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2021

Observatoire royal de Belgique

Koninklijke Sterrenwacht van België

Royal Observatory of Belgium

ORB - KSB

Cover illustration: Illustration of the new digital Planetarium inaugurated in April 2021. Credit: Hans Coeckelberghs.

Foreword

Dear readers,

I am happy to present you with the annual summary report of the Royal Observatory of Belgium (ORB-KSB). As in the previous years, we have decided to only present the highlights of our scientific activities and public services, rather than providing a full, detailed and lengthy overview of all of our work during the year. We hope to provide you, in doing so, with a report that is more interesting to read and gives a taste of life at the ORB-KSB. If you need more or other information on ORB-KSB and/or its activities, contact rob_info@oma.be or visit our website http://www.observatory.be.

A list of publications and staff statistics are included at the end. To also suit our international readers & collaborators and to give it an as wide visibility as possible, the report is written in English.

Ronald Van der Linden

Director General

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Life at the Royal Observatory of Belgium

COVID-19

On March 11, 2020, the World Health Organization declared the COVID-19 crisis as a pandemic. To control it, the Belgian government issued since March 12, 2020, global restrictions impacting Belgian cultural and economic activity and its citizens' daily life. ORB-KSB and its Planetarium were also impacted by those restrictions. In 2021, there is an ease of COVID-19 regulations, but some restrictions still remain.

From this date onwards, with periods during which restrictions were eased or reinforced, the majority of ORB-KSB's personal were advised or mandated to work remotely partially or full time if the nature of their function allows it. The IT infrastructure and administrative procedures were quickly adapted so that all of the staff could perform their work, research and administrative tasks remotely.

Moreover, lockdown periods have prevented scientists from travelling to missions or conferences abroad, most of the latter being converted into an online and remote version.

Despite those disturbances, the staff quickly adapted to the new ways of working and doing scientific research. All the service activities of ORB-KSB regarding time keeping, seismic and GNSS[1] network monitoring, continuous gravimetric measurements, solar observations, space weather forecasts and PECASUS and astronomical information were maintained and functioned as usual.

Nanok Expedition – Two Belgian adventurers work with scientists of the ORB-KSB for climate research

The Belgians Gilles Denis and Nathan Goffart collaborate with scientists from the Royal Observatory of Belgium (ORB-KSB), the Université libre de Bruxelles (ULB), the Université de Liège (ULiège) and the Geological Survey of Greenland and Denmark (GEUS) for climate research during their sport challenge in Greenland in April 2022.

Their challenge, called Nanok Expedition, consists in an untypical triathlon, combining successively a 600 km crossing of the inlandsis with skis and pulka along the Arctic Circle, a 1000 km sea kayaking journey down the east coast and a 1 km vertical rock-climbing ascent for the opening of a new route. Nanok is the spirit of the polar bear in Inuit culture, hence the name.

Thanks to a GNSS receiver placed on the adventurer's pulkas during their traverse of the inlandsis, Dr Nicolas Bergeot and his colleagues from Time-Ionosphere section of the ORB-KSB will be able to gather valuable satellite data. GNSS, an acronym for Global Navigation Satellite Systems, is a satellite system with which precise positions could be determined. Those data will notably be used to calibrate ice sheet elevation models in Greenland.

For the ULB, Denis and Nathan will collect snow and cryoconite, a type of crushed stone consisting of dust, soot and microbes that lies on ice and snow. Those samples would help researchers understand the dust contribution to algae growth as well as the extension on the Greenland Ice Sheet and its accelerated melting. Furthermore, ULB scientists will assess the impact of microplastics on remote seawater along the Greenlandic east coast.

[1] GNSS stands for Global Navigation Satellite Systems, such as GPS and Galileo.

For ULiège and the GEUS, they will perform snow pit measurements of winter snowfall accumulation. Those measurements will help to validate the researcher's current modelled surface mass balance on the Greenland Ice Sheet.

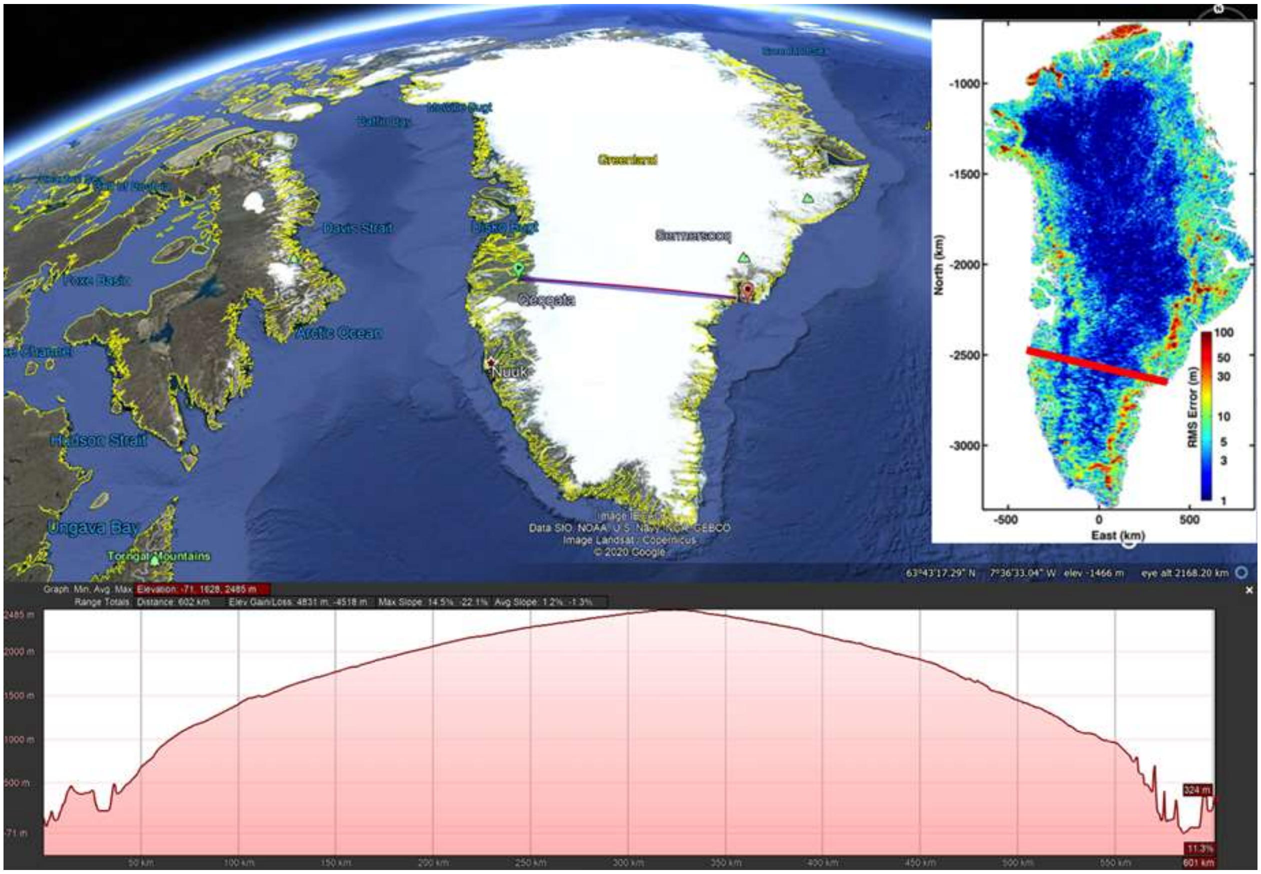


Figure 1: Gilles and Nathan crossed Greenland following the straight line on the map. The height profile of the crossing can be seen below.

On March 12, 2021, the two friends head back to the North to prepare for this expedition and to test the experimental setups.

The 10 June 2021 Solar Eclipse

Figure 2: The 10 June 2021 solar eclipse observed by SWAP onboard PROBA2. Credit: ESA/ORB-KSB.

An annular solar eclipse took place on Thursday 10 June 2021 and was partially visible in Belgium. In Uccle, the eclipse was visible between 11:17 (first contact) and 13:25 (last contact), and its maximum took place at 12:19 in Belgian time (UTC + 2 h). At that moment, in Brussels, about 26% of the Sun's diameter was covered by the Moon.

Solar instruments operated by the ORB-KSB observed this solar eclipse. This is the case with the SWAP camera and the LYRA radiometer on board of the PROBA2 satellite and the USET solar telescopes at Uccle.

On that day, an eclipse question challenge was also organised by the team of the PROBA2 Data Center of the ORB-KSB.

Prizes, Awards and Grants

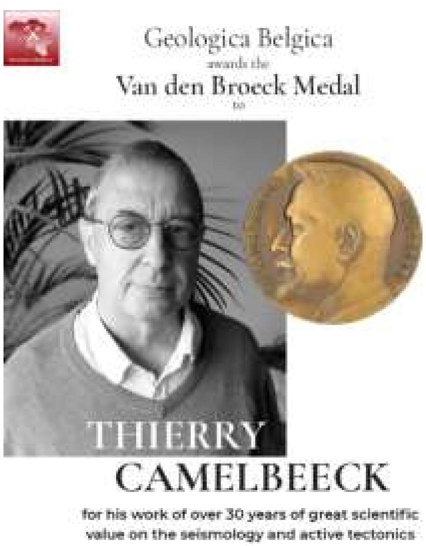
Two scientists of the ORB-KSB in the top 2% most-cited researchers in the world

Stanford University recently released a list that represents the top 2% of the most-cited scientists in the world in various disciplines. It was created to provide updated analyses and a publicly available database of top scientists. Updated databases and code are freely available in Mendeley (https://dx.doi.org/10.17632/btchxktzyw).

This list of the top 2% most-cited scientists is composed of 159,684 researchers, of which 1,413 scientists are affiliated to Belgian institutes, with 9 of them listed in the top 10% in their research field. Two of the researchers who made it onto the list come from the Royal Observatory of Belgium (ORB-KSB): Martin Groenewegen and Véronique Dehant.

According to the Stanford ranking, Martin Groenewegen and Véronique Dehant are, in the field Astronomy and Astrophysics, the 400th and 1516th out of 42,624 in the world respectively. Moreover, Martin Groenewegen comes as the most cited of the six astronomers affiliated to a Belgian institute in this list.

Thierry Camelbeeck: 2021 Laureate of the Van den Broeck Medal



Thierry Camelbeeck was awarded the Van den Broeck medal in Tervuren during the 7th International Geologica Belgica Meeting at the Royal Museum for Central Africa in Tervuren on Friday 17 September 2021. The Van den Broeck medal was created in 1987 in honour of the first General Secretary of the Société belge de géologie. Geologica Belgica, i.e. Belgium's current society for geologists, awards this medal to a scientist to honour his/her career work and his/her dedication to the Geology of Belgium. Thierry Camelbeeck, Belgium's seismologist at the Royal Observatory of Belgium, is the 2021 Laureate and is honoured because of his great work in seismology and active intraplate tectonics. At the onset of his career, Thierry Camelbeeck installed the first Belgian modern seismometer network. This achievement allowed to study earthquakes in and around Belgium that occurred during the last decades. His career work valuably contributed to our understanding of the causes of intraplate earthquakes.

Véronique Dehant Received her Prix Quinquennal of the FNRS at Bozar

Véronique Dehant, researcher at the Royal Observatory of Belgium, has just been officially awarded the Dr De Leeuw-Damry-Bourlart Prize in Fundamental Exact Sciences, one of the five Prix Quinquennaux of the FNRS (Fonds de la Recherche Scientifique).

The award ceremony took place on Monday 4 October 2021 at 10:00 at the Palais des Beaux-Arts (Bozar), in the presence of King Philippe. It was the occasion to reward the five new laureates of the Prix Quinquennaux of the FNRS as well as the five laureates of the Excellentieprijzen of the FWO (Fonds Wetenschappelijk Onderzoek). The Prix Quinquennaux were awarded on 14 September 2020. Due to the sanitary restrictions caused by the COVID-19 pandemic, the official ceremony has been postponed to 2021.

The FNRS wishes, by means of these prizes, to honour every five years the exceptional work and careers of researchers from the Wallonia-Brussels Federation from various disciplines (exact sciences, biomedical sciences, humanities and social sciences).

The Prix Quinquennal of the FNRS awarded to Véronique Dehant underlines the importance of her work on the rotation and interior of the Earth, planets and moons, as well as her key role in the development of space missions and instruments such as RISE on board NASA's InSight mission and LaRa on ESA's second ExoMars mission, scheduled for launch in 2022.

Two 2021 Prizes of the Académie royale de Belgique Awarded to Scientists of the ORB-KSB

Laurent Mahy and Jérémy Rekier, researchers at the Royal Observatory of Belgium, received respectively the 2021 Paul & Marie Stroobant Prize and the 2021 prize of the annual competition of the science division of the Académie royale des sciences, des lettres et des beaux-arts de Belgique. These prizes highlight the quality of their research in the field of astronomy and the rotation and interior of the Earth respectively.

Laurent Mahy, Winner of the Paul & Marie Stroobant Prize

The Paul & Marie Stroobant Prize is awarded every two years to the author of a work in observational or theoretical astronomy. This prize was created in 1950 in honour of Paul Stroobant, director of the Royal Observatory of Belgium from 1925 to 1936 and member of the Academy. This year it was awarded to Laurent Mahy, senior researcher at the Observatory, for his significant contribution to the study of the fundamental properties of massive stars and their evolution.

Laurent Mahy is particularly interested in massive stars in multiple systems and the stellar winds produced by these stars. Using different observational techniques to study massive binary stars, he has been able to show that what was thought to be stellar black holes in binary star systems are in fact stars that rotate very fast.

The researcher also took advantage of the 42 orbits of the Hubble Space Telescope to study the stellar winds produced by massive stars in the Large and Small Magellanic Clouds. The data are being processed as a pilot study for the ongoing ULLYSES project (Hubble UV Legacy Library of Young Stars as Essential Standards), which is producing a library of ultraviolet spectra of young stars in our universe from Hubble data.

Jérémy Rekier, Winner of the 2021 Contest of the Académie royale

Jérémy Rekier is a postdoctoral researcher in the physics of the Earth's rotation and interior, which he studies by developing numerical models. He received the award in response to a question from the Academy, which is looking for new research in the field of astronomy and physics this year.

The question of this year concerned 'an original contribution, experimental or theoretical, to the physics of the Earth's core or that of the telluric planets'. The Academy focused its attention on Dr Rekier's manuscript, entitled 'The role of inertial waves in the internal dynamics of terrestrial planets'.

Jérémy Rekier's master's thesis presents recent theoretical developments based on numerical and analytical modelling by him and his team at the Royal Observatory of Belgium on the dynamics of liquid cores of rotating planets. The jury praised the effort made to highlight the link between these developments and the founding work of great scientists such as W. Thomson (Lord Kelvin), G. H. Bryan, S. Hough, E. Cartan, or H. Poincaré, whose contribution was so central that the fundamental equation of the discipline bears his name. The jury also judged that the results presented were 'original, significant and of high quality'.

Space Missions and Scientific Services

DART Launch – The ORB-KSB Participates in a NASA Planetary Defence Mission

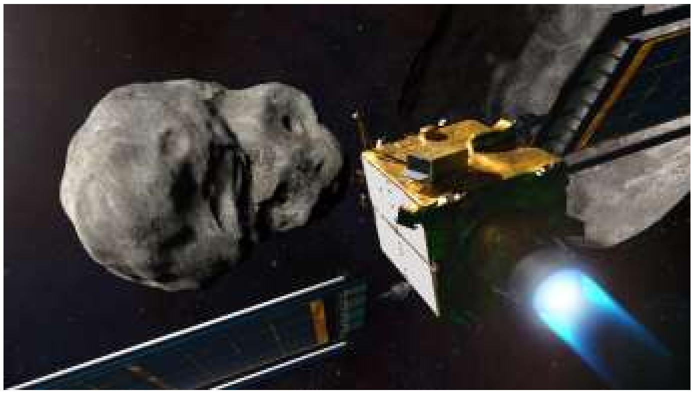


Figure 3: Artist view of the DART mission

On November 24, 2021, NASA's DART spacecraft took off from the Vandenberg Space Force base in California (USA) as part of a planetary defence mission against asteroids. The ORB-KSB is involved in this mission.

The DART mission, which stands for Double Asteroid Redirection Test, aims to see whether sending a spacecraft to crash on the surface of an asteroid can deflect it sufficiently so that it no longer poses a threat to the Earth. Between September 26 and October 1, 2022, DART will approach a binary asteroid system consisting of Didymos, a 780 m diameter asteroid, and Dimorphos, which is 160 m long.

DART will collide with the Dimorphos asteroid at a speed of 24,000 km/h (6.6 km/s). This collision will change the orbital period of Dimorphos around Didymos, which will be measured from Earth. Thanks to this measurement, scientists will be able to obtain information on the best way to deflect an asteroid from its trajectory.

Özgür Karatekin and his team of the ORB-KSB are involved in the DART mission as part of the international Asteroid Impact and Deflection Assessment (AIDA) collaboration of which NASA and ESA, with its Hera mission scheduled for launch in 2024, take part.

Scientists of the ORB-KSB will participate in the processing of DART data. Analysing the data from this mission will allow them to better understand the internal structure of asteroids, in the framework of the European projects PIONEERS (Planetary Instruments based on Optical technologies for an iNnovative European Exploration using Rotational Seismology) and NEO-MAPP (Near-Earth Object Modelling and Payloads for Protection) to which the ORB-KSB contributes. The experience with DART will also help to better prepare the next mission, Hera, which will carry the GRASS gravimeter, developed by the Observatory with its Spanish industrial partner EMXYS.

The research of the ORB-KSB related to this mission is funded by the Belgian Federal Science Policy (BELSPO) with support from the ESA PRODEX programme. The PIONEERS and NEO-MAPP programmes have received funding from the European Union's Horizon 2020 research and innovation programme.

Solar Orbiter Last Flyby to the Earth

On 27 November 2021, the Solar Orbiter spacecraft returned from its voyage in deep space, and passed at only a few hundred kilometres above the Earth's surface. This manoeuvre was needed to get Solar Orbiter in a new orbit to go yet closer to the Sun. During this flyby, Solar Orbiter had to cross the clouds of space junk that surround Earth, making it a risky visit to our planet.

