integrated into the launch vehicle. After a brief one-day delay, PROBA-3 mission was successfully launched on 5 December 2024 by the Indian Space Research Organisation’s (ISRO) commercial branch NewSpace India Limited (NSIL) from the Sriharikota launch base on Satish Dhawan Space Centre (SDSC).

## 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 (solar imaging, spectroscopy, and photospheric magnetic field) and four in-situ instruments that measure the 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), and the Spectral Imager of the Coronal Environment (SPICE) instrument. EUI and SPICE provide imaging and spectroscopy data, respectively. Solar Orbiter observations are divided into observation campaigns, which are periods where the spacecraft`s instruments focus on the same scientific goal. The operations support for EUI and SPICE on Solar Orbiter is provided by ESA Prodex.

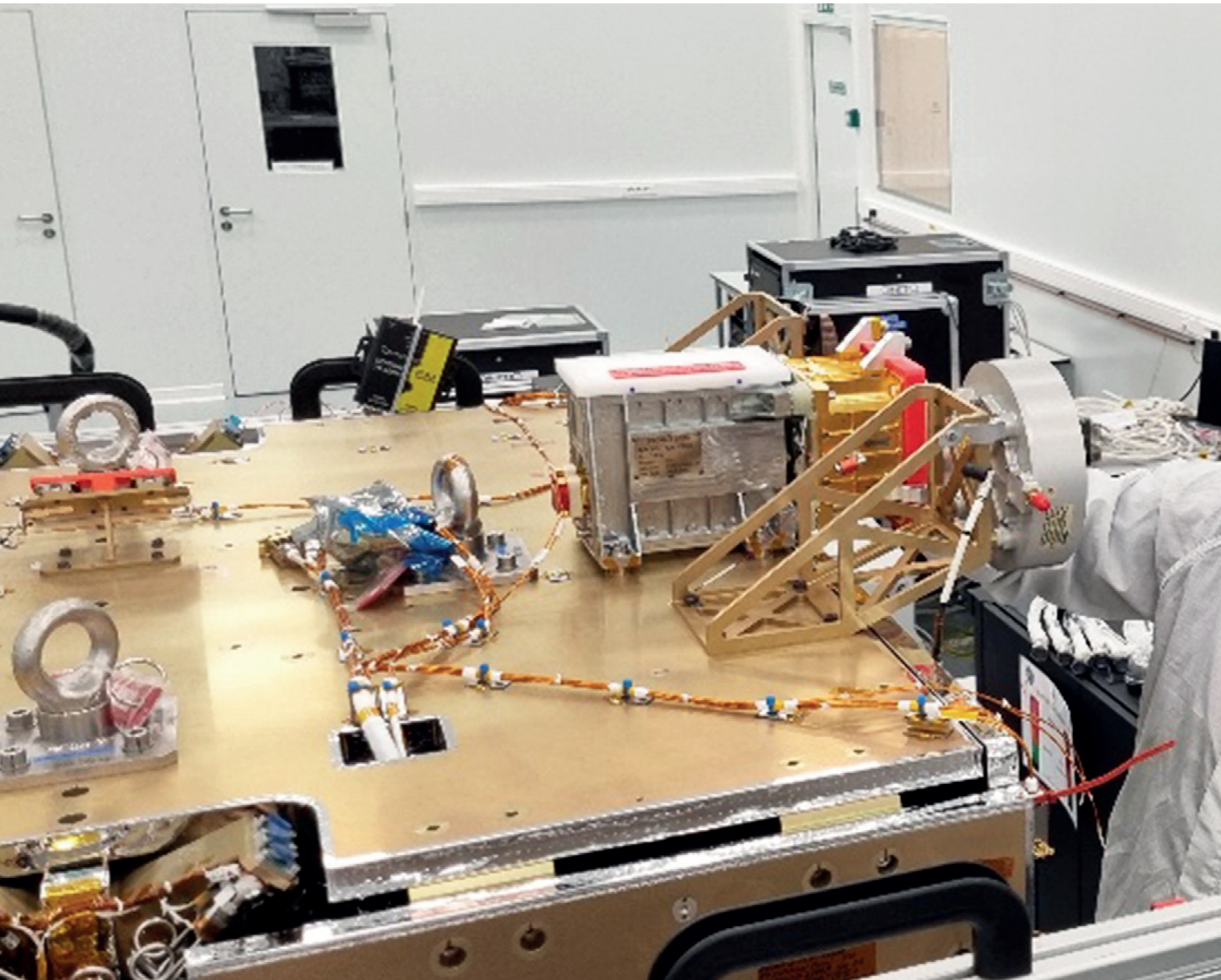
We provide assessment of the data return for EUI and SPICE. For EUI, we check that the campaign was carried out correctly. We use a semi-automatic code to compare the EUI expected observations and the EUI obtained observations for completeness. A visual inspection of the EUI data is performed, which 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 visual inspection.

We coordinated the Solar Orbiter Observing Plan (SOOP) for Long-Term Planning (LTP) from 6 - 9 April 2024. The scientific goal was to observe the Sun during the Solar Orbiter quadrature with respect to Earth. During the SOOP, a total solar eclipse was observed from Earth. We used the observation plan:

L_FULL_HRES_HCAD_Eruption-Watch. All expected observations from this campaign were obtained successfully.

Solar Orbiter provides simultaneous observations with Earth-orbiting and ground-based telescopes. In October 2024 a coordinated campaign was run between Solar Orbiter and the Earth-orbiting satellites: Interface Region Imaging Spectrometer (IRIS) and Hinode; as well as the ground based-telescope - Daniel K. Inouye Solar Telescope (DKIST). The aims of this coordinated observation were to study the active region (Figure 4) and the plasma upflow regions at the border of active regions. The Solar Orbiter, IRIS and Hinode coordinated observation was successful. However, DKIST did not observe due to bad weather condition in Hawaii. We are preparing the next coordinated observation campaign for April 2025.

To scientifically exploit overlapping observations between Solar Orbiter instruments and other observatories (in space and on the ground), it is important to provide a systematic overview of Solar Orbiter observations to the scientific community. Toward this goal, we developed a field-of-view (FOV) visualisation tool for the SPICE spectrometer. This tool is publicly released and has been updated to include data throughout 2024. In contrast to the EUI Full Sun Imager (EUI/FSI), SPICE only observes a small part of the Sun providing spectral information. The FOV tool allows other researchers quick-look access to find out the pointing of SPICE at the time of scientific interest. Its user-friendliness has been improved and it now contains more detailed study parameters at a glance. A detailed user tutorial has been added online. In Figure 5, we show the FOVs of several SPICE calibration and science measurements obtained on 16 April 2024. The SPICE FOVs are overlaid over the EUI/FSI 174Å images.



To gain an overview of solar events, such as flares and coronal mass ejections with potentially related energetic particle emission, a working group from several instruments compiles a catalogue of these events over the course of the Solar Orbiter mission. This catalogue serves as a starting point for combined case studies with several instruments and as a comprehensive basis for statistical event studies. With respect to EUI, we continuously update the event list together with the Energetic Particle Detector (EPD), the Spectrometer / Telescope for Imaging X-Ray (STIX), and Radio and Plasma Wave (RPW) instrument teams. We provide information about the EUI data availability, observation time, image cadence, and the approximate position of solar flares. The list currently contains (January 2025) more than 580 flare-associated events observed between November 2020 and November 2024 with EUI, EPD, STIX, and RPW.

In 2024, the systematic study of so-called cosmic ray (CR) particle hits on the EUI/FSI sensor continued. The overall damage from the CRs is small compared to previous solar missions, which is mostly due to the sensor`s location behind the Solar Orbiter heat shield and the use of more robust CMOS detector technology.

We have also started to study minor CR events where the hits do not fully saturate the sensor pixels. This might be due to secondary particle showers that can be created in the spacecraft or instrument shielding and a detailed investigation is ongoing. The results of these studies help to assess the expected impact of CRs for the future JEDI instrument onboard the upcoming ESA Vigil mission, which is built with contributions from PMOD/WRC.

*Figure 3. Integration of DARA onto the PROBA-3, Occulter Spacecraft. Image shows Daniel Pfiffner, PMOD/WRC.*

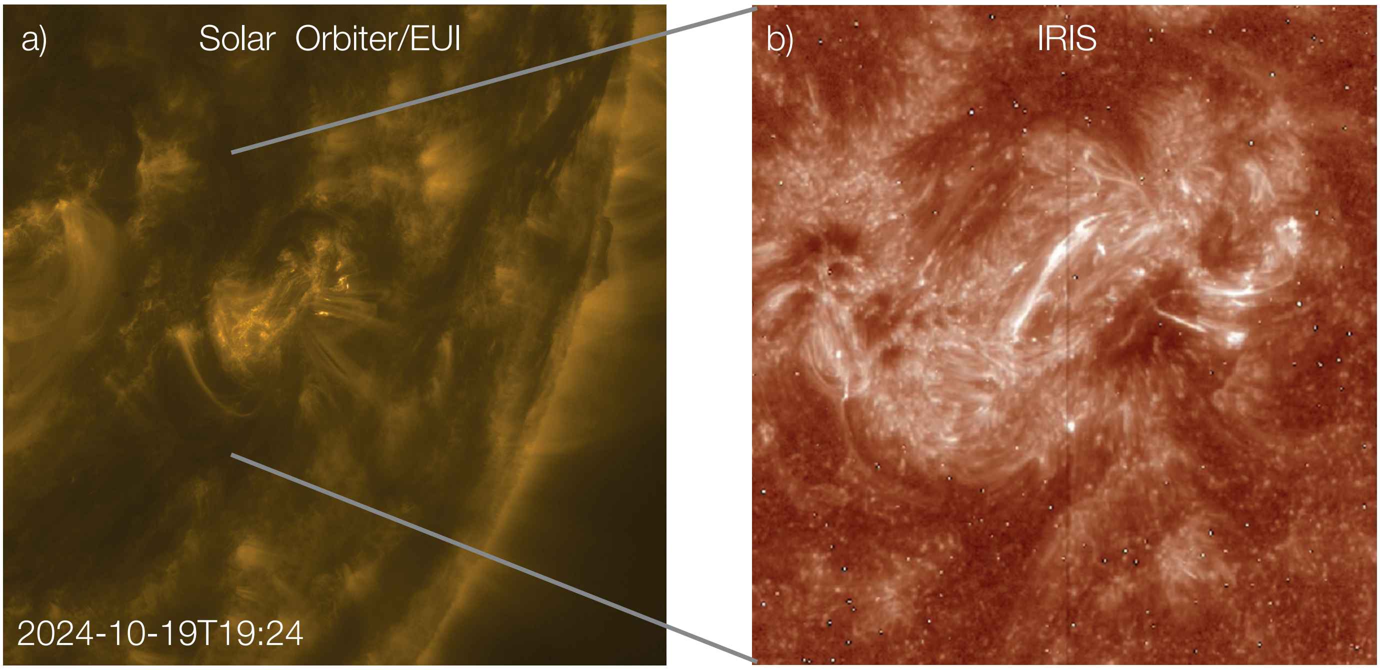



*Figure 4. Example of solar atmosphere images obtained during coordinated observations between: left panel a) Solar Orbiter, and right panel b) IRIS. Images show observations from an active region obtained from two vantage points separated by 23°.*

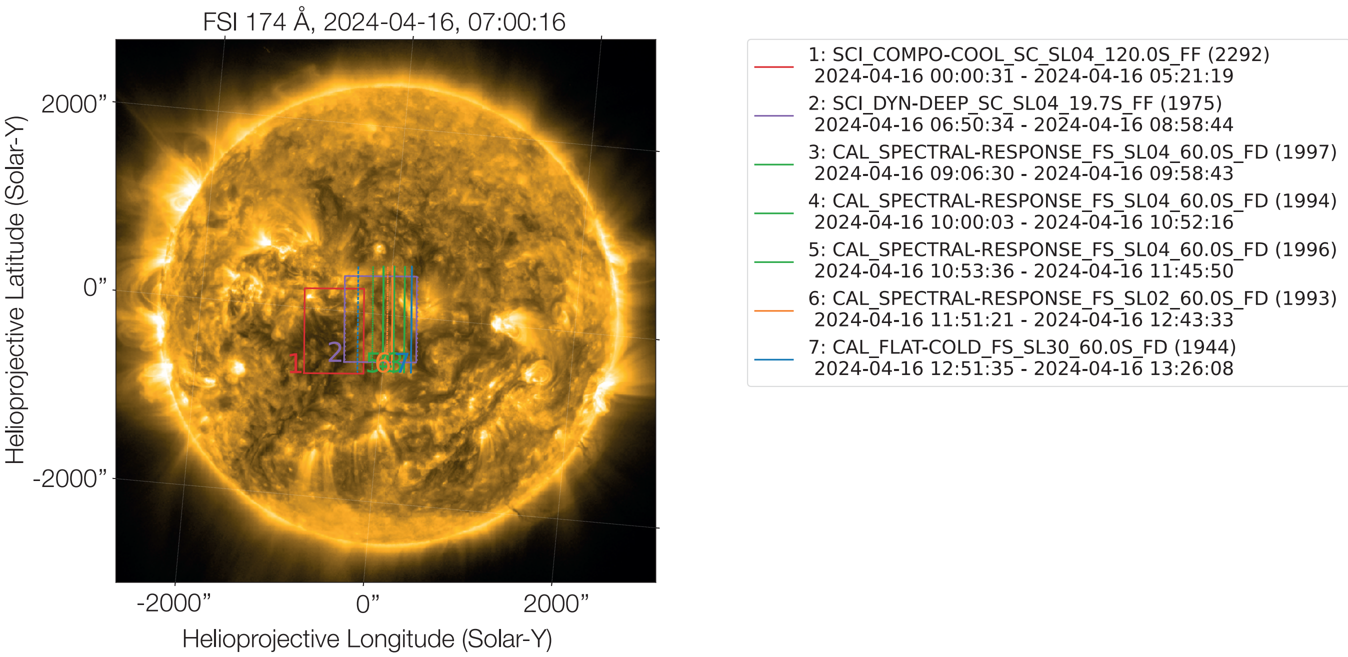



*Figure 5. Example output of the SPICE FOV visualisation tool for coordinating remote-sensing observations with the Solar Orbiter spacecraft. The field-of-views (FOVs) of the SPICE spectrometer for several scientific and calibration measurements on 16 April 2024 are overlaid over a full-sun image of the EUI-FSI instrument in the 174 Å channel.*

## Space Missions in the Build Phase

*Krzysztof Barczynski, Valeria Büchel, Wolfgang Finsterle, Etienne de Coulon, Manfred Gyo, Louise Harra, Nils Janitzek, Silvio Koller, Patrik Langer, Leandro Meier, Andri Morandi, Daniel Pffifner, Florian Reinhard, Marcel Spescha, Pascal Schlatter and Oliver Schwahofer*

PMOD/WRC is involved in four Space missions at different design and development stages up to finalisation. Vigil is ESA's space weather mission at the L5 Lagrange point. In May 2024, our instrument team was selected for the NASA contribution to the first ESA space weather mission, Vigil. Our instrument, the Joint EUV coronal Diagnostic Investigation, or JEDI, will capture images of the Sun in extreme ultraviolet light to understand and predict solar eruptions on the Sun. We will 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. We are part of the competitive phase A study for a mission to Mars – we are developing our spectral irradiance concept for understanding space weather at Mars. The mission is called M-Matisse.

### Vigil – ESA's first space weather mission

Over the last years, PMOD/WRC has been involved in the development of front-end electronics for an EUV Imager on ESA's first space weather mission (originally called Lagrange and now Vigil; Figure 1). We were funded to carry out pre-development work on the electronics and this work was completed during 2024. NASA announced a Focused Mission of Opportunity (FMO) investigation for a remote sensing extreme ultraviolet (EUV) imager instrument to be hosted on ESA's Vigil mission. The proposal selected in May 2024 is the EUV coronal Diagnostic Investigation (JEDI) led by Don Hassler from the Southwest Research Institute (SwRI; Boulder, USA). JEDI will capture images of the Sun in extreme ultraviolet light, which will distinctly observe the Sun's activity. The instrument design builds on years of experience of EUV imagers within the team including the most recent one – the EUV Imagers onboard the Solar Orbiter mission.

JEDI has two telescopes – one of which will focus on the middle layer of the solar corona, a region of the Sun's atmosphere that plays a key role in creating the solar wind and solar eruptions that cause space weather. The other telescope provides 24/7 coverage of the EUV solar activity.

The Vigil space mission is planned to launch in 2031. It will be an operational space weather mission, with a goal to monitor the Sun from its unique position at the 5$^{th}$ Lagrange point of the Sun-Earth system. This is a gravitationally stable point about 60° degrees behind the Earth in its orbit, allowing early warning of solar storms that are most impactful to the Earth and its critical infrastructure. This will give scientists a trove of new data for research, while simultaneously supporting Vigil's ability to monitor space weather.

PMOD/WRC is responsible for the development of the front-end electronics in the project, working closely with Centre Spatial de Liège (CSL; Belgium), which is responsible for the characterisation of the Active Pixel Sensor (APS). This collaboration is crucial as the camera forms the core of the telescope. Following a successful de-risking in 2024, which established a solid foundation, significant advancements have been made in the development of the front-end electronics and for the entire JEDI instrument during Phase A2/B. Progress has been made by a collaborative engineering effort with SwRI. This included defining the most critical requirements and the detailed development of the entire electro-mechanical and thermal interfaces with the telescope.

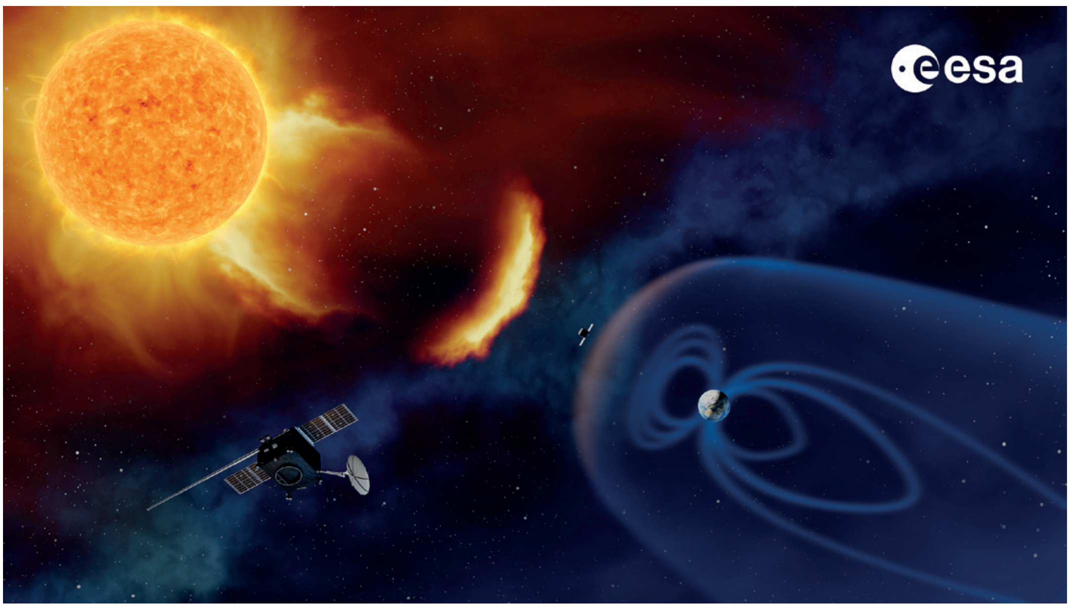



*Figure 1. Artistic illustration of the future Vigil mission. The Vigil spacecraft observing the Sun from the 5$^{th}$ Lagrange point (L5) in Space, is shown in the foreground. The Solar and Heliospheric Observatory (SOHO), on which PMOD/WRC have the VIRGO instrument, is located at L1 (not shown). Image courtesy of ESA.*

## CSAR (Cryogenic Solar Absolute Radiometer) Onboard TRUTHS

The Cryogenic Solar Absolute Radiometer (CSAR) onboard the ESA TRUTHS mission will measure the Total Solar Irradiance with unprecedented accuracy and do in-orbit calibration of the Hyperspectral Imaging Spectrometer, allowing SI-traceable hyperspectral images of the Earth to be taken. The launch is planned for 2030.

Phase B2 kicked-off at the beginning of 2024, which is dedicated to designing and building a prototype (breadboard) of the instrument to demonstrate the technology in a relevant environment. PMOD/WRC, as part of the Swiss consortium led by Thales Alenia Space Switzerland, designed, manufactured, and assembled the majority of the measurement block as well as the front-end electronics (FEE). The rest of the consortium (Thales Alenia Space Switzerland & Micos Engineering GmbH, Switzerland) was in charge of the breadboard cryostat and the precision apertures with the cover-plate that they are mounted on. Tests on the prototype instrument will be performed in the first quarter of 2025, and will culminate in a Preliminary Design Review (PDR) at the end of the year.

*Figure 2. Rear view of a TRUTHS CSAR cavity assembly prototype.*

Progress was made at PMOD/WRC in the area of: i) machining thin-walled absorbing black bodies, which are coated with carbon-nanotubes (Figure 2), ii) manufacturing cryogenic temperature sensors out of ultra-thin copper wire (ten meters of wire with a thickness of less than a quarter of a human hair), and iv) SI-traceable electrical power measuring electronics that will be able to fly on a satellite.

## SoSpIM 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 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 (JAXA) 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 together. 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. SoSpIM is funded by the Swiss Space Office through ESA Prodex.

The Preliminary Design Review (PDR) of SoSpIM was successfully completed in November 2023. Since then, extensive work has been carried out on the Engineering Model (EM; see Figure 3) with thermal and electromagnetic compatibility tests completed.

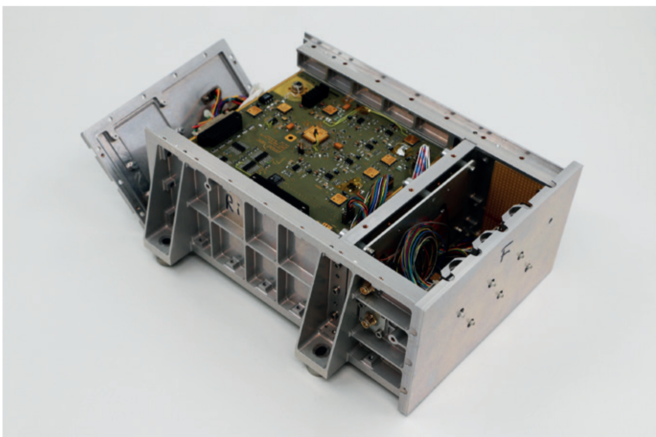


*Figure 3. The SoSpIM engineering model (EM) with the electronic boards integrated into the housing.*

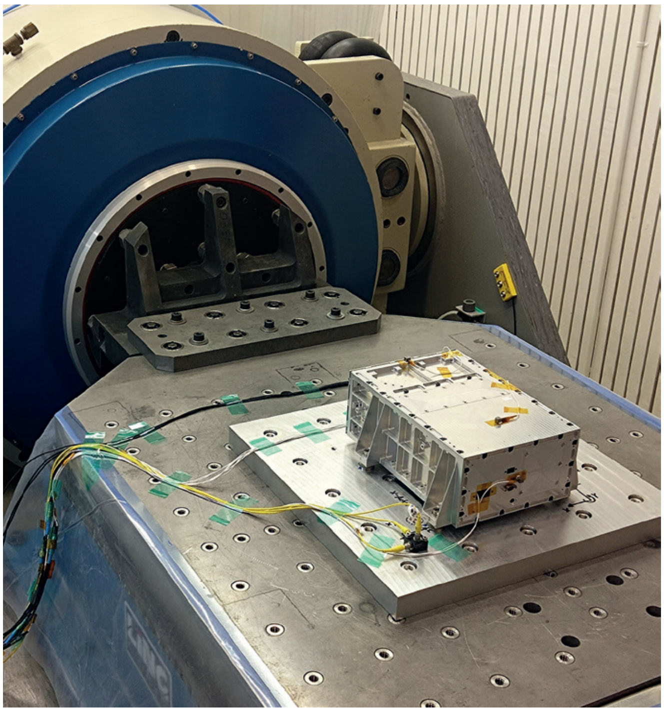


*Figure 4. Test setup of the SoSpIM Structural Thermal Model on the vibration shaker.*

An extensive electrical testing campaign over the year yielded valuable results for the development of the Qualification Model (QM). The EM is set to join the Communication & Interface Test Campaign in Japan with the EUVST Telescope Electronics Box (TEB) in May 2025.

The Structural Thermal Model was manufactured and fully assembled in-house at PMOD/WRC. Its structural integrity was confirmed through a vibration test (Figure 4), and its optical path stability was tested under thermo-elastic loads.

The SoSpIM instrument development is a collaborative effort involving three Swiss industrial partners and the Royal Observatory of Belgium (ROB; Belgium). Dlab GmbH (Switzerland) is tasked with developing the controller board and necessary firmware and electrical ground support equipment (EGSE) nanoTRONIC AG (Switzerland) is advancing the power supply, and MICOS Engineering GmbH (Switzerland) is designing and manufacturing the protective cover and shutter mechanism. ROB is integral in the scientific collaboration, selecting EUV and Lyman-alpha filters and detectors, which were characterised at the Physikalisch-Technische Bundesanstalt (PTB; Germany).

