

Sudden Stratospheric Warming as observed on the Earth Sensor measurement of Galileo Constellation

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Abstract

The Sun's constant outflow of solar wind fills space with a thin and tenuous wash of particles and plasma. This solar wind, along with other solar events like giant explosions called coronal mass ejections, influences the very nature of space and can interact with the magnetic systems of Earth. Such effects change the radiation environment through which our spacecraft travel. Moreover, the space environment around Earth can also vary significantly in response not only to the Sun, but from upwelling atmospheric events from below.

During the southern hemisphere winter season of 2019, a sudden stratospheric warming occurred. A sudden stratospheric warming is an event in which polar stratospheric temperatures rise by several tens of kelvins over the course of a few days. The driving force behind these events is the Polar Vortex, which behaves like a very large cyclone, covering the whole polar region down to the mid-latitudes. A sudden stratospheric warming is a significant disruption of the stratospheric polar vortex that begins with large-scale atmosphere waves getting pushed higher into the atmosphere. These waves can "break" (like waves in the ocean) on top of the polar vortex and weaken it. If waves are strong enough, the winds of the polar vortex can weaken so much that they can even reverse their directions leading to cold air descending and warming rapidly.

Galileo spacecraft are equipped with two InfraRed Earth Sensors (IRES), which detect the edge between the Earth disc and deep space by scanning the Earth horizon with four infrared pyroelectric detectors. Due to the high inclination of the Galileo orbits, Earth's Polar regions may fall inside the Earth sensor field of view; in particular, during the southern hemisphere winter season, the extremely low temperatures achieved can alter the local-emitted Earth infrared radiation, causing some disturbances on the measurement of the sensors since the edge between the Earth disk and deep space is not that sharp anymore. The spacecraft on-board software is designed to predict and discard the information provided by the sensors during these occurrences so that a good nadir pointing can always be maintained.

The data of the Earth sensor of Galileo spacecraft provides the evidence of this sudden stratospheric warming that was observed in 2019. Thanks to the robustness of the software this did not lead to any anomalous behaviour or to any on-board reconfiguration.

This paper describes how the southern stratospheric warming has been observed from Galileo constellation and also provides information on how this has been used as starting point to increase the usage of space weather data in Galileo operations.

Keywords: Galileo, IRES, SSW

Acronyms/Abbreviations:

IRES: InfraRed Earth Sensor
GCC: Galileo Control Centres
SSW: Sudden Stratospheric Warming
MEO: Medium Earth Orbit
FOV: Field of View
AOCS: Attitude Orbit and Control System
EMU: Environmental Monitoring Unit
GNSS: Global Navigation Satellite System

1. Introduction

Galileo is Europe's largest satellite constellation and the world's most precise satellite navigation system, delivering sub metre-level positioning accuracy to around four billion users worldwide [1]. It offers a highly precise, guaranteed global positioning service under civilian control and is presently delivering Initial Services ready to declare Full Operational Capability in 2025. This system is compatible with both the US GPS and the Russian Glonass systems, offering dual frequencies as standard and delivering real-time positioning accuracy down to the metre range.

The Galileo system consists of 24 satellites plus spares, currently a total of 32 satellite in flight, of which all but two are positioned in three circular Medium Earth Orbit (MEO) planes at an altitude of 23,222 km above the Earth. The orbital planes are inclined at 56 degrees to the equator.

Since the initial services became available on 15 December 2016, Galileo has been continuously developing and testing new services.

Galileo's ground infrastructure includes two Galileo Control Centres (GCCs) located on European ground. These centres control the satellites and manage the navigation mission. Data from a global network of Galileo Sensor Stations (GSSs) are transmitted to the GCCs through a redundant communications network. The GCCs use this data to compute integrity information and synchronize the time signal of all satellites with the ground station clocks. Data exchange between the Control Centres and the satellites is performed through up-link stations.

Galileo offers an Open Service, providing free access to position and timing information. Additionally, it includes a High Accuracy Service for precise navigation and a Public Regulated Service, ensuring high-continuity, controlled-access positioning and timing for specific users.[2]. Additionally, Galileo provides a global Search and Rescue (SAR) function based on the operational Cospas-Sarsat system. Satellites are equipped with transponders that relay distress signals from user transmitters to regional rescue coordination centres, which then initiate rescue operations.

Galileo constellation is not only providing navigation services to the global community, but it could also be used to monitor atmospheric effects in the carbon dioxide levels, making it a valuable tool for environmental research and climate change studies. The InfraRed Earth sensor (IRES) on-board each satellite measures the Earth's radiance in the Carbon dioxide 15 μm InfraRed band, may provide additional data for these studies.