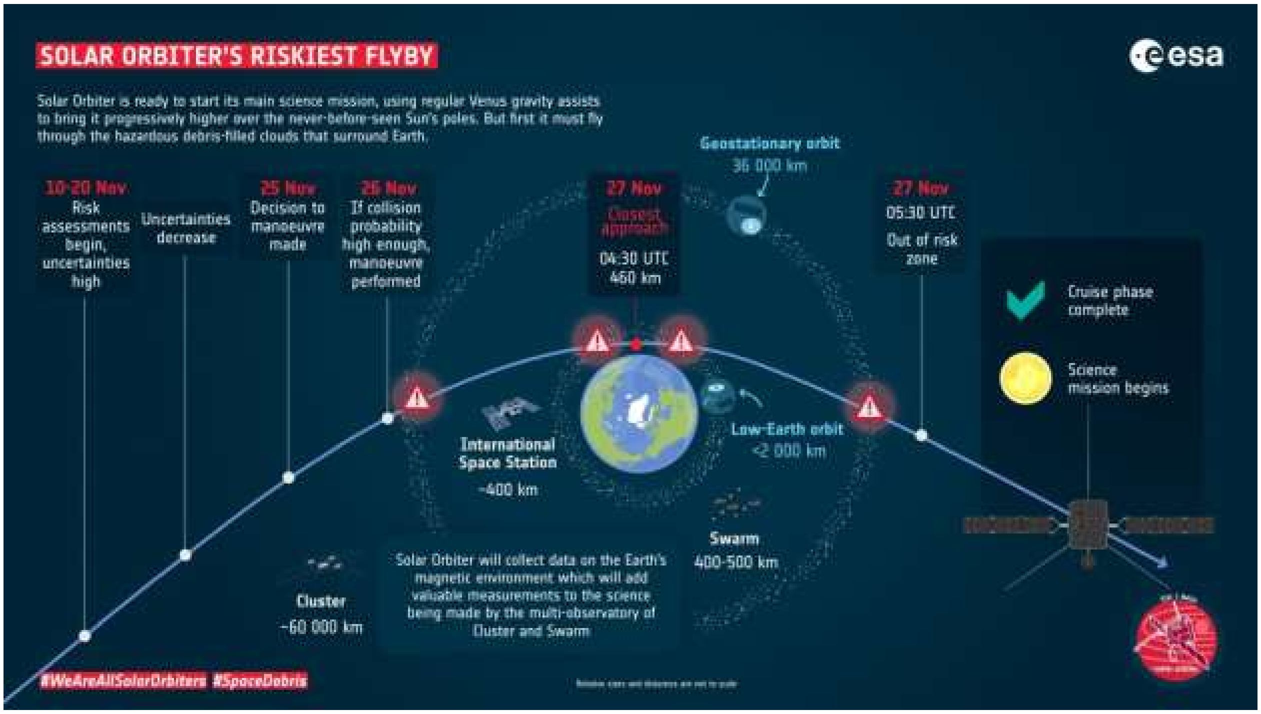


Figure 4: Solar Orbiter's Earth flyby takes place on 27 November. At 04:30 UTC (05:30 CET) on that day, the spacecraft will be at its closest approach, just 460 km above North Africa and the Canary Islands.

The flyby marked a major milestone for Solar Orbiter. After this last goodbye to Earth, the spacecraft was put in orbit and started its scientific mission. Following the launch in February 2020, the spacecraft and all instruments onboard have been thoroughly tested. Despite Solar Orbiter not yet being in full science mode, the instruments were already taking data as often as possible and a lot of science has been produced, far exceeding the expectations. An upgrade to the ESA Ground Station Network allowed Solar Orbiter to send more data down to Earth, and the mission's scientists have fully taken advantage of this.

One of Solar Orbiter highlights is the enigmatic 'campfires' that the spacecraft saw at the first perihelion. The campfires could hold clues about how the Sun's outer atmosphere has a temperature of millions of degrees, while the surface has a temperature of thousands – which seemingly defies physics because heat should not be able to flow from a colder to a hotter object. Cis Verbeeck, Consortium Project Manager of the EUI instrument onboard that images the Sun at very high resolution, excitedly explains that these early observations have shown that campfires are everywhere in the solar atmosphere and appear to be small versions of solar flares at much lower heights than regular flares.

After the flyby, when Solar Orbiter re-emerges from the Earth's shadow, it will be on its course for a close rendezvous with the Sun. Unique observations have already been scheduled, and exciting times for our understanding of our mother star are expected!

2021 Seismic Activity of Belgium

In 2021, 256 natural earthquakes occurred in a zone between 1° and 8°E longitude and 49° and 52°N latitude. During the same period, the Royal Observatory of Belgium (ORB-KSB) also measured 6 induced events, 367 quarry blasts and at least 9 explosions at sea linked to controlled explosions of WW1 and WW2 bombs by the Belgian, Dutch or French Armies. The 2021 ORB-KSB catalogue is complete for natural earthquakes with a local magnitude above 1.5 and contains a selection of quarry blasts and earthquakes induced by human activities, e.g. linked to (rock) mass removal in mines or geothermal exploitation.

Of the 256 measured tectonic earthquakes 31 took place in Belgium, 2 occurred in France, 17 in The Netherlands and 207 in Germany.

The largest earthquakes recorded on Belgian territory in 2021 occurred on 20 June 2021 in Dampremy near Charleroi and 28 August 2021 in Baelen near Eupen. Both events had a local magnitude of 1.7 and were not felt by the local population. Five of the measured induced events are related to the deep geothermal Balmatt energy project in Dessel. The seismic monitoring network of the ORB-KSB has remained fully operational during 2021 and currently includes 30 seismometers and 18 accelerometer stations.

In comparison, last year in 2020, 52 earthquakes occurred in and around Belgium. The largest earthquake was the 5 May 2020 Modave earthquake with a local magnitude of M_L 1.7.

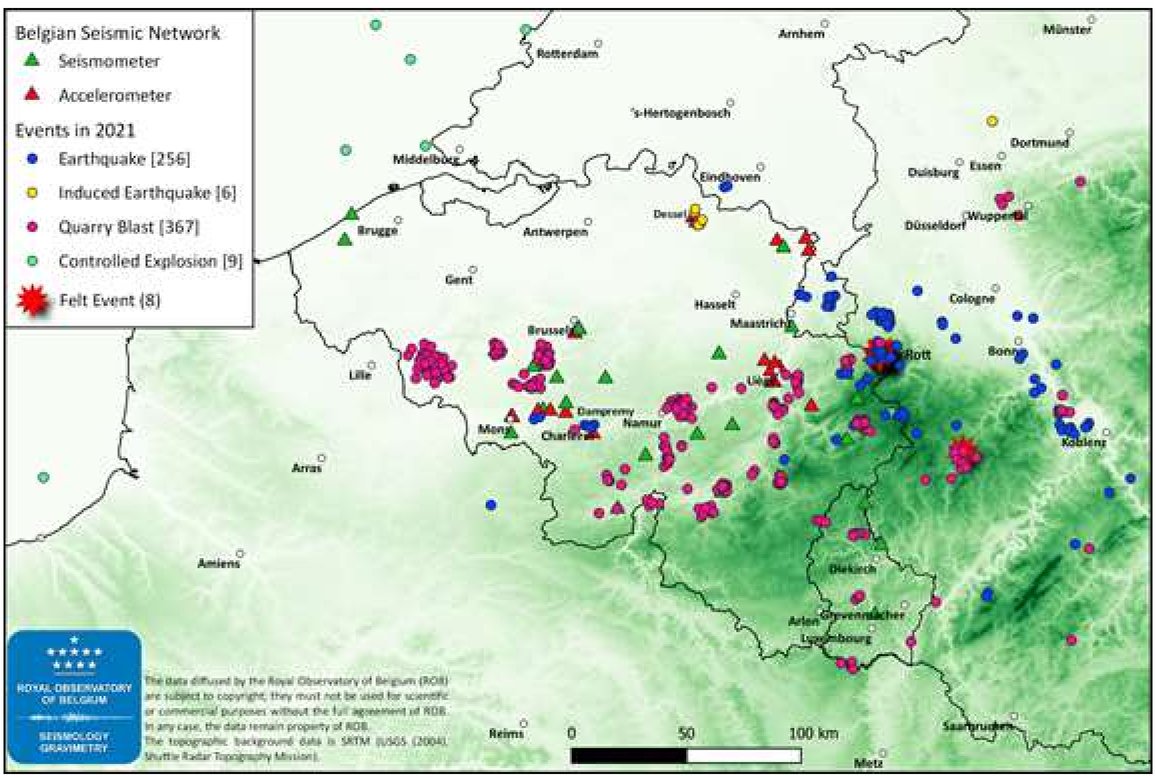


Figure 5: Events recorded in 2021 by the Belgian Seismic Network of the ORB-KSB in a zone of 49°-52°N and 1°-8°E.

Compared to the last 20 years, more events were measured in 2021, which is mainly related to the occurrence of small tectonic events in three seismic swarms in Rott (Eifel, Germany), Eschweiler (Lower Rhine Embayment, Germany) and Voerendaal (The Netherlands). The largest seismic activity measured by the ORB-KSB in 2021 occurred in a radius of 1.5 km around the town of Rott in the Eifel mountains just across the German border. During this seismic sequence, 126 earthquakes were located at an average depth of 9.7 km below the surface. Seven events of this sequence were felt by the local population who spontaneously answered the collaborative ORB-KSB-Bensberg "Did You Feel It?" questionnaire on the ORB-KSB website. The two largest events, which happened on 2 and 14 January 2021, both had a local magnitude of 2.6 and were felt from Rott up to the cities of Aachen (DE) and Eupen (BE).

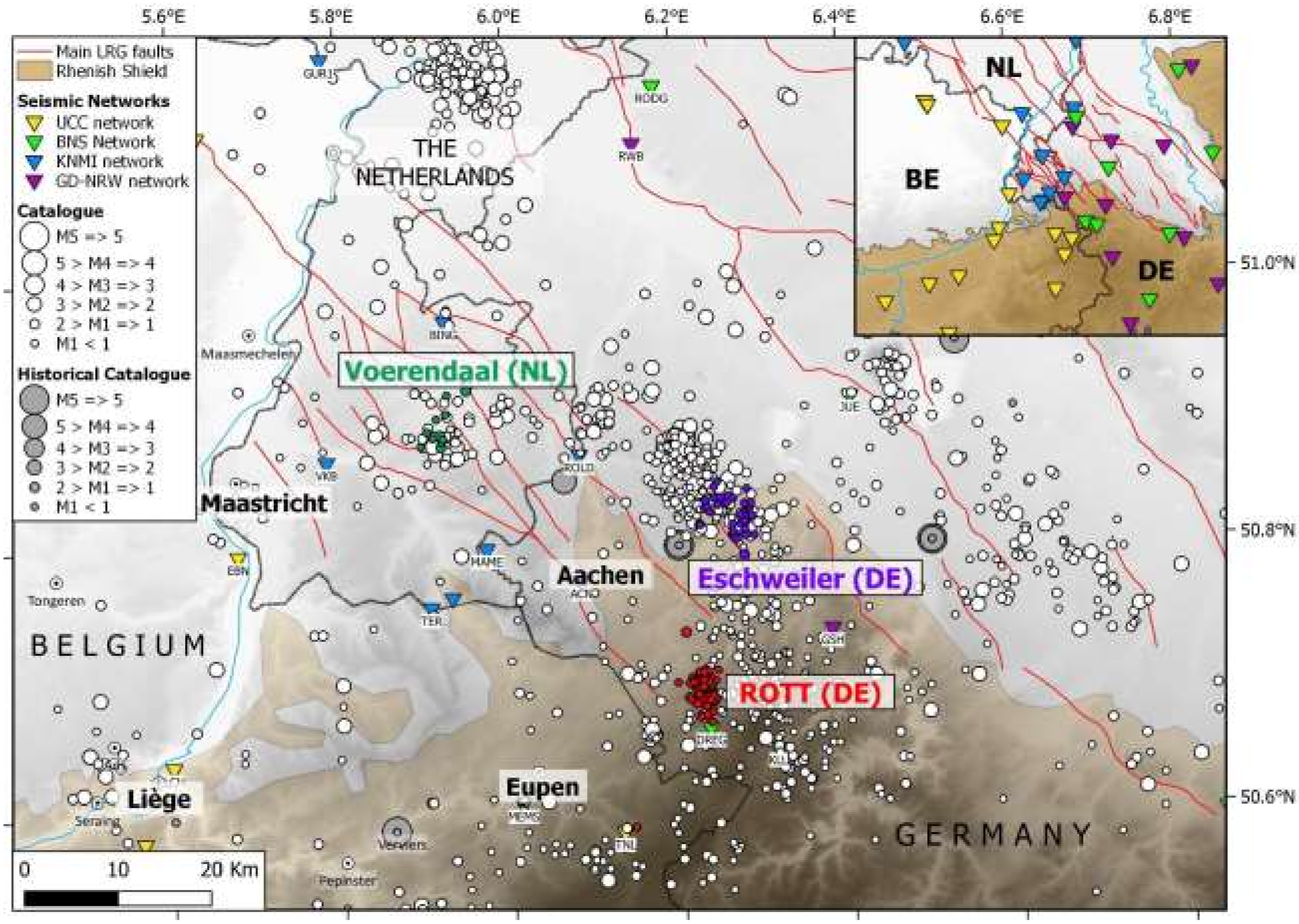


Figure 6: Overview of swarm activity in the Lower Rhine Graben. White dots show the full ORB-KSB earthquake catalogue. Coloured dots show the three seismic swarms active in 2021. The inlet shows the Belgian, Netherlands and German seismic networks used to monitor these earthquake swarms.

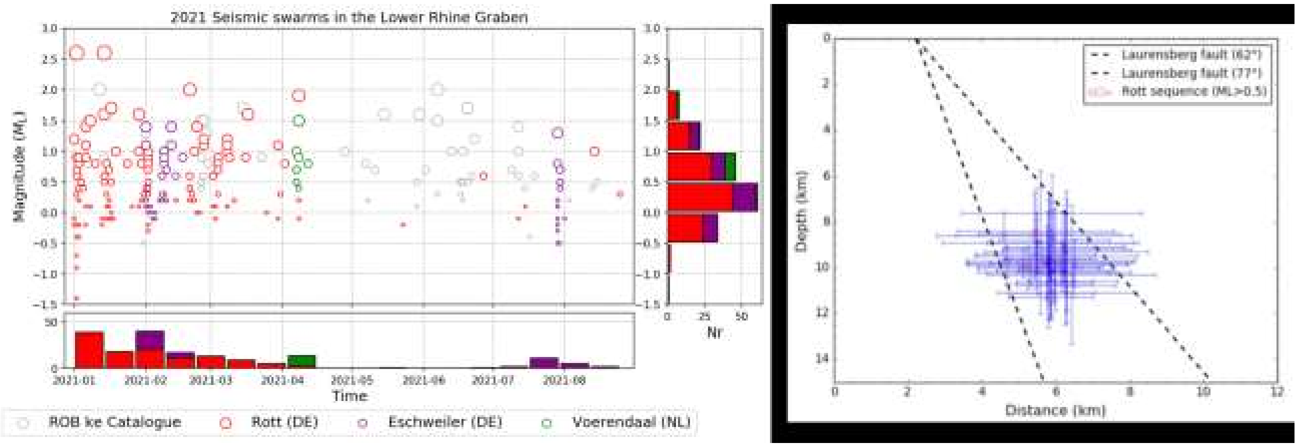


Figure 7: (Left) Swarm evolution in the Lower Rhine Graben. The Rott seismic sequence was mainly active in the first four months of 2021. Grey dots in the background show the full 2021 ORB-KSB earthquake catalogue. (Right) Depth evaluation of the Rott events and their potential relationship with the Laurensberg border fault.

Citation: Van Noten, K., Lecocq, T., Vanneste, K., Lefevre, M., Camelbeeck, T., Knapmeyer-Endrun, B., Carrasco, S., Kadmiel, S., "Recent seismic swarm activity in the Lower Rhine Graben (Germany, The Netherlands)" (2021). Talk presented at 37th General Assembly of the European Seismological Commission, Corfu, Greece on 2021-09-22.

Research at the Royal Observatory of Belgium

Seismology and Gravimetry

Improving Global GNSS Vertical Land Motion Assessment

Monitoring vertical land motions (VLMs) at the level of 0.1 mm/yr remains one of the most challenging scientific applications of Global Navigation Satellite Systems (GNSS[2]). Such small rates of change can result from climatic and tectonic phenomena, and their detection is important to the prediction of coastal sea-level change – if the land goes down while the sea moves up, this enhances the problem! – and the understanding of deformation processes acting within tectonic plates.

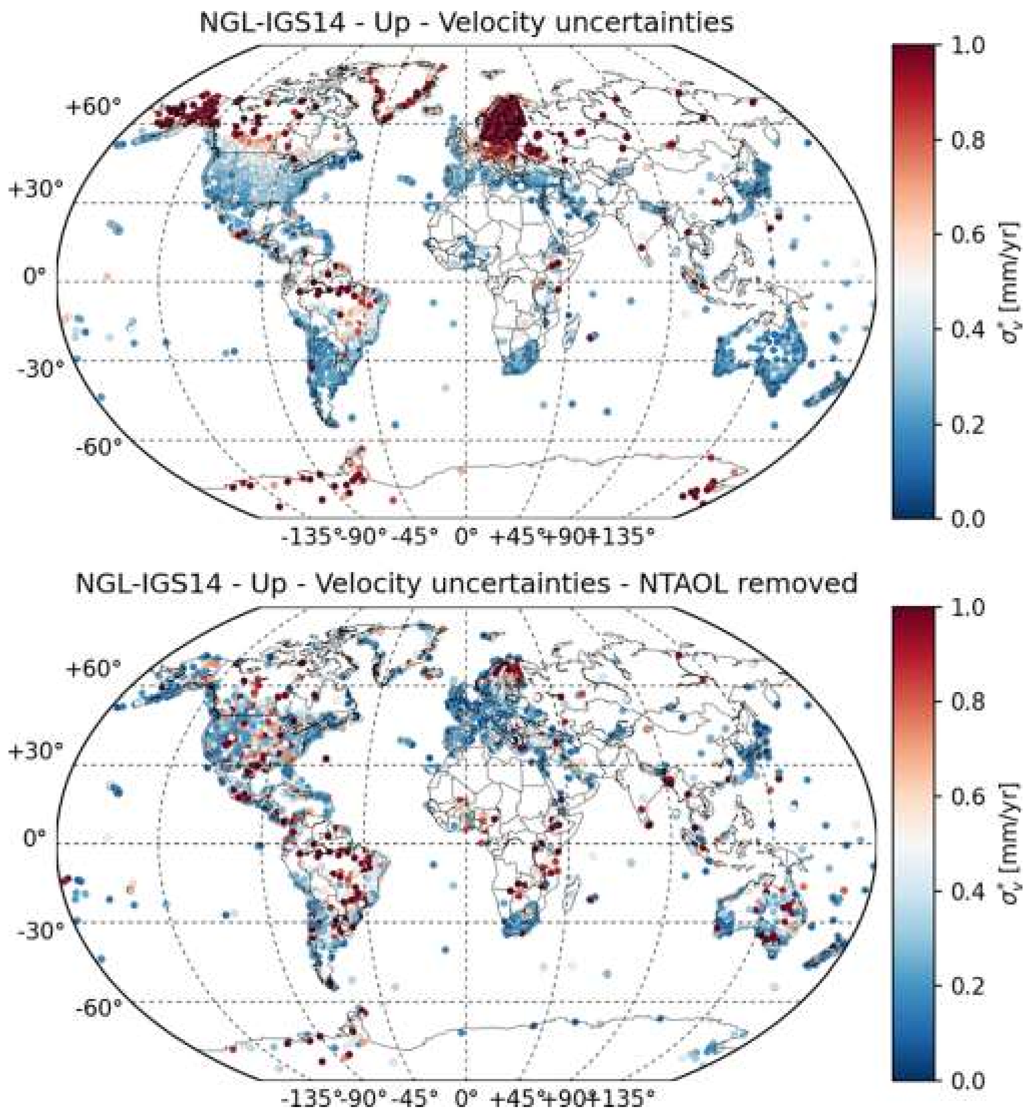


Figure 8: (Top) Global variability of the minimum velocity uncertainty for 8-year-long GNSS time series before removing non-tidal atmospheric and oceanic loading (NTAOL) deformations and (Bottom) after removing NTAOL deformations. Note the dramatic decrease (down to 70%!) in uncertainties for latitudes higher than 45° (Gobron et al., JGR, 2021).