## M-Matisse – a Solar Spectral Irradiance Monitor for Mars (M-SoSpIM)

The M-Matisse mission is the Mars Magnetosphere ATmosphere Ionosphere and Surface SciencE space mission (Figure 5). This will investigate the global dynamic response of the Martian plasma-atmosphere system to space weather activity with observations from two spacecraft.

Our instrument, M-SoSpIM, will be on each spacecraft. M-Matisse would shed light on how the solar wind influences Mars's atmosphere, ionosphere and magnetosphere. The mission aims to investigate the impact of these interactions on Mars's lower atmosphere and surface, which is a key aspect to understand the Red Planet's habitability, as well as the evolution of its atmosphere and climate.

M-Matisse is led by Beatriz Sanchez-Cano from the University of Leicester (UK) and has collaborations across Europe to develop the payloads. ESA made the selection of three potential medium class missions at the end of 2023. M-Matisse is one of these and is now in a competitive phase-A study. During this phase-A study the missions teams work with the two potential spacecraft prime partners. One candidate M-class mission will be chosen by ESA in 2026.

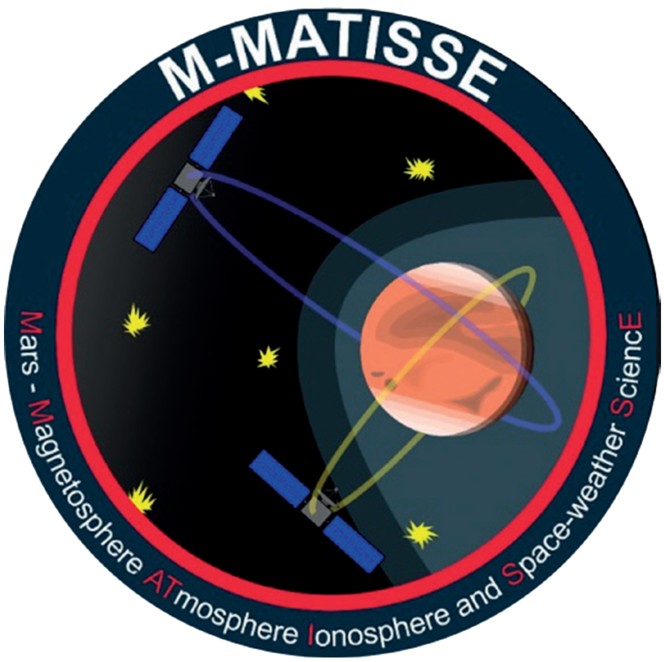



*Figure 5. The M-Matisse logo.*

# Upgrades and Characterisation of the Cryogenic Solar Absolute Radiometer and the WSG 2.0 Concept

*Wolfgang Finsterle, Natalia Engler and Ricco Soder*

PMOD/WRC has been operating the Cryogenic Solar Absolute Radiometer (CSAR) since 2010. CSAR is a core component of the planned redefinition of the World Radiometric Reference (WRR) and plays a crucial role in the so-called WSG 2.0 strategic plan. In order to meet the performance requirements for this purpose, the thermo-mechanical design of the CSAR was reviewed and upgrades were implemented to improve the temperature stability and reliability of the cooling chain.

## The Cryogenic Solar Absolute Radiometer (CSAR)

CSAR was designed and built by the National Physical Laboratory (NPL, England), the Federal Institute of Metrology (METAS, Switzerland) and PMOD/WRC, and has been operated at PMOD/WRC since 2010. It participated in three International Pyrheliometer Comparisons (IPCs) in 2010, 2015, and 2021. The WMO Expert Team on Radiation References (ET-RR) recommends a redefinition of the World Radiometric Reference (WRR) based on CSAR. In support of these plans PMOD/WRC has developed the WSG 2.0 strategic plan.

## The WSG 2.0 Concept and Strategy

The WRR is defined as the average reading of a group of pyrheliometers, the so-called World Standard Group (WSG). This scale definition based on artefacts without a fully established uncertainty budget is not compatible with modern concepts of metrological traceability. CSAR is directly comparable to the SI primary standards for radiant power, and the uncertainty budget was established in 2012 (Winkler, 2012) and revised in 2024 (Fig. 1; Table 1; publication in preparation). After implementation of the new WRR scale, based on CSAR, the WSG pyrheliometers will be calibrated against CSAR on a regular basis as they continue to serve as working references for calibrating field pyrheliometers and pyranometers. The implementation of this so-called WSG 2.0 concept is supported by the WMO expert team on radiation references (WMO ET-RR) and planned to be complete before the 15th International Pyrheliometer Comparison (IPC-XV, 2030).

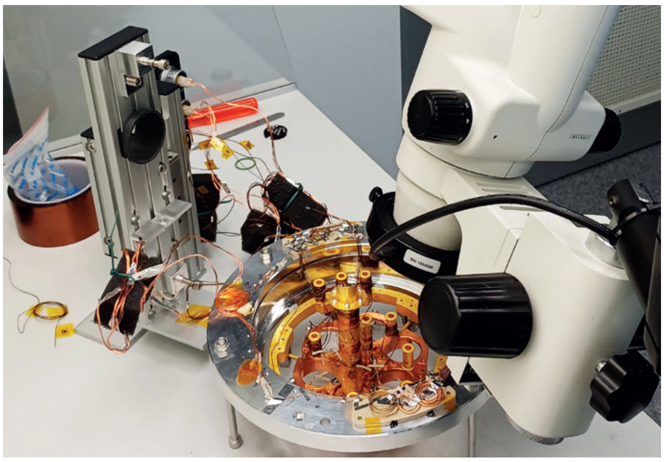


*Figure 1. The CSAR reference block in the clean-room during re-wiring of the thermistors and preparation for re-characterisation of the cavity absorptance.*

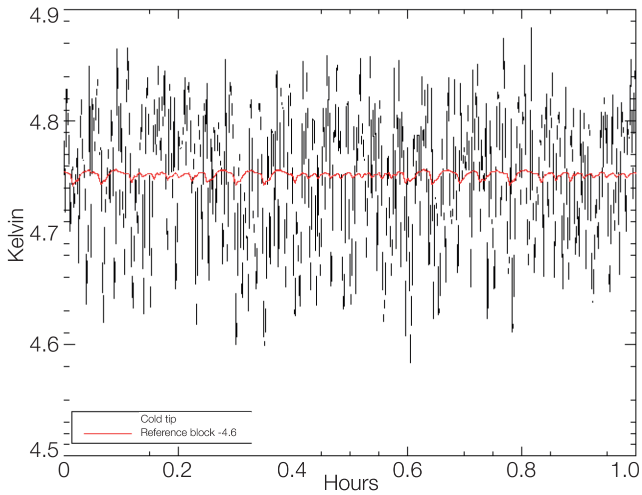



*Figure 2. The temperature of the cold tip fluctuates with the frequency of the mechanical cooler. The re-designed Pb-block in the cooling chain reduces the oscillations of the reference block temperature by an order of magnitude. The periodically occurring oscillations of the reference block are due to the slow read-out of the thermistors (~2 s per thermistor), which limits the bandwidth of the active temperature control-loop. We are currently investigating the possibilities to switch to a faster temperature readout scheme without reducing the measurement accuracy. Slightly increasing the reference block temperature to ~25 K would also help as it lowers the thermal response time of the reference block.*

## Thermo-Mechanical Upgrades of CSAR

The cooling capacity of the original cooling chain (thermal links between the 1st and 2nd stage cooler on one side, and the reference block and intermediate stage cryostat on the other side) suffered from degradation after a few thermal cycles. Re-tightening of the connections required disassembling of CSAR. To avoid this tedious and risky procedure, we redesigned the cooling chain with customised thermal links (Cu braids), a new Pb-block to reduce temperature oscillations (Fig. 2), and spring-loaded bolts on all thermal interfaces. The bolts on the thermal interface are accessible (e.g. for tightening) via a port on the vacuum tank. At the same time, the modularity of the set-up was improved and now allows the CSAR radiometer unit to be removed from the vacuum tank without being disassembled.

*Table 1. The reflectivity of the CSAR cavity was measured at four wavelengths in the visible and near infrared. The results confirm the original characterisation.*

| Wavelength [nm] | 532 | 808 | 1064 | 1550 |
|---|---|---|---|---|
| Reflectivity [ppm] | 40 | 70 | 190 | 250 |

Acknowledgement: We thank the Karbacher Foundation for the funding of the work presented in this article.

References: Winkler, R.: 2012, Cryogenic Solar Absolute Radiometer – A potential SI standard for Solar Irradiance, PhD thesis Univ. College London, https://core.ac.uk/download/pdf/17187322.pdf

# 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 and solar imaging.

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: 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 2024, 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, EURAMET and the Simons Fondation. These funding sources supported 11 PhD thesis projects (eight of these at ETH and three students based at other universities and jointly supervised), three post-doctoral positions, four instrument scientists, and partially several senior 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. ESA Prodex also funds the operations of our space instruments.

In the area of climate modelling, the research studies both long and short-term changes in the Earth's atmosphere, driven by the solar, volcanic, and anthropogenic influences. Solar scenarios for the Sun range from the current day Sun to the highly active and quiet modes. Studies of volcanic activity effects included the recent Hunga Tonga-Hunga Ha'apai event as well as a historical satellite-based dataset preparation. The ozone layer evolution is being modelled and predicted. In addition, work is proceeding on understanding outgoing radiation at the top of the Earth's atmosphere using data from the NorSat-1 CLARA mission. A new important research direction has recently started, focusing on the risks of potential future solar radiation management scenarios.

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 and 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 intercomparisons in 2024, acting as a reference for atmospheric longwave irradiance, total solar irradiance, spectral solar UV irradiance and aerosol optical depth.

We collaborated with a number of departments at ETH ( D-PHYS, D-USYS, D-CHAB, D-ERDW, D-INFK), resulting in 18 students carrying out projects with us. This includes the ETH studio Davos in collaboration with Lab-42 and departments in ETH covering environmental science, physics, informatics, and engineering.

The research carried out at PMOD/WRC is intertwined with 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, reaching more than 28,000. There are now over 800 refereed publications.

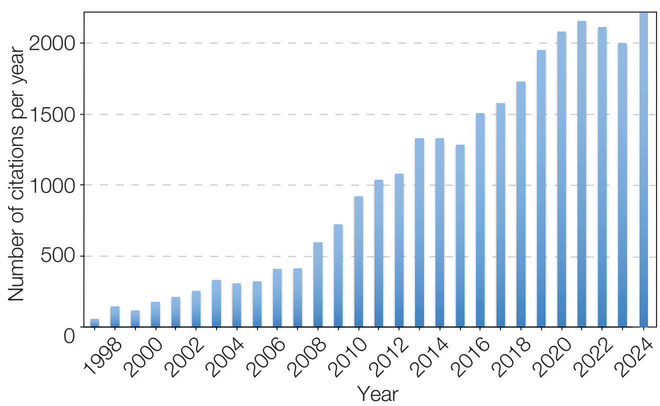



Figure 1. Number of annual citations to articles including an author with a PMOD/WRC affiliation. In January 2025, there were 28,400 citations to 815 articles included in Thomson Reuter's Web of Science. The articles were selected using the search criteria address = (World Rad* C*) OR (PMOD* NOT PMOD Technol* OR pmodak) OR (Phys* Met* Obs*).

## First coordinated observations between Solar Orbiter and the Daniel K. Inouye Solar Telescope (DKIST)

*Krzysztof Barczynski, Louise Harra, Yingjie Zhu, and collaborators from Solar Orbiter and the DKIST Team*

Solar Orbiter and the Daniel K. Inouye Solar Telescope (DKIST) are two of the newest facilities available to the solar physics community. In October 2022, we conducted the first coordinated solar observations with these facilities. The data collected open new possibilities for observing solar features never seen before and for studying their physics. Our observations focus on an active region.

Active regions are the most dynamic structures on the solar disk. They contain numerous features with a wide range of sizes and lifetimes. The evolution of an active region over different timescales, the role of small-scale structures within the active region, and the processes responsible for plasma upflow at the active region's border, remain open issues.

The main aim of our study was to address these open questions using high-resolution observations of the solar atmosphere obtained from various vantage points. We carried out coordinated observations of an active region using the Solar Orbiter spacecraft and the ground-based Daniel K. Inouye Solar Telescope (DKIST) for the first time. Solar Orbiter is a multi-instrument spacecraft launched in February 2020, which orbits the Sun.

Solar Orbiter is an ESA mission in collaboration with NASA. It provides high spatial and temporal resolution data, including imaging, spectroscopy, magnetic field measurements, and in-situ data of solar wind plasma conditions measured at the spacecraft. DKIST is a four-meter diameter ground-based telescope, the largest dedicated to solar observation, located in Hawaii, US. Its multi-instrument design allows for imaging, spectroscopy, and magnetic field data collection with the highest spatial resolution ever achieved.

We observed the active region in October 2022. Solar Orbiter and DKIST were positioned with an angle of separation between 52° and 72° with respect to the Sun (Figure 1), allowing a stereoscopic view. Instruments onboard Solar Orbiter and DKIST provide unprecedented high-spatial and temporal simultaneous observations of the active region, from the photosphere to the corona (Figure 2). Coordinated high-resolution observations were successfully conducted at several distinct times over the week. Despite the active region itself being in an advanced decayed phase, a range of interesting features is evident in the sampled data. As such, a variety of research topics can be advanced using these observations. We focus on three specific topics as representative examples:

- Coronal loop physics.
- The formation and evolution of small-scale active region brightenings.
- Coronal rain dynamics.

The results of the first coordinated observations between Solar Orbiter and DKIST were summarised in Barczynski et al. (2025, in prep) and presented during the European Solar Online Seminar (https://science-media.org/video/356). The detailed analysis of the mentioned event is an ongoing task of the International Space Science Institute group entitled "Active Region Evolution Under the Spotlight, with Unprecedented Coordinated High-Resolution Stereoscopic Observations and Numerical Simulations," led by Krzysztof Barczynski. The PMOD/WRC team continued coordinated observations between DKIST and Solar Orbiter in October 2023 and plans to conduct the next coordinated observations in 2025.

Acknowledgement: Solar Orbiter is a mission of international cooperation between ESA and NASA, operated by ESA. The research reported herein is based in part on data collected with DKIST, a facility of the National Science Foundation. DKIST is operated by the National Solar Observatory under a cooperative agreement with the Association of Universities for Research in Astronomy, Inc. DKIST is located on land of spiritual and cultural significance to Native Hawaiian people.

References: Barczynski, K., Janvier, M., et al.: 2025, First coordinated observations between Solar Orbiter and the Daniel K. Inouye Solar Telescope, in prep.

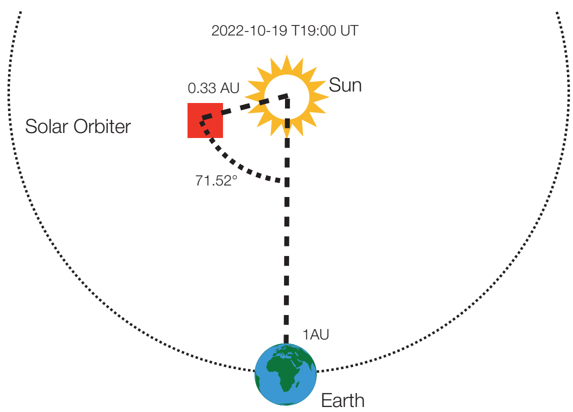



*Figure 1. The relative positions of the Solar Orbiter spacecraft, the Earth and the Sun during coordinated observations between Solar Orbiter and DKIST on 19 October 2022.*

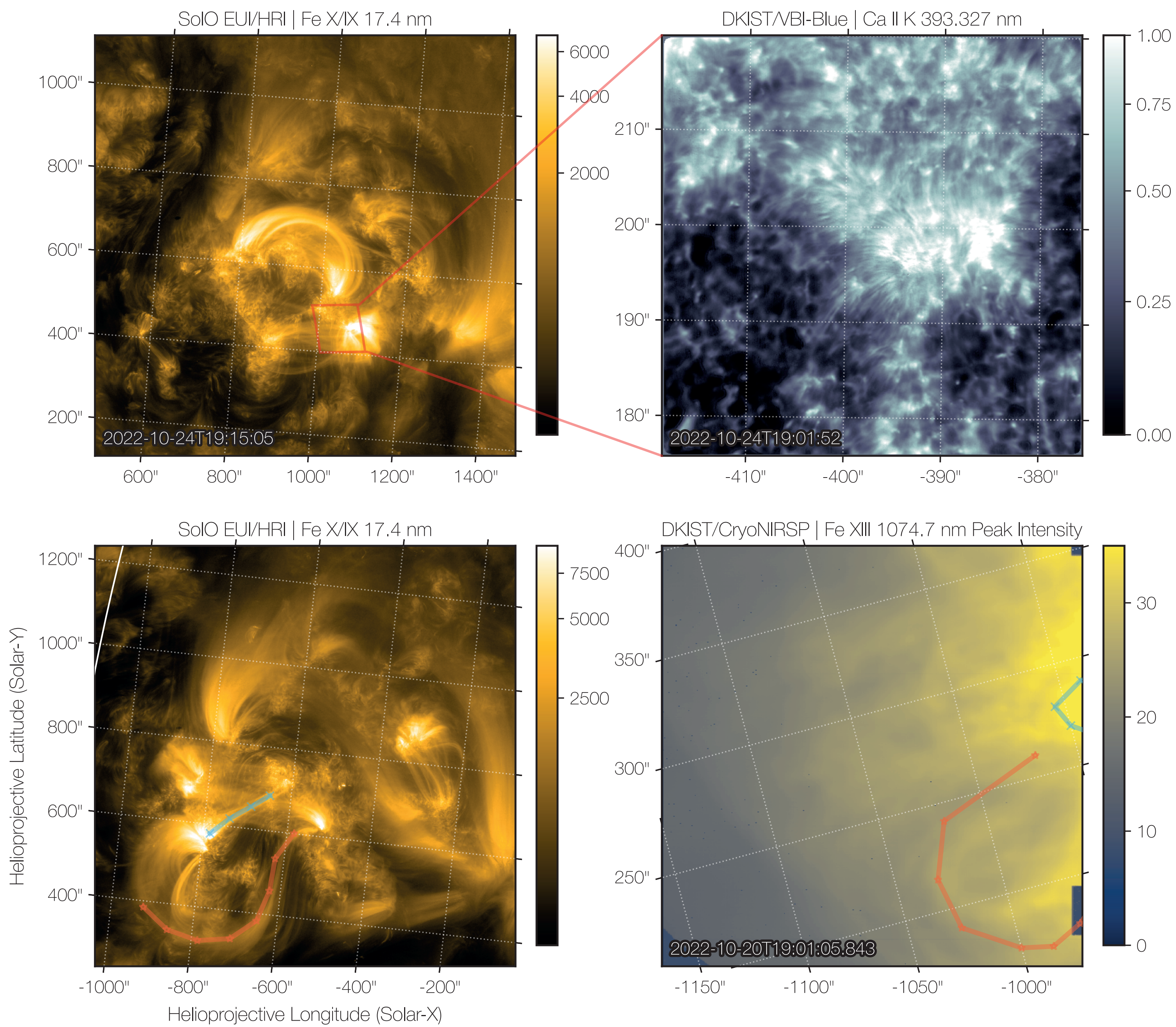



*Figure 2. The stereoscopic observation of an active region, obtained during coordinated observations between Solar Orbiter (left panels) and DKIST (right panels). The upper panels show the small-scale structures observed with Solar Orbiter/ Extreme-Ultraviolet Imager and DKIST/ Visible Broadband Imager. The bottom panels show the loops system observed with stereoscopic view with Solar Orbiter/ Extreme-Ultraviolet Imager and DKIST/ Cryogenic Near-IR Spectro-Polarimeter (Cryo-NIRSP). The red and green lines in the bottom panels highlight the corresponding loops.*

## Understanding the Relationship between Solar Flares and Energetic Particles

*Nils Janitzek, Fabian Kistler, Louise Harra, Krzysztof Barczynski and Yingjie Zhu*

Eruptions on the Sun often produce high energy electrons and ions that can be associated with solar flares or coronal mass ejections. These so-called solar energetic particles (SEPs) are a major aspect of space weather because they can cause radiation hazards to astronauts and damage to spacecraft and impacts on the ground. The exact mechanism of particle acceleration and release in solar flares is still under investigation, which makes it challenging to predict such SEP events in time and size. Based on data from the ESA/NASA Solar Orbiter mission, we conducted case studies and statistical analysis of solar flares and related SEP events to improve our understanding of the physical relation between the two phenomena.

The Solar Orbiter spacecraft was launched in 2020 and travels to the Sun at distances as close as 0.3 AU (30 % of the distance between Earth and Sun). It carries ten instruments for imaging the Sun and exploring the plasma environment in the inner solar system. The Spectrometer/Telescope for Imaging X-rays (STIX) measures hard X-rays that originate from solar flares. As shown in Figure 1, these can be associated with the outflow of high-energy electrons from the Sun, which cause characteristic radio emission (known as Type-III bursts) and are measured with the Radio and Plasma Waves (RPW) instrument onboard Solar Orbiter. Finally, these particles can also be directly observed in the form of SEP intensity increases measured with the Energetic Particle Detector (EPD). In Figure 2, we can see four of these SEP events that are measured while the spacecraft was at about half the distance between the Sun and Earth in March 2022.

Using the timing information from three Solar Orbiter instruments as well as modelling of the interplanetary magnetic field conditions (along which the particles travel), we can link the SEP events to the observed flares on the Sun - originating in the same active region, AR12961.

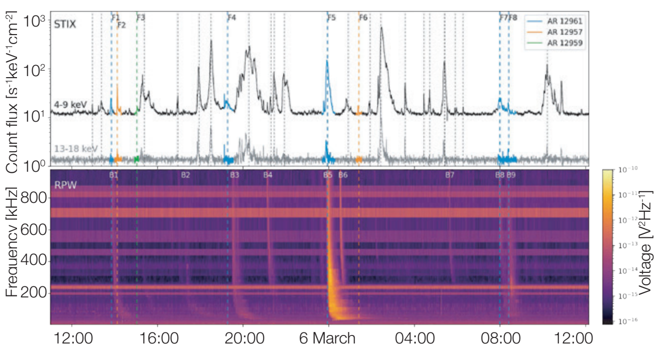



*Figure 1. Solar flares are observed as an intensity increase in X-rays measured with the Solar Orbiter STIX instrument (upper panel) and simultaneously measured Type-III radio bursts from RPW (lower panel) that indicate the outflow of solar energetic electrons into interplanetary space. The events, that can be associated with flares from an Earth-directed region, are marked in colour (green, blue, and orange with blue marking those from the identified source region, AR12961). Adapted from Janitzek et al. (2025).*

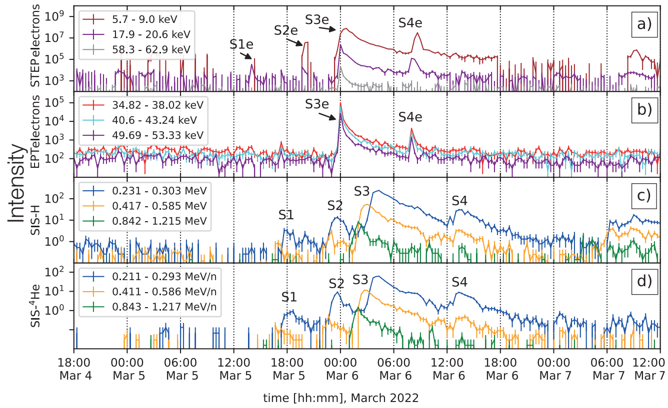



*Figure 2. Solar energetic particle events as measured in interplanetary space with the Solar Orbiter EPD instrument. The events can be recognised as particle intensity increases in different EPD sensors, measuring high-energy electrons (panels a and b) and ions (panels c – d). The four marked events correspond to the flares marked in blue in Figure 1. Adapted from Janitzek et al. (2025).*

The demonstrated precise link between a series of solar flares with the observed SEP events in interplanetary space allows the comparison between the eruption processes of the individual events and the properties of the energetic particle populations that are emitted. We find that all four SEP-associated flares in AR12961 are related to a twisted plasma filament that only shows a clear eruption in the two larger events, S3 and S4, while the smaller events, S1 and S2, are most likely associated with smaller activity in the form of nearby plasma jets. The events S3 and S4 are further associated with a stronger increase of solar He3 ions, which is an indicator for so-called *ion-cyclotron waves*. These waves might play a key-role in the acceleration of heavy elements (helium – iron) in flares.

The case study is complemented by a statistical investigation on the linkage between solar flares and energetic particle events carried out by an MSc student (Kistler et. al, in prep.). This study uses an automated approach using flare timing, location, magnetic field extrapolations, and energetic particle intensity increases as markers for the connection between the flares and the solar energetic particle events. For a large sub-sample of around 5000 flares observed with STIX in 2020 - 2022, the method was able to find about 100 physically verified connections.

References:

Janitzek, N., Roco-Moraleda, M., Barczynski, K, Zhu, Y., Harra, L., et al.: 2025, Linking solar flare observations to a series of impulsive solar energetic particle events measured with Solar Orbiter at 0.5 AU, submitted to A&A.

Kistler, F., Janitzek, N., Barczynski, K, Zhu, Y., Harra, L., et al.: An automated approach to link solar flares and energetic particle events based on modeled magnetic connectivity and Solar Orbiter data (in prep, 2025).