Potentially, as observed in 2019, Galileo can support monitoring activities for Sudden Stratospheric Warming (SSW) events, which are dramatic weather phenomena characterized by a rapid increase in stratospheric temperatures. These events can impact weather patterns in both hemispheres, making their study crucial for advancing meteorological forecasting and understanding climate variability.

This paper explores the potential use of Galileo constellation data for environmental monitoring, presenting key findings and future research directions.

2. Galileo Infrared Earth sensor: Function and Challenges

To understand how Galileo can contribute to environmental monitoring, it is essential to examine the role of the InfraRed Earth Sensors (IRES) onboard the satellites. Galileo's main purpose is the dissemination of navigation signals to ground and this is achieved with an Earth pointing attitude that keeps the navigation antenna continuously pointing towards nadir.

To accomplish this mission requirement, the Attitude Orbit and Control Subsystem (AOCS) is equipped with two InfraRed Earth Sensors N2 used to calculate roll and pitch. In particular, the operating principle is based on electro-mechanical modulation of the radiation coming from the Earth horizon in the 14-16.25 μm band. The sensor field of view consists of four infrared beams in a single telescope which oscillate along a scan path normally including Space and Earth portions.

The Earth sensor measurements are based on the cold-hot transition detection of the 4 pyro-detectors sensitive to the infrared radiation emitted by Earth. The Earth signal is generated, starting from the Space/Earth and Earth/Space transitions with the following logic:

- when a Space/Earth transition is detected the Earth signal goes high and it returns low when an Earth/Space transition is detected.
- The Earth signal does not change when an Earth/Space with a low level of the Earth signal or a Space/Earth with a high level of the Earth signal is detected.

The resulting information from the Earth/Space and Space/Earth detected discontinuities is electronically processed to obtain the pitch and roll output. When the Earth disk is within the sensor field of view (FOV) and the detector scanning paths cross the Earth edge, four chords (X1, X2, X3, X4) are detected by the IRES sensor as described in Fig. 1

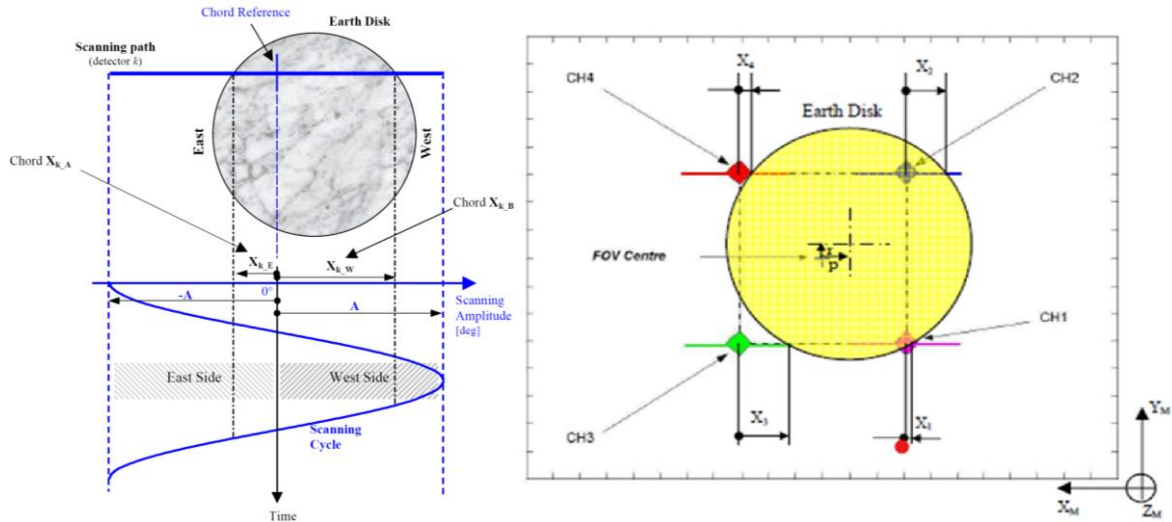


Fig. 1: Chord Detection for the calculation of Pitch and Roll

The IRES logic uses these chords to calculate the Pitch (1) and Roll (2) angular positions of the Earth.

$$p = \frac{X_1 + X_3 + X_2 + X_4}{4} \quad (1)$$

$$r = \left(\frac{X_2 - X_1 + X_3 - X_4}{4} \right) \quad (2)$$

However, the Moon or the Sun may enter the sensor's field of view in some satellite attitude modes. In these cases, the infrared radiation from these bodies gives a false detection of the Earth disk border resulting in disturbed data output from the IRES (see Fig. 2).