[2] GNSS stands for Global Navigation Satellite Systems, such as GPS and Galileo.

We investigated to what extent accounting for the deformation of the Earth's crust due to changes in the distribution of the atmospheric and oceanic pressure helps to detect small vertical ground deformation. By analysing the data from over 10,000 globally distributed GNSS stations, we showed that accounting for such atmospheric and oceanic deformation can reduce by 70% the uncertainty of the vertical velocity of GNSS stations at high latitudes, which will, for instance, improve sea-level change monitoring and small amplitude deformation analysis in these areas.

This work was achieved by K. Gobron, between 2018 and 2020 during his thesis under joint supervision with the service Seismology-Gravimetry of the Royal Observatory of Belgium, U. Liège and U. La Rochelle, and in 2021 during his postdoc at the service Seismology-Gravimetry, as part of the BRAIN-LASUGEO (monitoring LAnd SUbsidence caused by. Groundwater exploitation through gEOdetic measurements) project.

Citation of the paper : Gobron, K., Rebischung, P., Van Camp, M., Demoulin, A., & de Viron, O. (2021). Influence of aperiodic non-tidal atmospheric and oceanic loading deformations on the stochastic properties of global GNSS vertical land motion time series. Journal of Geophysical Research: Solid Earth, 126, e2021JB022370. https://dx.doi.org/10.1029/2021JB022370

Global Navigation Satellite Systems

European Plate Observing System – EPOS

The ambition and the organisation

Understanding how the Earth works as a system is critically important to modern society. Volcanic eruptions, earthquakes, floods, landslides, tsunamis, weather, and global climate change are all Earth phenomena affecting society.

The Royal Observatory of Belgium's (ORB-KSB) expertise touches several of these phenomena, and corroborates that progress in solid Earth science relies on the integration of harmonised multidisciplinary, freely accessible, data and products, which are – and here is the difficulty – originally generated by different communities with different data formats and processing procedures.

It is exactly the ambition of the European Plate Observing System (EPOS) to offer a collaborative framework to provide, through a unique portal, open access to these multidisciplinary data as well as visualisation and modelling tools. Together, they offer the key to understanding the complex Earth's dynamic system.

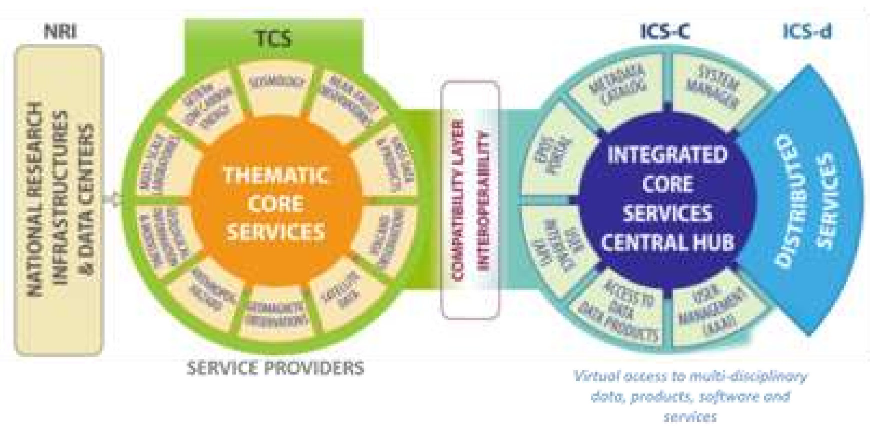


Figure 9: Functional diagram of EPOS.

EPOS is organised in *Thematic Core Services* (TCS) in which selected Service Providers (SP) provide services relative to a specific scientific discipline (see Figure 9). These services primarily aim at providing harmonised access to the data from the underlying *National Research Infrastructures* (NRI).

The **TCS "GNSS data and products" (also called "EPOS-GNSS")** is built on the EUREF Permanent GNSS Network, managed by the ORB-KSB, as well as on GNSS networks operated by NRI all over Europe. EPOS-GNSS will provide access to GNSS data, metadata and data products from more than 3000 GNSS stations. The provided data products measure precise ground deformations caused by volcanos, earthquakes, or anthropogenic subsidence due to water and natural gas withdrawal.

The **TCS "Seismology"** provides services for accessing earthquake data. Among others, it integrates data from ORFEUS (Observatories & Research Facilities for European Seismology) which coordinates digital seismology in Europe.

EPOS presently delivers pre-operational services, but it is expected to become operational by the end of 2022.

EPOS-BE

EPOS-BE stands for the Belgian contribution to the European Plate Observing System.

As one of EPOS founding members, Belgium, and especially ORB-KSB, is strongly involved in EPOS. In the initial phase, the Belgian Federal Science Policy Office (BELSPO) supported ORB-KSB through the EPOS-BE project (12/2018 - 06/2023) aiming at upgrading ORB-KSB's infrastructure to prepare it for the provision of data and services to EPOS.

Since December 2021, BELSPO additionally supports ORB-KSB (SERVE project in the ESFRI-FED programme) to strengthen the sustainability of the pan-European GNSS services it will provide to EPOS.

GNSS

ORB-KSB's contribution to EPOS-GNSS is threefold. It is involved in its governance and coordination, delivers GNSS data, and provides several, presently still pre-operational, pan-European GNSS services.

Governance and coordination: As a member of the EPOS-GNSS Consortium and chair of its Executive Board, ORB-KSB coordinates the day-to-day EPOS-GNSS activities, the implementation of mechanisms for quality checks of service provision, the compliance check with the EPOS data policy, the interface with EUREF, and it attracts new GNSS data suppliers to join EPOS. This last activity is also aiming at consolidating the sustainability of the overall EPOS infrastructure, which is the main goal of the EU project EPOS-SP (Sustainability Phase) to which ORB-KSB participates. In addition, since 2021, ORB-KSB is financially supported by EPOS-ERIC (European Research Infrastructure Consortium) for its EPOS-GNSS governance and coordination activities.

GNSS data provision: ORB-KSB renewed in 2021 part of the hardware in its GNSS stations and is delivering their data to EPOS. In addition, ORB-KSB also convinced the Vlaamse overheid and the Service public de Wallonie to share the data from their permanently tracking GNSS stations with EPOS. In 2022, ORB-KSB will be setting up a dedicated national EPOS data node providing access to all these Belgian GNSS data.

Pan-European GNSS Services: ORB-KSB's EPOS services have been built on ORB-KSB's EUREF services in operation for many years to maintain the European Terrestrial Reference System ETRS89. With the support of the EPOS-BE and SERVE projects, these EUREF services are upgraded to respond to EPOS needs, resulting in

- the pan-European data node making the EUREF data discoverable to EPOS;
- the GNSS station metadata management service M3G, guiding EPOS-GNSS towards application of FAIR data principles;
- the analysis centre computing the velocity field (Figure 10 and Figure 11) and the associated station position time series of the EPN stations. They provide information on ground deformations especially valuable for geophysical research.

In 2021, these upgraded services passed EPOS pre-operational testing and from 2022 on, EPOS ERIC will financially support their operation.

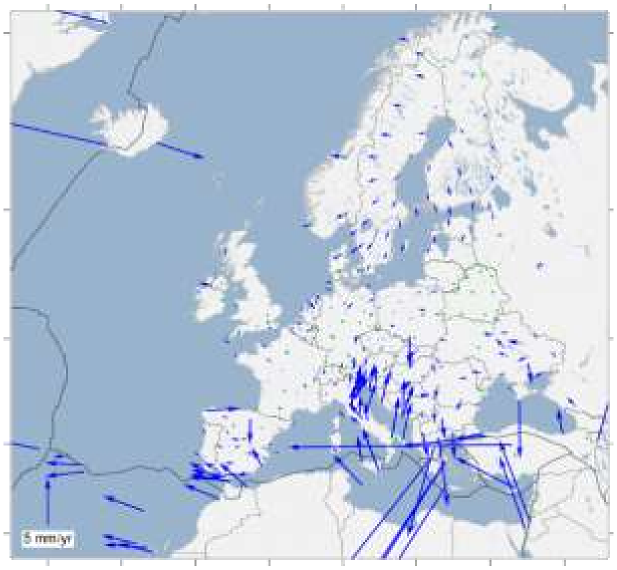


Figure 10: Horizontal velocities of the EPN stations expressed in the ETRS89.

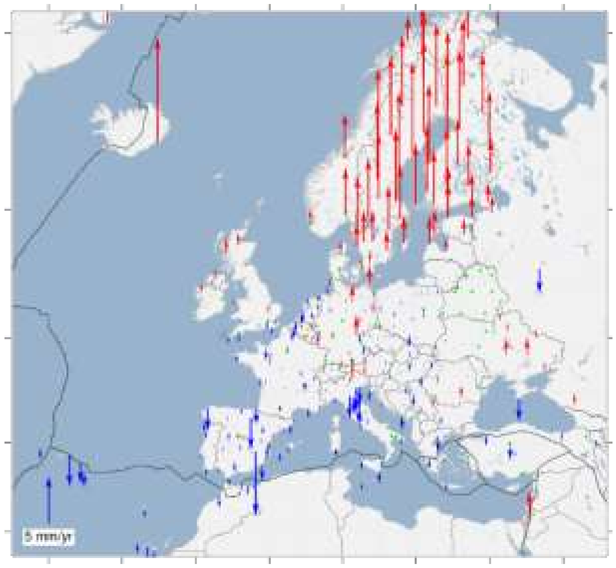


Figure 11: Vertical velocities of the EPN stations expressed in the ETRS89.

Seismology

The seismological part of the EPOS-BE project consists of two main tasks. In the first work package, the instrumentation of six stations of the Belgian permanent Seismic Network has been upgraded to increase the high-quality seismic data of the Belgian Network to ORFEUS. The previous short-period sensors (some even with only one component) are replaced by broadband sensors. If possible, we installed borehole instruments, which enhances the data quality by many orders as unwanted noise sources from mainly human influence (anthropogenic ambient noise) are suppressed. This upgrade strengthens the monitoring task of the Royal Observatory of Belgium with state-of-the-art data quality and guarantees that the Seismology-Gravimetry section of the ORB-KSB will be able to fulfil its Belgian federal missions adequately in future decades. Alongside the technical upgrade of the instruments, those stations will receive improved communication to stream waveform data in real time to ORFEUS. That allows direct and public access to the high-quality data by the international seismological community.

In the second stage of EPOS-BE, site-characterisation studies are performed for the newly equipped seismic stations and the other seismic stations within the Belgian seismic network, using primarily non-invasive geophysical methods. Site characterisation describes the analysis of the shallow subsurface underneath a seismic sensor or location of interest. This is not only important for seismologists to understand what a seismic sensor is recording and if the geology of the shallow subsurface is damping or amplifying seismic waves, but also for civil engineers, who need these observations to estimate the actual shaking of buildings or of fragile infrastructure that they are planning. The identified subsurface parameters are finally collected in the ORFEUS Station book of each seismic station. Through this platform, these newly generated data products are then shared alongside the waveform data to the mentioned communities.

Figure 12: Site-characterisation fieldwork in Seneffe (SNF), using seismic waves excited through hammer shots to analyse the subsurface structure in the vicinity of the seismic station placed in a shallow borehole next to the little building in the photo.

Figure 13: One of the main site-characterisation products, showing a shear-wave velocity (vS) model with depth for the seismic station in Uccle at the ORB-KSB.

Time

Testing the existence of Dark Matter objects close to the Earth using atomic clocks in Galileo satellites

The outstanding accuracy and stability of atomic clocks pave the way to new tests of fundamental physics. The availability of such atomic clocks at the Royal Observatory of Belgium (ORB-KSB) and onboard satellites from the Global Navigation Satellite Systems (GPS, Galileo, GLONASS, BeiDou), together with the high precision clock comparison techniques developed at the ORB-KSB provide excellent tools for such studies.

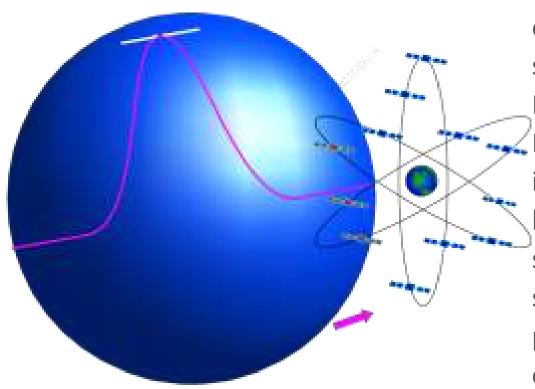


Figure 14: Encounter of the Earth with a transient dark matter (DM) object (illustrated here as a blue ball). The spatial variation of the fundamental constants, so the effect on the atomic clocks, is illustrated by the purple profile. The atomic clocks onboard Galileo satellites in orbit around the Earth will then be affected successively according to their trajectory and the trajectory of the DM object.

In particular, one possible explanation for the discrepancy existing between the luminous ordinary matter and the large-scale cosmological observations (Galactic motions, Cosmic Microwave background, gravitational lens...) is the existence of Dark Matter. Namely, an unknown type of matter of which the interaction with ordinary matter is so tiny that it has not yet been observed, except through its gravitational effect at large scale. A lot of theories are compatible with the existence of spatially extended structures of dark matter (DM) that could possibly regularly cross the Earth, and affect the fundamental constants, hence the properties of the electronic transitions and hence the atomic clocks. In what follows, these are called transient DM structures.

In this context, we collaborated with the ESA and the Observatoire de Paris to analyse the large network of atomic clocks onboard the Galileo satellites, providing a gigantic detector of 60000 km of aperture, in order to search for the signature of transient dark matter (DM) objects (Figure 14). This project, called GASTON (GAlileo Survey of Transient Objects Network), was funded by the ESA under the H2020-038 program (GNSS Evolutions Experimental Payloads and Science Activities. The goal was to carry out a systematic analysis of Galileo satellite atomic clocks, which are Hydrogen masers, the most stable clocks currently in orbit around the Earth. For a given model of dark matter structure, the signature on satellite clocks can be modelled. An example of satellite clock frequency variations over a 7-day period is shown in Figure 15; it corresponds to the effect of the passage of a transient object of size d = 1011 m, with the profile illustrated in Figure 14. From clock data analysis, observing these variations in the atomic clock frequency in a consistent way with the DM model would allow detecting indirectly the passage of DM structures. On the other hand, the non-observation of such variations is also very useful as it allows excluding some models.

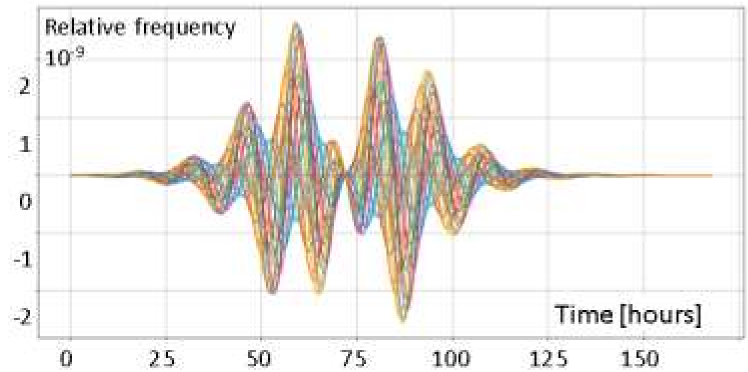


Figure 15: Modeling of the relative frequency differences for 21 Galileo satellite clocks (one colour per satellite) in case of an encounter with a transient object of size d = 1011 m. The modulated periodic behaviour originates from the combination of two effects: the periodic orbital motion of the satellites, and the fact that the effect on the clock follows the purple profile of Figure 14.

We developed a quick method, based on a “maximum reach analysis”, consisting of using the maximum clock variations observed over a 3-month period of Galileo clock data, allowing ruling out configurations of DM objects. The transient DM is characterised by several parameters, among which the size d of the DM objects and their weak interaction strength Λ with ordinary matter. Our study is the first ever that explores such transient variations of fundamental constants over the scale ranges 105-109 km by data mining. The results showed that transient objects with a radial profile close to a hyperbolic tangent (the one shown in Figure 14) and with a quadratic scalar coupling to ordinary matter (Λ) inferior to 108 TeV do not exist experimentally if their size d ranges between 108 and 1012 m (for a mean period of encounter of the order of one month).

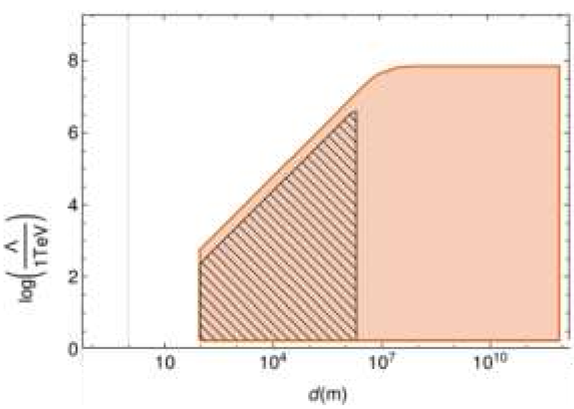


Figure 16: Exclusion area (in orange) for parameters of transient DM objects of size d (for a mean period of encounter of 1 month) resulting from the maximum reach analysis using 3-month of Galileo clock data. This graph was obtained using DM parameters of the Galactic halo, a hyperbolic tangent profile and a small scalar quadratic coupling to ordinary matter of strength Λ. The hatched region represents the constraints previously obtained with GPS clocks.

The second part of the project consisted of a full statistical analysis to directly detect transient dark matter (DM) from signatures like the example proposed in Figure 15. This analysis considers therefore correlations between the various clocks, their trajectories along the orbits and the trajectory of the transient DM. It requires huge machine computation times, and the interpretation of the results is less straightforward. While evidence of several significant events with high signal-to-noise ratio (SNR) were found, further analysis is currently carried out to ensure that these events cannot result from some systematic effects in the clock data able to produce a similar signature.