## Advances in Determining the Earth Radiation Budget

*Margit Haberreiter, Wolfgang Finsterle in collaboration with ROB (Belgium) and NPL (UK)*

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

Within the AVID Project, we have validated the TSI as well as OLR data from the CLARA radiometer (Finsterle et al. , 2014)) onboard the Norsat-1 satellite. A key part of the CLARA TSI is the validation against the VIRGO and TSIS datasets (Haberreiter et al., in prep). Another activity is the CLARA OLR data analysis. Here, new tools had to be developed, which included determining the geographical location on the Earth's surface that is within the CLARA line-of-sight. This work had already started before the AVID project, but some details still had to be verified and improved. We also determined the location where the CLARA line-of-sight intersects with the Earth. For this, we first had to analyse the instrument response function as a function of angle of the incident radiation. Subsequently, we determined the circular footprint to be a radius of about 40 km for a satellite altitude of 600 km at nadir pointing. Thus, the CLARA measurements give a spatial resolution of about 0.7° on the Earth's surface. Moreover, we have studied the latitudinal dependence of the CLARA OLR radiances. So far, we have not found a significant dependency. We expect that with a longer time-series, dependencies both in time and geographical location will become detectable. To validate the CLARA night-time measurements in detail, we will investigate the CERES Single Scanner Footprint (SSF) data product. The work to identify the temporally and spatially overlapping data has started and results are expected in the coming months.

TRUTHS Science Study - The TRUTHS Accompanying Consolidation and Operations Study (TACOS) started in December 2024 under the lead of NPL (UK). In this project, we investigate, in collaboration with NPL and the Academy of Athens (Greece), the sensitivity of solar spectral irradiance on the terrestrial atmosphere. Furthermore, we will exploit possible synergies between the CLARA OLR measurements and TRUTHS.

Earth Climate Observatory (ECO) - The climate sytem at Earth is governed by the delicate difference between the incoming solar radiation reaching the top of the atmosphere (ToA), and the outgoing radiation, which consists of 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. Today we find a difference of about 1 $Wm^{-2}$, i.e., less radiation is leaving the planet than entering. This accumulation of energy is the key to the climate problem. However, the exact quantification of this imbalance, which is increasing with time, is a challenge. This is the scientific goal of the ECO mission, selected as one out of four candidate missions of the $12^{th}$ ESA Earth Explorer Calls. The decision was announced in April 2024. As a member of the Mission Advisory Group of the ECO mission, Dr. Haberreiter will closely follow the science case of the mission. Dewitte et al. (2025) summarises the science rational of the ECO mission (see Figure 1 for an illustration of the concept).

Acknowledgements: MH acknowledges support from the Karbacher Funds.

References:

Dewitte, S., et al.: 2025, The Earth Climate Observatory space mission concept for the monitoring of the Earth Energy Imbalance, IRS 2024 Proceedings, accepted.

Finsterle, W., et al.: 2014, Soc. Photo-Optical Instrumentation Engineers (SPIE) Conf. Series, Vol. 9264, Earth Observing Missions and Sensors: Development, Implementation, and Characterization III, 92641S

Haberreiter, M., et al.: 2025, Compact Light-Weight Absolute Radiometer onboard NorSat-1 I. In flight performance and Total Solar Irradiance data release, in preparation.

Walter, B., Levesque, P.-L., Kopp, G., et al. 2017, Metrologia, 54, 674, doi: 10.1088/1681-7575/aa7a63

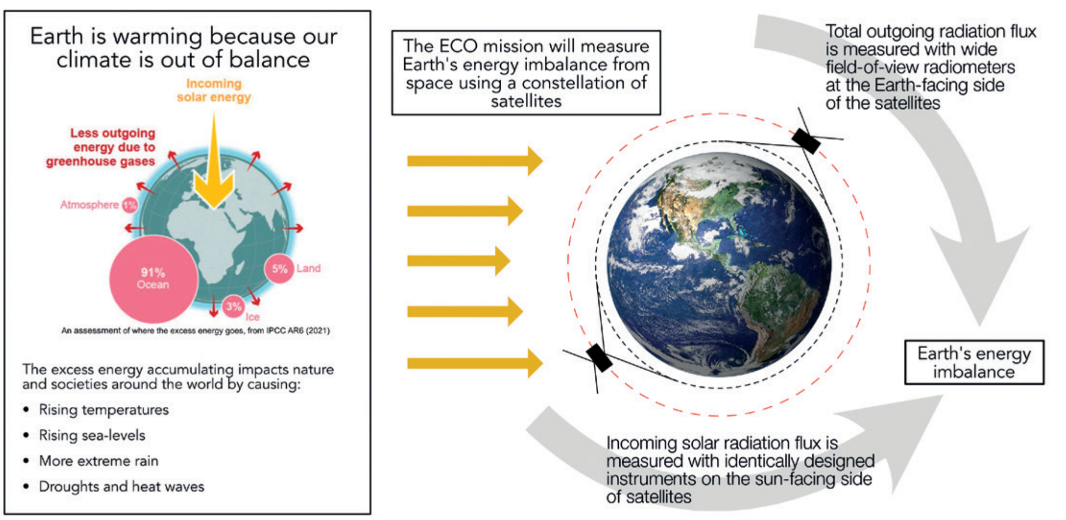



*Figure 1. Schematic Illustration of the concept of the ECO mission to determine the Earth Energy Imbalance from Space. Illustration courtesy of Thorsten Mauritsen.*

## Total Solar Irradiance (TSI) Data Analysis

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

We have: i) continued the dissemination of several products, including the new Total Solar Irradiance (TSI) composite time-series using all observations recorded by successive satellite missions launched since 1978 to the present, and the PMO6-v8 dataset from VIRGO/PMO6 observations, ii) processed new observations recorded by the DARA radiometer launched onboard the Chinese FY3E satellite, and iii) finalised the preflight calibration of the DARA radiometer, which was launched on 5 December 2024 on the ESA PROBA-3 mission.

### 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 (ML), PMOD/WRC now releases the VIRGO/PMO6-V8 product every quarter on our website at: https://www.pmodwrc.ch/en/research-development/space/soho/#SOHO-VIRGO.

*The 44-year TSI Composite produced by PMOD/WRC:* Since the late 1970's, successive satellite missions have been monitoring the Sun's activity, recording TSI. Some of these measurements ran for more than a decade. It is then mandatory to merge them to obtain a seamless record whose duration exceeds that of the individual instruments. Climate models can be better validated using such long TSI records, which can also help provide stronger constraints on past climate reconstructions (e.g., back to the Maunder minimum) (Shapiro et al., 2011; Montillet et al., 2023a).

The algorithm developed by Montillet et al. (2021, 2022) allows an updated TSI composite to be produced every quarter on the public data repository (Montillet et al., 2023b) and the PMOD/WRC website (https://www.pmodwrc.ch/en/research-development/solar-physics/tsi-composite).

### JTSIM-DARA / FY-3E Mission

*Data Analysis of the Observations*: JTSIM-DARA has been producing TSI measurements since August 2021. PMOD/WRC routinely analyses the observations from the DARA radiometer. The observations are corrected for various factors (e.g., shutter, aperture, reflectance, diffraction, radiative losses, and the World Radiometric Reference factor; Song et al., 2021, 2022). The radiative losses to deep space have been re-analysed, leading us to the updated first-light measurements of 1363.76 $Wm^{-2}$ ± 404 ppm for the main cavity (Cavity B), and 1363.92 $Wm^{-2}$ ± 412 ppm for the reference cavity (cavity A), and 1363.77 $W^{-2}$ ± 404 ppm for the back-up cavity (cavity C) on the WRR scale (Ye et al., submitted; Montillet et al., submitted; Montillet et al., 2024a and 2024b). On the SI scale, first-light is 1359.28 $Wm^{-2}$ ± 412 ppm, 1359.12 $Wm^{-2}$ ± 404 ppm and 1359.13 $W^{-2}$ ± 404 ppm for Cavity A, B and C respectively. The degradation correction is also modelled using the software based on ML, used for the VIRGO/PMO6 observations. The degradation is so far estimated at 158 ppm for the whole period covering August 2021 – September 2024.

The DARA-JTSIM data are at the moment released on the PMOD/WRC website (https://www.pmodwrc.ch/en/research-development/solar-physics/tsi-composite) and the public repository "ASTROMAT.org". Figure 1 shows the PMO6-v8 and JTSIM-DARAv1 products on the SI scale using daily sampling. We have limited the period of the PMO6-v8 product to the same time as the other product.

### 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 independent satellites in an highly elliptical Earth orbit in precise formation flying, close to one another with the ability to accurately control the attitude and separation of both satellites. One of the satellites carries a radiometer to record the TSI. The radiometer is the Digital Absolute Radiometer (PROBA-3-DARA) developed and manufactured in Switzerland by PMOD/WRC.

The data analysis from the pre-flight calibration campaign within the PMOD/WRC facilities and at LASP (Boulder, USA) has been re-analysed to correct the initial results from the 2023 analysis (Montillet et al., 2023c).

The PROBA-3 mission was launched on 5 December 2024. The first wake-up of the instrument was carried out on the 16 December 2024. The next phase is the post-launch commissioning report, which should be carried out in the first quarter of 2025.

### Opening the door to the future of processing TSI observations with Machine-Learning (ML)

In late 2023 and early 2024, a project in collaboration with the AI data center at ETH Zürich and PMOD/WRC, ran with four master students who looked into the possibility of using ML to process TSI data, and to look at the dependencies of observations using housekeeping data (sensor temperature, cavity temperature) (https://zenodo.org/records/10829361). A master student (Adriana De Sassi) at ETH Zürich from the solar physics department has studied the possibility to forecast the TSI composite using other datasets (e.g, sunspot numbers, Mg II) based on various ML algorithms (De Sassi, 2024). A review study was published in a broader scope on Earth and Space data, and ML techniques (Montillet et al., 2024c).

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.

References

De Sassi, A.: 2024, Forecasting Total Solar Irradiance Time Series using Machine Learning and Deep Learning, Master thesis, ETH Zürich, August 2024.

Montillet, J.-P., Finsterle, W., Kermarrec, G., Sikonja, R., Haberreiter, M., Schmutz, W., Dudok de Wit, T.: 2021, Solar noise in 40 year long TSI composite time series, AGU Fall Meeting, https://doi.org/10.1002/essoar.10509108.1

Montillet, J.-P., Finsterle, W., Kermarrec, G., Sikonja, R., Haberreiter, M., Schmutz, W., Dudok de Wit, T.: 2022, Data fusion of Total Solar Irradiance composite time series using 41 years of satellite measurements, J. Geophys. Res. Atmos., https://doi.org/10.1029/2021JD036146

Montillet, J.-P., Haberreiter, M., Rozanov, E.: 2023a, Monitoring the Earth radiation budget and its implication to climate simulations: Recent advances and discussions, J. Geophys. Res., 128, https://doi.org/10.1029/2023JD040075

Montillet, J., Finsterle, W., Schmutz, W., Haberreiter, M., Dudok de Wit, T., Kermarrec, G., Sikonja, R.: 2023b, Composite PMOD data fusion - updated January 2023, Version 1.0, Interdisciplinary Earth Data Alliance (IEDA). https://doi.org/10.26022/IEDA/112763, accessed 2023-02-16.

Montillet, J., Schmutz, W., Finsterle, et al.: 2023c, 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., Finsterle, W., Zhu, P., et al.: 2024a, Assessment of instrument performance of the FY3E/JTSIM/DARA radiometer through the analysis of TSI observations, ESS Open Archive, September 11, https://doi.org/10.22541/essoar.172606237.73898305/v1

Montillet, J.-P., Finsterle, W., Haberreiter, et al.: 2024b, The JSTIM-DARA product derived from the TSI observations recorded by the FY3E/JTSIM/DARA radiometer, EGU General Assembly 2024, Vienna, Austria, 14-19 Apr 2024, EGU24-5966, https://doi.org/10.5194/egusphere-egu24-5966

Montillet, J.-P., Kermarrec, G., Forootan, E., Haberreiter, M., He, X., Finsterle, W., et al.: 2024c, How big data can help to monitor the environment and to mitigate risks due to climate change: A review, IEEE Geoscience and Remote Sensing Magazine, 12, 2-24, https://doi.org/10.1109/MGRS.2024.3379108

Shapiro, A., et al., 2011, A new approach to the long-term reconstruction of the solar irradiance leads to large historical solar forcing, A&A, 529, A67, https://doi.org/10.1051/0004-6361/201016173

Song, B., Ye, X., Finsterle, W., et al.: 2021, The Fengyun-3E/Joint Total Solar Irradiance Absolute Radiometer: Instrument design, characterization, and calibration, Sol. Phys., 296, 52, https://doi.org/10.1007/s11207-021-01794-5

Song, B., Ye, X., Finsterle, W. et al.: 2022, Correction to: The Fengyun-3E/Joint Total Solar Irradiance Absolute Radiometer: Instrument Design, Characterization, and Calibration. Sol Phys, 297, 77, https://doi.org/10.1007/s11207-022-02028-y

Ye, X., Zhu, P., Montillet, J.-P., Finsterle, W., Fang, W., Koller, S., Yang, D., Pfiffner, D., Song, B., Haberreiter, M., Wu, D., Qi, J., Zhang, P., Schmutz, W., The first light from the joint total solar irradiance measurement experiment onboard the FY3-E meteorological satellite, submitted to ESS-AGU.

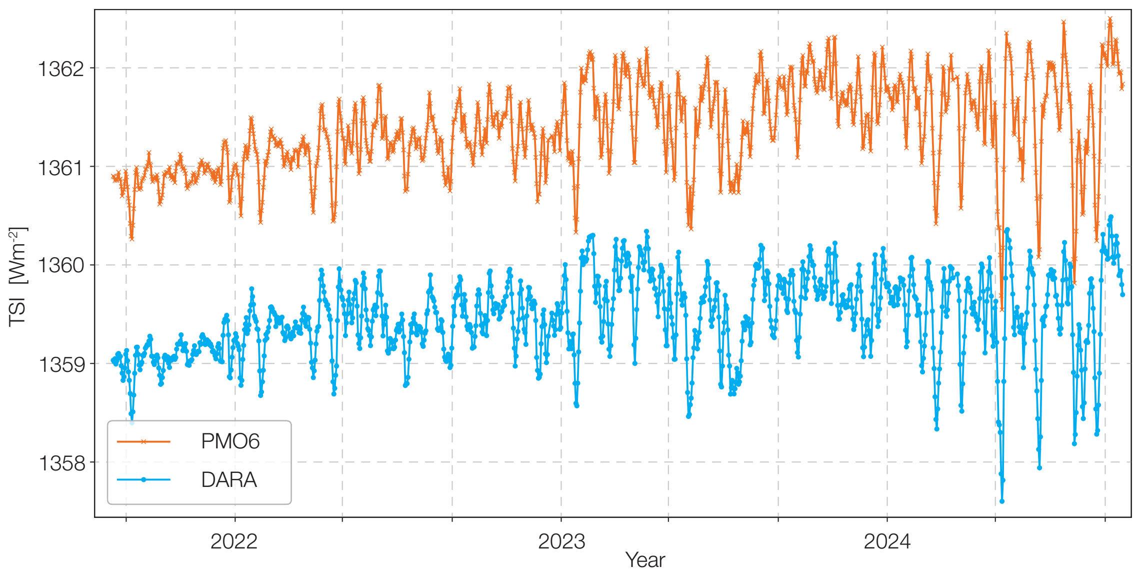



*Figure 1. PMO6-v8 and JTSIM-DARAv1 products on the SI scale using daily sampling.*

## Upflows at Solar Active Region Boundaries

*Yingjie Zhu, Louise Harra, Krzysztof Barczynski and Nils Janitzek*

The million-degree solar outer atmosphere – corona, exhibits continuous outflows of plasma, called the solar wind, filling the interplanetary space between the Sun and Earth. The solar wind might originate in regions in the lower part of the corona. For example, upflowing moving plasma is frequently observed at the boundary of active regions. These upflows are a potential candidate for source regions of the slow (< 450 km/s) solar wind. With coordinated observations from Solar Orbiter and near-Earth observatories, we explored upflows in the coupled solar atmosphere, which helped to identify their driving mechanisms.

The space between the Earth and Sun is not a true vacuum; it is filled with plasma flowing away from the Sun at supersonic speeds, known as solar wind. Empirically, the solar wind is categorised by it's speed in the near-Earth space and labelled "fast" (> 600 km/s) or "slow" (< 450 km/s). Scientists have a better understanding of fast wind source regions. Still, the origins of the slow solar wind remain a source of debate, ranging from the bright, active corona to the fainter, quiet Sun corona as possible sources. Upflows at the boundary of active regions are a potential source for the mysterious origin of the slow solar wind. A decaying solar active region (seen as bright patches in Figure 1) was continuously tracked by Solar Orbiter and other near-Earth observatories for tens of days. The coordinated observations reveal a comprehensive picture of how the flows of tens of kilometers per second are generated in the solar corona, their existence with small-scale dynamic structures, and how the lower atmosphere responds to these upflows. We identified two major upflows in the periphery of this active region using the observations made by the Extreme Ultraviolet Imaging Spectrograph (EIS), onboard the Hinode spacecraft, and the Spectral Imaging of the Coronal Environment (SPICE), onboard Solar Orbiter. We focused on the upflow at the eastern boundary of the active region, outlined by purple curves in Fig. 1. Blueshifts (upflows) were observed in two spectral lines originating from different temperatures; one is an Iron line (Fe XII) forming at 1.6 million degrees, the other is a Neon line (Ne VIII) forming at 0.6 million degrees. This suggests a consistent upflow through the temperature-stratified atmosphere. Inference of the coronal magnetic field, which controls plasma motions, confirms that the major flow component in both regions is driven by pressure imbalance along the magnetic field lines. This pressure imbalance is likely due to a process called magnetic reconnection, which occurs between high-pressure (bright) field lines in the active region and ambient low-pressure field lines.

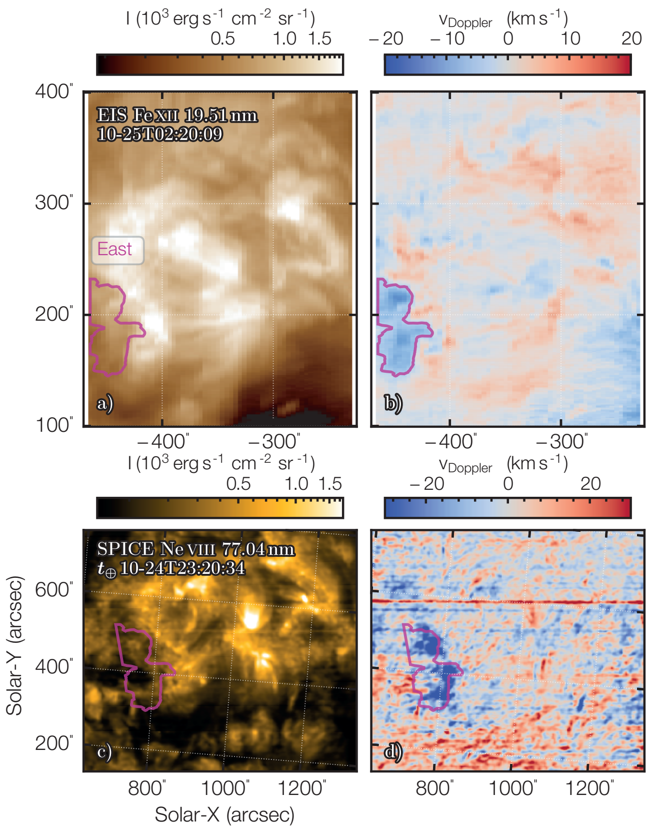



*Figure 1. Intensity and Doppler shifts of spectral lines emitted by Fe XII (Panels a and b) and Ne VIII ions (Panels c and d). One of the two upflow regions are outlined at the east boundary of the active region. Adapted from Zhu et al. (2025, in preparation).*

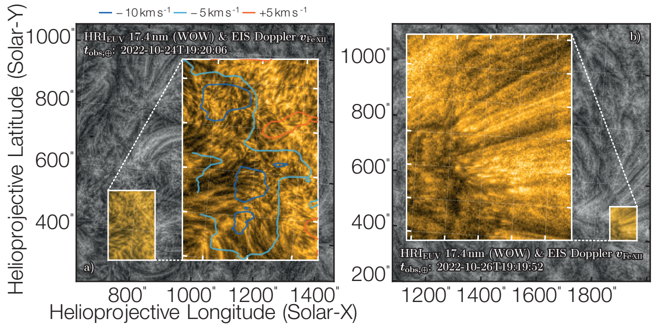



*Figure 2. Fine structures in the upflow regions observed by HRIEUV the images are zoomed in to reveal the small-scale dynamics. Adapted from Zhu et al. (2025, in preparation).*

Fine structures, on the scale of several megameters, were resolved in the upflow region by the Extreme Ultraviolet (EUV) channel of the High Resolution Imager (HRI) telescope. They appear in forms such as blobs, fibrils, and jets, revealing a highly dynamic and structured upflow region. Apparent motions of some dynamic structures, such as jets, suggest these small-scale events might contribute to the net upflow plasma. The Doppler shifts in the chromosphere and transition region were measured to explore the coupling of the lower atmospheric layers. Although these layers are dominated by downflows, we found a decrease in downflows and some distributed patches of upflows below the coronal upflows. We suggest a close tie between coronal upflows and the atmosphere beneath as the ultimate plasma source for its persistency for weeks. Our analysis unveils how upflowing materials are driven throughout the solar atmosphere, potentially contributing to the slow solar wind.

Acknowledgement: Y. Z. acknowledges support from the Karbacher Funds.

References: Zhu, Y., Harra, L., Barczynski, K., et al.: 2025, Active region upflows in various coronal structures, in preparation.

## Modulation of the Northern polar vortex by the Hunga Tonga-Hunga Ha'apai eruption and associated surface response

*Timofei Sukhodolov, Andrin Jörimann and Eugene Rozanov in collaboration with BOKU (Austria)*

The January 2022 Hunga Tonga-Hunga Ha'apai (HT) eruption injected sulphur dioxide and unprecedented amounts of water vapour (WV) into the stratosphere. Given the manifold impacts of previous volcanic eruptions, the full implications of these emissions are a topic of active research. In this study, we explored the dynamical implications of the perturbed upper atmospheric composition using an ensemble simulation with the Earth System Model, SOCOLv4. We found that this event caused unusual effects on stratospheric dynamics and surface circulation in the Northern Hemisphere (NH).

The 2022 HT eruption is unique, as it was an underwater event with a massive explosion. As a result, besides the usual volcanic injection of sulphur dioxide ($SO_2$), it also released between 140 and 150 Tg of sea water very high into the stratosphere, even reaching mesosphere levels. Typically, volcanic eruptions cause lower-stratospheric warming, which strengthens the polar vortex and via stratosphere-troposphere coupling results in surface warming over Eurasia and altered weather patterns in the NH. However, in the case of the HT eruption, this pronounced and canonical lower-stratospheric warming has not been identified, and its absence is most likely attributable to small emissions of $SO_2$. Instead, the HT eruption has led to significant anomalies in stratospheric and lower-mesospheric ozone concentrations. The increased OH concentrations induced by the excess WV from the HT eruption led to ozone depletion and temperature anomalies in the upper stratosphere and lower mesosphere (Fleming et al., 2024).

In our study, we aimed to investige the dynamical effects of such unusual ozone and temperature anomalies for a volcanic event. For this, we used our Earth System Model, SOCOLv4, with which we performed two ensemble experiments: without a volcano and with, being forced by the observed amounts of volcanic emissions of WV and $SO_2$. Our simulation results for the sulphate aerosol and WV plumes, ozone and temperature anomalies were found to be in good agreement with satellite observations and other models. We confirmed that the upper stratospheric/lower mesospheric negative temperature anomaly in the tropics was indeed mostly driven by a local ozone depletion, following the hydroxyl production from the volcanic WV.

Further, we focused on the 2022/2023 late winter season, over which this temperature anomaly was maximised and persistent (Fig. 1a). We found that the NH polar vortex responded to these tropical temperature changes via the thermal wind relation following a reduced horizontal hemispheric temperature gradient. This resulted in weaker zonal winds in the NH and local warming (Fig. 1b), associated with a negative northern annular mode (NAM) anomaly, which has then propagated downwards, followed by a positive NAM mode and a negative temperature anomaly. Finally, this resulted in a sea-level pressure anomaly (Fig. 1c), indicating a tropospheric circulation change that would lead to a cooling in Europe due to an increased cold air advection from the Arctic.