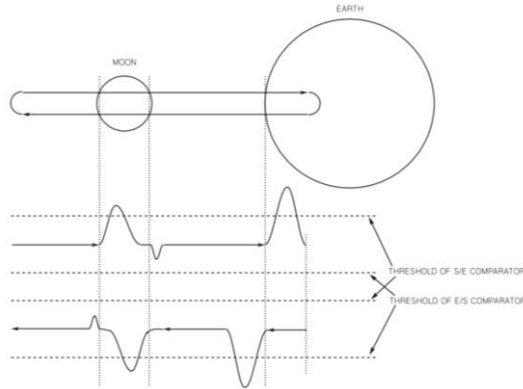


Fig. 2: Space/Earth transition observed in the IRES when both Earth and Moon are in the sensor field of view

Additionally, Galileo's experience indicates that, under specific winter conditions, the Arctic and Antarctic cold regions significantly impact the IRES unit due to radiance decay in these areas. High altitude jet streams and cold clouds represent an opaque body (at the same temperature of the atmosphere at that altitude), with a proper transmittance, that can reduce the resulting radiance of the portion of Earth affected by the presence of these cold clouds in the atmosphere within the $14 \div 16 \mu\text{m}$ wavelength band. Therefore, if the polar regions enter the IRES field of view during their coldest season, the distinction between the Earth Infra-Red (IR) radiation and deep space is not so sharp, resulting in disturbed data. Note that these IRES units are traditionally used in geostationary spacecraft with certain attitude, where the IRES never looks towards the poles.

These disturbances caused by either the Moon, the Sun, or the polar regions are known as “channel blinding”. This term indicates the fact that the concerned channel cannot provide reliable measurements if affected by a “blinding body”. To avoid the usage of the affected data, the channel itself needs to be “inhibited”: when a channel is inhibited, its raw data output (chord measurement) is not taken into consideration by the IRES logic to compute Roll and Pitch measurements. The Earth sensor provides its best accuracy when all the four channels are not inhibited (or “active”) but it is also satisfying the pointing requirements of the mission using only three active (not inhibited) channels.

Channel inhibition happens autonomously via the AOCS software, in fact when the On-Orbit-Propagator predicts that a blinding body is crossing the so-called “blinding region” of the channels. This is a subset of the Earth Sensor channel FOV, and it is different in size for each of the possible blinding bodies (as shown in Fig.3) [3].

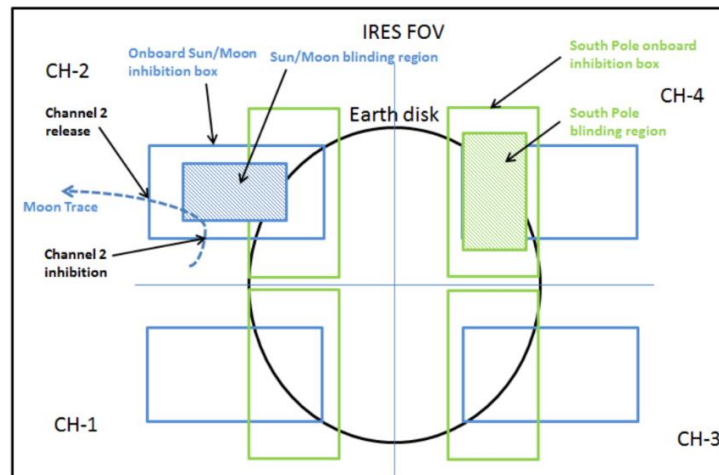


Fig. 3: Inhibition boxes of Moon and Antarctica region

1.2 Characterization of the different blinding bodies seen from the IRES Field of view

The dimension of the Earth from the IRES Field of view can be easily determined by considering the altitude of the orbit of Galileo Spacecraft (3).

$$\alpha_{Earth} = \arcsin\left(\frac{\text{Mean Earth Radius in } 14\text{--}16 \mu\text{m}}{\text{Mean Earth Radius} + \text{Satellite altitude}}\right) = 12.5^\circ \quad (3)$$

In a similar way it is possible to calculate the dimensions of the Moon and of the Sun as seen from the IRES field of view (4) (5).

$$\alpha_{Moon} = \arcsin\left(\frac{\text{Mean Moon Radius}}{\text{Mean distance Moon-Satellite (from the centre of the Moon)}}\right) = 0.25^\circ \quad (4)$$

$$\alpha_{Sun} = \arcsin\left(\frac{\text{Mean Sun Radius}}{\text{Mean distance Sun-Satellite (from the centre of the Sun)}}\right) = 0.26^\circ \quad (5)$$

To characterize the dimension of the cold area around the polar regions, for example Antarctica, this region is assumed to be within a certain latitude circle. Then, to calculate the cold Antarctic angular radius as seen from IRES field of view it is necessary to look to the specific geometry (see Fig. 4):