Planetary Science

Advances in understanding Mercury's composition and thermal evolution

The high density of Mercury indicates that metallic iron accounts for about 70 % of the planet's mass. This sets Mercury far apart from other solid objects in the Solar system of substantial size, which have iron contents below 35wt%. How this iron-rich planet formed in the Solar System, with all other major rocky objects dominated by rock instead of Fe-metal, has been an open-standing question for decades. One way of gaining understanding on this issue is by improving knowledge on the rest of Mercury's bulk composition. Mercury's Fe-rich core is a dominant part of Mercury's interior, but its precise composition cannot be assessed by hands-on or visual inspection.

Mercury's active magnetic field makes it the only rocky planet aside from Earth that currently hosts dynamo action in its liquid metallic core. This adds strongly to the interest in Mercury's core. Core dynamo action requires convective flow in the liquid core, which relies on a continuous supply of energy above the amount that can be transported through the core by diffusion (without convection). This sets the study of the magnetic field generation in Mercury in strong relation to the understanding of the planet's long-term thermal evolution.

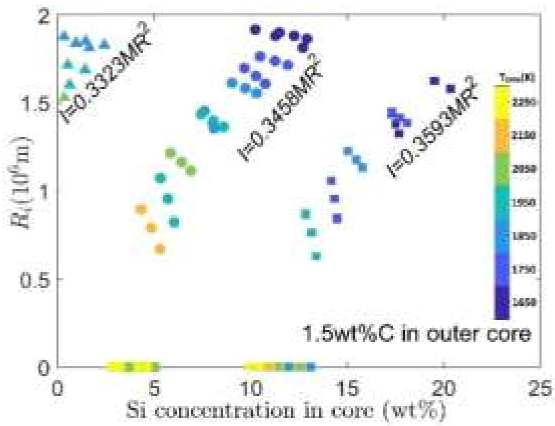


Figure 17: Core structure models of Mercury. Y-axis: Radius of inner core scaled by 1000 km. X-axis: Core-concentration of silicon. Color: Core-mantle boundary temperature (K). These models additionally contain 1.5wt% C in the liquid core. Square, circle, and pyramid symbols indicate models with moment of inertia I=0.3591 MR2, 0.3458 MR^2, and 0.3323 MR^2, which correspond to the upper limit, central value and lower uncertainty limit of Mercury's spin-axis's tilt.

Mercury was only observed by two space missions (NASA's Mariner 10 mission in 1974-1975 and MESSENGER in 2008-2015). However, scientists have a remarkably strong grip on its interior structure. The unique rotational state of Mercury – the planet completes exactly three rotations every two orbits – is key in this understanding. Due to this rotational state, the Sun exerts a strong torque on Mercury that oscillates in East-West direction with an orbital period. Much like quickly back and forth rotating a beach ball filled with air or liquid influences the fluid's angular momentum, the torque periodically changes the rotation of the solid outer shell above the core. These changes have been observed and inform on the moment of inertia of the solid shell. The moment of inertia of the entire planet can be derived from the tilt of Mercury's spin axis with respect to its orbital plane. Observations of the tilt of the spin axis and of East-West movements of Mercury's surface yield a good understanding of the sizes and densities of Mercury's rocky outer shell and metal core. To relate Mercury's core density to its composition, we need information on how the density of iron alloys depends on the amount of light elements most likely present in Mercury's core: silicon, sulfur, and carbon.

Experts of planet Mercury at the Royal Observatory of Belgium (ORB-KSB) (J. S. Knibbe, A. Rivoldini, T. Van Hoolst) have led an experimental campaign of measuring the density and sound velocity of liquid metal mixtures of iron, silicon and carbon at the high pressures relevant for Mercury's core. They collaborated with geologists of the Université de Liège (B. Charlier) and the KU Leuven (O. Namur), an expert in high-pressure research of the Vrije Universiteit Amsterdam (W. van Westrenen), and experimental scientists in Grenoble, France (M. Mezouar) and in Argonne, Illinois, USA (Y. Kono). They placed samples in a hydraulic press in a high-intensity X-ray beam produced by particle accelerators in Grenoble, France (the European Synchrotron Radiation Facility) for the density measurements and in Argonne Illinois, USA (the Advanced Photon Source Facility) for the sound velocity measurements. The measured sound velocity of liquids relates to the compressibility of the liquid metal and plays an important role in constraining the variation of density with pressure in Mercury’s core. The obtained relations between density and the composition of the liquid metals are incorporated in interior structure models for Mercury that meet the planet’s observed rotational behaviour.

The interior structure models show how the rotation observations can be used to estimate the core composition and the size of the inner core (Figure 17). If the tilt of the spin axis is near the lower limit of observations, the moment of inertia (I) is small, and the core is dense with only a few wt% of light elements silicon and carbon. If the tilt of Mercury’s spin axis is near the upper limit of observational uncertainties, I is large and the core hosts between 10-20 wt% of silicon, depending on the size of the inner core and the core temperature. This indicates that the range of possible core compositions of Mercury can be narrowed down by improving the accuracy on the position of Mercury’s spin axis. In the near future, ESA’s BepiColombo mission, launched in 2018, will measure the position of Mercury’s spin axis with high precision from Mercury’s orbit (beginning in 2025). These data will result in much improved information on Mercury’s composition and inner core size.

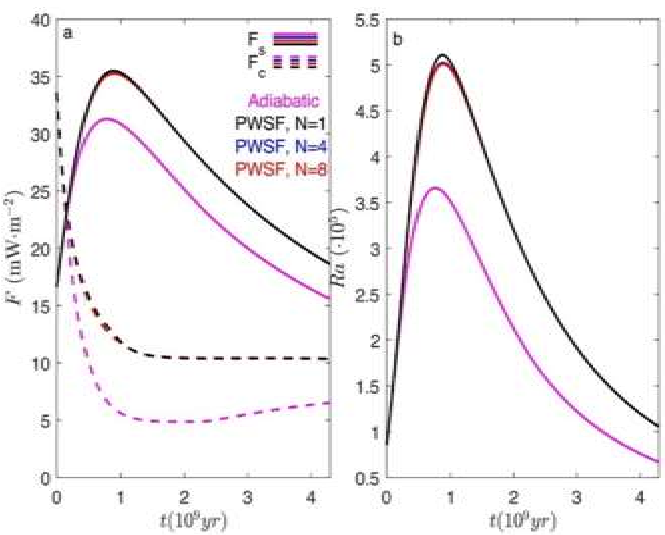


Figure 18: Characteristics of thermal evolution runs of Mercury. (a) The heat flux from the core into mantle (Fc, dashed lines) and from the mantle into lithosphere (Fs, solid lines), for thermal evolution runs with N = 1 (black), N = 4 (blue), and N = 8 (red), where N is the number of intervals, and for the thermal evolution run where the core's temperature profile is an adiabat and conductive region is neglected (magenta). (b) Rayleigh number of the mantle scaled by a factor 105. Blue lines are almost completely overplotted by red lines.

Better insight into the core will help to better understand Mercury’s formation and evolution. Thermal evolution models of terrestrial planets are often developed to describe an Earth-like planet with a thick convective mantle and a relatively small convective core. Mercury is, however, different in various ways: Mercury’s thin mantle may not be convective anymore, and interpretations of Mercury’s magnetic field suggest that the upper part of the large liquid core of Mercury is stable against convection.

Scientists at the ORB-KSB (Y. Zhao, A. Rivoldini, J. S. Knibbe, T. Van Hoolst) develop thermal evolution models in which the state of the mantle varies from convective to conductive and which incorporates a conductive region in the liquid core. Knibbe and Van Hoolst (2021) describe a new numerical method for the evolution of such a conductive layer. The conductive layer increases the heat flux from the core into the mantle by a factor of almost two with respect to models that neglect the conductive region (Figure 18a) and also increases the likelihood of mantle convection, as indicated by the larger Rayleigh number in Figure 18b. The conductive region also leads to faster cooling of the central regions of the core and therefore to an earlier start of the inner core, which may help to explain observational evidence of an early dynamo in Mercury.

More information:

Knibbe et al., J. Geophys Res. Planets (2021), 126(1), e2020JE006651.
Knibbe and Van Hoolst, Phys. Earth Planet. Inter. (2021), 321, 106805.

Isostatic Support of Topography on Planets and Satellites

At large scale, most of the continents and oceanic floor topography of the Earth is in isostatic equilibrium, which balances surface loads by buoyant support at depth. For example, the Himalayas are supported by iceberg-like crustal roots plunging in the denser mantle (Airy isostasy). In a similar way, the average depth of the oceans can be related to the thickness contrast between oceanic and continental crust, while the subsidence of the ocean floor away from mid-ocean ridges is connected to the density increase of the cooling tectonic plate. Besides providing a mechanism for topographic support, isostasy explains why gravity anomalies measured near mountain ranges are generally smaller than expected. On terrestrial-type planetary bodies, isostatic equilibrium occurs locally but has not yet been found to operate globally: geologic provinces with highly compensated gravity have been identified on Venus, Mars, and the Moon. More recently, isostasy found a new domain of applications in icy satellites with subsurface oceans, where the surface topography could be due to thickness variations of the icy shell. Gravity data suggest that isostasy operates on the Saturnian moons Enceladus, Dione, and Titan, as well as on the dwarf planet Ceres.

For more than a century, the isostatic concept has been applied very simply, by partitioning the crust into vertical columns assumed to be floating independently in a fluid and in mechanical equilibrium. Classical isostasy, however, is not self-consistent, neglects internal stresses and geoid contributions to topographical support, and yields ambiguous predictions of geoid anomalies. In particular, applying classical isostasy to Enceladus leads to the prediction of a thick icy shell above a vanishingly thin subsurface ocean, which contradicts with the large amplitude of the measured libration that requires a thin shell above a thick ocean. For this purpose, scientists of the ORB-KSB proposed five years ago a new isostatic model based on the crustal stress minimisation, which predicted the same icy shell thickness as the one obtained from libration data (Beuthe, Rivoldini and Trinh, Geophys. Res. Lett. 43, 10088-10096, 2016).

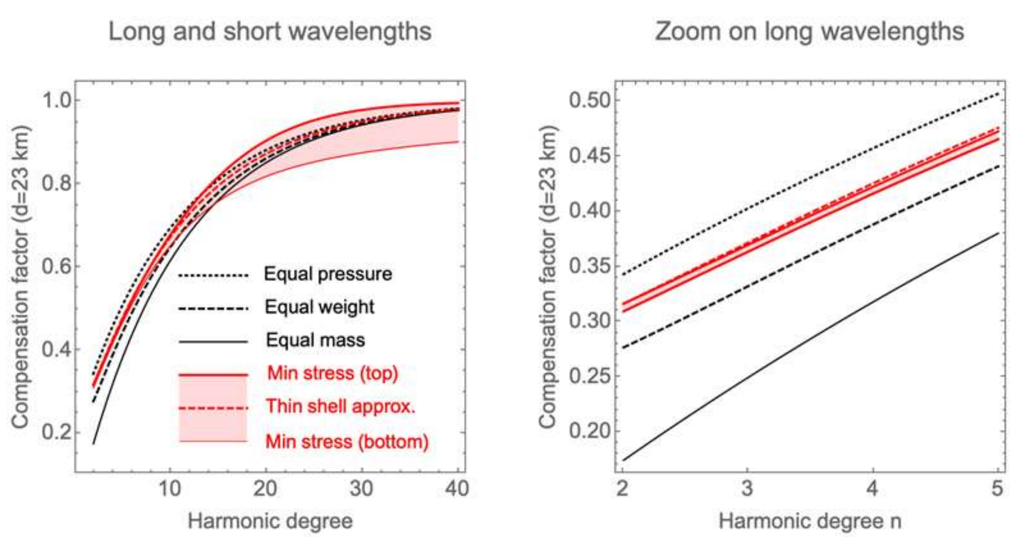


Figure 19: Isostatic compensation factor of Enceladus for different isostatic models as a function of harmonic degree. The higher the degree, the shorter the horizontal scale or wavelength considered. The right panel is a zoom of the left panel on the long-wavelength part. The crustal thickness is equal to 23 km. The compensation factor is the normalised ratio of the gravitational signal to the

surface topography: it vanishes if isostatic compensation is total and it tends to one if there is no compensation at all. Models in black are not consistent with the universal thin shell limit of elastic isostasy.

While this new isostatic model is based on the sound physical principle of minimum stress or energy, the difficulty of implementing it led other scientists to propose alternative isostatic models based either on arbitrary rules (equal pressure at depth) or resorting to viscous flow. The multiplicity of isostatic models has created a lot of confusion because various gravity-topography analyses can be based on different isostatic models, thus making comparisons rather difficult (Figure 19). For this reason, the ORB-KSB scientist M. Beuthe established a clear algorithm to compute minimum stress isostasy in terms of elastic or viscoelastic Love numbers, which describe the effects of deformations due to loads (M. Beuthe, ‘Isostasy with Love: I elastic equilibrium’, Geophys. J. Int. 225, 2157-2193, 2021). The Love number approach separates the physics of isostasy from the technicalities of viscoelastic-gravitational spherical deformations, and provides flexibility in the choice of the interior structure. An in-depth analysis shows that all consistent isostatic models belong to a one-parameter family depending on the choice of boundary conditions at the surface and bottom of the crust. At long wavelengths, the thin shell limit is a good approximation, in which case the influence of boundary conditions disappears as all isostatic family members yield the same predictions. At short wavelengths, topography is supported by shallow stresses so that Airy isostasy becomes similar to loading either at the top or at the bottom of the crust (Figure 20). Software implementing the minimum stress isostasy for a 3-layer model is publicly available (‘IsostasyWithLove: Mathematica and Fortran codes for analytical isostasy in 3-layer bodies’, Zenodo, doi:10.5281/zenodo.4297495).

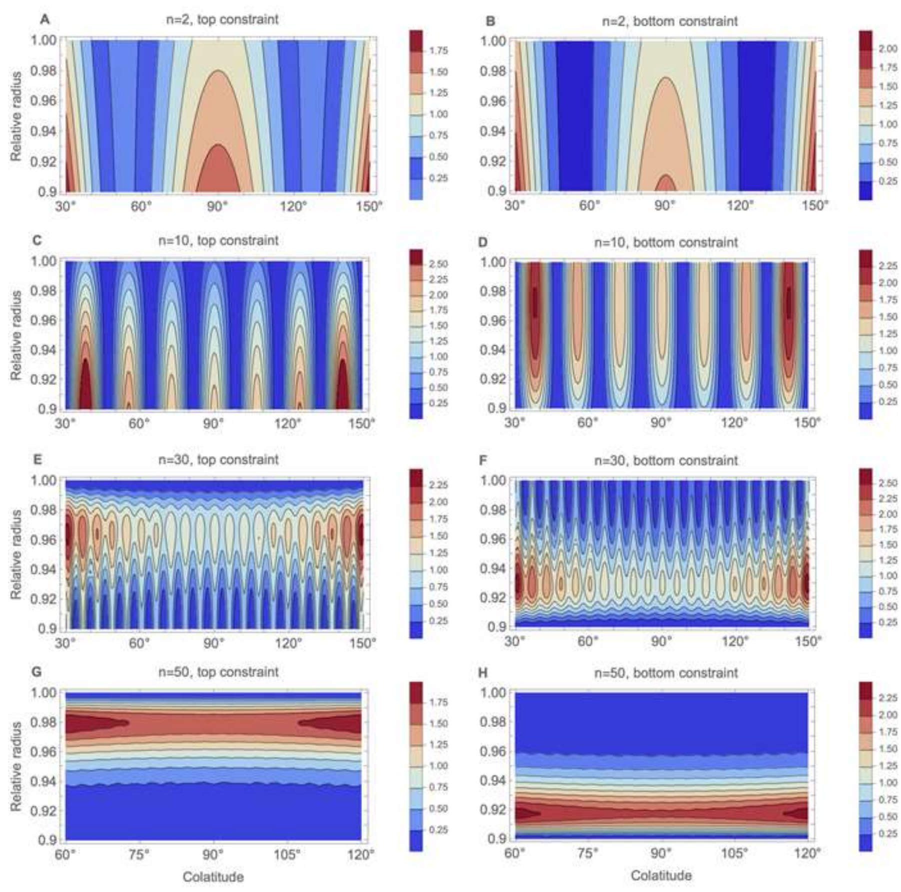


Figure 20: Stress within Enceladus’s shell, as a function of radial coordinate and colatitude. Left-hand (resp. right-hand) panels show minimum stress isostasy for a fixed surface (resp. bottom) shape described by a given harmonic degree (from top to bottom: n = 2, 10, 30, 50). The stress invariant is normalised by its mean. The shell thickness is 10 per cent of the surface radius Rs. With increasing

degree, the stress tends to a maximum value at a distance Rs/n from the fixed surface: the load is more and more supported from inside the crust, instead of being supported by a load at the other crustal boundary as it is the case for the lowest degrees.

As an alternative to the static elastic model, isostasy can be viewed as a dynamic process resulting from the viscous or viscoelastic relaxation of the non-hydrostatic crustal shape. Dynamic isostasy depends on the loading history, two examples of which are the constant load applied on the surface in the far past and the constant shape maintained by addition or removal of material at the basis of the crust. The former model results in a shape decreasing exponentially with time and has no elastic analogue, whereas the latter (stationary) model is equivalent to a form of elastic isostasy. Isostatic models thus belong to two independent groups: the elastic/stationary approaches and the time-dependent approaches. If the shell is homogeneous, physically consistent models predict a similar compensation of large-scale gravity perturbations. If the shell rheology depends on depth, stationary models predict more compensation at long wavelengths, whereas time-dependent models result in negligible compensation (M. Beuthe, 'Isostasy with Love: II Airy compensation arising from viscoelastic relaxation', Geophys. J. Int. 227, 693-716, 2021).

Solar Physics

The discovery of Campfires on the Sun

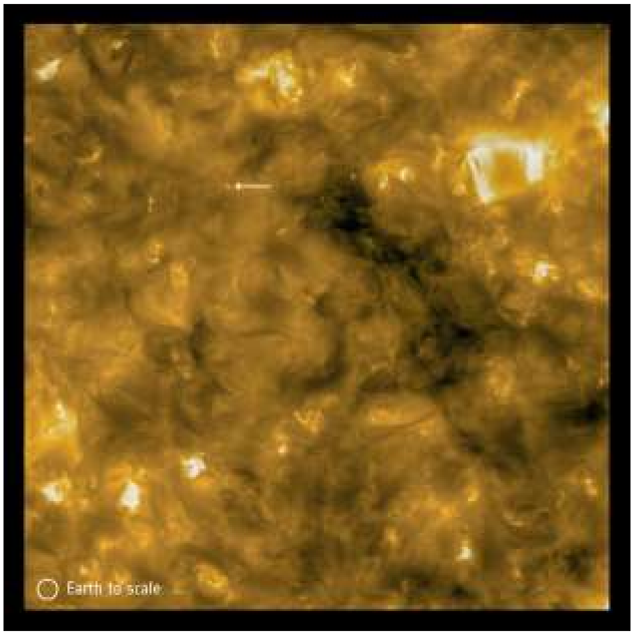


Figure 21: Snapshot from an ESA press release covering the campfires seen as tiny bright specs in the EUI images.