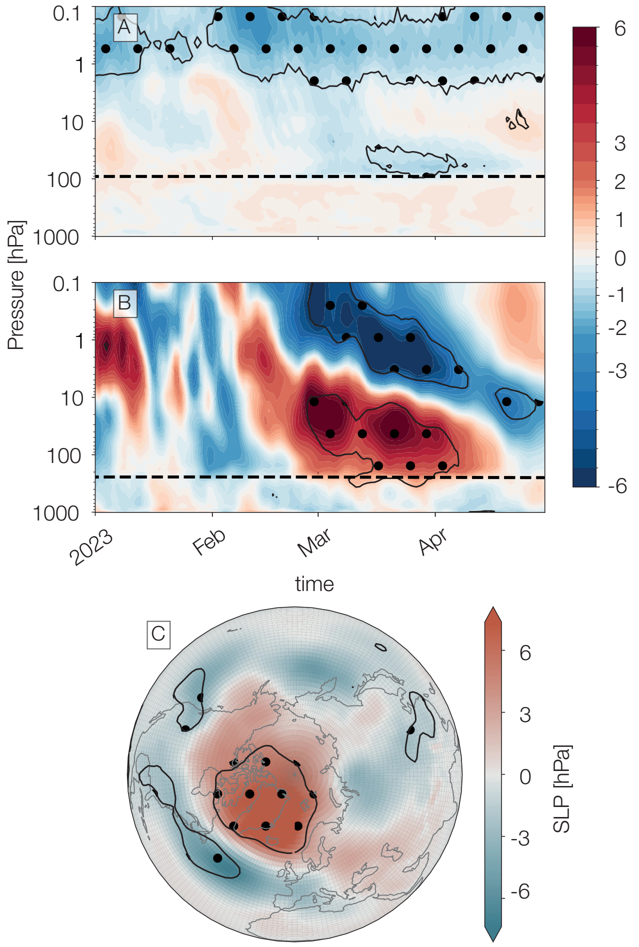



*Figure 1. Weighted zonally-averaged temperature anomalies averaged over: Panel A) 0° - 20°N (A) and Panel B) 60° - 90°N (B). Panel C: sea level pressure anomalies (SLP in hPa) in April 2023. Anomalies are expressed as the difference between the SOCOL simulation with and without HT forcing. The 2σ statistical significance from t-tests is indicated by dots and as a black contour line.*

This mechanism establishes a novel pathway, how water-rich volcanic eruptions can indirectly impact the surface climate via downward propagation of the dynamical perturbation from the stratosphere and the lower mesosphere. Thereby it adds to the manifestations of stratosphere-troposphere coupling on various time-scales. A paper describing these results was recently accepted for publication in the Atmospheric Chemistry and Physics Letters journal (Kuchar et al., 2024).

References:

Fleming, E. L., et al.: 2024, Stratospheric temperature and ozone impacts of the Hunga Tonga-Hunga Ha'apai water vapor injection, J. Geophys. Res., 129, e2023JD039298, https://doi.org/10.1029/2023JD039298

Kuchar, A., Sukhodolov, T., Chiodo, G., Jörimann, A., Kult-Herdin, J., Rozanov, E., Rieder, H.: 2024, Modulation of the Northern polar vortex by the Hunga Tonga-Hunga Ha'apai eruption and associated surface response, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2024-1909

# Geomagnetic Field and Environmental Crisis Occurrence (GECO)

*Tatiana Egorova*

The primary goals of the GECO project are to: (i) simulate how the weakening of the geomagnetic field affects cloud properties and climate and, (ii) determine whether this weakening could lead to an environmental crisis as suggested by paleo data. The project adopts a novel approach that involves detailed climate simulations, which are driven by the relationship between geomagnetic field strength, atmospheric ionisation rates, and the processes of coagulation in clouds that regulate their life-cycle.

The environmental crisis that emerged approximately 42,000 years ago has been convincingly documented in paleo archives by Cooper et al. (2021). They proposed that this crisis might have been caused by increased ionisation during a geomagnetic field weakening event known as the Laschamp excursion. Their simulations of atmospheric chemistry changes indicated potential impacts on surface UV exposure and circulation. However, they could not identify major climatic shifts that might explain the observed environmental changes. To tackle the issue, the coupled ocean-atmosphere climate model SOCOL-MPIOM (Muthers et al., 2014) was utilised, incorporating an added parameterisation that links cloud properties to ionisation rates. The ionisation rates themselves were computed using a model applicable to both regular and geomagnetic excursion periods. The model modifications focused specifically on cloud microphysics, particularly developing a parameterisation for the coagulation rates of cloud droplets. These parameters were determined as a function of fair weather vertical electric currents (Jz), which were interactively calculated from the simulated atmospheric ion concentrations and conductivity.

We conducted three simulations, each lasting 200 years: a reference run reflecting present-day geomagnetic conditions, an experimental run examining the chemical effects of increased ionization rates due to a weakened geomagnetic field (referred to as CHEM), and a similar run that additionally incorporates the coagulation response to changes in $J_z$ (referred to as CLOUD). The experimental run was initialised using existing long-term data to ensure proper boundary conditions. Comparing the reference run to the experimental runs allows us to understand how the climate system responds to the weakening of the geomagnetic field.

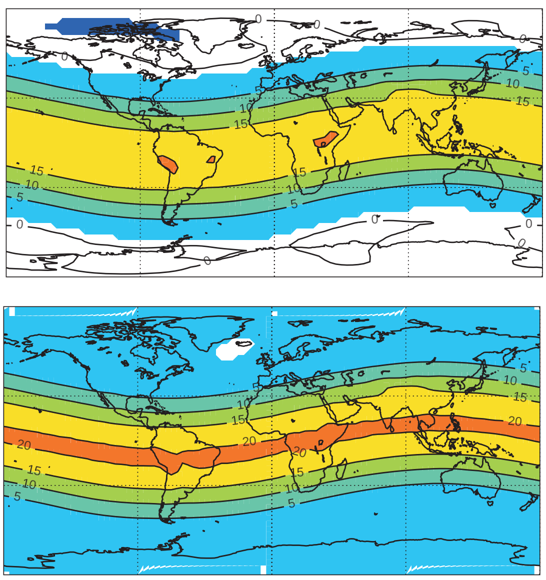


*Figure 1. The annual mean $J_z$ response (%) to the geomagnetic field weakening calculated as a relative deviation of the experimental runs (CHEM and CLOUD results) from the reference run. Statistically insignificant (less than 95%) changes are shown by white areas.*

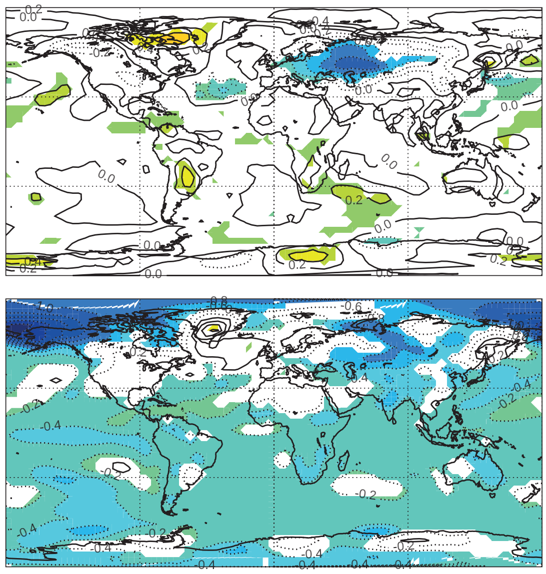


*Figure 2. The annual mean surface temperature response (K) to the geomagnetic field weakening calculated as a deviation of the experimental runs (CHEM and CLOUD results) from the reference run. Statistically insignificant (less than 95%) changes are shown by white areas.*

Figure 1 shows the annual mean $J_z$ response to the geomagnetic field weakening, calculated as a relative deviation of the experimental runs (CHEM and CLOUD results) from the reference run. The impact of the geomagnetic field weakening is most pronounced at middle and low latitudes, leading to an increase in $J_z$ of up to 20%. The influence of cloud modifications results in a slightly greater increase in $J_z$ across the globe. Figure 2 displays the response of surface air temperature. The patterns of the surface temperature response in the CHEM and CLOUD experiments differ significantly. The chemical effects are less pronounced on a global scale but result in noticeable cooling in Europe and warming in Greenland. In the CLOUD experiment, we observe a statistically significant global cooling of about 0.4 K with a substantial temperature drop of up to 2 K in the Northern Hemisphere.

Acknowledgment: The project (CRSK-2_221368) is funded by the Swiss National Science Foundation.

References: Cooper, A., et al.: 2021, A global environmental crisis 42,000 years ago, Science, 371, 6531, 811-818, https://doi.org/10.1126/science.abb8677

Muthers, S., et al.: 2014, The coupled atmosphere–chemistry–ocean model SOCOL-MPIOM, Geosci. Model Dev., 7, 2157-2179, https://doi.org/10.5194/gmd-7-2157-2014

## Late Glacial $^{14}C$ Spike Reveals the Record-Strong Solar Storm in 12,350 BC

*Eugene Rozanov in collaboration with Cosmic Rays Group (University of Oulu, Finland) and CEREGE (France)*

Extreme solar particle events (ESPEs) are rare, powerful solar storms, far stronger than solar flares during the satellite era. Their existence challenges current solar flare models, posing significant radiation hazards to Earth and technology. Recent findings have identified eight ESPEs in the past 12 millennia, with the strongest occurring in 775 AD. A newly discovered peak dated around 12,350 BC is nearly twice as strong but could not be analysed earlier due to lacking glacial climate models. Using a newly developed model, SOCOL:14C-Ex, we determined that this ESPE was 18% stronger than the 775 AD event. The newly-developed model extends our ability to analyse radiocarbon data even during the last glacial period.

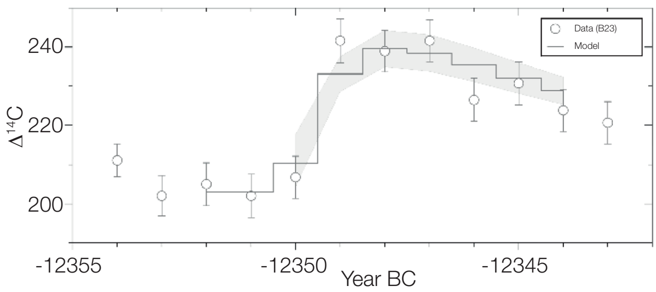



*Figure 1. Annual values of Δ$^{14}$C (in ‰) around the event. Black circles with error bars represent the measurements (Bard et al., 2023). The black line is the best-fit model result ($A_0$ = 1.18, $T_0$ = 67 day, $C_0$ = 203‰). The shaded area represents the range of the model results within the 68% confidence range.*

Extreme solar particle events (ESPEs) are several orders of magnitude stronger than solar flares observed during the recent decades. Their very existence is a challenge to the standard solar flare models. ESPEs have been discovered recently using records of cosmogenic radioisotopes, mostly $^{14}C$ radiocarbon, in natural terrestrial archives where they leave clear signatures.

We have developed a new version of the state-of-the-art chemistry-climate model SOCOL:14C-Ex and applied it to analyse the ESPE of 12,350 BC. Since the $^{14}C$ data for the 12,350 BC event (Bard et al., 2023) was obtained from a tree located in Southwestern Europe (44.31°N, 5.52°E), we discuss here the results for the corresponding model grid cell centred at 43.25°N, 5.62°E. Still, the model results are available for any other location on Earth since the SOCOL:14C-Ex model simulates the entire atmosphere.

The results are presented as the measurable quantity of Δ$^{14}$C. Figure 1 shows the evolution of the modelled and measured Δ$^{14}$C in near-surface air in Southwestern Europe. The date of the ESPE is arbitrarily set to 20 January, representing the middle of the Boreal winter. Near-surface Δ$^{14}$C values increase over approximately two years due to atmospheric transport; radiocarbon is mainly produced in the polar stratosphere and transported to the ground by the large-scale air motion. On top of the smooth growth, a tiny seasonal wave is superimposed, which is a combination of two factors: (i) the descent of $^{14}C$-rich stratospheric air caused by stratosphere-troposphere exchange (STE), which peaks in spring, and (ii) the enhanced sink of $^{14}C$ to the biosphere during the vegetation growth period that reduces its concentration.

Since these two effects partly compensate each other, the net seasonal wave appears small, with a slight peak occurring in early summer, specifically after the STE. After reaching its maximum at the beginning of the third year, Δ$^{14}$C starts to decline due to the sink to the biosphere and ocean. During this decline, the seasonal wave changes its phase so that the maximum of Δ$^{14}$C is found during early spring, just before vegetation begins to absorb carbon. Although the model calculates daily concentrations, the Δ$^{14}$C values measured in tree rings are reported with annual resolutions. To obtain the annual Δ$^{14}$C values from daily ones, we assumed that a tree absorbs carbon only during its growing season. Therefore, we averaged the daily values solely during the vegetation period, as estimated by the model.

By fitting the modelled Δ$^{14}$C curves to the measured values (Bard et al., 2023), we estimated the likely strength and occurrence time of the ESPE responsible for the 12,350 BC spike. In our analysis, we focussed on two free parameters: the scaling factor of the event strength, $A_0$, with respect to the model result obtained for the 775 AD event strength ($A_0$ = 1 indicates that the strength of the ESPE is equivalent to that of the 775 AD event), and the date $T_0$ of the event as the day of year in 12,350 BC.

The ESPE of 12,350 BC analysed here, is the only known one outside the Holocene epoch. This event serves as a key reference for radiocarbon studies, enabling researchers to better anchor floating chronologies well beyond the Holocene, where dating accuracy is generally lower (Heaton et al., 2024). The discovery of the record strongest known event of 12,350 BC pushes the bounds of extreme solar-terrestrial events even further. It forms a new worst-case scenario paradigm and provides a global tie point for dendrochronological dating before the Holocene.

Acknowledgement: This work was conducted within the Swiss National Science Foundation (SNSF) project, AEON (grant no. 200020E_219166).

References: Bard, E., Miramont, C., Capano, M., Guibal, F., Marschal, C., Rostek, F., Heaton, T.J.: 2023, A radiocarbon spike at 14,300 cal yr BP in subfossil trees provides the impulse response function of the global carbon cycle during the late glacial, Philosophical Transactions, Series A, Mathematical, Physical, and Engineering Sciences 381, https://doi.org/10.1098/rsta.2022.0206

Heaton, T., Bard, E., Bayliss, A., Blaauw, M., Bronk Ramsey, C., Reimer, P., Usoskin, I.: 2024, Extreme solar storms and the quest for exact dating with radiocarbon, Nature, 633, 306-317, https://doi.org/10.1038/s41586-024-07679-4

## Changes in Atmospheric Dynamics due to Changes in Total Solar Irradiance

*Jan Sedlacek, Timofei Sukhodolov, Tatiana Egorova and Eugene Rozanov*

Prior to industrialisation, long-term climate variations correlate closely with total solar irradiance (TSI). In addition, volcanic forcing also induces climate changes. The magnitude of these two natural forcings is still under debate and thus it is difficult to attribute a climate signal to a certain forcing. In this study, we modify the TSI and analyse the sensitivity of the climate to TSI changes. A special focus is given on the dynamics of the atmosphere.

Several simulations with different TSI forcings are carried out using the global climate model SOCOL-MPIOM. The actual solar forcing is described using 14 different spectral bands in such a way that the resulting TSI ranges from -10 $Wm^{-2}$ to 10 $Wm^{-2}$ around the pre-industrial TSI value. SOCOL-MPIOM has a more precise representation of the stratosphere and mesosphere in terms of chemistry and aerosol interactions as compared to other global climate models. Thus, interactions of solar irradiation and the atmosphere are well described. Furthermore, SOCOL-MIPOM includes interactive ocean, land, sea-ice and atmosphere components.

The surface pressure sensitivity shows a distinct pattern in relation to TSI changes (Fig. 1). The surface pressure in the high latitudes decreases. In the northern mid-latitudes, the quasi-stationary high-pressure systems, such as the Azores and Tibetan Highs, become stronger with increasing TSI value. In addition, also the mid-latitude high pressure band in the Southern Hemisphere increases in strength. Many of these quasi-stationary pressure patterns can be described with indices. For example, one such index for the pressure gradient in the Southern Hemisphere is the Southern Annular Mode (SAM). If SAM is positive, the Southern Subtropical Front moves closer to Antarctica and the Southern westerly winds are stronger. SAM also influences the dominant weather patterns in southern South America and in Australia. Even though the spread of the SAM index is quite large in relation to TSI changes, there is a shift to positive values with larger TSI values (Fig. 2a).

The North Atlantic Oscillation (NAO) is an important index for the climate in Europe. The NAO is defined as the surface pressure dipole between roughly the Azores and Iceland. As seen in Figure 1, the dipole strengthens, i.e., the NAO becomes more positive with higher TSI values (see also Fig. 2b). A positive NAO results in a colder and dryer southern Europe while Scandinavia is mild and wet. For southern Europe, there is an interesting and competing effect. On the one hand, higher TSI values lead to higher surface temperatures and on the other hand, higher TSI values cool that region due to the sign of the NAO.

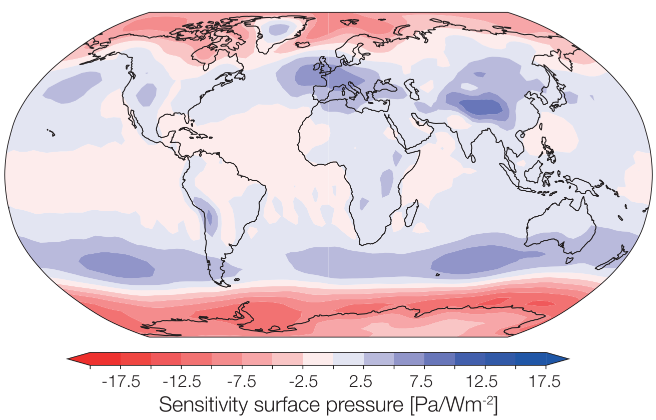



*Figure 1. Sensitivity of the surface pressure in relation to the change in total solar Irradiance (TSI).*

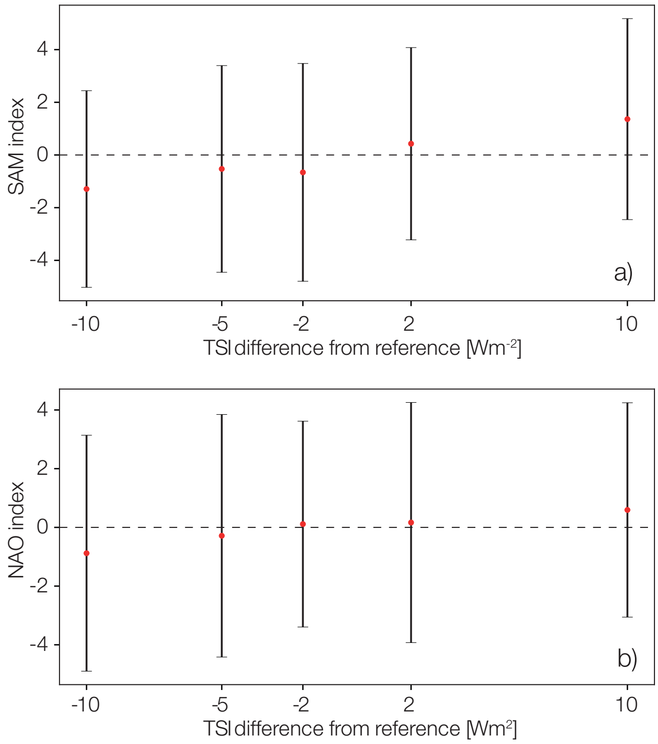



*Figure 2. Panel a): changes of the Southern Annular Mode (SAM) with changing total solar Irradiance (TSI). Panel b): same as a) but for the North Atlantic Oscillation (NAO).*

An additional index that is analysed is the Walker Circulation (not shown). This index summarises a complex pattern of ocean temperatures, pressure distribution and precipitation patterns in the tropical Pacific Ocean and is connected to the El Niño-Southern Oscillation. In the simulations, there is a small tendency to smaller index values, i.e., a reduced east-west pressure gradient and an eastward shift of convective precipitation. The Walker Circulation, however, includes quite a large part of internal variability which is partly ocean-driven. These changes will likely smoothen the atmospheric signal.

The next steps will be to analyse the mechanisms in more depth, which lead to the changes in the atmospheric dynamics. In addition, the coupling between processes in the stratosphere and troposphere with respect to TSI changes will be examined further.

Acknowledgement: This work is supported by the Karbacher Foundation.

## A Retrieval Method for Optical and Physical Aerosol Properties in the Stratosphere (REMAPv1)

*Andrin Jörimann and Timofei Sukhodolov in collaboration with ETHZ (Switzerland), CSIC (Spain) and University of Leeds (UK)*

The stratospheric aerosol has important effects on the climate. It can contribute to ozone destruction and the radiative properties of aerosols allow it to scatter parts of the incoming sunlight back to space, thus cooling the surface. It is important to include these aerosol effects in climate models, however, it is difficult to obtain the right data. Satellites can measure how much light aerosol particles attenuate, but these data cannot be directly used in models. To bridge this gap, we developed REMAP, a flexible method to convert satellite data to aerosol properties that models can ingest.

The stratosphere is characterised by its stable layering of air masses, contrary to the turbulent, readily mixed troposphere below, where our weather is created. Circulation inside the stratosphere operates on time-scales of roughly 3 - 4 years, meaning that aerosols that reach this height typically remain there for years. All the while, aerosol particles scatter solar radiation, preventing some of it from reaching the surface, and help to chemically destroy ozone under the right conditions. The first comprehensive scientific article about the stratospheric aerosol layer was published in 1961 by Junge et al. (1961). Not long after - by 1979 - continuous monitoring by satellites started. These satellite data have been used in the past to create forcing datasets for climate models. This process has often been time-intensive, especially for a large number of models, i.e. for model intercomparison projects (MIPs).

To improve this process, we built REMAP on an existing principle described by Arfeuille et al. (2013) to be easily adaptable to any model. To mathematically model the radiative effects of aerosol particles, their size distribution is required. The stratospheric aerosol is generally well-approximated by a unimodal log-normal size distribution. In REMAP, we retrieve this by going through all possible combinations of size distribution parameters and computing the theoretical optical properties of each resulting collection of aerosol particles - called aerosol ensemble. After comparing all theoretical properties against the actual observed satellite measurements, we select the size distribution that best matches the observations.

Once the aerosol size distribution is known, various properties of the aerosol ensemble can be calculated from established physical theory. In particular, optical properties, which are wavelength-dependent, can be computed for any given wavelength or wavelength bands. Figure 1 shows a data product from using REMAP on the Global Satellite-based Stratospheric Aerosol Climatology (GloSSAC). It portrays the evolution of the stratospheric aerosol layer including volcanic eruptions that strongly modulate it until the particles are removed after a few years.

We describe REMAP in our paper that was recently submitted to the Geoscientific Model Development journal and also includes a series of records that have been used in several MIPs in the past, including the Coupled Model Intercomparison Project Phase 6 (CMIP6) that helped inform the 6th Assessment Report of the IPCC.

Acknowledgement: This work was conducted within the Swiss National Science Foundation (SNSF) project, AEON (grant no. 200020E_219166).

References:

Arfeuille, F., et al.: 2013, Modeling the stratospheric warming following the Mt. Pinatubo eruption: uncertainties in aerosol extinctions, Atmos. Chem. Phys., 13, 11221-11234, https://doi.org/10.5194/acp-13-11221-2013

Junge, C. E., Chagnon, C. W., Manson, J. E.: 1961, Stratospheric aerosols, J. Atmos. Sci., 18, 81-108, https://doi.org/10.1175/1520-0469(1961)018<0081:SA>2.0.CO

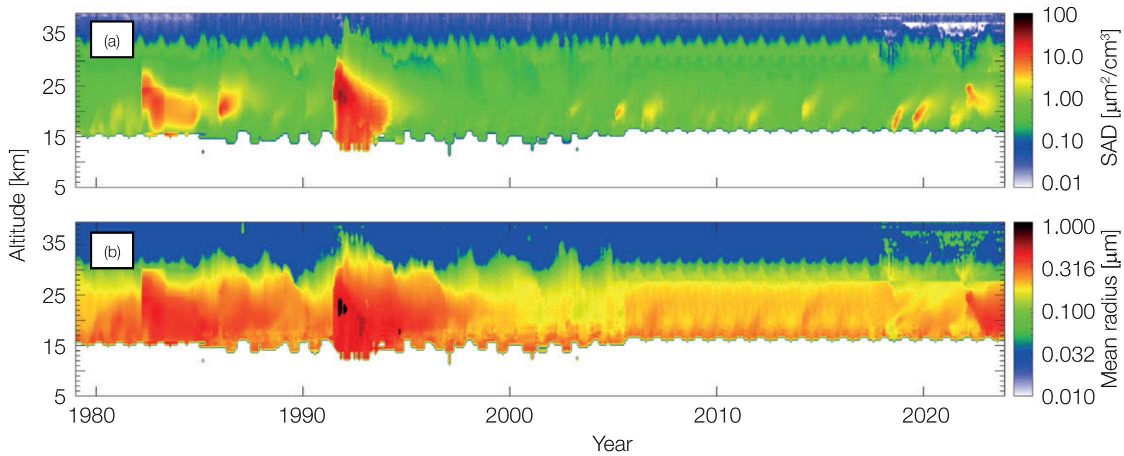



*Figure 1. Vertical time-series of: a) surface area density (SAD), and b) mean aerosol radius for the time period, 1979 - 2023, derived from the GloSSAC satellite composite for the latitude band, 0° – 5°N. The stratospheric aerosol was highly elevated after the 1982 El Chichon and 1991 Pinatubo volcanic eruptions. Several other smaller eruptions enhanced the stratospheric aerosol, as well as its chemical and radiative effects.*

## Injections of Solid Particles for Solar Radiation Modification can Reduce Impacts on Ocean and Climate Compared to Injections of $SO_2$

*Iris Schuring, Timofei Sukhodolov and Jan Sedlacek in collaboration with ETH (Switzerland) and CSIC (Spain)*

Solar Radiation Modification (SRM) is a general description of different techniques to counteract human-induced climate change. One of these ideas is to inject aerosols into the stratosphere and thus reduce the incoming solar radiation. In this study, we investigate the climatic impacts of different injected materials. In particular, the effect of sulphur, alumina, calcite and diamonds on the ocean properties are examined in more depth. The large heat capacity of the ocean acts as a memory effect for the future climate. Variations of ocean properties may thus have a large impact on the long-term climate state.