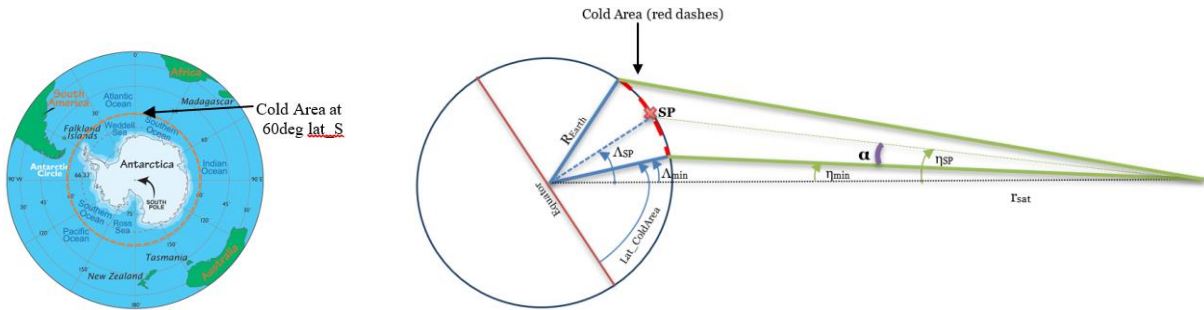


Fig. 4: (left) Example of cold Antarctic latitude circle area; (right) Antarctic angular radius as seen from the satellite IRES field of view

In general terms, for a given latitude circle of cold area the angular radius α_{Ant} , understood as the maximum aperture to the South Pole, can be computed as:

$$\alpha_{Ant} = \eta_{SP} - \eta_{min} = \text{atan}\left[\frac{R_{Earth} \sin(\lambda_{SP})}{r_{sat} - R_{Earth} \cos(\lambda_{SP})}\right] - \text{atan}\left[\frac{R_{Earth} \sin(\lambda_{min})}{r_{sat} - R_{Earth} \cos(\lambda_{min})}\right] \quad (6)$$

As shown in equation (6) and Table 1, the maximum angular radius from the spacecraft depends on how the Antarctic latitude circle is defined.

Table 1: Max. angular radius for different definition of cold Antarctic latitude circle

Cold Antarctica latitude circle (deg)	66.5	66	65	64	63	62	61	60	59	58
Max angular radius α_{Ant} (deg)	5.6	5.8	6.1	6.3	6.6	6.9	7.1	7.4	7.7	8.0

However, the real cold area around the Antarctic that may affect the IRES depends on the atmospheric dynamics of temperature, winds and clouds, mainly in the stratospheric layer, which are not fully predictable and can change from one season to another and even from week to week.

For the Antarctica radiance estimation in winter (see Fig. 5), the radiance decay has been integrated in the 14÷16 μm wavelength range to simulate the radiance budget decay seen by the IRES sensor.

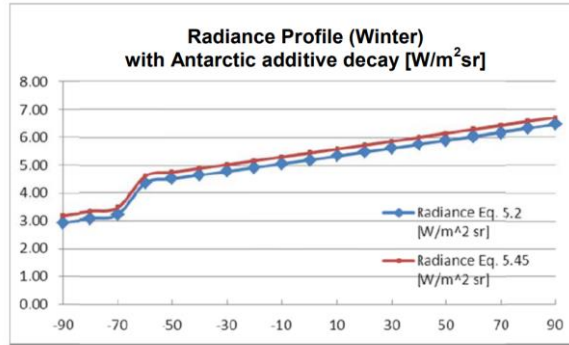


Fig. 5: Radiance Antarctica model vs latitude considering two nominal profiles based on two equatorial radiance possible values (5.2 and 5.45 W/m² ·sr), moving from South Pole to North Pole latitudes during winter in the southern hemisphere.

Based on the radiance model, the IRES behaviour has been analysed studying its possible effects on one IRES channel, with different positions of the Antarctic region along the detector scanning path.

Firstly, the drop in the radiance starting at a latitude around 62.5 deg South is considered a priori as the latitude circle, giving a maximum angular radius of Antarctica in the IRES field of view of 7 deg. This is in line with the collected in-orbit data perturbations observed by the IRES.

Additionally, to design the autonomous inhibition of the channel due to the South Pole blinding, the presence of the Antarctica cold area was analysed in terms of disturbed pitch/roll sensor performance for a set of different positions with respect to the channel scanning path (Fig. 6). It was concluded that the most critical positions of the Antarctica/Arctic are those near to the Earth border. Specifically, when the distance between the Antarctica/Arctic cold area border and the Earth infrared border is less than 1.84 deg (the diagonal of the infrared detector in the field of view), the higher effects on the pitch/roll performance. On the contrary, when the Antarctica cold area is at a distance from the Earth border greater than 1.84 deg, it has lower effects.