The "Extreme Ultraviolet Imager" (EUI) is a combination of 3 telescopes onboard Solar Orbiter. In particular, the HRIEUV telescope ("High Resolution Imager in the EUV") has an outstanding performance taking images of the solar corona at extreme resolution. Depending on the distance to the Sun, a footprint of a HRIEUV pixel can be as small as 100 km on the solar surface, and the imaging cadence can be as fast as 2s. Such a performance in the solar corona has only been reached by one earlier instrument that operated only for a few minutes, as it was mounted on a sounding rocket. HRIEUV is therefore one of the success stories on Solar Orbiter, which started its nominal mission phase on November 27, 2021, for an expected duration of about 10 years.

Before the start of the nominal mission phase, however, HRIEUV already took many series of test images. In one of the early sequences (May 30, 2020, see Figure 21) short-lived brightening were discovered (Berghmans et al. 2021), which were jokingly called campfires to illustrate their very small size. In reality these small brigthenings are still between 400 and 4000 km large, but as compared to the big solar flares, they are tiny. Tiny flares have been observed before and are of particular interest as they might collectively contribute more to the heating of the solar corona than their bigger cousins that can even influence the space weather around the Earth.

Nevertheless, campfires turned out to be special. Never were flare-like brightenings observed so sharply at such small scales.

The next best telescope (SDO/AIA) could confirm most of the campfires but only sees fuzzy patches, where HRIEUV can clearly see tiny loop-like structures interacting. Moreover, triangulation between HRIEUV and AIA revealed that campfires live at the lower boundary of the corona, barely sticking out of the cooler chromosphere as shown in Figure 22 (Zhukov et al. 2021).

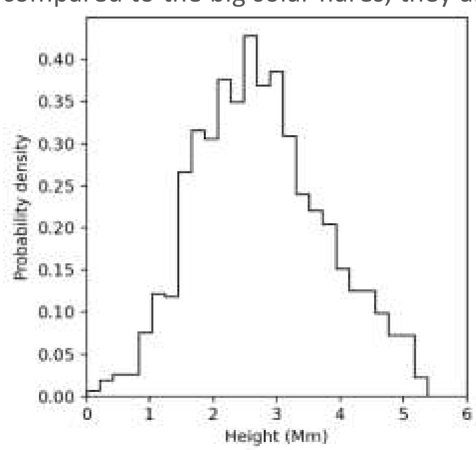


Figure 22: The height of campfires above the solar surface (reproduced from Zhukov et al, 2021).

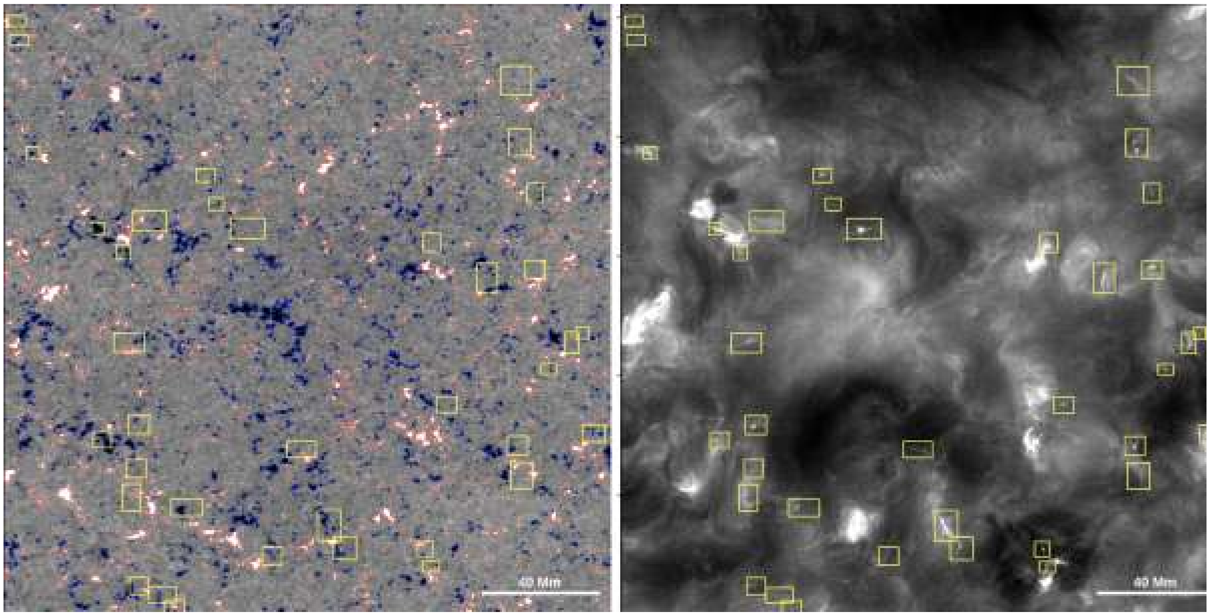


Figure 23: Distribution of campfires (yellow boxes) as seen in PHI magnetograms (left) and EUI/HRIEUV images (right). Blue and red contours on the left correspond to negative and positive magnetic flux. The scale indicator (40Mm) corresponds to Earth circumference (reproduced from Kahil et al. 2022).

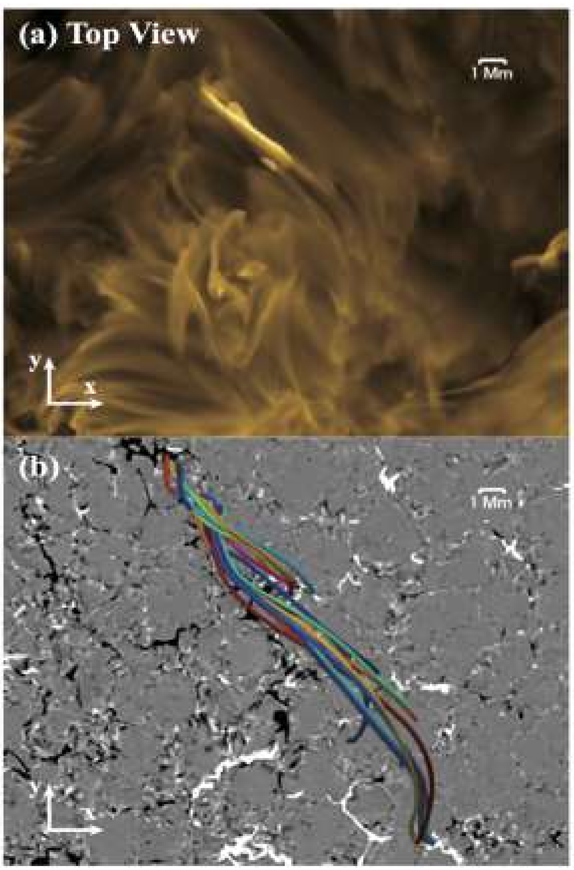


Figure 24: A simulated campfire, showing at the bottom its magnetic field configuration (reproduced from Chen et al 2021).

Follow-up observations were made with another high-resolution instrument onboard Solar Orbiter, the "Polarimetric and Helioseismic Imager" (PHI). PHI can make magnetic maps of the solar surface (see Figure 23) and these showed that most of the campfires coincide with magnetic cancellation events in which magnetic flux disappears from the solar surface (Kahil et al. 2022). With the help of 3D simulations of the solar corona, it was shown (see Figure 24) that magnetic energy can indeed be converted and released, resulting in brightening in the EUV emission that we see as campfires (Chen et al. 2021). Several other publications studied the dynamics in campfires, sometimes seen as tiny jets.

Finally, the relevance of campfires for the coronal heating mystery is being addressed by studying statistically if a large number of campfires can collectively make a significant contribution to the heating of the million degrees solar corona.

World Data Centre for Sunspot Index

The Sunspot Number (SN) is the longest scientific experiment still ongoing and a crucial benchmark to study solar activity, space weather and climate change. The Royal Observatory of Belgium (ORB-KSB) plays a central role in the continuation of this experiment, as it hosts the Sunspot Index and Long-term Solar Observations World Data Centre (WDC-SILSO-WDC). This World Data Centre aims at collecting solar data, as well as producing and distributing the International Sunspot Number, which is used in about two hundred scientific publications on an annual basis.

The BRAIN.be project ValUSun (2017-2021) aimed at valorising the long-term solar observations from the ORB-KSB. In collaboration with UCLouvain and PhD student Sophie Mathieu, we conducted a comprehensive statistical analysis of WDC-SILSO sunspot numbers collection, and laid the ground for a future monitoring of all active stations in near-real time. We summarise here the main results of Sophie Mathieu's PhD thesis.

Uncertainty Quantification in Sunspot Numbers

To be able to alert observers when they start deviating from the network, one needs to first study the errors in the SN, in other words, to develop an uncertainty model. We consider the period 1947-2013, and a dataset of 21 stations with records of the number of spot Ns, the number of groups Ng, and the composite Nc= Ns+ 10Ng based on the original formula by Pr. Rudolf Wolf in 1849. Our uncertainty model is valid for Ns, Ng, and Nc and contains three types of errors [Mathieu et al. 2019].

1. A short-term, rapidly-evolving, error, denoted ε1(i,t), that describes counting error and variable seeing conditions at station i and time t
2. A station-specific long-term error, ε2(i,t), that accounts for systematic biases. We are interested in estimating its mean and see if it experiences sudden jumps or drifts on longer time scale.
3. An error term, ε3(i,t), which captures what happens during minima of solar activity when there are few or no sunspots during extended periods.

An observer typically makes larger errors when the Sun is more active and produces more sunspots, which means that ε1(i,t) and ε2(i,t) should be multiplicative errors. With Yi(t) denoting in a generic manner Ns, Ng, or Nc observed at time t by a station i, and with s(t) being a latent (unobserved) variable representing the 'true' solar signal, our model writes:

$$Y_i(t) = \begin{cases} \big(\varepsilon 1(i,t) + \varepsilon 2(i,t)\big) s(t) if s(t) > 0, \\ \varepsilon 3(i,t) if s(t) = 0 \end{cases}$$

Having devised a procedure for estimating s(t), we get access to observed values of errors. Those exhibit an excess of zeros, i.e. an unusual local peak in the density at zero due to solar minimum periods, as well as several modes. In order to account for these characteristics, we use zero-altered mixture of Probability Density Functions (PDF) to fit those values. The Interquartile range (IQR) is an appropriate measure of the dispersion in these PDF. Figure 25 represents a scatter plot of the long-term (mean ε2(i,t)) versus short term (ε1(i,t)) empirical IQR of the number of spot Ns for several stations. Basically, it provides us with a view on the stability of stations outside periods of solar minima. Typically, we see that teams of observers (in red) experience more short-term variability than individual observers (in black), but show a better long-term stability.

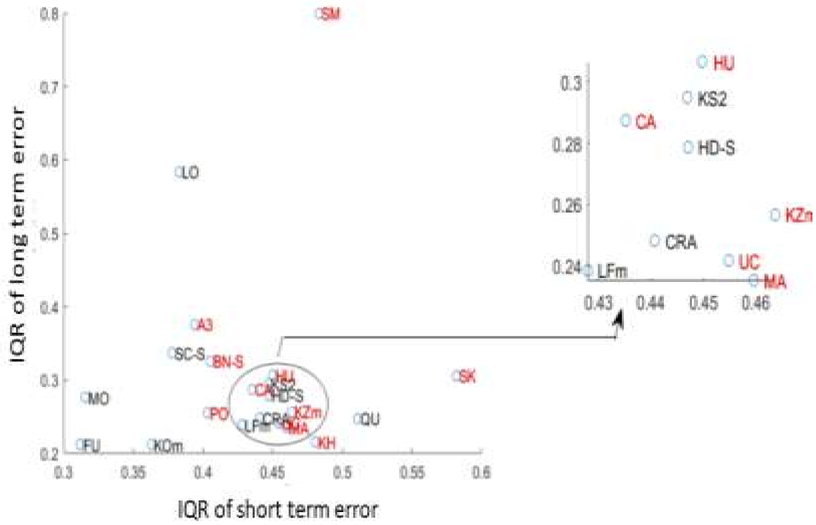


Figure 25: Scatter plot of long- vs short-term error IQR for the number of spot Ns. Red stations are teams of observers, black ones are individual. Teams usually have larger short-term error. MO (Mochizuki, Japan), FU(Fujimori, Japan), and KOm (Koyama, Japan) correspond to long-time observers with stable observation practices, and have low variability both on short- and long-term. UC (Uccle, Belgium) shows a great variability in the short-term, due to many observers, but has an interesting long-term variability.

Monitoring the Sunspot Number Observations by Stations

Now that we have determined an uncertainty model, we need to monitor the stations. The so-called 'Cumulative sum' (CUSUM) Control chart is a sequential analysis technique used for monitoring change detection. It was first designed for normally distributed errors, and in the presence of In-Control (non-deviating) observations. We saw that for the time series of the SN composite Nc exhibits strong noise, a complex autocorrelation structure, non-normality, and missing values. Hence in [Mathieu et al., 2022], we devised a monitoring strategy tailored to Nc. We first select a group of In-Control stations and use them to standardise all the stations. Second, the standardised data are monitored by the CUSUM chart adapted to time series. This control scheme was applied on past observations to study the deviations of the sunspot numbers, as seen in Figure 26.

The VAL-U-SUN project, thanks to Sophie Mathieu's work, has given the WDC-SILSO the means to use the most advanced statistical methods to monitor its network and to compute the International Sunspot Number in near real time.

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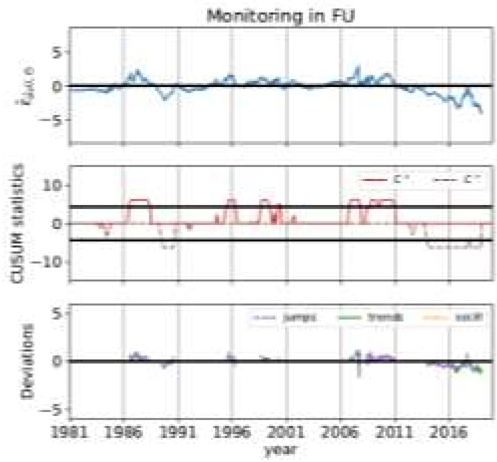
Mathieu S., von Sachs R., Ritter C., Delouille V., Lefèvre L., 2019, ApJ, 886, 7. doi:10.3847/1538-4357/ab4990

Mathieu S., Lefèvre L., von Sachs R., Delouille V., Ritter C., Clette F., 2022, Journal of Quality Technology, doi: 10.1080/00224065.2022.2041376



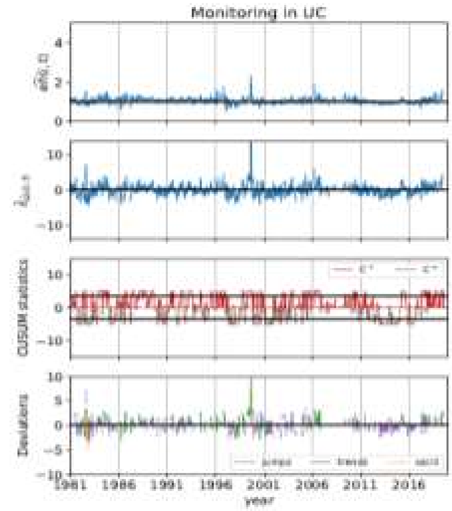


Figure 26: (Left) Control scheme for Nc (smoothed over 365 days) of the FU station, which is composed of a single dedicated observer in Japan, who observed without interruption since 1968 until today. Although the series was remarkably stable for decades, it suffers from recent deviation, see e.g. the downward trend beginning in 2011 which might be associated with the health condition of the observer. (Right) Control scheme for Nc (smoothed over 27 days) for the UC (Uccle, Belgium). ROB's station is stable over time but suffers from a large jump in 1999, due to the intense participation of a particular observer that did not count with the same precision as the other members of the team. He was recruited at a time where there was a lack of observers but finally stopped observing.

The F10.7cm Radio Flux Revisited

The flux at 10.7cm (Hz) is a long-term reference index of solar activity that represents the background radio flux when there are no flares. Its source is mostly thermal radio emission from the lower corona. It is a good standard long-term proxy of the UV solar irradiance back to 1947. It is closely related to the Sunspot Number SN available since 1700. The F10.7/SN proxy relation allows backward reconstructions of UV irradiance over multiple centuries.

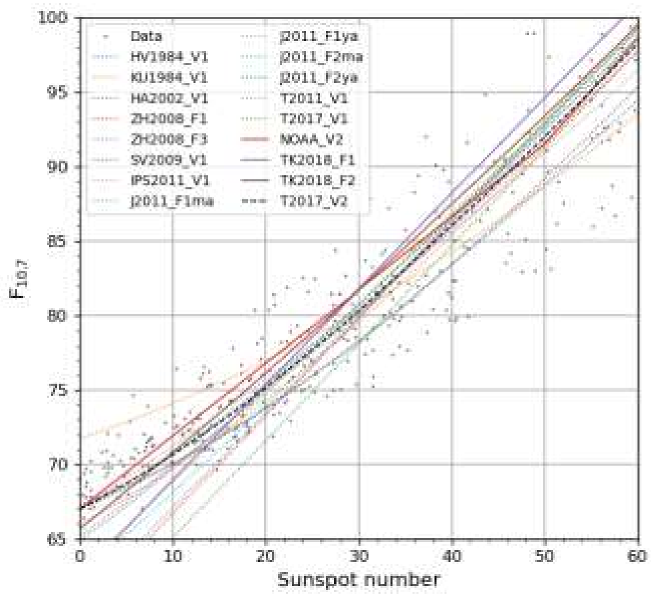


Figure 27: Different relations between SN and F10.7

However, over the years, a confusing picture arose as to the exact relation between F10.7 and SN. Namely, we count 12 publications and 18 different formulae that mostly disagree (Figure 27), and no determination of error bars. Since the Sunspot Number was re-evaluated in 2015 (Clette & Lefèvre, 2016), it was time to re-evaluate the F10.7/SN relation.