Traditionally, SRM through stratospheric aerosol injection (SAI) uses sulphur as injected material. However, sulphur not only reflects back solar radiation, it has also the property of absorbing the solar radiation and thus heating the lower stratosphere. This in turn modifies the dynamics of the stratosphere substantially and through coupling with the troposphere the climate at the surface is altered. These side-effects of SAI are not desired, and thus alternative materials are explored. Ideally these alternative materials would scatter back the shortwave radiation to space without absorbing the radiation. In the SOCOL4 model, different alternative aerosols are implemented, which have close properties to the ideal SRM aerosol, namely alumina, calcite and diamond. These particles reduce the side-effects (see for example Stefanetti et al. (2024)).

In this study, we especially examine the behaviour of the ocean under SRM scenarios with different types of aerosols. The ocean plays a critical role in shaping the climate because of its large heat capacity. It acts as a smoother of short-term climate variability. However, it also acts as a long-term memory of changes in climate, especially if the deep ocean is affected. As the base scenario, SSP5-8.5 is chosen, and the target scenario is SSP2-4.5. The simulations are computed until the end of the century with the four different aerosol types under a SSP5-8.5 scenario. At each decade, the aerosol loading is evaluated, and the injection load is recalculated in order to get the global mean temperature as close to the SSP2-4.5 as possible. The injection occurs in the tropics on the prime meridian. Newer injection scenarios suggest that it would be better to inject the aerosols in different places between the northern and southern mid-latitudes.

In Figure 1, the maximum Atlantic Meridional Overturning Circulation (AMOC) is shown. This is a measure of how much deep water is formed. The AMOC of the SSP5-8.5 scenario decreases by about 4-5 Sv during the 21$^{st}$ century and thus the transport of surface waters to the deep ocean will decrease. In the SRM scenarios, the AMOC can be kept close to the SSP2-4.5 values except for the sulphur scenario during the 2060s. Since the behaviour of the AMOC is quite similar between the SRM scenarios, the temperature distribution below the thermocline is also very similar between the SRM scenarios (not shown).

Close to the surface of the ocean, some regional side-effects are visible between the different aerosol types (not shown). Generally speaking, the tropical region is colder compared to the SSP2-4.5 temperatures and the mid-latitudes are warmer. On one hand this might be due to the injection scenario, i.e., where the aerosols are injected into the stratosphere. On the other hand, it is a result of dynamical and thermodynamical changes due to the side-effects. The temperature anomalies are visible to a depth of about 1000 m in the sulphur and alumina case, and to about 600 m for the calcite and diamond scenarios. The strongest side-effects are visible if sulphur is injected, followed by alumina, calcite and diamond. In the region of the sea-ice edge in the Arctic, there is a positive sea surface temperature anomaly in all the SRM scenarios. This change in temperature is related to shifts in insulating sea-ice ice cover.

Acknowledgement: This work is supported by the Simons Foundation.

References: Stefanetti, F., Vattioni, S., Dykema, J. A., Chiodo, G., Sedlacek, J., Keutsch, F. N., Sukhodolov, T.: 2024, Stratospheric injection of solid particles reduces side effects on circulation and climate compared to $SO_2$ injections, Environ. Res., Climate, 3(4), 045028, https://doi.org/10.1088/2752-5295/ad9f93

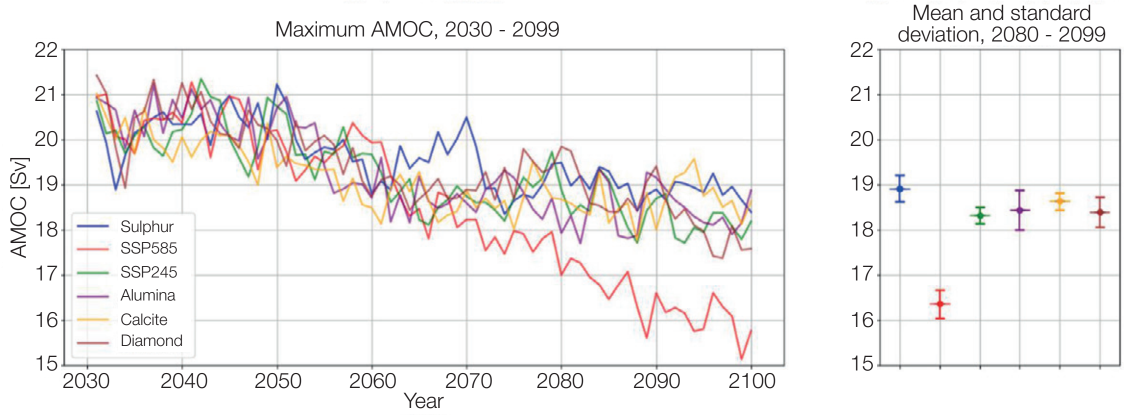



*Figure 1. The maximum Atlantic Meridional Overturning Circulation (AMOC).*

## Calibration of Three Novel Personal UV Dosimeters

*Gregor Hülsen, Salim Ferhat and Julian Gröbner*

The WCC-UV is participating in Work Package 1 of the MeLiDos (Metrology for wearable light loggers and optical radiation dosimeters) Project running in the frame of the European Partnership in Metrology (EPM). In the first year of the project, three UV dosimeters were characterised for their relative spectral and angular responsivity (SRF and ARF). The absolute sensitivity was determined by outdoor measurements relative to the Qasume reference spectroradiometer. The associated uncertainties of the calibration are similar to standard UV radiometers.

The MeLiDos project started in June 2023. The main task for the WCC-UV is the calibration of the ultraviolet (UV) dosimeters selected for this activity. The main difference between personal dosimeters and standard UV radiometers is their very compact design and data accessibility, which only use mobile phone applications. Three different dosimeters have been selected so far:

- SunSense Pro
- Sglux UVMicrolog
- Scienterra Waveband

The first two instruments have one UVB channel, while the Scienterra Waveband has six channels in total from UVB to the infrared. At PMOD/WRC, only the UVB channels were considered. For this project, the SunSense data was read out using a dedicated APK supplied by the manufacturer using an Android mobile phone. Scienterra dosimeters were connected to a serial interface board and the Sglux instrument was read out using an USB interface connected to a PC. The calibration of the dosimeters follows the procedure described by Hülsen and Gröbner (2007). The SRF measurements were carried out in the laboratory. Due to the independent data acquisition, special care was taken to synchronise the wavelength setting of the tunable source with the sampling of the dosimeter. The SRFs of the Scienterra D3001 and SunSense 310822 showed significant deviations from the erythmal action spectra in the UVB and UVA spectral range while the Sglux 187 is in good accordance with the erythemal action curve. The measured ARFs show large deviations from a Lambertian receiver, especially for larger zenith angles. Figure 1 shows the cosine error of the dosimeters. At 70°, the cosine error is 20% and rises even further to 60%. This leads to a diffuse cosine error of 0.814 (Scienterra), 0.915 (sglux) and 0.905 (SunSense).

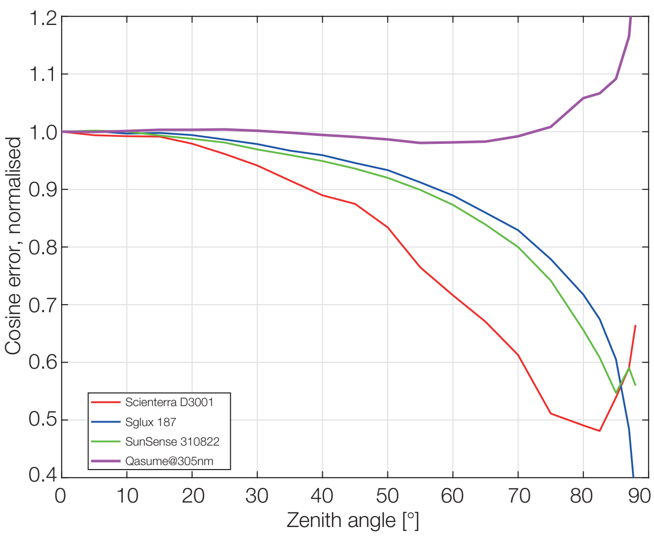



*Figure 1. Cosine error of the selected three dosimeters. The magenta line shows the cosine error of the Qasume input optic for comparison.*

*Figure 2. Outdoor calibration showing the four dosimeters: two Scienterra (front left), Sglux (front right), and SunSense (back left).*

The outdoor responsivity calibration was affected by poor weather conditions in the autumn of 2024. Only one day could be used for the calibration in September and two days in October. The latter are, however, outside of the nominal calibration period due to solar zenith angles larger than 50°. Figure 2 shows how the devices were mounted on the roof platform at PMOD/WRC. Because of its rounded shape, the levelling of the SunSense induces a larger total uncertainty of 5.9%. This is also true for the ARF measurement described above. Table 1 summarises the results of the outdoor calibration. Both the Sglux and the SunSense manufacturer calibrations were well inside the calibration uncertainty. No manufacturer calibration is currently available for the Scienterra dosimeter. All expanded uncertainties shown in Table 1 are comparable to standard UV radiometers. The larger uncertainty of the SunSense is caused by levelling problems.

*Table 1. Calibration factor of the dosimeters with the expanded uncertainty U.*

| | Scienterra D3001 | Sglux 187 | SunSense 310822 |
|---|---|---|---|
| C | 0.02009 mW$^2$/cnts | 1.00071 | 1.04703 |
| U | 4.5% | 3.3% | 5.9% |

Acknowledgement: The project 22NRM05 has received funding from the EPM programme co-financed by the Participating States and from the EU Horizon 2020 research and innovation programme.

References: Hülsen, G., Gröbner, J.: 2007, Characterisation and calibration of ultraviolet broadband radiometers measuring erythemally weighted irradiance, Applied Optics, 46, 5877-5886, https://doi.org/10.1364/AO.46.005877

## Time-Series of Quality Controlled Surface-Based Total Ozone Measurements from Nairobi, Kenya

*Luca Egli and Julian Gröbner in collaboration with MeteoSwiss (Switzerland) and Kenya Meteorological Department (Nairobi, Kenya)*

The Kenya Ozone Monitoring Station, based at the Kenya Meteorological Department in Nairobi, is the only ozone monitoring facility in equatorial Africa. Operating since 1984, it uses Dobson and Brewer spectrometers and balloon-based soundings under NASA's SHADOZ programme. Satellite comparisons confirm consistent data, however, the Brewer instrument requires field re-calibration. Despite challenges, its reliable measurements are important for tracking ozone trends globally. Since February 2024, PMOD/WRC is in charge of both quality assurance and scientific valorisation of data from the station, further enhancing its contribution to atmospheric research.

Since 1984, the regional GAW (Global Atmosphere Watch) station in Nairobi has been an important station of ozone monitoring in equatorial Africa. Situated at the Kenya Meteorological Department (KMD) headquarters in Dagoretti Corner, Nairobi, at an altitude of 1795 meters above sea level, this station is the only active ozone monitoring facility in the region. This makes it a critical resource for global ozone data collection and research at the equator. The station began its work with the Dobson 018 spectrophotometer, manually operated (Figure 1) at the University of Nairobi from 1984 to 1999. After a failure in 2002, it was refurbished by experts from the Czech Hydrometeorological Institute, Deutscher Wetterdienst, and the support of MeteoSwiss. Resuming operations in 2005 under KMD, it continues to receive operational and scientific support from MeteoSwiss for sustained data quality and reliability.

In 2019, ozone monitoring advanced with the installation of the automatic Brewer 071 spectrometer, donated by Environment Canada and calibrated in Arosa, Switzerland. By 2020, both instruments were integrated into standard quality assurance protocols provided by PMOD/WRC in Davos. In addition, since 1998, the station has conducted balloon-based ozone soundings as part of NASA's SHADOZ program (Thompson et al. 2024), providing detailed vertical ozone profiles. Since February 2024, PMOD/WRC has also taken responsibility for the scientific valorisation of data from Nairobi. In this respect, ground-based measurements are compared with satellite data, including a merged product from AURA-TOMS. Long-term comparisons show a difference of 2.5%, narrowing to just 1% since 1996 (Figure 2). However, the larger bias observed before 1996 remains unexplained and warrants further study. The Brewer 071 instrument has shown a bias of 2.7% compared to the Dobson 018 (Figure 1). Part of this discrepancy of about 1.2% is attributed to differences in ozone temperature and cross-section data used in the analysis. However, the larger bias of about 1.5%, observed in Nairobi, highlights the need for re-calibration of the Brewer spectrometer. Ozone data from SHADOZ soundings reveal a small bias (-1.5%) relative to Dobson measurements (Figure 1), confirming the reliability of these methods during 2005 - 2020. Therefore, the station remains essential for tracking ozone trends in equatorial regions

*Figure 1. Manual measurements of total column ozone with the Dobson D018 in Nairobi, Kenya.*

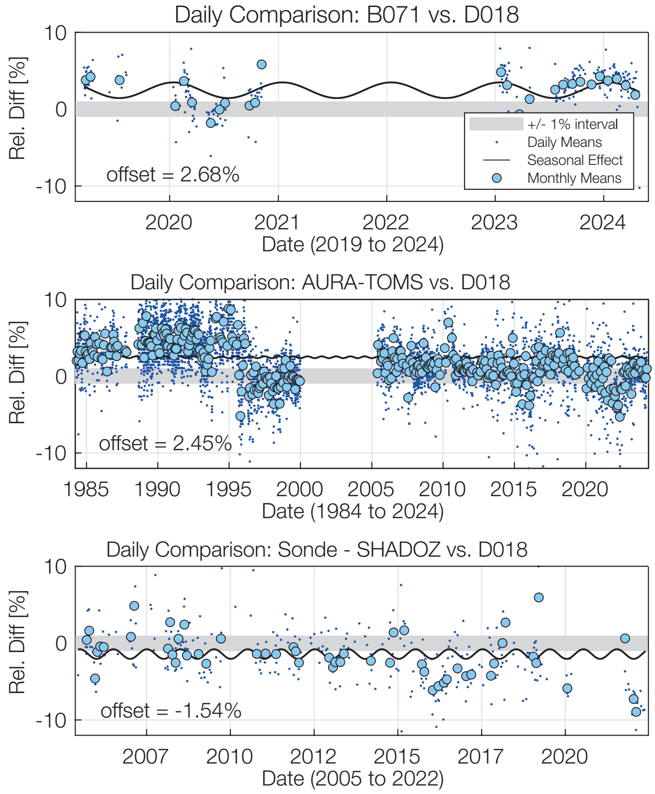



*Figure 2. Long-term relative differences of Brewer 071, AURA-TOMS satellite data and SHADOZ ozonesondes to Dobson 018.*

Acknowledgment: Jörg Klausen, Gonzague Romanens and Christian Félix (all three from MeteoSwiss) and Syprose Nyadida and Josiah Kariuki (both from Kenya Meteorological Department) are acknowledged for their extensive work on the Nairobi data.

References: Thompson, A. M., Witte, J. C., Oltmans, S. J., Schmidlin, F. J.: 2004, SHADOZ-A tropical ozonesonde-radiosonde network for the Atmospheric Community, Bull. Am. Meteorol. Soc., 85, 1549-1564,1215, https://doi.org/10.1175/BAMS-85-10-1549

## A Primary Irradiance Standard for Spectroradiometer Calibration

*Salim Ferhat, Gregor Hülsen and Julian Gröbner in collaboration with SINTEF (Norway), JV (Norway)*

Improved predictable quantum efficient photodetectors provide exceptionally reliable measurements in the visible range, which find potential in numerous applications, especially in metrology. Efforts to extend the spectral range into the UV have included studying the risk of damage caused by UV exposure to detectors. In addition, results have been obtained to integrate a standard detector as a primary reference into an optical setup for in-lab spectral calibrations of spectroradiometers.

The S-CALe Up (Self-calibrating photodiodes for UV and exploitation of induced junction technology) project aims to develop a photonic, self-calibrating, easily integratable measurement system based on the Predictable Quantum Efficient Detector (PQED). PQED is a trap-structured detector with extremely low charge-carrier losses and an external quantum deficiency below 100 ppm (Porrovecchio et al., 2022). This detector has shown remarkable stability over time, with no detectable drift after 10 years of continuous operation (Koybasi et al., 2021). As a result, a PQED approximates an ideal quantum detector, producing a photocurrent that directly links the optical power of the source to the fundamental constants.

These properties offer remarkable potential for various applications such as photonic integrated sensors, and medical diagnostic instruments, as standards for lab-based calibration procedures in metrology ("NMI-on-a-chip"). The UV range is particularly important for the health and atmospheric sciences. However, current PQEDs lack stability in the UV range, with risk of damage after UV exposure. As part of the S-CALe Up project, PMOD/WRC has contributed to the development of a new generation of PQEDs by investigating the effects of UV exposure (325 nm) of the detector's active surface. Samples of PQED photodiodes were irradiated at 325 nm with doses ranging from 10 J/cm² to 100 J/cm². Responsivity studies at 473 nm (visible) and 325 nm (UV) after UV exposure, and real-time photocurrent monitoring during UV exposure, showed no signs of degradation in the PQED photodiodes. This conclusion oriented the project focus on UV degradation occurring at wavelengths below 300 nm.

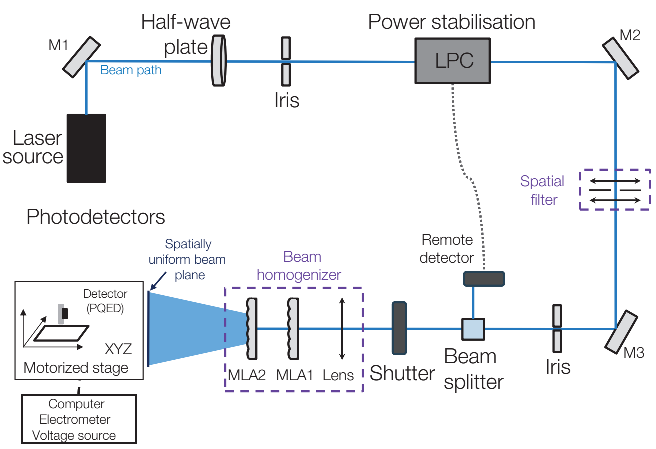



*Figure 1. Schematics of the optical setup combining the PQED with a stable, uniform, monochromatic light source.*

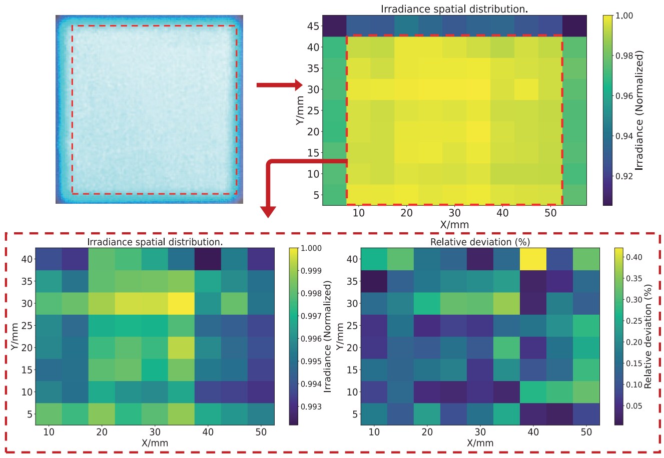



*Figure 2. Homogenised "flat-top" beam (image) and its spatial irradiance distribution obtained through detector scanning measurements. The beam is used for instrument calibration.*

Furthermore, PMOD/WRC intends to exploit this technology as a primary reference for spectral irradiance in-lab calibration of spectroradiometers and shortening its traceability chain to the SI units. The PQED has been combined with a temporally ultra-stable, spatially uniform monochromatic light source in an optical setup (Figure 1). In this system, the laser power drifts within ±40 ppm over multiple hours of continuous operation, and the laser beam is expanded into a 40 x 40 mm$^2$ "flat-top" irradiance distribution with uniformity above 99.5% (Figure 2). Multiple comparisons between PQED-based primary irradiance standard and traditional 1 kW FEL lamp-based irradiance calibrations (Gröbner and Sperfeld, 2005) at 473 nm have been conducted. The relative differences of the obtained irradiances, measured with both approaches, were below 0.8%, which falls within the combined uncertainty of calibrations using transfer standards.

The feasibility of using this optical system as a primary reference for spectral irradiance at selected wavelengths in laboratory calibrations of spectroradiometers has been demonstrated. Further understanding and optimisation of PQED performance, when the measured beam is expanded and overfills the aperture of the detector, is required. As an end-user, PMOD/WRC showed the utility and applicability of the PQED for spectroradiometer metrological applications, which is necessary to increase the technological readiness level for the S-CALe Up project.

Acknowledgement: The project 22IEM06 has received funding from the EPM programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

References

Gröbner J., Sperfeld, P.: 2005, Metrologia, 42, 134-139, https://publications.jrc.ec.europa.eu/repository/handle/JRC31611

Koybasi, O., et al.: 2021, Sensors, 21, 7807, https://doi.org/10.3390/s21237807

Porrovecchio, G. et al.: 2022, Metrologia 59, 065008, https://doi.org/10.1088/1681-7575/ac938c

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

*Stelios Kazadzis, Natalia Kouremeti, Akriti Masoom and Harmonia COST Action Collaborators*

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. Harmonia‘s grant-holder institute is PMOD/WRC. The main aim of the Harmonia COST Action is: “To Establish a network involving institutions, instrument developers, scientific and commercial end-users, in order to improve, homogenise and valorise 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. Common retrieval techniques of aerosol columnar properties, consist of 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 a 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 and hardware developers is needed. The objective of the Harmonia Action 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 interactions and knowledge exchanges between several atmospheric aerosol network measurement scientists and users.

• Standardising and improving existing aerosol products and tools, towards a “harmony” in the aerosol photometry.

• Stimulating the communication between operational agencies and academia with the aim of increasing 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.

To achieve the main objectives of Harmonia, networking is a key aspect since different instruments/networks and related algorithms have to be unified. During the first two years of the Harmonia Action, we managed to create a network of 140 members dealing with aerosol sun photometry and aerosol remote sensing. During 2024, Harmonia organised two schools for early career researchers, workshops for stakeholders and a Harmonia session in the European Meteorological Society conference with 19 oral presentations and 12 posters related to Harmonia. In addition,

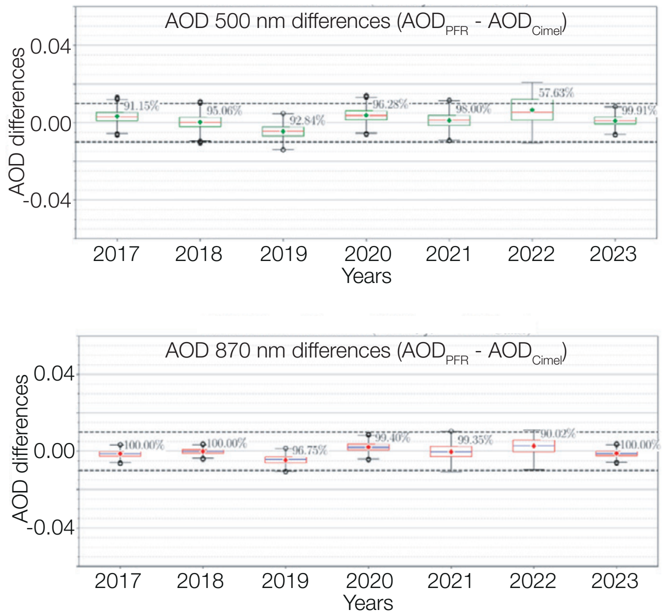



*Figure 1. AOD differences ($AOD_{PFR}$ - $AOD_{Cimel}$) at: upper panel) 500 nm and lower panel) 865 nm. The mean differences (rhombus) and the median differences (line) are shown within each box. The percentages show the proportion of values within WMO limits. The black dashed lines represent the ±0.01 limits.*

during the first two years, 17 publications have acknowledged Harmonia-related work. Finally, a number of short-term scientific missions (9), virtual mobility grants (27) and IT conference grants (10) were awarded.

Various aspects on sun-photometry were dealt with during the first two years of HARMONIA. One of them was the “differences and harmonisation possibilities in AOD retrieval methods”. One example is the exploitation of long-term series of AOD measurements with different instruments. As an example, a 7-year comparison of a CIMEL and PFR instrument at Lindenberg Observatory (Germany) is shown in Figure 1.

The foreseen impacts of Harmonia are focused on different research communities. Harmonia-related work 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 aerosol modelling applications, that have a more direct impact on important aspects, such as: climate (Earth’s radiative balance, solar energy potential and use), health (air quality) and weather (aerosol assimilation related).

All Harmonia publications can be found at: https://harmonia-cost.eu/publications

A list of all science awarded grants and their related reports can be found at: https://harmonia-cost.eu/grantees

HARMONIA deliverables can be found at: https://harmonia-cost.eu/deliverables

## Traceability of the GAW-PFR reference Precision Filter Radiometers to the SI

*Natalia Kouremeti, Julian Gröbner and Stelios Kazadzis, in collaboration with PTB (Braunschweig, Germany)*

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

Within the framework of the Global Atmosphere Watch (GAW) programme, Aerosol Optical Depth (AOD) is monitored based on direct solar irradiance measurements performed by Precision Filter Radiometers (PFRs). All instruments are calibrated against the WMO AOD reference (GAW-PFR TRIAD), which is maintained and operated at PMOD/WRC. PFR 98-N-001 is part of the GAW-PFR TRIAD and its stability is monitored on a yearly basis against Langley calibrated travelling standards and/or Langley calibration at the GAW-PFR network calibration sites, Izaña and Mauna Loa.