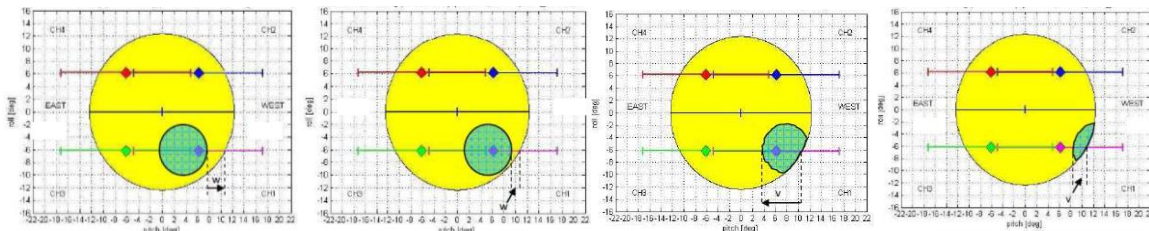


Fig. 6: The presence of the Antarctica has been evaluated with possible effects on IRES Channel 1 (CH1), assuming a set of different positions of the Antarctic region in the CH1 scanning path.

While these predictable disturbances have been accounted for through onboard software design, unexpected atmospheric phenomena—such as Sudden Stratospheric Warming (SSW)—can introduce new challenges.

3. Sudden Stratospheric Warming

During the winter season of a respective hemisphere, strong winds are formed around the pole (poleward 50 deg latitude) high up in the atmosphere (15 km to 50 km) as a result of the big temperature gradient between low and high latitude, and spinning up due to the Coriolis effect (see Fig. 7). The large-scale region of air contained by this cyclonic west-to-east jet stream that circles the polar region is called the stratospheric polar vortex. The winds regularly exceed 50 m/s (180 km/h), i.e., the strength of the strongest hurricanes, while the temperatures within the vortex are cold, with values below 190 K over a wide region. In addition, relative lower values of total ozone are found. In the southern hemisphere the polar vortex is stronger, larger, and longer lasting than the northern vortex.

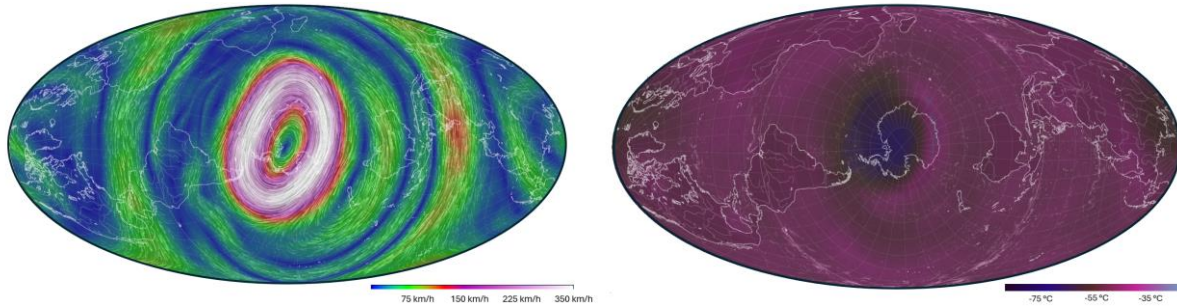


Fig. 7. Example of southern polar vortex (left) winds and (right) temperature at 10 hPa – 30 km. Source earth.nullschool.net

On some occasions, there is a significant disruption of this stratospheric polar vortex in what is called Sudden Stratospheric Warming. The origin of this disruption is Rossby waves whose amplitude increases rapidly and are pushed higher into the atmosphere, breaking on top of the polar vortex.

The Rossby waves, also known as planetary waves, result from the latitudinal gradient of the Coriolis force that balances variations of the pressure gradient force [4]. This effect manifests as a meandering of jet streams; hence the term wave (see Fig. 8). They have substantial influence on the wind speeds, temperature, distribution of ozone, and other characteristics of the middle atmosphere structure.