Thus, in 2021, Frédéric Clette (Clette, 2021), researcher at ORB-KSB, established a new polynomial regression with errors, of which the equation is shown below.

$$\hat{F}_{10.7} = 67.73(\pm 1.13) + 0.337(0.056)S_N + 3.69(\pm 0.77.).10^{-3}S_N^2 - 1.52(\pm 0.38).10^{-5}S_N^3 + 1.33(\pm 0.62).10^{-8}S_N^4$$

However, F. Clette also discovered a very interesting fact, unbeknownst to everyone until now: this relationship is not stable over time and there is an abrupt change of more than 10% in 1980 (Figure 28), with the relation being stable before and after this jump (Figure 29).

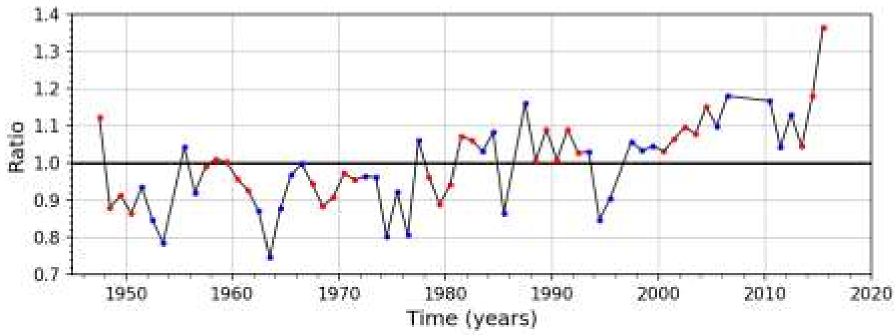


Figure 28: Ratio of SN and F10.7 series (1947-present).

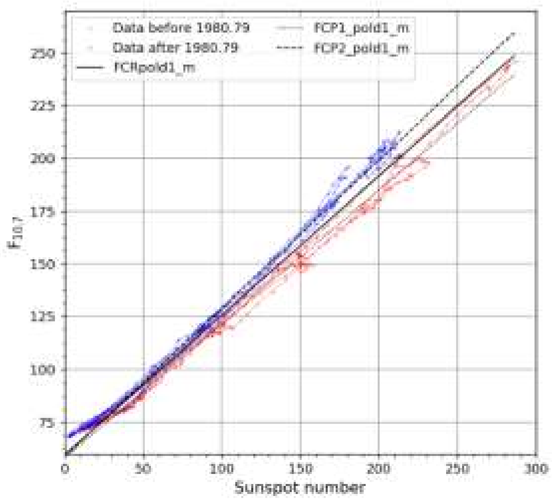


Figure 29: Relation before (red) and after 1980 (blue).

Although the timing is suspiciously close to the time when the sunspot number SN was transferred from Zurich to Brussels in 1981, there is no evidence that this jump occurs in SN, so it points towards an undocumented change in the flux at 10.7cm. The exact reason is still being investigated.

Our conclusions are that the base F10.7/SN relation is fully linear except for the 0 point, and the non-linearity is entirely due to the temporal smoothing. The mean quiet-Sun F10.7 flux varies with the number of spotless days with an invariable base flux of 67 sfu. The optimal proxy is a 4th-order polynomial based on monthly means. And there is a 10.5% upward jump occurring in 1980-1981.

Reference:

Clette, F., Lefèvre, L. (2016). The New Sunspot Number: Assembling All Corrections. Solar Physics, 291, 2629-2651, DOI: 10.1007/s11207-016-1014-y

Clette, F. (2021), Is the F10.7cm – Sunspot Number relation linear and stable?, J. Space Weather and Space Climate, Vol. 11, id.2, 25 pp. DOI:10.1051/swsc/2020071

Improving Data Access to Solar Physics Data

At the Royal Observatory of Belgium (ORB-KSB) we collect, store and distribute data from the Sun obtained with space-based instruments (e.g. SWAP and LYRA on board the PROBA2 mission or EUI on the Solar Orbiter mission) as well as with ground-based instruments (e.g. solar telescope from USET or radio antenna from Humain Radioastronomy Station). In order to allow for an extensive usage of these different datasets and for a maximum return in terms of new discoveries, we are dedicated to making them as easily available to the global solar physics community as possible by developing user-friendly tools to find and access the data.

In recent years, there has also been an international drive from academia, industry and funding agencies to make scholarly data more reusable; this has resulted in the creation of guidelines summarised in the 'FAIR' Data Principles, where 'FAIR' stands for 'Findable', 'Accessible', 'Interoperable' and 'Reusable'. The FAIR guidelines put emphasis on enhancing the ability of machines to automatically 'find' and get 'access' to the data, as well as the possibility of a smooth transfer from one software to another, e.g. for plotting the data (interoperability) and, of course, the ability to 'reuse' the data thanks to the adoption of standard data format. In 2021, our team has been more and more accustomed to the FAIR principles and we have used them to improve our data management at the ORB-KSB. All these efforts also improved international collaboration and scientific output.

In 2021, one of our major achievements regarding improving data access was to turn the Solar Virtual Observatory (SVO) (URL: https://solarnet.oma.be/) into an operational system. A Virtual Observatory is a collection of interoperating data archives and software tools connected through the internet and our SVO does this specifically for solar data.

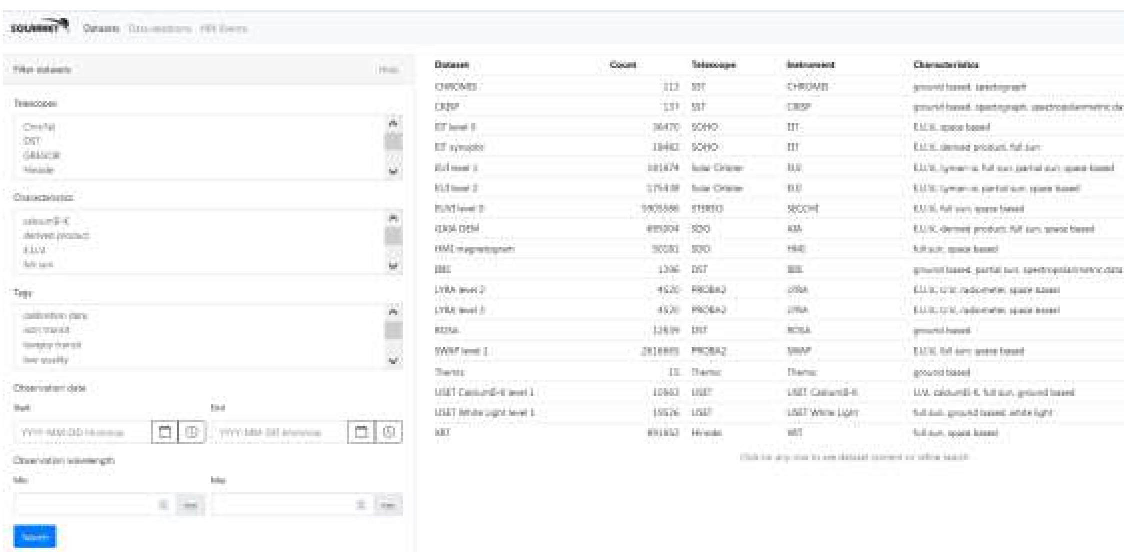


Figure 30: The SVO web interface datasets search tab.

Development on the SVO started in the EU FP7 SOLARNET project with a prototype version. Further development continued in the EU H2020 SOLARNET project, where the SVO was turned into an operational system. Additionally, new features are being developed in the framework of the EU H2020 ESCAPE project. We are also continuously expanding the number of datasets that are made available through the SVO.

Via the SVO, users can search and access solar physics data from ROB and other research institutes through a web interface (see Figure 30), software libraries (Python and IDL) and through an Application Programming Interface (RESTful API). Users can search across multiple datasets, which let them quickly see which solar telescopes were taking measurements at a certain time. This is quite useful as obviously ground based solar telescopes can only take data during sunny days, and not in a continuous manner as for space-based telescopes. Whenever available you can also see a quick-look version and meta data description of the data.

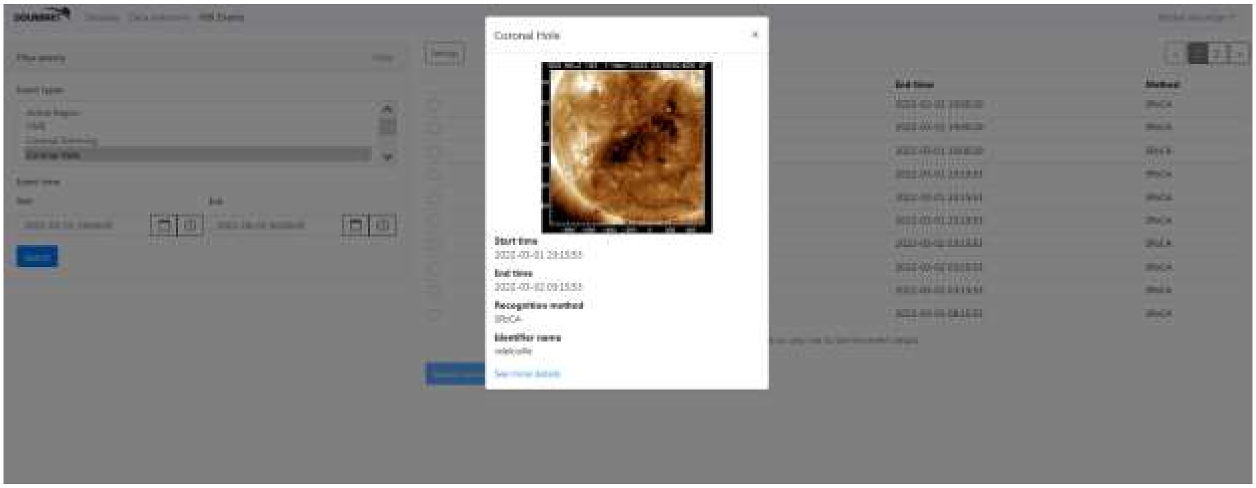


Figure 31: The SVO web interface event search tab showing a quick-look image of a coronal hole.

It is also possible to search on events from the Heliophysics Events Knowledgebase (HEK) database, which allows for quick look visualisation, see Figure 31. One of the new features that we are developing is to let users search for data with the ROB Solar Event Database as well.

Once a user has made a selection of data, they can easily share this data with collaborators as the SVO provides an ftp address.

We are working on expanding the number of datasets available through the SVO as well as the ways in which our database can be queried by setting up a Table Access Protocol (TAP) service (which follows an international standard for Virtual Observatory) and by interfacing the SVO with it.

A final area of development is to interface the SVO with tools like jHelioviewer, which lets users visualise and combine different solar datasets like ours.

Astronomy and Astrophysics

TMBM - Tarantula Massive Binary Monitoring

The Tarantula Nebula (NGC 2070, or 30 Doradus) in the Large Magellanic Cloud (LMC) is a highly complex nebula and the brightest H II region in the Local Group. It is a prototype starburst similar to those found in high redshift galaxies. This region is illuminated by the massive central star cluster R136 that contains some of the most massive stars known to date (200–300 $M_\odot$). At a distance of 50 kpc, the Tarantula nebula is a unique star-forming region that allows us to study massive-star evolution, star formation and cluster evolution in great detail. It is a template for distant, unresolved starbursts and can be used to explore their role in galaxies and the overall cosmos. Stars in the LMC are also particularly interesting to study, because the global metallicity content of this dwarf galaxy is expected to be half that of the Milky Way. By probing lower-metallicity environments, scientists want to understand the effects of the metallicity on the formation and evolution of (massive) stars within conditions closer to those at the earliest stages of the Universe, when the first stars were born.

Figure 32: The Tarantula Nebula in the Large Magellanic Cloud observed by Hubble in the frame of the Hubble Tarantula Treasury (https://apod.nasa.gov/apod/ap160226.html).

The VLT-FLAMES Tarantula Survey (VFTS) provided a homogeneous, multi-epoch spectroscopic data set aimed to establish the stellar and binary properties of the massive-star content in this region. About 800 targets were observed through the VLT-FLAMES Tarantula Survey with the FLAMES/GIRAFFE spectrograph mounted on the

VLT/UT2 at ESO Paranal. Among the 800 objects, 360 were classified as O-type or early, evolved B-type stars. Of these 360 objects, 32% were identified as spectroscopic binaries. The analysis of these data led to the publications of 32 papers in scientific reviews, between 2011 and today where multiplicity, rotation, surface composition, stellar parameters were studied, among others.

The VFTS relies on an observing strategy based on six observations per object, covering different wavelength ranges of their electromagnetic spectrum. While it was possible to derive physical properties of presumably single stars, the strategy based on six observing epochs prevents us from characterising the orbital parameters of binary or multiple systems, but only to detect them as such. To develop this topic further, the Tarantula Massive Binary Monitoring (TMBM) project was set up. This follow-up project relies on the existing collaboration between scientists from more than 20 different institutes, most of them in Europe and in America, and was awarded 45 hours of observing time. TMBM aimed to acquire 32 additional epochs with the Multi-Object Spectrograph FLAMES/GIRAFFE. These additional epochs have been secured for the 32% of stars classified as binary or multiple systems in order to measure their orbital properties as well as the physical parameters of their individual components. A first paper published in 2017 led to the characterisation of orbital parameters for 31 double-lined spectroscopic binaries and 51 single-lined. Knowing the orbital parameters of massive stars is important for a wide range of topics from stellar feedback to binary evolution channels and from the distribution of supernova types to gravitational wave progenitors. This study showed that the orbital parameter distributions (orbital periods, eccentricities, mass ratios) appear to be universal across massive OB stars (from 8 $M_\odot$ and higher), and no matter the metallicity environment.

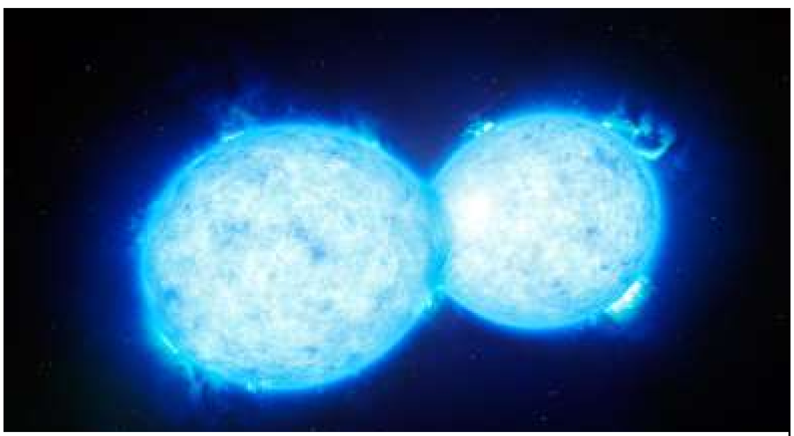


Figure 33: Artist impression of the over-contact binary VFTS 352 in the Tarantula region.

In-depth analyses of several interesting objects were published in 2017, 2019, and 2021, and a more general analysis of all the double-lined spectroscopic binaries in the Tarantula region was published in 2020. For that purpose, we applied a technique called "Spectral disentangling" that allows us to separate the individual spectral contributions of each component from a time series of composite spectra of the systems.

For each system, two spectra are thus produced, one for the primary star and one for the secondary, and each object can be studied as if the star was single. We then applied atmosphere codes to produce synthetic spectra that fit the most of our observations to derive the fundamental parameters of each component (e.g. surface temperatures, gravities, projected rotational velocities, masses, radii), as well as their helium, carbon and nitrogen surface abundances. Among the 31 systems that we studied, we identified between 48 and 77% of them as detached, likely pre-interacting systems, 16% as semi-detached systems (i.e. systems where one component is transferring its mass and angular momentum to its companion), and between 5 and 35% as systems in or close to contact phase (i.e. both stars overflow their Roche lobes simultaneously, as shown in Figure 33). The individual properties of the components allowed us to classify them, notably through a Hertzsprung-Russell diagram (Figure 34). From their surface abundances, we showed that the effects of tides on chemical mixing are more limited than mass and angular momentum exchanges.

These studies allowed us to highlight very interesting and unique systems:

1. VFTS 527 which the most massive binary system known to contain two O supergiants (~ 90 M⨀ + 90 M⨀),
2. VFTS 061, VFTS 176, VFTS 450, VFTS 538 and VFTS 652, five high-mass analogues of classical Algol systems, i.e. systems where one component is transferring its mass and angular momentum to its companion,
3. VFTS 352, one of the most massive over-contact binaries (29 M⨀ + 29 M⨀ Figure 33),
4. VFTS 399, a potential X-ray binary,
5. R145, which is the most evolved object in the sample composed of two nitrogen-rich Wolf-Rayet stars, and,
6. R144, a wind-eclipsing binary composed of two hydrogen-rich Wolf-Rayet stars with a total mass higher than ±140 M⨀.

We also provided LMC-based empirical mass-luminosity and mass-radius relations, and we compared them to other relations given for the Milky Way, the LMC, and the Small Magellanic Cloud. These relations differ for different mass ranges, but do not seem to depend on the metallicity regimes.

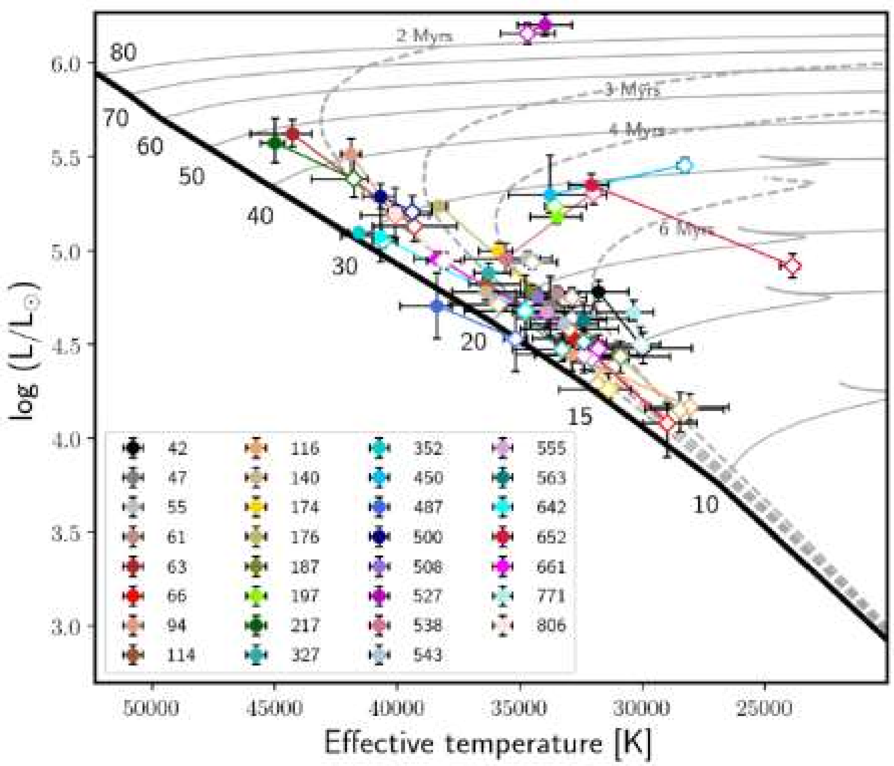


Figure 34: Hertzsprung-Russell diagram for all the individual components that are members of double-lined spectroscopic binaries in the Tarantula region. Filled (open) circles (diamonds) refer to the primary (secondary) of each binary system. The names of the systems are colour-coded in the legend of the figure.