The equivalence of SI-traceable AOD retrievals to those from standard Langley ones was demonstrated in Kouremeti et al. (2022), and was based on the TSIS 1 HSRS (Coddington et al., 2021) and QASUMEFTS (Gröbner et al., 2017) high resolution ToA solar spectra, and PTB calibration of PFR-98-N-001. The SI-traceability of this PFR, is monitored within the framework of the EURAMET 1161 project, establishing a long-term collaboration with PTB, with the aim of linking the GAW-PFR TRIAD to SI, and to have a better understanding of the capabilities of a laboratory calibration. PFR-98-N-001 has been calibrated three times at PTB in intervals of approximately 3 years. The instrument has shown remarkable stability, with integrated spectral responsivity degradation rates ranging from 0.08%/yr to 0.33%/yr, while the shape of the responsivity of the four channels and centroid wavelengths shows negligible differences (Table 1).

In Figure 1, the change of the responsivity based on the Langley transfer and laboratory calibrations (normalised to 2021) are presented. The degradation of the four channels is monitored by two independent methodologies, within less than 0.5%. The PFR-98-N-001 laboratory calibrations combined with the current state of the art ToA high resolution solar spectra TSIS 1 HSRS and QASUMEFTS agree with the Langley based calibration to within 0.5% for the 500 nm and 863 nm channels and within 0.7 - 1.0% for the 368 nm and 412 nm ones, depending on

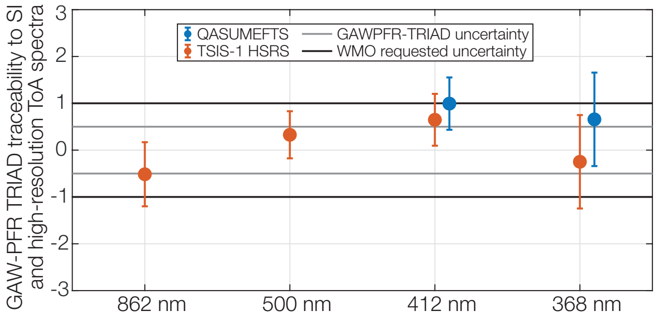



*Figure 2. GAW-PFR-TRIAD traceability to the SI based on the 3 PTB calibrations and the ToA solar irradiance spectra QASUMEFTS and TSIS 1 HSRS for the 4 PFR channels. The error bars represent the relative combined uncertainty (k = 2) of the difference, accounting for the calibration uncertainty and standard deviation of the difference for N01.*

the ToA spectrum (Figure 2). The relative combined expanded uncertainty of the difference is 1.0% for the 368 nm channel and less than 0.7% for the others. Accounting for the uncertainty of the GAW-PFR TRIAD (less than 0.8%, k = 2) the current status of the traceability to the SI is better than 1.0 ± 1.3%, opening new calibrations possibilities for the retrieval of AOD with the recommended WMO accuracy.

*Table 1. Responsivity and CW changes of PFR-98-N-001 based on PTB calibration relative to the reference 2021 calibration. Change in responsivity with respect to the 2021 calibration (%). Change in centroid wavelength (pm).*

| | 863.0 nm | 500.8 nm | 412.0 nm | 367.6 nm |
|---|---|---|---|---|
| 2018, Dec. | 0.27 (58) | 0.40 (10) | 0.81 (5) | 0.80 (0) |
| 2024, Aug. | -0.28 (0) | -0.34 (0) | -0.92 (2) | -1.00 (-2) |

Acknowledgements: We would like to thank the PTB team Saulius Nevas, Kerstin Schwind, Philip Schneider, for making this work possible. This work has been supported by EMPIR 19ENV04 MAPP and EURAMET-1161 projects.

References: Coddington, O. M., et al.: 2021, Geophys. Res. Lett., https://doi.org/10.1029/2020GL091709

Gröbner, J., et al.: 2017, Atmos. Meas. Tech., https://doi.org/10.5194/amt-10-3375-2017

Kouremeti, N., et al.: 2022, Metrologia, https://doi.org/10.1088/1681-7575/ac6cbb

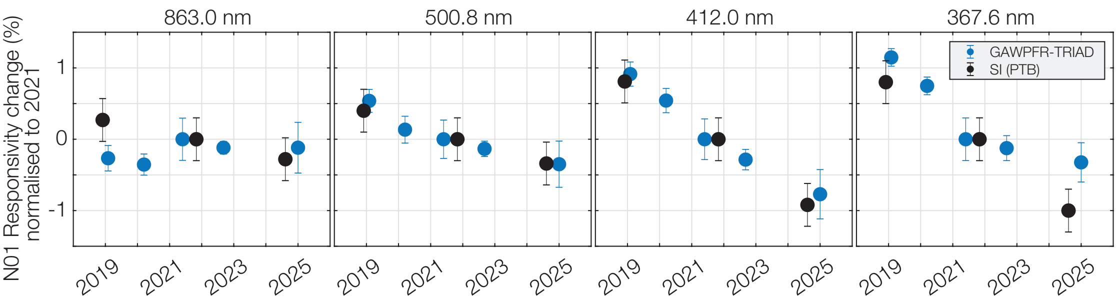



*Figure 1. Changes in the responsivity of PFR-98-N-001 based on Langley-transfer (blue) and PTB laboratory (black) calibrations. The responsivities are normalised to the 2021 calibration while error bars show the relative combined expanded uncertainty of the calibration.*

## Solar Radiation/Energy Research at PMOD/WRC

*Stelios Kazadzis, Kyriaki Papachristopoulou and Xinyuan Hou in collaboration with NOA (Greece) and Armines ParisTech (France)*

Scientific research focused on estimating and forecasting solar energy levels reaching the Earth's surface is crucial for supporting solar energy production and management, from rooftop installations to large-scale solar parks. PMOD/WRC participates in various EU-funded projects related to solar radiation and energy research (Eiffel, Excelsior, E-Shape) dealing with aerosol and cloud effects on incoming solar radiation nowcasts and forecasts.

The NextSENSE2 operational system has been upgraded and validated. This system produces real-time estimates (nowcasting) and forecasts of surface global horizontal irradiance (GHI) up to 3 hours ahead, with high spatial (~5 km) and temporal (15 minutes) resolution, for a domain covering Europe and the Middle East/North Africa region, based on Earth observation (EO) data (Papachristopoulou et al., 2024). The estimates of GHI for cloudless conditions are pre-calculated from the previous day using fast radiative transfer model techniques and all relevant atmospheric parameters as inputs, with atmospheric aerosols being the most significant under cloudless conditions. The Copernicus Atmospheric Monitoring Service forecasts provide the aerosol input. The NextSENSE2 GHI forecasts are based on a cloud motion vector technique applied to MSG satellite images. For benchmarking, we compared our model (green points) with the persistence forecasting method (black points), which assumes the same cloud conditions for future time-steps. Results for 10 ground-based baseline surface radiation network stations are presented in Figure 1.

EO data and very high resolution digital surface models were used in order to explore the effects of clouds and aerosols in combination with shadows on solar energy potential on urban rooftops (Figure 2). The results of this investigation show that the atmosphere and building shadows lead to a monthly solar radiation loss of 30 - 60 kWh m$^{-2}$ on urban rooftops in Athens (Greece). The monthly cloud effect reaches up to 30%, whereas aerosols and shadows generally account for <5% of the reduction in solar radiation received on rooftops in most months. Findings demonstrate the use of radiative transfer modelling in quantifying atmospheric and building shadowing effects on urban rooftop solar energy systems.

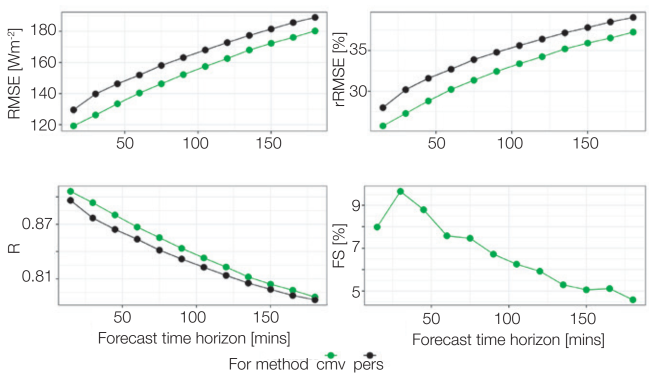



*Figure 1. Performance statistics for forecasted global horizontal irradiance (GHI) by NextSENSE2 (green points) and by the persistence method (black points) for every 15 minute time-step up to 3 hours ahead.*

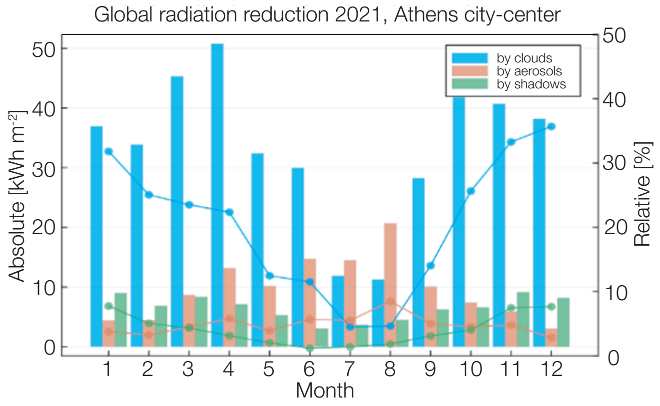



*Figure 2. Monthly global radiation reduction by clouds (blue), aerosols (orange) and shadows (green) in the city-center of Athens in 2021 in absolute terms (kWh m$^{-2}$, bars based on the left-hand y-axis), and relative terms (%, curves based on the right-hand y-axis).*

Given certain cloud fractions in the sky, derived from satellite observations or sky images, surface solar radiation (SSR) attenuated by clouds can differ when the sun is visible (based on sunshine duration threshold defined by the World Meteorological Organisation) or shaded by clouds. Thus, sun visibility is among the most uncertain factors in solar forecasting. With sky images taken by sky cameras and solar radiation measurements at the World Radiation Center in Davos, this work examines the relationship between cloud cover and sun visibility. By integrating sun visibility into a forecasting system, an improvement in accuracy and reliability of the SSR forecast is envisaged.

Towards this goal, intra-hour solar radiation forecasting based on sun visibility for different cloud types was derived. We integrated sun visibility into a forecasting system based on a multivariate deep learning model based on a Long- and Short-term Time-series network. The model is trained with extensive cloud information including cloud fraction and cloud types extracted from sky images taken at a ground station and predicts intra-hour (15 minutes to 1 hour forecast) sun visibility and the cloud modification factor (CMF).

With the distinct patterns of visible and occulted sun, initial CMF forecasts are post-processed, based on the prediction bias. The experimental results show a high accuracy of 96% for the 15-minute forecast of sun visibility. Compared with the persistence reference, our forecast method achieved a significant skill score of 47% for the 15-minute forecast. Higher skill scores were found for certain cloud types, e.g. 55% for stratus-altostratus.

References: Papachristopoulou, K., et al.: 2024, Effects of clouds and aerosols on downwelling surface solar irradiance nowcasting and short-term forecasting, Atmos. Meas. Tech., 17, 1851-1877, https://doi.org/10.5194/amt-17-1851-2024

## Retrieval of Aerosol Size Properties from Aerosol Optical Depth Observations

*Angelos Karanikolas, Natalia Kouremeti, Julian Gröbner and Stelios Kazadzis in collaboration with GRASP-SAS (France), University of Lille (France) and Deutscher Wetterdienst (Germany)*

Sun photometers provide direct solar radiation measurements suitable for the retrieval of aerosol optical depth (AOD) at measurement frequencies ranging from one measurement every 1 to 15 minutes. Additional aerosol properties can be retrieved using sky radiance measurements, which are performed once per hour and are further limited by partial cloud cover. In this study, we investigate the capabilities and limitations of retrieving the parameters that define the aerosol size distribution using only AOD measurements as input to the inversion model, Generalized Retrieval of Aerosol and Surface Properties (GRASP), and the effect of aerosol properties on the accuracy of the retrievals.

Aerosols are a crucial atmospheric component affecting weather, climate and air quality. One of the most important parameters related to aerosol climate effects is the aerosol optical depth (AOD), which describes their overall direct effect on the extinction of incoming solar radiation. AOD is measured by sun photometers, sometimes organised in large networks on a global scale. Since aerosols are a mixture of particles with different shapes, sizes and chemical compositions, there are several aerosol properties that influence their interactions with radiation and ecosystems. Aerosol size is a key parameter related to different effects. Smaller aerosols, which are more commonly emitted by human activities, tend to be more hazardous when inhaled and scatter mostly the shorter wavelengths of solar radiation. Larger aerosols constitute the majority of naturally emitted aerosols and their interaction with different radiation wavelengths is more uniform (indicated by weaker AOD spectral dependence, as represented by the Ångström Exponent or AE). The size of the aerosols also affects their absorptivity and their interactions with clouds.

In this study, we focus on the parameters describing the aerosol size distribution (SD) of the total aerosol column (corresponding to the whole atmosphere). These parameters are the volume concentration ($C_V$), volume median radius ($R_V$), and geometric standard deviation ($\sigma_V$) of each SD mode. The SD is typically retrieved through inverse modelling of sky radiance measurements, but the availability of such data is limited. However, methodologies exist that allow the inversion of these parameters using only AOD as an input while also providing an *a priori* aerosol complex refractive index (RI). The model we used here is the Generalized Retrieval of Aerosol and Surface Properties (GRASP) (Torres and Fuertes, 2021), which also separates AOD into the fine ($AOD_f$) and coarse modes ($AOD_c$). Using the retrieved SD parameters, we can also compute the total volume concentration ($C_{VT}$, the integral of the entire SD) and the effective radius ($R_{eff}$, a weighted average radius) of aerosols. Our aim was to retrieve SD parameters using the AOD measurements from the Precision Filter Radiometers (PFRs) belonging to the GAW-PFR (Global Atmosphere Watch-Precision Filter Radiometer) network and assess the accuracy of the output. To validate the PFR AOD-based retrievals of SD parameters (GRASP-PFR), we selected four stations with different characteristics that overlap with the AErosol RObotic NETwork (AERONET) and compared the GRASP-PFR output with the sky radiance retrievals provided by AERONET (AER-SKY). The stations are: i) Davos in Switzerland, ii) Izaña in Tenerife, Spain, iii) Hohenpeissenberg, and Lindenberg in Germany. The comparisons showed good agreement for the AOD modal separation and volume concentrations (examples in Fig. 1). The retrieval of the radii was less accurate but showed improvement for $R_{eff}$ and fine mode radius ($R_{Vf}$) when restricting the data to AOD at 500 nm > 0.1 and AE > 1 (or small $R_{eff}$). The coarse mode radius ($R_{Vc}$) showed very low sensitivity to the provided AOD. We also repeated the retrievals with different RI selections: one being the climatology per station and another being a fixed value for all stations and months. We found no significant effect from the RI assumptions on the comparisons.

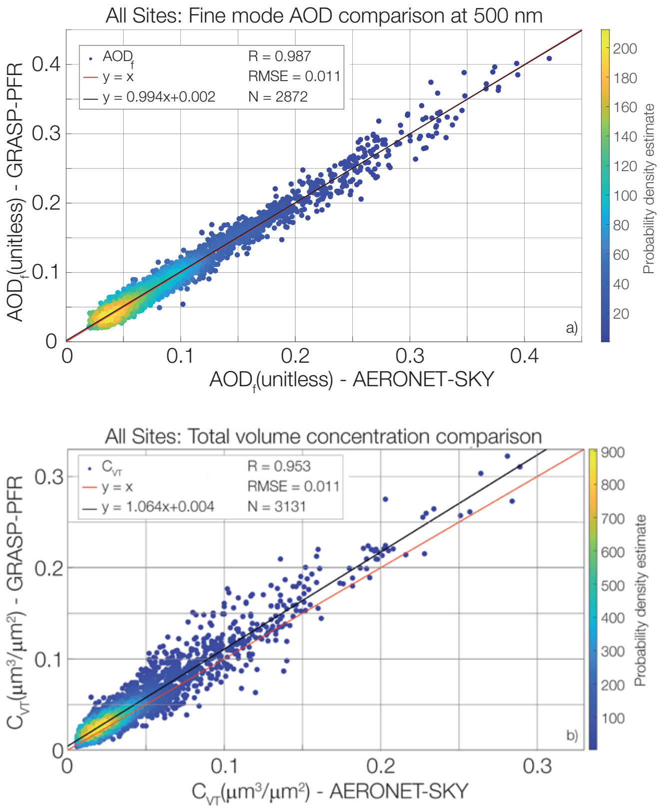



*Figure 1. Scatter plot of: a) $AOD_f$, and b) $C_{VT}$, between the AERONET output (x-axis) and GRASP retrievals using PFR AOD (y-axis). The plots include the linear fit parameters between the datasets: correlation coefficient (R), root mean square error (RMSE) and the linear fit equation.*

In summary, our study demonstrates that we can achieve reliable retrievals of AOD modal separation and volume concentrations, as well as effective and fine mode radius under certain conditions using the PFR AOD as a known input parameter to GRASP. This indicates that it is possible to expand the output parameters of the GAW-PFR network and enhance the data availability of SD parameters in particular cases.

References: Torres, B., Fuertes, D.: 2021, Characterization of aerosol size properties from measurements of spectral optical depth: a global validation of the GRASP-AOD code using long-term AERONET data, Atmos. Meas. Tech., 14, 4471-4506, https://doi.org/10.5194/amt-14-4471-2021

## Comparison of Solar Spectral Irradiance Measurements with Pyrheliometer Total Solar Irradiance Data

*Dhrona Jaine and Julian Gröbner*

Accurate solar irradiance measurements are essential for solar energy optimization, climate modelling, and environmental research. This study compares total solar irradiance (TSI) pyrheliometer data with integrated spectral solar irradiances from a BTS spectroradiometer system by extending its spectral range to 5000 nm using a radiative-transfer model.

Solar irradiance measurements play a crucial role in advancing knowledge on the atmosphere and processes, climate modelling, and environmental research. Pyrheliometers have been the standard instrument to measure reliable Direct Normal Total Solar Irradiance (DNI) readings for decades and are traceable to the World Radiometric Reference (WRR). However, these instruments provide data for the entire integrated solar spectrum as a single value, without detailed information about the spectrum's distribution, which limits their use in studying spectral solar irradiance.

We are evaluating a spectroradiometric system composed of two compact array spectroradiometers measuring the direct spectral solar irradiance over the spectral range from 300 nm to 2150 nm, and traceable to the SI using laboratory-based calibrations (Gröbner et al., 2023) and comparing it to a collocated pyrheliometer.

The BTS spectroradiometer captures nearly 97 % of the total irradiance contained in the solar spectrum, spanning the ultraviolet, visible, and part of the infrared regions. However, the remaining approximate 3 % of the total solar irradiance is significant as it influences accurate energy modelling, climate studies, and comparison to total solar irradiance standards, such as the pyrheliometer.

To account for this missing portion, we used Libradtran, an atmospheric radiative transfer model, which extends the solar spectrum from 2150 nm to 5000 nm, enabling the comparisons between the BTS spectroradiometer and pyrheliometer data. Although Libradtran provides accurate spectral extensions, its computational intensity poses practical challenges. So, to tackle the difficulty, we developed a function using sensitivity analysis, identifying critical parameters influencing spectral behaviour, including solar zenith angle, water vapour, and aerosol characteristics such as the Ångstrom parameters, $\alpha$ (particle size distribution) and $\beta$ (aerosol loading). This function closely matched the results from Libradtran and achieved high precision with a mean value of 96.52 % and a standard deviation of 0.20 %.

The comparison presented in Figure 1a highlights the good agreement between the total solar irradiances from the BTS and those from the pyrheliometer. As shown at the bottom of Figure 1 (b), the mean ratio between BTS and pyrheliometer for TSI is 0.9897, with a relative standard deviation of 0.0149 for the whole of 2023. The observed differences are within the combined uncertainties of the BTS and pyrheliometer measurements, which are estimated to be of the order of 1.1 %. The study will be extended to the years 2024 and 2025. Furthermore, a detailed uncertainty budget for the total and spectral solar irradiances from the BTS will be established.

This development bridges the gap between broad-spectrum pyrheliometer data and high-resolution BTS measurements, ensuring detailed and traceable solar irradiance monitoring. It can also be used as a viable tool for advanced solar research.

References: Gröbner, J., Kouremeti, N., Hülsen, G., Zuber, R., Ribnitzky, M., Nevas, S., Sperfeld, P., Schwind, K., Schneider, P., Kazadzis, S., Barreto, Á., Gardiner, T., Mottungan, K., Medland, D., and Coleman, M.: Spectral aerosol optical depth from SI-traceable spectral solar irradiance measurements, Atmos. Meas. Tech., 16, 4667-4680, https://doi.org/10.5194/amt-16-4667-2023

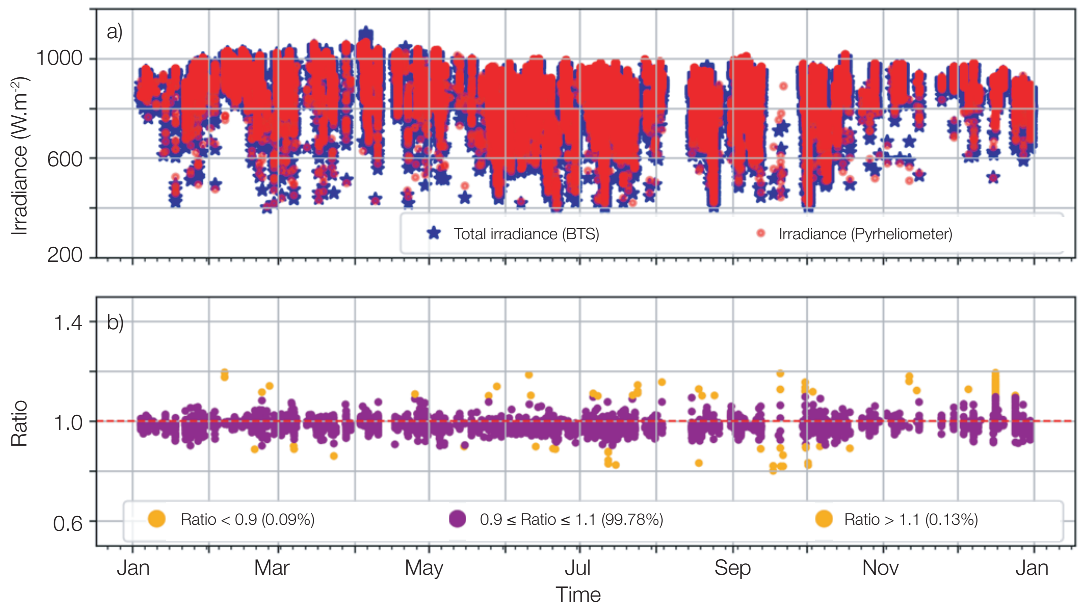



*Figure 1. Analysis of data from the year 2023. Panel a): comparison of total solar irradiance measured using a pyrheliometer and a BTS spectroradiometer. Panel b): ratio between the pyrheliometer and BTS measurements, with violet points indicating closely matching values (ratio between 0.9 and 1.1) and orange points highlighting deviations beyond this range.*

## Assessment of the $NO_2$ Contribution to Aerosol Optical Depth Measurements at Several Worldwide Co-Locations of Sunphotometers and Spectroradiometers

*Akriti Masoom and Stelios Kazadzis with collaborators from the ESA QA4EO project*

Aerosol optical depth (AOD) calculations from sun photometer direct sun measurements using the Lambert-Beer law requires an estimate of the contribution from atmospheric molecules and trace gases such as $O_3$ and $NO_2$. This analysis focused on the uncertainty in the representation of the $NO_2$ vertical column and its impact on AOD (columnar) uncertainty in the 340 - 500 nm spectral range. A global AOD measurement network uses satellite-based $NO_2$ for optical depth estimation in AOD calculations. The investigation of the differences of satellite-based $NO_2$ climatology from ground-based $NO_2$ measurement and the corresponding impact on AOD measurements showed that these differences can lead to AOD differences reaching to the limit or even above the reported AOD uncertainty at some locations.

This analysis deals with the impact of $NO_2$ absorption on aerosol optical depth (AOD) and Ångström exponent (AE) retrievals by sun photometers with accurate $NO_2$ optical depth estimation from co-located spectroradiometer (33 stations) measurements with ~7 years of data (2017 - 2023). Aerosol Robotic Network (AERONET) sun photometers use the OMI (Ozone Monitoring Instrument) satellite-based climatology for $NO_2$ optical depth representation, which was reconstituted using Pandora spectroradiometer-based (belonging to Pandonia Global Network: PGN) $NO_2$ measurements.