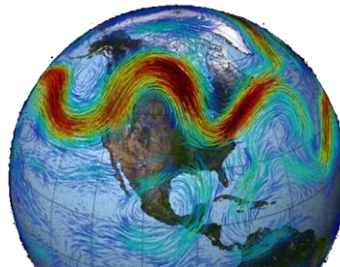


Fig. 8. Representation of atmospheric planetary waves (credit: NASA's Goddard Space Flight Center)

Rossby waves are strongly dispersive and are typically trapped, so they usually do not propagate vertically. However, when the amplitude of planetary waves increases rapidly and there is a blocking effect, the large-scale waves are pushed higher into the atmosphere, breaking on top of the polar vortex depositing momentum and energy upon dissipation. If they are strong enough, the winds of the polar vortex can weaken, or even reverse the circulation. This causes cold air descending and warming very rapidly in the polar vortex, such that the temperature in the stratosphere rise very rapidly, as much as 50 Kelvin over only a few days [5]; hence the term sudden stratospheric warming. Moreover, it can lead to a displacement or splitting of the polar vortex, so instead of extreme cold air being locked above the polar region, it can spill out further into mid-latitudes with stratospheric cooling at tropical latitudes.

For the same reason that the southern hemisphere polar vortex is stronger than the northern one, SSWs are less common in the southern hemisphere, about once every 20-30 years, compared to the northern hemisphere, about six times per decade [6]. The reason behind this is the orography of the southern hemisphere, with not have major mountain ranges and is mainly covered by water. There, large amplitude planetary waves going up into the stratosphere are most of the times weaker. However, despite the lower frequency of SSWs in the southern hemisphere, they can exert remarkable impacts on both the stratosphere, like a reduction on the Antarctic ozone hole [7], and the troposphere, influencing the tropospheric circulation favouring conditions that drive extreme surface weather situations and ultimately natural hazards [8]. These south SSWs may raise the risk of increased rainfall in the latitudinal band of 35–50 degrees South; meanwhile, the associated hot and dry weather conditions over austral subtropical continents might increase the risk of wildfires over these regions (for example, the 2019 SSWs was linked to the conditions that favour wildfires over Australia).

Last South SSW in (late) August - September 2019 was comparable to or even greater than the previous one in 2002 [9] (see Fig. 9a), but in this case the wind reversal in the polar vortex did not occur. The 2019 event was characterized by the sudden wind deceleration, from 80 m/s to 10 m/s, and a temperature increase of 50 Kelvin. The

exceptionally strong and long-lasting atmospheric waves, propagating upward from the troposphere into the stratosphere, were potentially caused by anomalous tropical convections and by zonal winds in the tropical upper stratosphere, setting a favourable background condition. The negative extrema of the planetary wave pattern were located south of South America and the positive extrema situated south of Australia [10]. As seen in [9], the temperatures around the South Pole raised at the beginning of the event as an anticyclone developed in southern Australia. Later, the high temperature area expands, and low temperatures shift from the South Pole towards South America (Fig. 9 b and c). Next days, the temperatures dropped at the polar vortex edge while the vortex weakens, and the low temperature region shifts off the centres of the vortices.