All these parameters derived through these different studies are useful because they give us strong observational constraints to test the single and binary evolution theories. In two subsequent papers published in 2021 and 2022, a large grid of detailed evolutionary models of short-period massive binaries and follow-up population synthesis calculations was used to derive probability distributions of the observable properties of massive Algols and massive contact binaries. For Algols, the comparisons between these models and the observational derived parameters pointed out that the mass transfer in massive binaries can be rather conservative in some systems, while very inefficient in others.

For contact systems, while our theoretical distributions work particularly well for contact binaries with periods < 2 days and total masses < 45 M⨀, we expect stellar winds, non-conservative mass transfer and envelope inflation to have played a role in the formation of the more massive and longer-period contact binaries.

At the moment, the analysis of the TMBM data and their comparison with theory is far from finished. The 51 single-lined spectroscopic binaries are currently under investigation. That will be useful to constrain the low-mass end of the companion mass function, and search for possible neutron stars or stellar-mass black holes as companions as predicted by the binary evolution theory.

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Shenar et al. 2021, A&A, 650A, 147: "The Tarantula Massive Binary Monitoring. V. R 144: a wind-eclipsing binary with a total mass ≳140 M⨀";

Menon et al. 2021, MNRAS, 507, 5013: "Detailed evolutionary models of massive contact binaries - I. Model grids and synthetic populations for the Magellanic Clouds";

Sen et al. 2022, A&A, 659A, 98: "Detailed models of interacting short-period massive binary stars"

The Parallax Zero-Point Offset From Gaia EDR3 Data

Ever since the first Gaia data release (DR), it is known that sources at, essentially, infinity, like quasi-stellar objects (QSOs), do not have, on average, a parallax of zero. In DR2 data, the sky-averaged parallax of QSOs was -29 µas (Lindegren et al. 2018). It also became clear that this, so called, parallax zero-point offset (PZPO) depended on sky position but also on magnitude and colour as several studies showed. This offset and its uncertainty hamper the accurate calibration of local distance scale indicators, including that of Classical Cepheids (CCs), considered to be the primary local distance indicators (Riess et al. 2018, Groenewegen 2018)

It was therefore not surprising that the Gaia team had a close look at this issue for the early-DR3 (EDR3; Gaia Collaboration 2021). As part of the Gaia EDR3, Lindegren et al. (2021; hereafter L21) provided a Python script that returned the PZPO (without error bars) as a function of ecliptic latitude (ß), magnitude and colour.

At the ROB, the dependence of the PZPO on several parameters was investigated independently, and the results are described in the article "The parallax zero-point offset from Gaia EDR3 data" (Groenewegen 2021, hereafter G21).

The main difference with the work of L21 is that the dependence of the PZPO on sky position is chosen not to be a function of ecliptic latitude but on the actual sky position as parameterised through the HEALPix scheme (Gorkí et al. 2005). The latter is a scheme to divide the sky into pixels, and the number of pixels depends on the 'level' one chooses, from 12, 48, 192, 768 and 3072 pixels, for levels 0, 1, 2, 3 and 4, respectively, that are considered in G21.

The samples of objects used to determine the PZPO are similar to those used in L21, but, again, constructed independently. At the faint end, an initial sample of 855 000 high-confidence QSOs is selected from The Million Quasars (Milliquas) catalogue (Flesch 2019) that have a match within 0.15" of a GEDR3 source and have a parallax, and a G (broad pass band), Bp (blue photometer) and Rp (red photometer) magnitude. A further selection is made to purify the sample. The parallax and proper motions need to be consistent with zero within 5 sigma, and a quality parameter of the astrometric solution called the goodness-of-fit (GOF) is selected to be in the range -4 to +5. The final sample contains 824 000 QSOs for which the median parallax is -20 µas. Figure

35 shows the sky-averaged PZPO for QSOs as a function of magnitude (left panel) and ecliptic latitude (right panel).

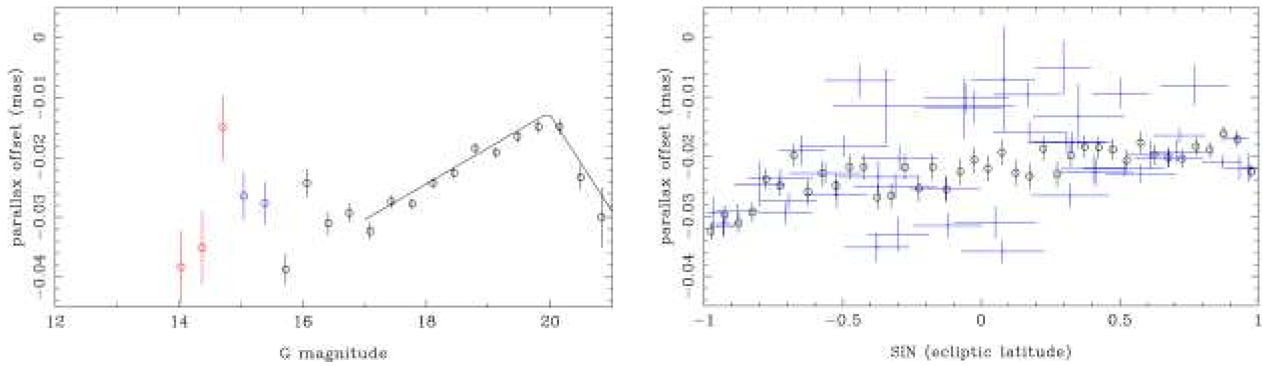

Figure 35: PZPO for the QSO sample as a function of G-mag and ecliptic latitude (open circles). Only bins with ≥5 objects are plotted. Bins with 100 objects or less are plotted in blue, with 30 objects or less in red. The blue points in the right-hand panel indicate the PZPO for the 48 HEALPix level 1 pixels. The horizontal bar gives the range in sin ß (where ß is the ecliptic latitude) for each HEALPix pixel. From G21.

At the faint end, the dependence on magnitude can be approximated by piecewise linear functions (as was done in L21). The right-hand panel shows the large scatter when the PZPO is plotted as a function of HEALPix pixels rather than sin(ß), indicating that the behaviour of the PZPO is not a simple function of ecliptic latitude, as was also found by Huang et al. (2021). When considering the HEALPix scheme, the median parallax of the QSOs in each pixel is determined (with 1.4826 MAD [the median absolute deviation] as the error estimate). The number of known QSOs is not uniform over the sky and so the number of QSOs that is contributing to the average depends on the HEALPix pixel and level, and can vary from 0 to a few 1000.

The second sample that is used to constrain the PZPO are 784 000 wide physical binaries (based on El Bady et al. 2021). The advantage of using physical binaries is that they are, for all practical purpose, at the same distance and at the same location on the sky. In other words, any difference in parallax between the components in the binary must be due to other parameters, like magnitude and colour. The left-hand panel in Figure 36 shows the difference in parallax between the primary (=the brighter one by construction) and secondary component as a function of the magnitude of the primary. One observes clear patters that can be ascribed to different read-out schemes of the Gaia CCDs as a function of magnitude (see L21 and references therein). Assuming again a linear dependence of the PZPO as a function of magnitude (as in L21) one can derive this piecewise function, and the result is shown in the right-hand panel, where a comparison to the results in L21 is also shown. The overall agreement is good although they differ in detail.

The results of the paper are files that give the PZPO at a fiducial magnitude of G = 20 for all pixels at HEALPix levels 0 to 4 (the spatial correction), and a piecewise linear function in G between 5.3 and 21 mag to provide the magnitude correction. In practice, a user needs to make a decision which HEALPix level they want to use, and this depends on the application. Does it apply to a sample of sources or a single source? One has to balance the accuracy of the correction (better with fewer sky pixels and more QSOs) and the variation over the sky that is better sampled with more sky pixels.

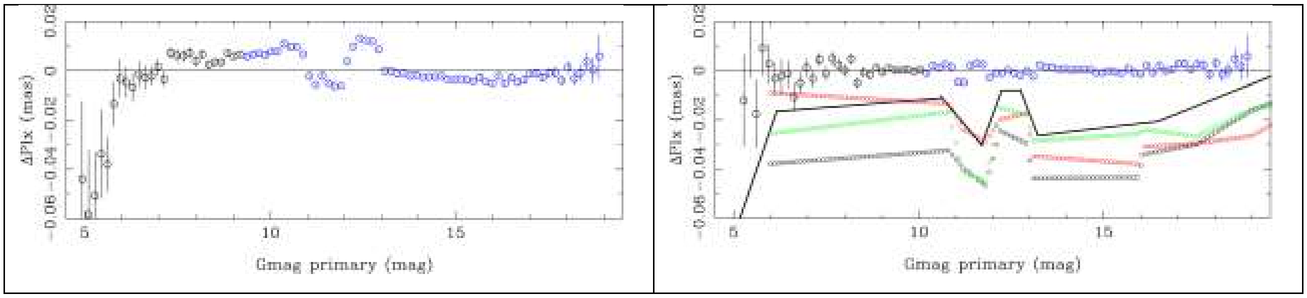

Figure 36: Left panel: parallax difference between the primary and secondary components in wide binaries as a function of primary G magnitude. Bins with more than 1000 objects are plotted in blue. Right panel: The applied correction (see Eq. 7 in G21) is shown as the black line, leading to a residual as shown by the open circles. The small black, red, and green circles represent the L21 correction for ß = 0, -60, and +60°, respectively. There is an offset as the L21 corrections are absolute, while the corrections applied to the wide binary sample are relative to the correction at G = 20 mag. From G21.

In June 2022, Gaia DR3 will be released. One big improvement is that the astrometric solution will also allow for non-single stars. This means that the parallax (and other parameters) will be improved for the many objects that are in binary systems (in particular unresolved binaries). It will also improve sample selections as the number of objects that were now excluded because of a poor astrometric solution (a poor GOF) should diminish.

References:

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Outreach and Communication

Outreach Initiatives with Accents to Gender Equality in Science

Soapbox Science Brussels 2021

Soapbox Science is a science outreach initiative that aims to promote the visibility of women and non-binary scientists and their research by bringing them on the streets to reach the public. Soapbox Science events transform public areas in discussion forums based on Hyde Park's Speaker's Corner where women and non-binary scientists, on their soapboxes, talk about their research to the people passing by. Soapbox Science was founded in 2011 in London, by Dr Seirian Sumner, from the University of Bristol, and Dr Nathalie Pettorelli, from the Zoological Society of London. The concept went on with great international success, with 42 events in 13 countries in 2019.

Figure 37: Soapbox Science Brussels 2021 event at the Place de la Bourse in Brussels

Soapbox Science aims at tackling stereotypes, and shows to the public that science is not an 'old white man's' business and that anyone has the opportunity to enjoy science in an interactive way.

In 2019, a team of six researchers and science communication officers of the Royal Observatory of Belgium (ORB-KSB) and the Royal Belgian Institute of Space Aeronomy (IASB-BIRA), decide to organise Soapbox Science events in Brussels. The administrative costs are managed by the ORB-KSB and the IASB-BIRA. Funding of Soapbox Science Brussels goes through sponsoring from different entities. In 2021, Soapbox Science Brussels Sponsors are Belspo, ULiège, UHasselt and Europlanet Benelux.

Online Event in 2020

The first Soapbox Science Brussels event was organised on October 10, 2020. Due to COVID-19, the event was held online and was broadcast live on YouTube and Facebook. This online event was also the first Soapbox Science Brussels event organised in Belgium.

The First In-person Event of Soapbox Science in Brussels

The very first Soapbox Science event held in-person in Brussels took place on June 26, 2021. This is also the first in-person Soapbox Science event in Belgium. On this day, four soapboxes were installed on the Place de la Bourse/Beursplein of Brussels, and 12 speakers took turns talking about their research and interact with the public passing by for one hour each. Talks were in French, Dutch and English, three languages widely used in Brussels.

There was a good reception from the visitors, from the communication from the institutes of the speakers, and from the press with which some interview where done. On this occasion, videos of the event were made by Marc Vandenbrande. Those videos are displayed in the Soapbox Science Brussels YouTube channel.

Soapbox Science Brussels' social media in 2021:

- Facebook: https://www.facebook.com/SoapboxScienceBrussels
- Twitter: https://twitter.com/SoapboxscienceB

Belgian Women in Science – BeWiSe and the WiseNight Festival

History & Objectives

BeWiSe is a non-profit association that is dedicated to promote the participation of women in sciences.

The association was officially created in December 2003, a few months after eight female scientists decided to form an association that would help to enhance the position of women in scientific careers in Belgium during its first General Assembly. BeWiSe's main objectives are to support the position of women in science, both in academia and private sectors, and to improve the communication among women in the Belgian and European scientific communities. The General Assembly is held once a year, with a private session for members only, and a public session for all members, mentors and mentees, and supporters.

Examples of BeWiSe Realisations, Events and Activities

- **Science needs You**! In 2010, BeWiSe produced a video presenting the portraits of six scientists (four women, two men) in their (natural) environment and showing why they chose a career-path in science. It describes their main interests and hobbies and disseminates their messages to stimulate teenagers and youngsters to choose scientific studies. This video was produced in collaboration with the sociologist Monique Chalude (MC2Chalude Consultancy) and is still broadcast today to raise the interest of girls for scientific careers, e.g. at the Green Light For Girls event at the ULB.
- The **BeWiSe Mentoring Programme**. BeWiSe offers a unique mentoring programme where the candidate mentees (at PhD level) are matched with an experienced mentor (with over 10 years of experience) across different disciplines and across the linguistic and community borders of Belgium. Both women and men, with a priority given to (young) women, can participate to this programme.
- The **Lunch & Learn** lectures. In these recurrent events occurring at lunchtime, discussed topics include how to build self-confidence, how to improve the work-life balance, career paths outside of academia as well as practical workshops such as writing a strong CV, obtaining funding, etc.
- **WiseNigh**t, a science event funded by the European Commission that took place on 24-25 September 2021 (see the Paragraph, "The WiseNight Festival").
- **Advocacy for Women in Science**. BeWiSe advocates for women in science in Belgium during national and international events such as those organised by the European Parliament, the EU Gender Summit, the European Platform of Women in Science (EPWS) and the Women and Society Platform of Fedactio (Federation of Active Associations in Belgium).

The WiseNight Festival: a Collaboration between BeWiSe and the Planetarium of the ORB-KSB

In 2021, BeWiSe organised and coordinated an inclusive two-day science festival on September 24 & 25, 2021 the Planetarium of Brussels and the Museum of Natural Sciences. WiseNight was an initiative of seven organisations involved in research, science outreach and gender equality in scientific careers in Belgium: BeWiSe, the Planetarium of the Royal Observatory of Belgium and the Royal Belgian Institute of Natural Sciences, Jeunesses scientifiques de Belgique, BOS+, Ekoli, GoodPlanet. The specific research themes were Land & Forest, Oceans & Water and Space.

The science festival was held in the context of the European Researcher's Night with the purpose to bring the (young and old) public in contact with science and scientists, with a focus on women scientists and science in Europe, in an interactive and fun way. This project received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie actions (grant agreement No 101036009).

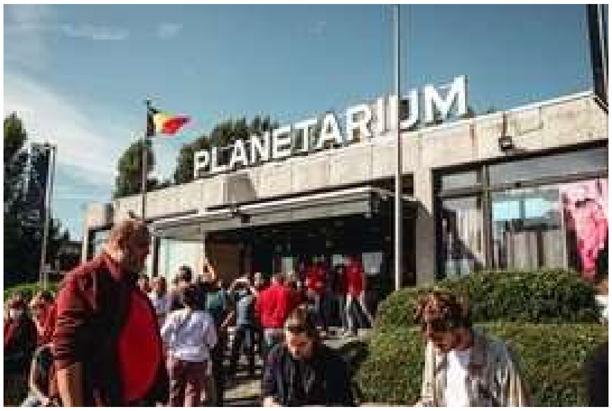

Figure 38: Pictures of the WiseNight Event at the Planetarium

The activities on Friday were mainly targeted to schools; the activities of Saturday were for the public. The festival is free of charge, but registration is required for practical purpose.

- The Planetarium of Brussels hosted a variety of activities:
- The screening of the movie Proxima;
- Two activities related to space weather:
    - 'Panic in the Space Weather Room': an interactive tour in the Space Weather office, where the space weather forecast is being prepared;
    - Northern Lights: enjoy a spectacular show of the Northern lights, while listening to a local legend;
- An EU4U booth highlighting the European Union's involvement in Research and Innovation, with live sessions where you can interact with researchers who received a Marie Skłodowska-Curie Actions (MSCA) grant;
- A booth presenting the Soapbox Science Brussels initiative;
- A photographic exhibition of scientists in Belgium (on display until 9 October 2021).

The 2022 Calendar of the Royal Observatory of Belgium

Since 2020, the ORB-KSB publish its annual calendar, as a way to present the Observatory to the public. The pictures of the calendar represent the research performed at the Observatory. For each picture, a short text in French and Dutch describe the picture and the context behind it. Astronomical events visible to the naked eye and selected from the Yearbook of the ORB-KSB are also mentioned in the calendar. A glossary at the end of the calendar explains the different phenomena mentioned.

This year, the calendar format is a big format of 32 × 32 cm. In addition to the information presented in the 2021 calendar, each month of the 2022 calendar also mentions the periods of visibility of the five planets visible with the naked eye (Mercury, Venus, Mars, Jupiter and Saturn).

The VR Filming Project

In September 2020, the ORB-KSB and the Royal Belgian Institute of Space Aeronomy (BIRA-IASB) applied Belspo to get outreach funding for a virtual reality (VR) filming project of the three Space Pole institutes at the Uccle Site. The filming of the project took place in December 2020 and January 2021 and a review of the VR was performed in June 2021. The VR will be displayed in the Planetarium in the frame of its VR activity when the COVID-19 situation allows to do so.

Information to the Public, Website, News and Press Releases

In 2021, the Communication and Information service replied to questions from authorities, public and the media send by email (624, with 312 in French, 260 in Dutch and 52 in English), by telephone (110), by letter or fax (14), and in social media of the ORB-KSB (Facebook and Twitter, 6), hence 740 replies in total. 38 questions come from authorities (courts, police…) or particulars such as lawyers, with 26 in Dutch and 12 in French. As usual, most questions were about sunset and sunrise, astronomical phenomena, calendars and time, satellite and space station flybys, night observations, and the history of ORB-KSB. Questions related to other fields of expertise such as seismology or space weather are forwarded to the respective services. Due to lockdown and COVID-19 safety measurements (put in place since March 12, 2020), visits are restricted and strongly discouraged.