$NO_2$ absorption affects AOD measurements in the UV-Visible range, and the AOD bias was found to be affected by $NO_2$ differences, the most at 380 nm, followed by 440, 340, and 500 nm, respectively. AERONET AOD was found to be overestimated in half of the cases, while also underestimated in other cases as an impact of the $NO_2$ difference from "real" (PGN $NO_2$) values. About one-third of the 33 stations showed a mean difference in $NO_2$ and AOD (at 380 and 440 nm) above $0.5 \times 10^{-4}$ mol.m$^{-2}$ (two examples shown in Figure 1) and 0.002, respectively. However, under the extreme $NO_2$ loading case (i.e. 10 % highest differences)

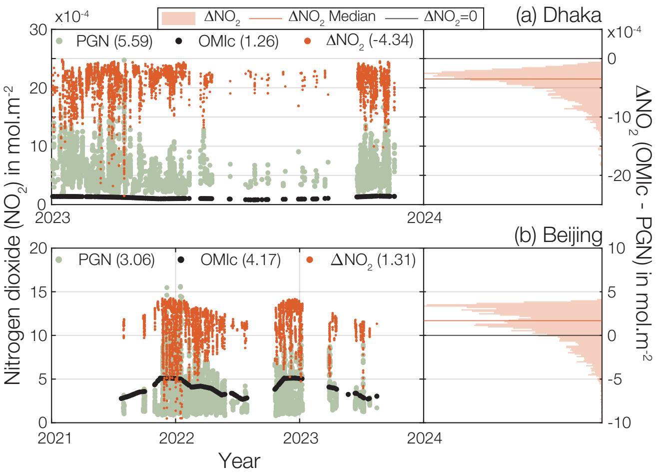



*Figure 1. Variation of $NO_2$ differences between the AERONET OMI climatology and Pandora (PGN) measurements at two stations.*

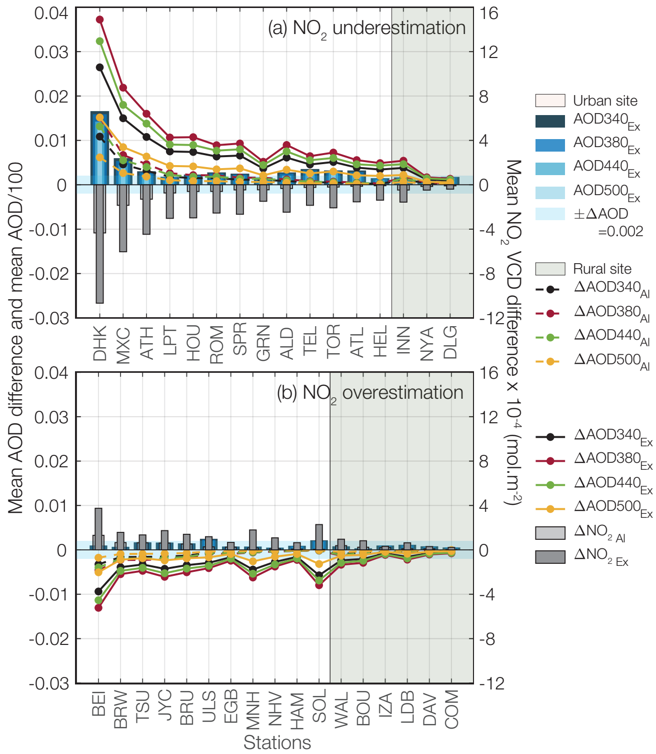



*Figure 2. Average $NO_2$ and AOD differences based on the AERONET OMI climatology and PGN measurements. "Ex" and "Al" represent Extreme and All case scenarios, respectively. (Please refer to Masoom et al. (2024) for more details about the stations).*

at urbanised/industrialised locations, higher AOD differences were observed (Figure 2) that were at the limit of or higher than the reported 0.01 (Giles et al., 2019) uncertainty in AOD measurement. The AOD derivative product, AE, was also affected by the $NO_2$ correction of the spectral AOD.

This analysis suggested that a satellite-based $NO_2$ climatology used for AOD calculations can be updated with a focus on urban areas that can have high diurnal variability in $NO_2$ concentrations. Different instrument/networks can potentially be used to improve stand-alone algorithms and retrievals using different outputs from co-located instrumentation (e.g., in this analysis the PGN $NO_2$ output was used as an input in AERONET AOD calculations). This analysis highlights the importance of an accurate $NO_2$ representation with the best possible scenario, however, concerning implementation into global AOD networks, satellite-based synergistism is required to account for spatial and temporal coverage.

Acknowledgement: ESA QA4EO project, ACTRIS Switzerland project and COST ACTION HARMONIA CA21119.

References: Giles, D. M., et. al.: 2019, Atmos. Meas. Tech., 12, 169-209, https://doi.org/10.5194/amt-12-169-2019

Masoom, A., Kazadzis, S., et. al.: 2024, Atmos. Meas. Tech., 17, 5525-5549, https://doi.org/10.5194/amt-17-5525-2024

# Publications and Media

## Refereed Publications


Agache, I., et al.: 2024, EAACI guidelines on environmental science for allergy and asthma: The impact of short-term exposure to outdoor air pollutants on asthma-related outcomes and recommendations for mitigation measures., Allergy, 1–31, https://doi.org/10.1111/all.16103.2024

Almansa, A. F., et al.: 2024, The Langley ratio method, a new approach for transferring photometer calibration from direct sun measurements, Atmos. Meas. Tech., 17, 659–675, https://doi.org/10.5194/amt-17-659-2024

Amiridis, V., Kazadzis, S., et al.: 2024, Natural Aerosols, Gaseous Precursors and Their Impacts in Greece: A Review from the Remote Sensing Perspective, Atmosphere, https://doi.org/10.3390/atmos15070753

Arsenović, P., et al.: 2024, Global impacts of an extreme solar particle event under different geomagnetic field strengths, Proc. Nat. Acad. Sci., https://doi.org/10.1073/pnas.2321770121

Bergner, J. B., et al.: 2024, JWST Ice Band Profiles Reveal Mixed Ice Compositions in the HH 48 NE Disk, Astrophysical Journal, 166, https://doi.org/10.3847/1538-4357/ad79fc

Biver, N., et al.: 2024, Chemical composition of comets C/2021 A1 (Leonard) and C/2022 E3 (ZTF) from radio spectroscopy and the abundance of HCOOH and HNCO in comets, Astronomy & Astrophysics, A271, https://doi.org/10.1051/0004-6361/202450921

Booth, A. S., et al.: 2024, Measuring the 34S and 33S Isotopic Ratios of Volatile Sulfur during Planet Formation, Astrophysical Journal, 72, https://doi.org/10.3847/1538-4357/ad7817

Brodowsky, C. V., et al.: 2024, Analysis of the global atmospheric background sulfur budget in a multi-model framework, Atmos. Chem. Phys., 5513–5548, https://doi.org/10.5194/acp-24-5513-2024

Brown, T. F. M., Bannister, M. T., Revell, L. E., Sukhodolov, T., Rozanov, E.: 2024, Worldwide rocket launch emissions 2019: An inventory for use in global models, Earth and Space Science, https://doi.org/10.1029/2024EA003668

Campanelli, M., et al.: 2024, Evaluation of on-site calibration procedures for SKYNET Prede POM sun–sky photometers, Atmospheric Measurements and Techniques, 5029–5050, https://doi.org/10.5194/amt-17-5029-2024

Campanelli, M., et al.: 2024, Evaluation of on-site calibration procedures for SKYNET Prede POM sun–sky photometers, Atmospheric Measurements and Techniques, 17, 5029–5050, , 2024., https://doi.org/10.5194/amt-17-5029-2024

Campanelli, M., et al.: 2024, Evaluation of on-site calibration procedures for SKYNET Prede POM sun–sky photometers, Atmos. Meas. Tech, 5029-5050, https://doi.org/10.5194/amt-17-5029-2024

Collier, H., et al.: 2024, Localising pulsations in the hard X-ray and microwave emission of an X-class flare, Astronomy and Astrophysics, 684, A215, https://doi.org/10.1051/0004-6361/202348652

Doronin, G., Mironova, I., Bobrov, N., Rozanov, E.: 2024, Ozone Depletion during 2004–2024 as a Function of Solar Proton Events Intensity, Atmosphere, https://doi.org/10.3390/atmos15080944

Eleftheratos, K., Raptis I.-P., Kouklaki D., Kazadzis S., Founda D., Psiloglou B., Kosmopoulos P., Fountoulakis I., Benetatos C., Gierens K., Kazantzidis A.: 2024, Richter A., Zerefos C., Atmospheric parameters affecting spectral solar irradiance and solar energy (ASPIRE), AIP Conference Proceedings, 2988 (1), art. no. 110002, 2998, https://doi.org/10.1063/5.0183678

Esplugues, G., et al.: 2024, Evolution of Chemistry in the envelope of HOt CorinoS (ECHOS): II. The puzzling chemistry of isomers as revealed by the HNCS/HSCN ratio, Astronomy & Astrophysics, A5, https://doi.org/10.1051/0004-6361/202451902

Fountoulakis, I., et al.: 2024, A sensitivity study on radiative effects due to the parameterization of dust optical properties in models, Atmospheric Chemistry and Physics, 4915-4948, https://doi.org/10.5194/acp-24-4915-2024

Fragkos, K, Fountoulakis,I, Charalampous, G, Papachristopoulou, K, Nisantzi, A, Hadjimitsis, D, Kazadzis, S.: 2024, Twenty-Year Climatology of Solar UV and PAR in Cyprus: Integrating Satellite Earth Observations with Radiative Transfer Modeling, Remote Sensing, 1878, https://doi.org/10.3390/rs16111878

Funke, B., Dudok de Wit, T., Ermolli, I., Haberreiter, M., Kinnison, D., Marsh, D., Nesse, H., Seppälä, A., Sinnhuber, M., and Usoskin, I.: 2024, Towards the definition of a solar forcing dataset for CMIP7, Geoscientific Model Development, 17, 1217-1227, https://doi.org/10.5194/gmd-17-1217-2024

Garane, K., Ilias Fountoulakis, Angelos Karanikolas, Alkiviadis F. Bais, Charikleia Meleti.: 2024, Thirty years of solar ultraviolet spectral irradiance measurements in Thessaloniki: Variability and trends, AIP Conf. Proc., 2988, https://doi.org/10.1063/5.0183293

Golubenko, K., Rozanov, E., Kovaltsov, G., Baroni, M., Sukhodolov, T., Usoskin, I.: 2024, Full Modeling and Practical Parameterization of Cosmogenic 10Be Transport for Cosmic-Ray Studies: SOCOL-AERv2-BE Model, Journal of Geophysical Research: Space Physics, https://doi.org/10.1029/2024JA032504

Gröbner, J., Christian Thomann, Ibrahim Reda, David D. Turner, Moritz Feierabend, Christian Monte, Allison McComisky, Reiniger, M.: 2024, Traceability of surface longwave irradiance measurements to SI using the IRIS radiometers, AIP Conf. Proc., https://doi.org/10.1063/5.0183304

Gröbner, J., Natalia Kouremeti, Ralf Zuber, Gregor Hülsen, Stelios Kazadzis: 2024, Spectral aerosol optical depth retrieved from calibrated solar spectral irradiance measurements, AIP Conf. Proc., https://doi.org/10.1063/5.0183303

He, X., et al.: 2024, Space and Earth observations to quantify present-day sea-level change, Advances in Geophysics, 25, https://doi.org/10.1016/bs.agph.2024.06.001

Hülsen, G., Gröbner, J.: 2024, Towards a traceable global solar UV monitoring network, AIP Conf. Proc., https://doi.org/10.1063/5.0183025

Ilyushin, V. V., et al.: 2024, Rotational spectroscopy of CH3OD with a reanalysis of CH3OD toward IRAS 16293-2422, Astronomy & Astrophysics, A220, https://doi.org/10.1051/0004-6361/202449918

Karanikolas, A., Athanasios Natsis, Ilias Fountoulakis, Dimitris Karagkiozidis, Charikleia Meleti, Kleareti Tourpali, Alkiviadis Bais.: 2024, The UV index in the 21st century over Thessaloniki, Greece, from measurements and simulations in relation to the Montreal Protocol, AIP Conf. Proc., 2988, https://doi.org/10.1063/5.0182767

Karanikolas, A., Kouremeti, N., Campanelli, M., Estellés, V., Momoi, M., Kumar, G., Nyeki, S., Kazadzis, S.: 2024, Intercomparison of aerosol optical depth retrievals from GAW-PFR and SKYNET sun photometer networks and the effect of calibration, Atmos. Meas. Techniques, 17, 6085–6105, https://amt.copernicus.org/articles/17/6085/2024

Karlicky, J, Rieder, H. E., Huszár, P., Peiker, J., Sukhodolov, T.: 2024, A cautious note advocating the use of ensembles of models and driving data in modeling of regional ozone burdens, Air Quality, Atmosphere & Health, https://doi.org/10.1007/s11869-024-01516-3

Kepko, L., et al.: 2024, Heliophysics Great Observatories and international cooperation in Heliophysics: An orchestrated framework for scientific advancement and discovery, Advances in Space Science, 5383, https://doi.org/10.1016/j.asr.2024.01.011

Koval, A. V., Gavrilov, N. M., Zubov, V. A., Rozanov, E., Golovko, A. G.: 2024, Modified Parameterization Scheme of Orographic Gravity Waves in the SOCOL Chemistry-Climate Model, Pure Appl. Geophys., https://doi.org/10.1007/s00024-024-03619-5

Kulterer, B. M., et al.: 2024, Post-outburst chemistry in a Very Low-Luminosity Object: Peculiar high abundance of nitric oxide, Astronomy & Astrophysics, A281, https://doi.org/10.1051/0004-6361/202450792

Masoom, A., et al.: 2024, Assessment of the impact of NO2 contribution on aerosol-optical-depth measurements at several sites worldwide, Atmospheric Measurement Techniques, 5525-5549, https://doi.org/10.5194/amt-17-5525-2024

Masoom, A., Kosmopolous P., Bansal A., Kazadzis S., 2024, Solar resource assessment and forecasting using CAMS-MACC and physical modeling in tropical climate, AIP Conference Proceedings, 2988 (1), art. no. 080005, https://doi.org/10.1063/5.0183310

Mazzola, M., et al.: 2024, Monitoring aerosol optical depth during the Arctic night: Instrument development and first results, Atmospheric Research, 107667, https://doi.org/10.1016/j.atmosres.2024.107667

Mazzola, M., et al.: 2024, Monitoring aerosol optical depth during the Arctic night: Instrument development and first results, Atmospheric Research, 107667, https://doi.org/10.1016/j.atmosres.2024.107667

Montillet, J.-P., G. Kermarrec, E. Forootan, M. Haberreiter, X. He, W. Finsterle,R. Fernandes, and C.K. Shum: 2024, A review on how Big Data can help to monitor the environment and to mitigate risks due to climate change, IEEE Geoscience an Remote Sensing, 17, https://doi.org/10.1109/MGRS.2024.3379108

Moustaka, A., Korras-Carraca, M.-B. Papachristopoulou, K, Stamatis, M. Fountoulakis, I, Kazadzis, S. Proestakis, E, Amiridis, V.Tourpali, K, Georgiou, T.: 2024, Assessing Lidar Ratio Impact on CALIPSO Retrievals Utilized for the Estimation of Aerosol SW Radiative Effects across North Africa, Middle East and Europe, Remote sensing, 1689, https://doi.org/10.3390/rs16101689

Nerobelov, G., Timofeyev, Y., Polyakov, A., Virolainen, Y., Rozanov, E., Zubov, V.: 2024, An Investigation of the SOCOLv4 Model's Suitability for Predicting the Future Evolution of the Total Column Ozone, Atmosphere, https://doi.org/10.3390/atmos15121491

Nerobelov, G., Virolainen, Y., Ionov, D., Polyakov, A., and Rozanov, E.: 2024, WRF-Chem Modeling of Tropospheric Ozone in the Coastal Cities of the Gulf of Finland, Atmosphere, MDPI, https://doi.org/10.3390/atmos15070775

Noble, J. A., et al.: 2024, Detection of the elusive dangling OH ice features at 2.7 µm in Chamaeleon I with JWST NIRCam, Nature Astronomy, 1169-1180, https://doi.org/10.1038/s41550-024-02307-7

Nyeki, S., Julian Grobner, Laurent Vuilleumier, Christian Lanconelli, Amelie Driemel, Wouter Knap, Marion Maturilli, Nozomu Ohkawara, Laura Riihimaki, Holger Schmithlisen: 2024, Extending the calibration traceability of longwave radiation time-series (ExTrac), AIP Conf. Proc., https://doi.org/10.1063/5.0183543

Papachristopoulou, K., Fountoulakis, I., Bais, A. F., Psiloglou, B. E., Papadimitriou, N., Raptis, I.-P., Kazantzidis, A., Kontoes, C., Hatzaki, M., and Kazadzis, S.: 2024, Effects of clouds and aerosols on downwelling surface solar irradiance nowcasting and short-term forecasting, Atmos. Meas. Tech., 1851–1877, https://doi.org/10.5194/amt-17-1851-2024

Peat, A. W, Labrosse, N, Barczynski, K, Schmieder, B.: 2024, Solar prominence diagnostics and their associated estimated errors from 1D NLTE Mg II modelling, A&A, 686, A291, https://doi.org/10.1051/0004-6361/202348589

Rocha, W. R. M., et al.: 2024, Ice inventory towards the protostar Ced 110 IRS4 observed with the James Webb Space Telescope. Results from the ERS Ice Age program, Astronomy & Astrophysics, https://doi.org/10.48550/arXiv.2411.19651

Schmutz, W.: 2024, HD 214220 (BD+56 2813): An eclipsing binary with its primary component at the end of the main sequence, A&A, 681, https://doi.org/10.1051/0004-6361/202347810

Sergeev, V. A., Stepanov, N. A., Ogawa, Y., Rozanov, E. V., Shukhtina, M. A.: 2024, Local time distribution and activity dependence of extreme electron densities in the auroral D-region as an image of energy-dependent energetic electron precipitation, Journal of Geophysical Research: Space Physics, https://doi.org/10.1029/2024JA032913

Shapiro, A. V., Egorova, T. A., Shapiro, A. I., Arsenovic, P., Rozanov, E. V., Gizon, L.: 2024, Transition of the Sun to a regime of high activity: Implications for the Earth climate and role of atmospheric chemistry, Journal of Geophysical Research: Atmospheres, https://doi.org/10.1029/2023JD039894

Shiokawa, K., Marsh, D., Pallamraju, D., Patsourakos, S., Pedatella, N., Ratnam, M. V., Rozanov, E., Srivastava, N., Tulasiram, S.: 2024, Special issue of SCOSTEP's 15$^{th}$ Quadrennial Solar-Terrestrial Physics Symposium (STP-15), Journal of Atmospheric and Solar-Terrestrial Physics, https://doi.org/10.1016/j.jastp.2024.106236

Skinner, S. L., Zhekov, S. A., Güdel, M., Schmutz, W.: 2024, X-Ray Observations of the Enigmatic Wolf-Rayet System θ Mus: Two's Company but Three's a Crowd, APJ, 961, 174, https://doi.org/10.3847/1538-4357/ad12cc

Stefanetti, F., Vattioni, S., Dykema, J. A., Chiodo, G., Sedlacek, J., Keutsch, F. N., and Sukhodolov, T.: 2024, Stratospheric injection of solid particles reduces side effects on circulation and climate compared to SO2 injections, Environ. Res.: Climate, https://doi.org/10.1088/2752-5295/ad9f93

Sturm, J. A., et al.: 2024, A JWST/MIRI analysis of the ice distribution and polycyclic aromatic hydrocarbon emission in the protoplanetary disk HH 48 NE, Astronomy & Astrophysics, A92, https://doi.org/10.1051/0004-6361/202450865

Usacheva, M., Rozanov, E., Zubov, V., Smyshlyaev, S.: 2024, Temperature and Ozone Response to Different Forcing in the Lower Troposphere and Stratosphere, Atmosphere, https://doi.org/10.3390/atmos15111289

Uusitalo, J., Golubenko, K., Arppe, L., Brehm, N., Hackman, T., Hayakawa, H., Rozanov, E.: 2024, Transient offset in 14C after the Carrington event recorded by polar tree rings, Geophysical Research Letters, 51, https://doi.org/10.1029/2023GL106632

Varesano, T., et al.: 2024, SPICE connection mosaics to link the Sun's surface and the heliosphere, Astronomy and Astrophysics, 685, A146, https://doi.org/10.1051/0004-6361/202347637

Vargin, P., Koval, A., Guryanov, V., Volodin, E., Rozanov, E.: 2024, Variations of Planetary Wave Activity in the Lower Stratosphere in February as a Predictor of Ozone Depletion in the Arctic in March, Atmosphere, https://doi.org/10.3390/atmos15101237

Vattioni, S., Käslin, S. K., Dykema, J. A., Beiping, L., Sukhodolov, T., Sedlacek, J., Keutsch, F., Peter, T., Chiodo, G.: 2024, Microphysical interactions determine the effectiveness of solar radiation modification via stratospheric solid particle injection, Geophysical Research Letters, https://doi.org/10.1029/2024GL110575

Vattioni, S., Stenke, A., Luo, B., Chiodo, G., Sukhodolov, T., Wunderlin, E., and Peter, T.: 2024, Importance of microphysical settings for climate forcing by stratospheric $SO_2$ injections as modeled by SOCOL-AERv2, Geosci. Model Dev., 4181–4197, https://doi.org/10.5194/gmd-17-4181-2024

Vattioni, S., Weber, R., Feinberg, A., Stenke, A., Dykema, J. A., Luo, B., Kelesidis, G. A., Bruun, C. A., Sukhodolov, T., Keutsch, F. N., Peter, T., and Chiodo, G.: 2024, A fully coupled solid-particle microphysics scheme for stratospheric aerosol injections within the aerosol–chemistry–climate model SOCOL-AERv2, Geosci. Model Dev., 7767-7793, https://doi.org/10.5194/gmd-17-7767-2024

Voglmeier, K., Velazco, V. A., Egli, L., Gröbner, J., Redondas, A., and Steinbrecht, W.: 2024, The transition to new ozone absorption cross sections for Dobson and Brewer total ozone measurements, Atmos. Meas. Tech., 2277–2294, https://doi.org/10.5194/amt-17-2277-2024

Wunderlin, E., Chiodo, G., Sukhodolov, T., Vattioni, S., Visioni, D., Tilmes, S.: 2024, Side effects of sulfur based geoengineering due to absorptivity of sulfate aerosols., Geophysical Research Letter, 51, https://doi.org/10.1029/2023GL107285

Yang, Zihao, Tian, Hui, Zhu, Yingjie, Xu, Yu, Chen, Linyi, Sun, Zheng: 2024, Is It Possible to Detect Coronal Mass Ejections on Solar-type Stars through Extreme-ultraviolet Spectral Observations?, The Astrophysical Journal, 966-24, https://doi.org/10.3847/1538-4357/ad2a44

Yardley, S. L., et al.: 2024, Multi-source connectivity as the driver of solar wind variability in the heliosphere, Nature Astronomy, 953-963, https://doi.org/10.1038/s41550-024-02278-9

Yingjie, Z., et al.: 2024, Spectroscopic Observations of the Solar Corona during the 2017 August 21 Total Solar Eclipse: Comparison of Spectral Line Widths and Doppler Shifts between Open and Closed Magnetic Structures, The Astrophysical Journal, 966-122, https://doi.org/10.3847/1538-4357/ad3424

## Media - Selected Highlights

3 Feb. 2024
• News item
• "Wenn uns die Sonne den Stecker zieht"
• Südostschweiz Newspaper
• https://www.pmodwrc.ch/wp-content/uploads/2024/02/PressArticle_20240203_SOS.pdf

13 Mar. 2024
• TV news item with Jan Sedlacek (in Rumantsch)
• "La midada dal clima è ina sfida per ils eveniments in il glatsch"
• RTR TV
• https://www.rtr.ch/play/tv/telesguard/video/telesguard-dals-13-03-2024?urn=urn:rtr:video:265da2f4-4790-4404-8cf5-d9f9aeda49ff

20 Apr. 2024
• Public talk, Nils Janitzek
• "Mit Solar Orbiter Orbiter zur Sonne"
• Annual meeting of the Swiss Astronomical Society

26 Apr. 2024
• News item
• "Ehrungen zum Schluss und zum Anfang"
• Davoser Newspaper
• https://www.pmodwrc.ch/wp-content/uploads/2024/04/PressArticle_20240426_DZ.pdf

27 May 2024
• Podium discussion with experts including Jan Sedlacek
• "Seeanlässe: Optimismus oder Pessimismus?"
• Engadiner Post, Newspaper

30 Jul. 2024
• News item
• "Sonnenprotonen und Leben auf der Erde"
• Davoser Newspaper
• https://academiaraetica.ch/assets/artikel_dz_2024/2024-07-30_dz_pmod_sonnenprotonen.pdf

• 13 Aug. 2024
• Online news item with Tatiana Egorova and Eugene Rozanov
• "How scientists uncovered and corrected a specific bias in climate models"
• Swiss National Supercomputing Centre
• https://www.cscs.ch/science/earth-env-science/2024/how-scientists-uncovered-and-corrected-a-specific-bias-in-climate-models

22 Aug. 2024
• Podium discussion with experts including Jan Sedlacek
• Naturforschende Gesellschaft Davos (NGD) - Wissenschaftscafé, Davos
• "$CO_2$ - Wohin damit?" Podium discussion with experts, including Jan Sedlacek

25 Sep. 2024
• Wolfgang Finsterle
• Unterstützung bei den Recherchen zum Roman "Der Zauberberg, die ganze Geschichte"
• Norman Ohler, Diogenes, ISBN  978-3-257-07318-8

16 Oct. 2024
• TV news item with Wolfgang Finsterle amonst others
• "Davos zieht immer mehr Startups an"
• Swiss Television, SRF
• https://www.srf.ch/play/tv/schweiz-aktuell/video/schweiz-aktuell-vom-15-10-2024?urn=urn:srf:video:f55a2555-9605-4455-aac9-93cb36a6f401

4 Nov. 2024
• Online news item with Timofei Sukhodolov
• "Solares Geoengineering – berechtigte Kritik oder Schwarzmalerei?"
• Watson.ch
• https://www.watson.ch/wissen/leben/819683735-solares-geoengineering-berechtigte-kritik-oder-schwarzmalerei

7 Nov. 2024
• ESA Website Article
• "Proba-3 will constantly measure Sun’s energy output"
• https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Proba_Missions/Proba-3_will_constantly_measure_Sun_s_energy_output

4 Dec. 2024
• TV news item with Dany Pfiffner and Margit Haberreiter
• "Ein Stück Davos im Weltall - aber nicht ganz ohne Hindernisse"
• Südostschweiz TV
• https://www.suedostschweiz.ch/sendungen/ein-stueck-davos-im-weltall-aber-nicht-ganz-ohne-hindernisse-04-12-24

6 Dec. 2024
• Radio news item
• "Ein Stück Davoser Forschung im Weltall"
• Radio Grischa
• https://www.suedostschweiz.ch/sendungen/radio-grischa-info-kompakt/ein-stueck-davoser-forschung-im-weltall-06-12-24

6 Dec. 2024
• News item
• "Davoser Ingenieurskunst im Weltall"
• Davoser Newspaper
• https://www.pmodwrc.ch/wp-content/uploads/2024/12/PressArticle_20241206_DZ.pdf

27 Dec. 2024
• Radio interview with Louise Harra
• "Parker Solar Probe's closest approach to the Sun"
• BBC World Service

# Administration

## Personnel Department

*Eliane Tobler and Kathrin Anhorn*

### External Outreach

The year 2024 began with an ETH event at the Institute, held during the World Economic Forum in Davos. Numerous other events for the public followed throughout the year, including the Institute's participation in the “Davos Mäss” (Fig. 1) and the “Graubünden Forscht” congress.