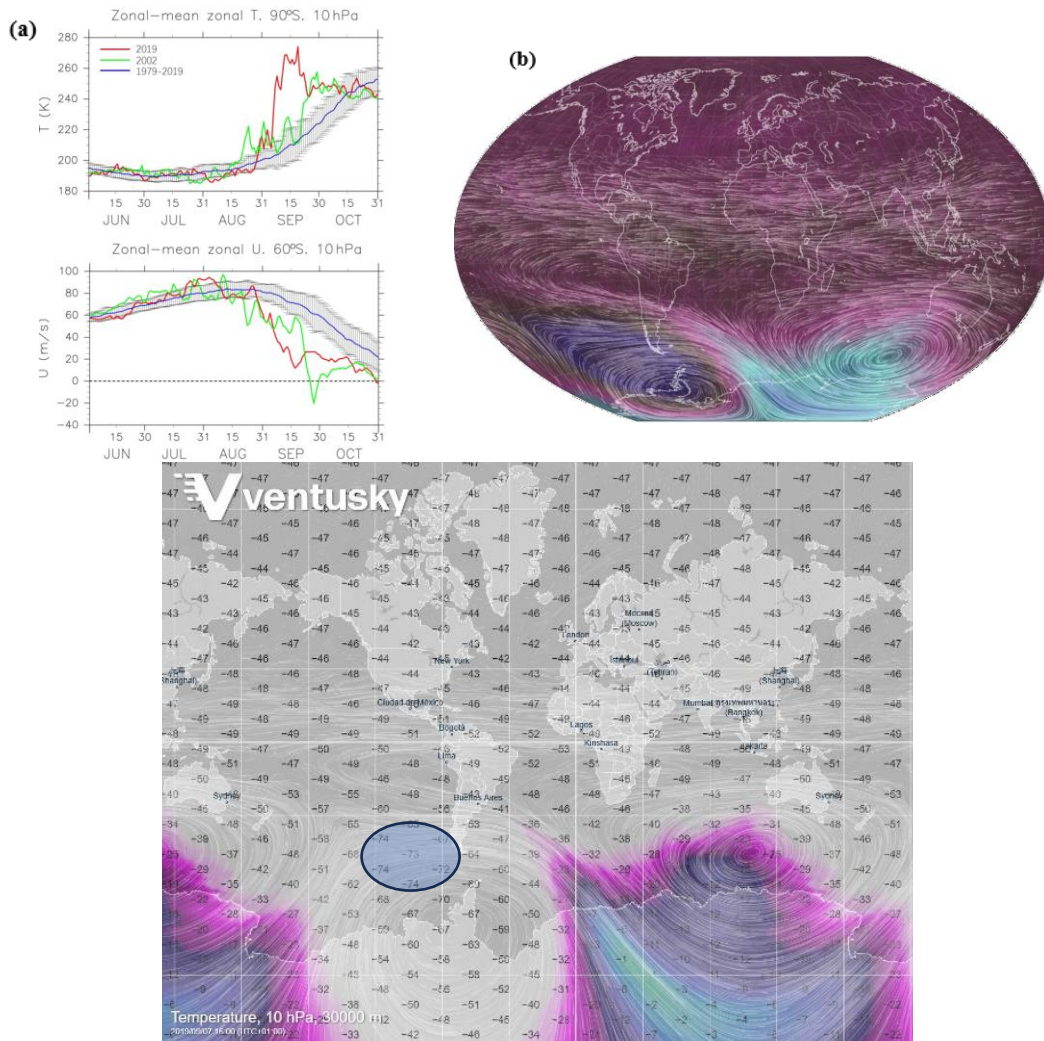


Fig. 9. South SSW in September 2019: (a) Zonal mean Temperatures and winds at 10 hPa – 30 km compared to previous winters and SSWs; (b) Perspectives of wind streams at 10 hPa – 30 km scale on 7th September 2019 (source earth.nullschool.net) [9]; (c) World map Temperature at 10 hPa – 30 km on 7th September 2019 – coldest area encircled (source ventusky.com)

3.1 2019 South Sudden Stratospheric Warming as seen from Galileo spacecraft

The data of the Earth sensor of Galileo spacecraft provides the evidence of this sudden stratospheric warming that was observed at the beginning of September 2019. In fact, the change in temperature distribution of the air/CO₂ masses over the Antarctica is creating a gradient of radiance. This is slightly affecting the IRES sensor and the way the unit is working by making the earth to sky transition less evident to be detected for the sensors.

From the analysis of the telemetries of different Galileo spacecraft in different orbital planes it was possible to see some disturbances on the roll and pitch data before or after the inhibition of the blinded channel (see Fig. 10,11,12,13). The behaviour has been confirmed to be fully independent with respect to the orbital plane and to be only linked to the South Pole trajectory on the IRES field of view. In fact, in all the cases, the IRES scan path termination on the Earth surface was at around -45° latitude and -90° longitude.

Note that this area coincides with the low temperatures shift from the South Pole to South America experienced during the sudden stratospheric warming (Fig. 9 b and c), where stratospheric temperatures reach the -74 K. As this area is outside of the usual characterization of the Antarctic region managed by the IRES some perturbations were noticed. However, thanks to the robustness of the software this did not lead to any anomalous behaviour or to any on-board reconfiguration and there was no need to perform any ad-hoc activities from ground or any modification of the on-board configurations.

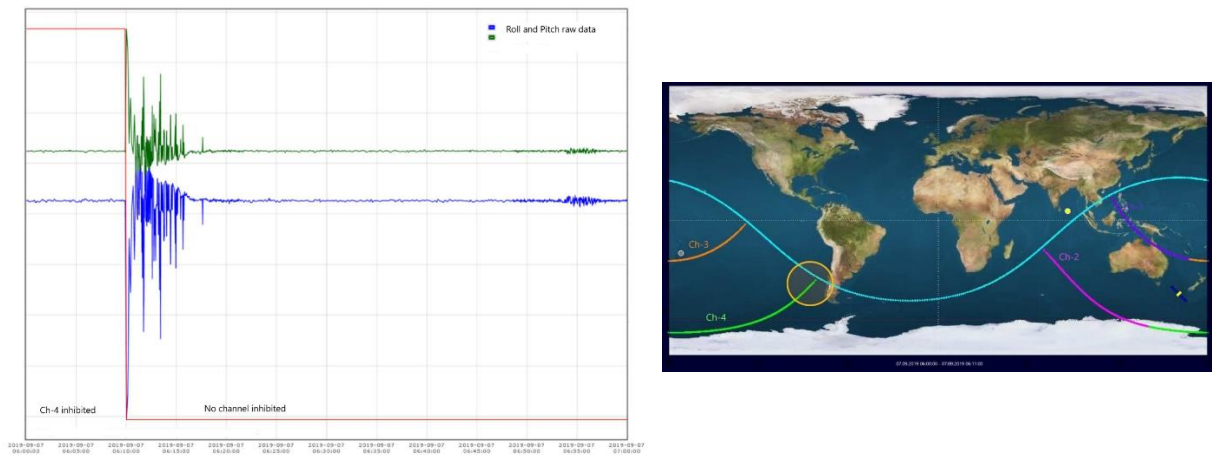


Fig. 10: Antarctic perturbations on the IRES raw data and IRES scan path termination on the Earth surface as seen from a spacecraft in Plane A