In 2021, the main website of the ORB-KSB got 422,382 visits on the main website (comprising the information service website) and a mean duration of 1 min 32 s per visit. 17 topics were published in the 'News' section of the ORB-KSB's website (always in three languages: NL/FR/EN), including 2 press releases. The most important news of this year is related to the launch of the NASA DART mission to the asteroids Didymos and Dimorphos.

Social Media

On 31 December 2021, the ORB-KSB Facebook webpage has 1199 likes (with 155 new likes since end 2020), and the ORB-KSB Twitter account got 1022 followers (105 new followers since end 2020). The themes of the published posts and videos are related to all services of the institutes, comprising shared posts from the Planetarium Facebook page, from the Seismologie.be Facebook page and Twitter account, from the EUI Twitter account and also from the Royal Belgian Institute of Spatial Aeronomy and the Royal Meteorological Institute.

The most successful Facebook post of the year is a post announcing the annular solar eclipse of June 10, 2021, which is partially visible in Belgium. On Twitter, the most successful Twitter post is a post in Dutch in April 3, 2021, announcing that the Planetarium is open again after renovation.

The Planetarium

Daily Activities

The year 2021 at the Planetarium was again affected by the COVID-19 pandemic, which meant periods of closing (particularly during the end-of-year holidays), reduced capacity throughout the year and schools being denied field trips. The Planetarium was also closed in March to allow for the installation of the new digital projection system (see below). Nevertheless, 32,265 paying visitors were welcomed, thanks in particular to a very strong response from the family public during the spring holidays (when the Planetarium reopened) and during the summer (more visitors were received in July and August 2021 than in the same pre-COVID period in 2019). However, school audiences were hard to come by in order to reach the usual attendance figures.

A total number of 828 sessions were given, divided between 83 school group courses, 6 workshops and 739 film screenings (individual visits, families, tourists). These figures, compared to a normal year like 2019 (1657 sessions including 222 school group courses, 40 workshops and 1395 film screenings), give a clear idea of the impact of the school closing and lockdown periods on the Planetarium's daily activities.

The Facebook page continued its upward curve as the year 2020 ended with 2963 followers (+945 over the year) and 2846 likes (+899).

The New Digital Planetarium

The Planetarium has acquired eight state-of-the-art projectors based on phosphor laser technology. With a brightness of 7500 lumens each (instead of 2800 lumens with the previous projectors) and an individual resolution of 3840 x 2400 pixels (previously 2048 x 1536), the 360° films are now projected in 8K UHD. The images benefit from a dynamic contrast of 50,000:1, which shows bright, point-like stars against a deep black sky, an auto-calibration system that takes into account all light variations, geometric correction and striking colours.

The installation work was carried out in March, during which time the Planetarium was completely closed to the public. This period was used to install a new counter for the ticket office and the shop, as well as a corner specifically dedicated to an upcoming virtual reality experience.

The inauguration of the new digital projection system took place on April 1 and was immediately followed by a great public success thanks to excellent press coverage (e.g. VRT and VTM news items): all the spring holiday sessions were quickly sold out (due to the limited capacity and the influx of reservation requests).

LE NOUVEAU PLANETARIUM NUMERIQUE
01 avril 2021

HET NIEUWE DIGITAAL PLANETARIUM
01 april 2021

Monsieur Thomas Dermine
Secrétaire d'État chargé de la Politique scientifique fédérale

Monsieur Ronald Van der Linden
Directeur général de l'Observatoire royal de Belgique

Monsieur Rodrigo Alvarez
Responsable du Planétarium de l'Observatoire royal de Belgique

Ont l'honneur de vous inviter au Planétarium de Bruxelles

Le jeudi 1er avril à 10h30
A la conférence de presse de présentation du nouveau planétarium numérique

Réponse souhaitée avant le 30 mars par courriel: planetarium@planetarium.be

De heer Thomas Dermine
Staatssecretaris belast met het Federaal Wetenschapsbeleid

De heer Ronald Van der Linden
Algemeen directeur van de Koninklijke Sterrenwacht van België

De heer Rodrigo Alvarez
Verantwoordelijke van het Planetarium van de Koninklijke Sterrenwacht van België

Hebben de eer u uit te nodigen in het Planetarium van Brussel

Op donderdag 1 april om 10.30 u.
Voor de persconferentie van de presentatie van het nieuwe digitaal planetarium

Antwoord a.u.b voor 30 maart: planetarium@planetarium.be

Nationale Loterij
creëert kansen
créateur de chances
Loterie Nationale

How to get there

PLANETARIUM

Special Activities

As in 2020, the number of events promoting science and educational and cultural activities was very low given the health context. Nevertheless, we can list:

- The filming of a LiveFacebook concert (30,000 views) by the young artist-singer Roman Roses on June 4.
- Participation in the Nocturnes des Musées on June 10 with a concert by the group GOING.
- Co-organisation of the Brussels Planetarium Poetry Festival on September 10 and 11.
- The co-organisation with the ORB-KSB and the BeWise association of the WiseNight (Night of the Researchers) on September 24 and 25, with workshops, an exhibition of portraits, the Soapbox Science stand, the activities "Aurora Borealis" and "Panic in the space weather room" and the screening of the film Proxima. (See Highlight “The WiseNight Festival: a Collaboration between BeWiSe and the Planetarium of the ORB-KSB”.)
- The presence (screening of our films) at the KNAL Festival (Leuven) on November 28.
- Participation in the Rouge-Cloître Night of Darkness on 9 October 2020.
- Rental of rooms (projection room or auditorium) on July 3 (VVS Astronomy Olympiad), on September 30 (La Financière de l'Echiquier), on October 14 (Warner Music, presentation of the Coldplay album), on October 28 (Belgian Nuclear Society).
- Media interviews: La Libre Belgique (February 24), Radio Vivacité (April 8, September 15, and December 12), Radio Nostalgie (June 1), Le Vif-Express (June 7).

Annex 1: Publications

Publications with peer review

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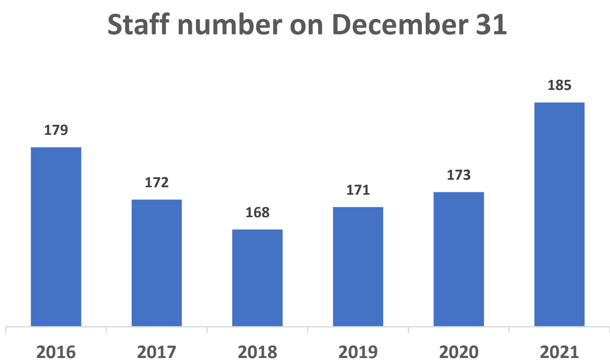
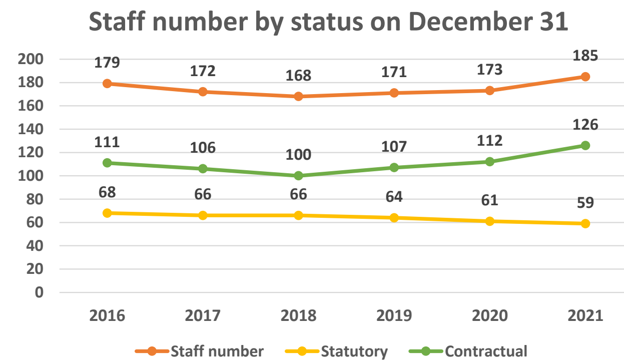
Annex 2: Workforce

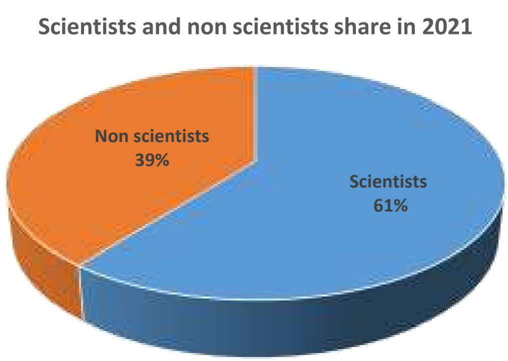
Staff statistics

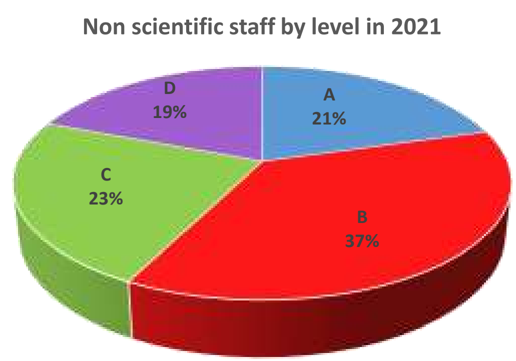
On 31 December 2021, 185 employees are working at the ORB-KSB (including people working at the Planetarium). The staff includes twelve more employees than last year (173 employees on 31 December 2020), which corresponds to an increase of 7% of the personnel.





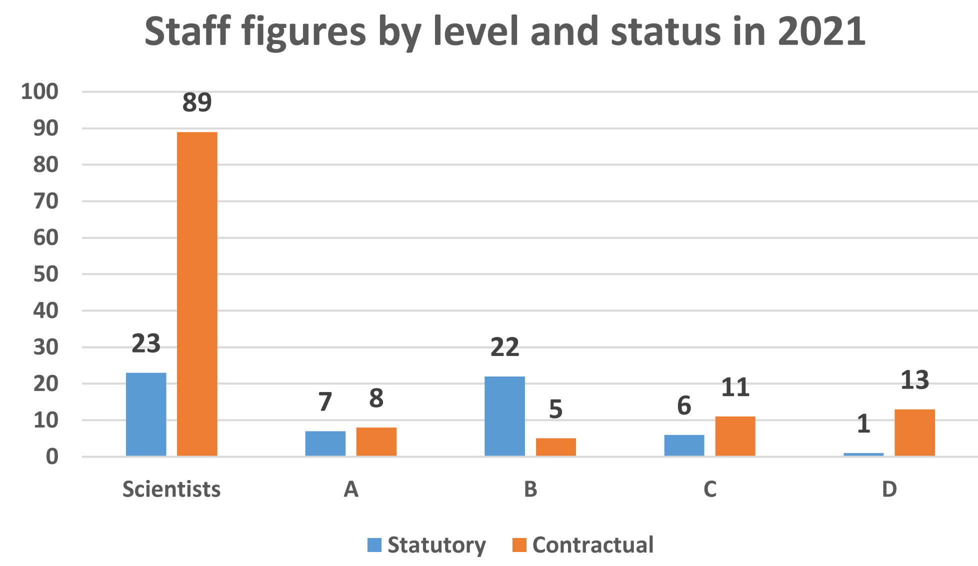
Most of the newly engaged collaborators are scientists, which constitute the main part of the personnel (112 agents, or 61% of the staff). Compared to last year, there were 16 newly employed scientists (96 scientists on 31 December 2020), which corresponds to an increase of 17% of the scientific staff. On the other hand, the number of non-scientist collaborators slightly declined (73 on 31 December 2021 compared to 77 on 31 December 2020).





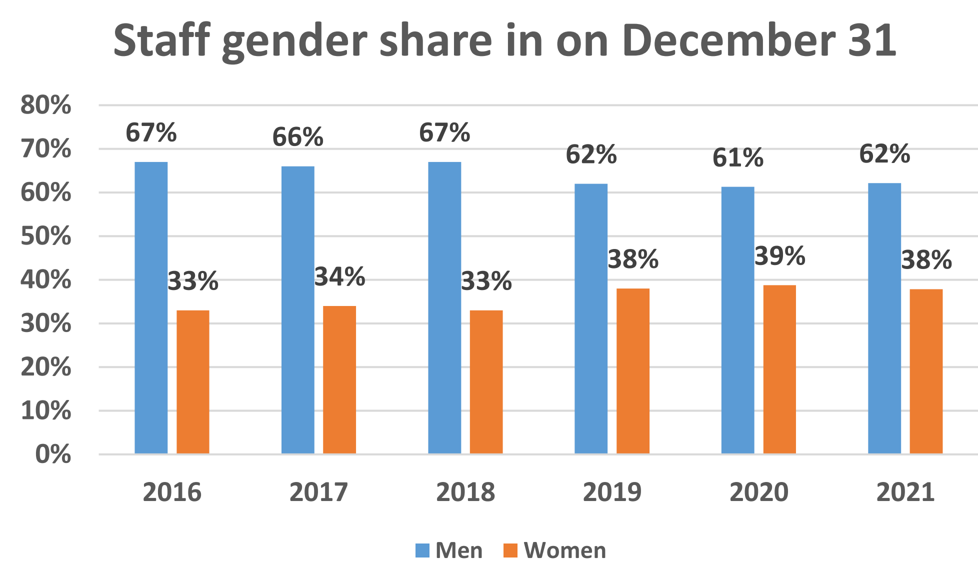
The majority of the staff (68%) are contractual agents. This is particularly true for scientists, in whom 79% are contractual which is a higher percentage than in 2020 (on 31 December 2020, 75% of the scientists were contractual), since the totality of the 16 new scientific collaborators are contractual. The fact that more and more scientists are contractual is because scientific research is more and more funded by external projects while the federal dotation is shrinking.

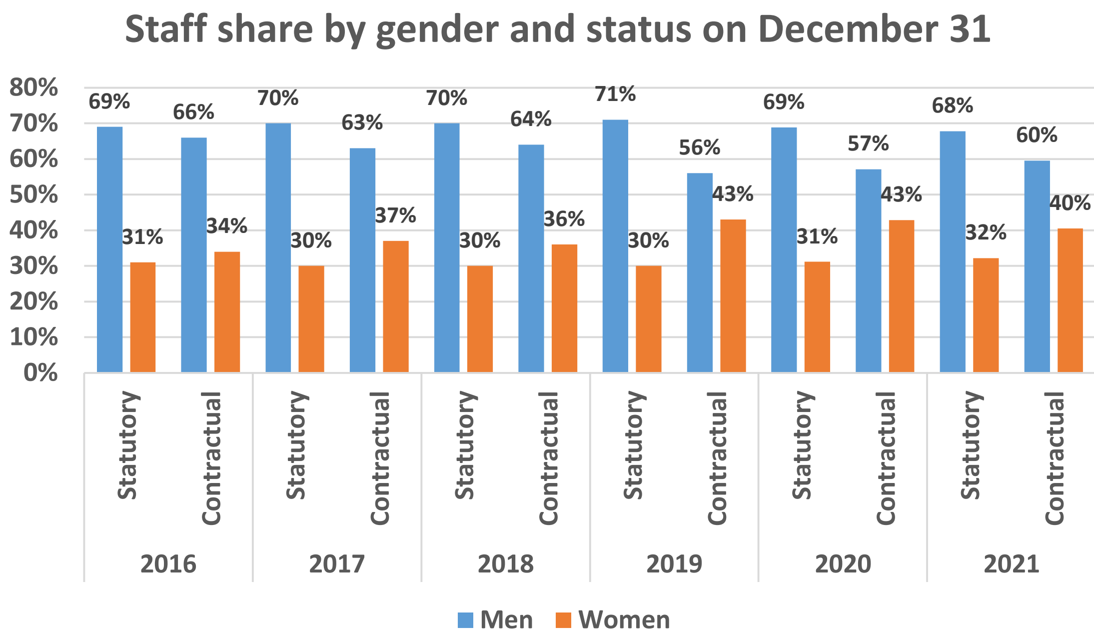
The proportion of contractual to statutory is even higher for employees of level D (93% of them are contractual). Only agents of level B are in the vast majority statutory (82% of level B agents).

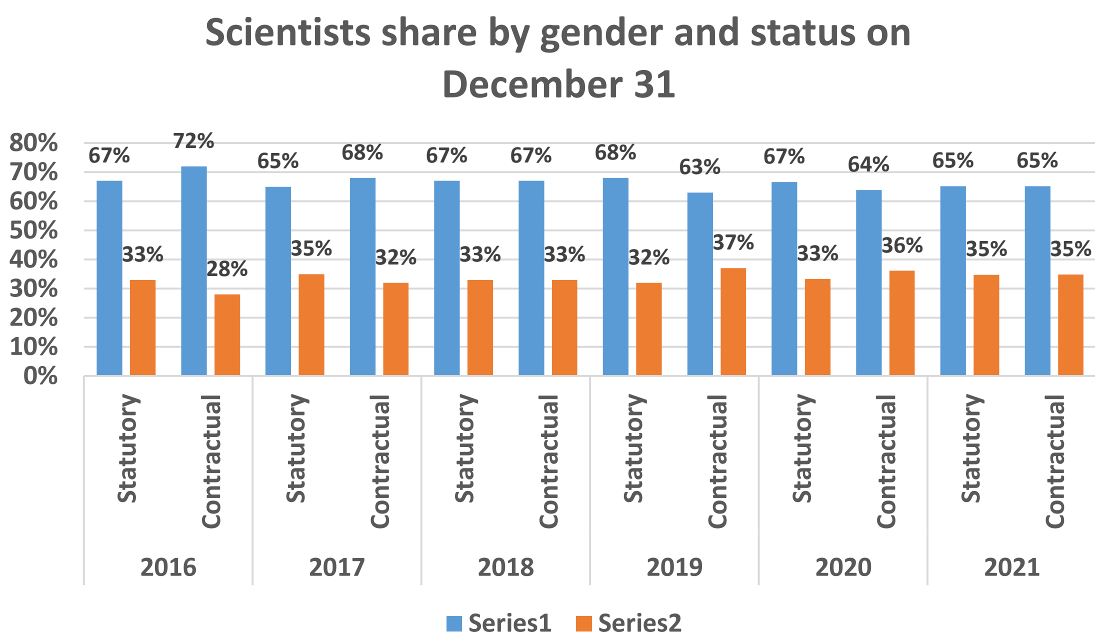


38% of the agents are women (70 women and 115 men), which is a slight decrease compared to 2020 (39%) and a similar value to 2019.

Among statutory agents, the proportion is lower as only 32% of them are women. Actually, 73% of the female employees are contractual, compared to 65% of the male employees. At the scientists' level, the women proportion is slightly lower than the women proportion for the whole staff (with 35% of scientists being women).




Staff share by gender and status on December 31
80%
70%
60%
50%
40%
30%
20%
10%
0%
69%
31%
66%
34%
70%
30%
63%
37%
70%
30%
64%
36%
71%
30%
56%
43%
69%
31%
57%
43%
68%
32%
60%
40%
Statutory
Contractual
2016
2017
2018
2019
2020
2021
Men
Women


Scientists share by gender and status on December 31
80%
70%
60%
50%
40%
30%
20%
10%
0%
67%
33%
72%
28%
65%
35%
68%
32%
67%
33%
67%
33%
68%
32%
63%
37%
67%
33%
64%
36%
65%
35%
65%
35%
Statutory
Contractual
2016
2017
2018
2019
2020
2021
Series1
Series2

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