The Institute was also in demand for a wide range of artistic activities: our director gave advice about solar science for the Theatre piece, “Sonnensturm”, in Chur. In August, the “Davos Festival” held several concerts in our building, taking advantage of the unique atmosphere.

Of course, our numerous house tours were also highlights for young and old, especially on 5 December when a school class was able to follow the rocket launch of our PROBA-3 mission, live at PMOD/WRC.

### Team Highlights

Under the motto “Get to know Davos better” and in perfect weather, we held our institute excursion at the end of August. We visited various local manufacturers in Davos, starting the day with homemade chocolate bars at Schneider's. At the second stop, with Christoffel Röteli, we were shown how “Röteli” schnapps is made. This included a tasting and pouring a bottle of the traditional schnapps ourselves.

After an enjoyable day, we then held a Team-Yoga session (Fig. 2) with a beautiful view of the “Hoch-Ducan” mountain in the nearby Sertig valley.

### Team Changes

At the end of July, we celebrated the retirement of our long-term employee Silvio Koller (former Co-Head Technology Department; Fig. 3). We wish him all the best and are looking forward to see him around the institute from time-to-time. At the end of November and December, we also said goodbye to Natalia Engler and Akriti Masoom. We wish you all the best for your future.

We welcomed the following new employees and former employees to our team during the course of 2024:

January: Yingjie Zhu, PostDoc.

April: Andrin Jörimann, PhD Student (former Msc student).

June: Dhrona Jaine, PhD Student.

August: Sarina Heim, Electronics Apprentice and Kyriaki Papachristopoulou, PostDoc (former PhD student).

September: Adriana Da Sassi, PhD Student (former Msc Student).

October: Etienne De Coulon, Systems Engineer (former employee).

December: Ioannis Kontogiannis, PostDoc.

December: Oliver Schwahofer, Mechanical Engineer.

In addition, we were able to support Maria Drozdovskaya in her Scholarship provided by the Holcim Foundation.

### Work Anniversaries

We are very proud that former long-term employees as well as apprentices are returning to the institute. In line with our tradition, we celebrated our jubilarians during our annual Christmas dinner:

- Wolfgang Finsterle: 20 years.
- Marco Senft: 15 years.
- Patrik Langer: 10 years.
- Pascal Schlatter: 10 years.
- Louise Harra: 5 years.
- Ricco Soder: 5 years.
- Franz Zeilinger: 5 years.

Many thanks for your loyalty and commitment to the institute. We are looking forward to your next anniversary with us.

### 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 everyone for being a member of our staff.

Finally, we'd like to thank all our civil servants for their hard work and commitment:

Jonathan Vermeirssen, Lukas Bertoli, Cedric Renda, Sirio Sailer, Alessio Bollazzi, Marvin Wagner, Robert Hoffner, Raphael Burkhardt, and Alain Keller.


*Figure 1. Krzysztof Barczynski and Marco Senft were among several other PMOD/WRC staff who welcomed the general public during the Davoser Mäss on 22 July 2024.*

*Figure 2. Team-Yoga session in Davos Sertig.*

*Figure 3. Silvio Koller (right) receiving a farewell present from Louise Harra during his retirement celebration.*

# Personnel

## Scientific Personnel

| | |
|---|---|
| Prof. Dr. Harra, Louise | Director, affiliated Prof. at ETH-Zurich, Head of Solar Astrophysics Group, Solar Physicist |
| Prof. Dr. Schmutz, Werner | PI DARA/PROBA-3 Scientist, former Director, Physicist |
| Dr. Barczynski, Krzysztof | Postdoc, Solar Physics Group, Physicist |
| Da Sassi, Adriana | PhD student, ETH Zurich |
| Dr. Drozdovskaya, Maria | Scholarship Holcim Foundation, (until 31.08.2024) |
| Dr. Janitzek, Nils | Postdoc, Solar Physics Group, Physicist |
| Dr. Kontogiannis, Ioannis, | PostDoc, ETH Zurich |
| Dr. Zhu, Yingjie | Postdoc, Solar Physics Group, Physicist, (since 01.01.2024) |
| | |
| Dr. Gröbner, Julian | Co-Head WRC, Head WRC-Sections IR, WORCC, WCC-UV and Ozone Section, Physicist |
| Dr. Egli, Luca | Scientist, WCC-UV and Ozone Sections, Physicist |
| Dr. Ferhat, Salim | Scientist, Optical Radiometry, WRC Section, Physicist |
| Dr. Hülsen, Gregor | Scientist, WCC-UV Section, Physicist |
| Jaine, Dhrona | PhD student, WRC-WORCC Section, (since 01.06.2024) |
| Dr. Kouremeti, Natalia | Scientist, WRC-WORCC Section, Physicist |
| Thomann, Christian | Technician |
| Zeilinger, Franz | Technical Engineer, BSc, Ozone Section |
| | |
| Dr. Kazantzis, Stylianos A. | Scientist, WRC-WORCC Section, Physicist |
| Hou, Xinyuan | PhD student, WRC-WORCC Section |
| Karanikolas, Angelos | PhD student, WRC-WORCC Section |
| Dr. Masoom, Akriti | Postdoc, WRC-WORCC Section, Physicist, (until 31.12.2024) |
| Moustaka, Anna | PhD student, WRC-WORCC Section, (since 01.11.2024) |
| Dr. Papachristopoulou, Kyriakoula | Postdoc, WRC-WORCC Section, Physicist, (since 01.09.2024) |
| | |
| Dr. Finsterle, Wolfgang | Co-Head WRC, Head WRC-Section Solar Radiometry, Physicist |
| Dr. Engler, Natalia | Instrument Scientist, WRC-SRS Section, Physicist, (until 30.11.2024) |
| Dr. Haberreiter, Margit | Project Manager/Scientist Space, Instrument Scientist, WRC-SRS Section |
| Dr. Montillet, Jean-Philippe | TSI Instrument Scientist, Geoscientist |
| Soder, Ricco | Research Engineer, Quality Systems Manager |
| | |
| 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 |
| Jörimann, Andrin | PhD student, Climate Group, (since 01.04.2024) |
| Dr. Sedlacek, Jan | Scientist, Climate Group, Climate Scientist |

## PhD and Project Students

| | |
|---|---|
| Bajzath, Peter | MSc student, ETH Zurich |
| De Sassi, Adriana | MSc student, ETH Zurich, (until 02.2024) |
| Jentgens, Henrik | MSc student, ETH Zurich, (since 09.2024) |
| Kistler, Fabian | MSc student, ETH Zurich), (until 04.2024) |
| Schuring, Iris | MSc student, ETH Zurich, (until, 05.2024) |
| | |
| Battaglia, Andrea | PhD student, ETH Zurich, FHNW |
| Charalambous, Georgia | PhD student, Cyprus Univ. Technology, Greece, (since 01.2024) |
| Collier, Hannah | PhD student, ETH Zurich, FHNW |
| Kouklaki, Dimitra | PhD student, National and Kapodistrian Univ. Athens, Greece |
| Stiefel, Muriel | PhD student, ETH Zurich, FHNW |
| | |
| Jentgens, Henrik | ETH Studio Davos student, (until 07.2024) |
| Li, Jessi | ETH Studio Davos student, (until 01.2024) |
| Moll, Remy | ETH Studio Davos student, (until 07.2024) |
| Tào, Michel | ETH Studio Davos student, (until 07.2024) |

## Technical Personnel

| | |
|---|---|
| **Büchel, Valeria** | Co-Head Technical Department, Project Manager Space, (Co-head since 01.09.2024) |
| **Pfiffner, Daniel** | Co-Head Technical Department, Project Manager Space |
| Koller, Silvio | Co-Head Technical Department, Project Manager Space, (until 31.07.2024) |
| Dr. De Coulon, Etienne | Systems Engineer, (since 01.10.2024) |
| El Sammra, Karim | Electronics Apprentice, 3rd year |
| Gander, Matthias | Electronics Engineer, BSc |
| Gyo, Manfred | Electronics Engineer, MSc |
| Heim, Sarina | Electronics Apprentice, 1st year, (since 01.08.2024) |
| Hiltbrunner, Philipp | Mechanics Engineer, since (01.08.2024) |
| Langer, Patrik | Mechanics Engineer, MSc |
| Meier, Leandro | Electronics Engineer, BSc |
| Morandi, Andri | Project Manager Space, BSc |
| Reinhard, Florian | Project Manager Space |
| Schlatter, Pascal | Mechanic, Head of Workshop, Safety Officer |
| Schwahofer, Oliver | Mechanics Engineer, MSc, (since 01.12.2024) |
| Senft, Marco | IT Systems Administrator |
| Spescha, Marcel | Technician / Mechanics Dept. |
| Vignali, Fabrizio | IT Systems Administrator |

## Administration

| | |
|---|---|
| **Tobler, Eliane** | Head HR / Finances, Accountant, MSc |
| Anhorn, Kathrin | Senior Financial Project Coordinator |
| Keller, Irene | Administration, Import/Export |
| Mark, Nina | Administration Apprentice, 2nd year |
| Dr. Nyeki, Stephan | Media Officer |

## Caretaker

| | |
|---|---|
| Ferreira Pinto, Maria Sofia | General caretaker, cleaning |

## Civilian Service Conscripts

| | |
|---|---|
| Bertoli, Lukas | 08.01.2024 - 10.07.2024 |
| Bollazzi, Alessio | 15.04.2024 - 07.06.2024 |
| Burkhardt, Raphael | 23.09.2024 - 08.12.2024 |
| Hoffner, Robert | 01.08.2024 - 27.09.2024 |
| Keller, Alain | 21.10.2024 - 20.12.2024 |
| Renda, Cedric | 05.02.2024 - 01.03.2024 |
| Sailer, Sirio | 12.02.2024 - 12.04.2024 |
| Vermeirssen, Jonathan | 20.08.2023 - 14.02.2024 |
| Wagner, Marvin | 08.07.2024 - 06.09.2024 |

## Participation in Commissions, Editorial Boards, International Consortia

| | |
|---|---|
| Louise Harra | Honorary Professor at University College London<br>PI SoSpIM instrument on Solar-C<br>Co-I IRIS space mission<br>Co-PI Solar Orbiter EUI<br>Member of the editorial board of RAS instruments and techniques<br>Member of scientific board of Congressi Stefano Franscini<br>Member of SNSF postdoc mobility committee<br>Advisory Board for the Solar Physics journal<br>Secretary of Swiss Committee on Space Research<br>Chair of ESA Heliophysics User archive committee<br>Board of Davos Science City<br>Subject editor for Proceedings of the Royal Society A: Mathematical, Physical & Engineering Sciences<br>Co-chair of the Scientific Advisory Board of the MPS<br>Member of the Presidium of the Platform MAP (Mathematics, Astronomy, and Physics, map.scnat.ch ) of the Swiss Academy of Sciences<br>Swiss Commission for Astronomy (SCFA) of the Swiss Academy of Sciences (SCNAT)<br>GCOS JSG 3: Space Weather Monitoring and Prediction study group<br>Reviewer for ESA IRIS science planners |
| Werner Schmutz | Honorary Member of the International Radiation Commission (IRC, IAMAS)<br>PI-DARA. On PROBA-3 |
| Wolfgang Finsterle | Member of the Swiss Society for Astronomy and Astrophysics<br>Member of WMO Expert Team on Radiation References<br>Board member of the Davos branch of the SCNAT NGD<br>Member of the International Radiation Commission Solar Irradiance Working Group<br>Member of the Schweizerische Normen-Vereinigung<br>Member of ISO/TC180-SC1 |
| Julian Gröbner | Member of the Dobson Ad-Hoc Committee, http://www.o3soft.eu/dobsonweb/committee.html since 2021<br>Member of the Scientific Advisory Group for Ozone and UV in the Global Atmosphere Watch programme of the WMO, since 2016<br>Chair of the Scientific Committee of the Conference "New Developments and Applications in Optical Radiometry" (NEWRAD), since 2014<br>Member of the Swiss Global Atmosphere Watch Programme managed by Meteoswiss, since 2005<br>Member of the Expert Team on Radiation References of the Standing Committee on Measurements, Instrumentation and Traceability (SC-MINT) of the WMO, since 2014<br>Member of the WG-IR of the Baseline Surface Radiation Network (BSRN), since 2006<br>Member of the Regional Brewer Scientific Group - Europe (RBCC-E, 2005 - ongoing)<br>Elected member of the International Radiation Commission, and Chair of the Working Group on Solar UV Radiation, IAMAS, since 2009<br>Member International Ozone Commission, IAMAS, since 2016<br>member Beirat für Umwelt und Klima der Physikalisch-Technischen Bundesanstalt (PTB), since 2024<br>Technical committee for photometry and radiometry of EURAMET, observer |
| Margit Haberreiter | President Swiss Society for Astrophysics and Astronomy (SSAA)<br>Topical Editor Annales Geophysicae<br>Swiss Representative at WMO's Expert Team on Space Weather (ET-SWx)<br>SCOSTEP Science Discipline Representative<br>Member of the Solar Irradiance Working Group in the International Radiation Commission (IRC)<br>Member of ISSI Working Group on Solar Forcing for CMIP7<br>Member Swiss National SCOSTEP Committee<br>Member of the Mission Advisory Group of the Earth Climate Observatory (ECO) |

| | |
|---|---|
| Stelios Kazadzis | Member of the International Radiation Commission (IRC)<br>Member of the Expert Team of Atmospheric Composition Measurement Quality of the World meteorological Organization (ETMQ)<br>Member of the Expert Team on the Atmospheric Composition Network Design and Evolution of the World meteorological Organization (ACNDE),<br>Action Chair, COST Action Harmonia, sun photometer measurement homogenization<br>Editor in Atmospheric Chemistry and Physics journal<br>Head of ACTRIS/CARS Aerosol sun photometric Unit PMOD-WRC<br>Action group leader of EuroGEO on Renewable Energy<br>Co-PI of the Expert Group on Satellite validation (EG-SAT) of ACTRIS<br>Scientific Advisory Group for Aerosols WMO |
| Timofei Sukhodolov | Member of the APARC project “High Energy Particle Precipitation in the Atmosphere”, HEPPA-4<br>Co-lead of the APARC activity “Interactive stratospheric aerosol model intercomparison”, ISA-MIP<br>Co-PI of the SOCOLv4 model in the APARC activity “Chemistry-climate model initiative phase 2”, CCMI-2<br>Member of the International Commission on the Middle Atmosphere, ICMA<br>Member of the APARC activity “Hunga Tonga-Hunga Ha’apai stratospheric impacts”, HT-MIP<br>Guest editor of the research topic “The evolution of the stratospheric ozone: Volume II” in Frontiers in Earth Science journal |
| Krzysztof Barczynski | Co-I EUI instrument onboard Solar Orbiter<br>Co-lead of Solar Orbiter – DKIST-IRIS-Hinode coordinated observations group<br>Member EPD – STIX – EUI coordinated flare observations team<br>Member of Program Committee of Academia Raetica<br>Representative of Akademischer Mittelbau am Physikdepartement ETH Zurich (AMP, Scientific Staff Association) to Departementskonferenz (DK) at ETH Zurich<br>Member of Solar-C Science Working Group<br>Member of M-MATISSE Science Study Team<br>Board member of European Solar Physics Division of the European Physical Society |
| Jean-Philippe Montillet | Topical Editor - Earth and Space Science<br>Editorial board member of Discover Data - Springer |
| Natalia Kouremeti | Member of COST Action Harmonia (working group leader) |
| Luca Egli | Member of the International Radiation Commission (IAMAS-IRC) |
| Akriti Masoom | Working Group 1 Co-leader, COST ACTION HARMONIA CA21119<br>Guest Editor in a Special Issue of Atmosphere Journal |
| Maria Drozdovskaya | Internal Science Assessor ALMA Proposal Review Committee (APRC; 2024 Cycle 11)<br>Advisor of the International Astronomical Union (IAU) Executive Committee (EC) Working Group of Junior Members (up to and incl. Aug 2024) |

## Public Seminars given at PMOD/WRC

25 Jan. 2024 Susanne Bekker (Queens University, N. Ireland) "Influence of Solar Flares on the Earth's Iono-sphere. Experimental data and theoretical results".

29 Apr. 2024 Sophie Musset (ESA, Nederlands, France) Talk/hybrid, "Solar energetic particles, coronal jets, and citizen science".

6 May 2024 Karen Meyer (Univ. Dundee, UK) Talk/hybrid, "Long-term simulations of the Sun's global coronal magnetic field".

19 Sep. 2024 Philippe-André Bourdin (Univ. Graz, Austria) Talk/hybrid (in person at PMOD/WRC and online): "Models of the solar corona above sunspots and active regions with observable signatures in the solar wind".

11 Oct. 2024 Kanya Kusano (Univ. Nagoya, Japan) "Space weather and space climate".

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

| | |
|---|---|
| 17 Jan. 2024 | ETH WEF event at PMOD/WRC, "Rethinking Observations" - Introduction by Louise Harra. |
| 8 Apr. 2024 | "Sky over Berlin" school on sun-photometry, FU Berlin, Germany. |
| 16 Apr. 2024 | European Geophyscial Union Session, Advances in Determining the Earth Energy Imbalance, Solar Irradiance, and ToA Outgoing Radiation. |
| 2 May 2024 | PMOD/WRC Advisory Commission (Aufsichts-Kommission) meeting. |
| 21 May 2024 | Harmonia project meeting in Reykjavik, Iceland. |
| 24 May 2024 | Davos Science City Annual Meeting. |
| 24 Jun. 2024 | SoSpIM science meeting. |
| 24 Jun. 2024 | PMOD/WRC Board of Trustees (Stiftungsrat) meeting. |
| 27 Jun. 2024 | TRUTHS for Science Workshop, Harwell, ESA Convention Center, UK. |
| 14 Jul. 2024 | Quadrennial ozone symposium. |
| 22 Jul. 2024 | Davoser Mäss, participation by PMOD/WRC. |
| 22 Jul. 2024 | ISSI Workshop "Exocomets: Bridging our Understanding of Minor Bodies in Solar and Exoplanetary Systems", Bern, Switzerland. |
| 10 Aug. 2024 | Guided Tour: Davos Festival. |
| 3 Oct. 2024 | Annual Meeting of the Swiss Society for Astrophysics and Astronomy. |
| 9 Nov. 2024 | Science Noon during Graubünden Forscht 2024. |
| 11 Nov. 2024 | PMOD/WRC Advisory Commission (Aufsichts-Kommission) meeting. |
| 16 Nov. 2024 | Guided Tour: Fachhochschule Nordwestschweiz FHNW. |
| 20 Nov. 2024 | Excelsior workshop on solar radiation and aerosols. |
| 19 Dec. 2024 | PMOD/WRC Board of Trustees (Stiftungsrat) meeting. |

## Bilanz per 2024 (inklusive Drittmittel) mit Vorjahresvergleich

| | 31.12.2024 | 31.12.2023 |
|---|---|---|
| **Aktiven** | CHF | CHF |
| Flüssige Mittel | 3'385'384.29 | 3'035'880.59 |
| Forderungen | 28'035.60 | 59'260.85 |
| Aktive Rechnungsabgrenzungen | 810'349.80 | 332'297.05 |
| Warenvorräte | 1'000.00 | 1'000.00 |
| Total Aktiven | 4'224'769.69 | 3'428'438.49 |

| **Passiven** | | |
|---|---|---|
| Verbindlichkeiten | 134'951.58 | 102'744.75 |
| Kontokorrent Stiftung | 0.00 | 0.00 |
| Passive Rechnungsabgrenzung | 1'885'279.01 | 1'595'398.53 |
| Rückstellungen | 1'780'000.00 | 1'380'000.00 |
| Eigenkapital | 424'539.10 | 350'295.21 |
| Total Passiven | 4'224'769.69 | 3'428'438.49 |

## Erfolgsrechnung 2024 (inklusive Drittmittel) mit Vorjahresvergleich

| **Ertrag** | CHF | CHF |
|---|---|---|
| Beitrag Bund Betrieb WRC | 1'459'400.00 | 1'489'200.00 |
| Beitrag Bund (BBL), Unterhalt Gebäude | 85'824.50 | 98'521.05 |
| Beitrag Kanton Graubünden WRC | 550'000.00 | 509'268.00 |
| Beitrag Kanton Graubünden für ETH Prof. | 240'000.00 | 240'000.00 |
| Beitrag Gemeinde Davos | 710'000.00 | 664'191.00 |
| Beitrag Gemeinde Davos, Mieterlass | 160'000.00 | 160'000.00 |
| Dienstleistungsauftrag MeteoSchweiz OZON | 293'283.18 | 279'986.55 |
| Dienstleistungsauftrag WMO Genève | 21'881.00 | 21'881.00 |
| Anstellungsverhältnisse | 180'325.65 | 0.00 |
| Overhead Projekte | 368'999.85 | 190'655.30 |
| Instrumentenverkäufe | 233'574.70 | 175'214.50 |
| Reparaturen und Kalibrationen | 262'043.30 | 242'352.20 |
| Ertrag Dienstleistungen | 72'857.67 | 112'051.96 |
| Übriger Ertrag | 8'231.10 | 4'578.07 |
| Finanzertrag | 8'632.13 | 0.00 |
| Ausserordentlicher Ertrag | 2'814.67 | 8'880.19 |
| Drittmittel | 3'350'796.04 | 2'330'781.23 |
| Total Ertrag | 8'008'663.79 | 6'527'561.05 |

| **Aufwand** | | |
|---|---|---|
| Personalaufwand | 5'344'004.70 | 4'620'459.50 |
| Investitionen Observatorium | 268'346.41 | 228'770.28 |
| Investitionen Drittmittel | 49'351.44 | 102'266.40 |
| Unterhalt Gebäude (Beitrag Bund) | 85'824.50 | 98'521.05 |
| Unterhalt | 83'557.93 | 93'747.95 |
| Verbrauchsmaterial Observatorium | 143'291.88 | 112'452.45 |
| Verbrauchsmaterial Drittmittel | 511'898.98 | 182'455.26 |
| Verbrauch Commercial | 67'228.02 | 74'066.35 |
| Reisen, Kurse | 137'048.64 | 134'264.10 |
| Raumaufwand/Energieaufwand | 213'890.57 | 219'122.75 |
| Versicherungen, Verwaltungsaufwand | 261'477.16 | 104'211.05 |
| Finanzaufwand | 8'149.56 | 6'491.57 |
| Übriger Betriebsaufwand | 360'350.06 | 236'405.26 |
| Ausserordentlicher Aufwand | 0.05 | 14'254.63 |
| Total Aufwand | 7'534'419.90 | 6'227'488.60 |
| **Jahresergebnis vor Bildung/Auflösung Rückstellungen** | 474'243.89 | 300'072.45 |
| Auflösung Rückstellungen | 0.00 | 0.00 |
| Bildung Rückstellungen | 400'000.00 | 230'000.00 |
| **Jahresergebnis** | 74'243.89 | 70'072.45 |
| | 8'008'663.79 | 6'527'561.05 |

# Abbreviations

| | |
|---|---|
| ACTRIS-CARS | Aerosols, Clouds, and Trace gases Research Infrastructure Network, Center for Aerosol Remote Sensing |
| AERONET | Aerosol Robotic Network, GSFC, USA |
| AOD | Aerosol Optical Depth |
| APARC | Atmospheric Processes and Their Role in Climate |
| 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) |
| 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 and Operational Programme focussing on atmospheric composition |
| GCM | General Circulation Model |
| GCR | Galactic Cosmic Rays |
| 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 |
| MeteoSwiss | Federal Office of Meteorology and Climatology MeteoSwiss, Zurich, 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) |
| 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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