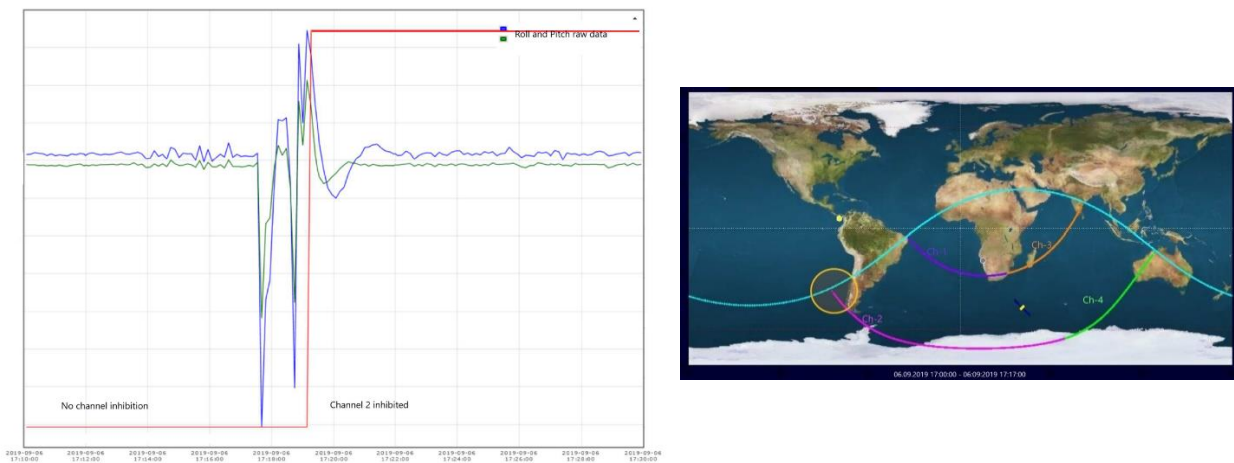


Fig. 11: Antarctic perturbations on the IRES raw data and IRES scan path termination on the Earth surface as seen from a spacecraft in plane B

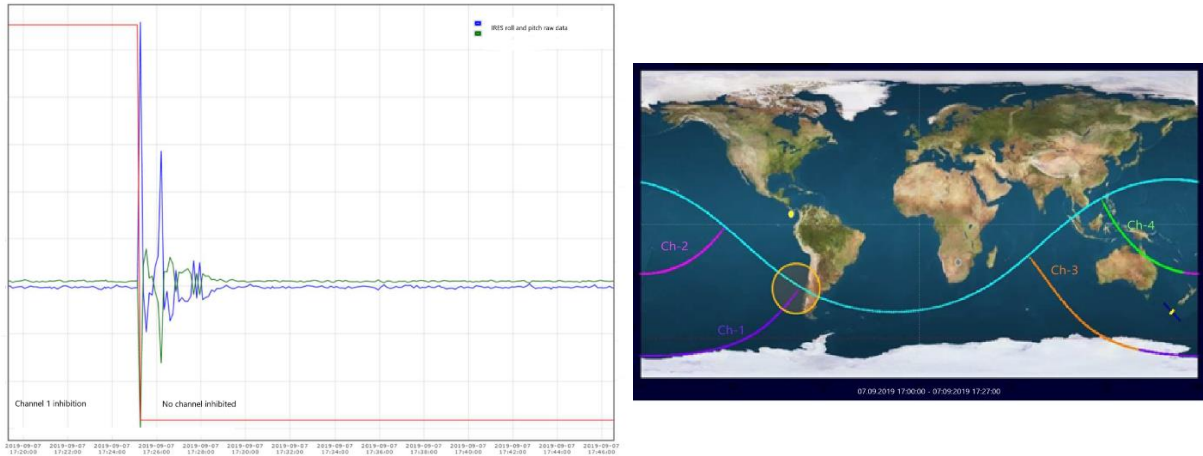


Fig. 12: Antarctic perturbations on the IRES raw data and IRES scan path termination on the Earth surface as seen from a spacecraft in plane C

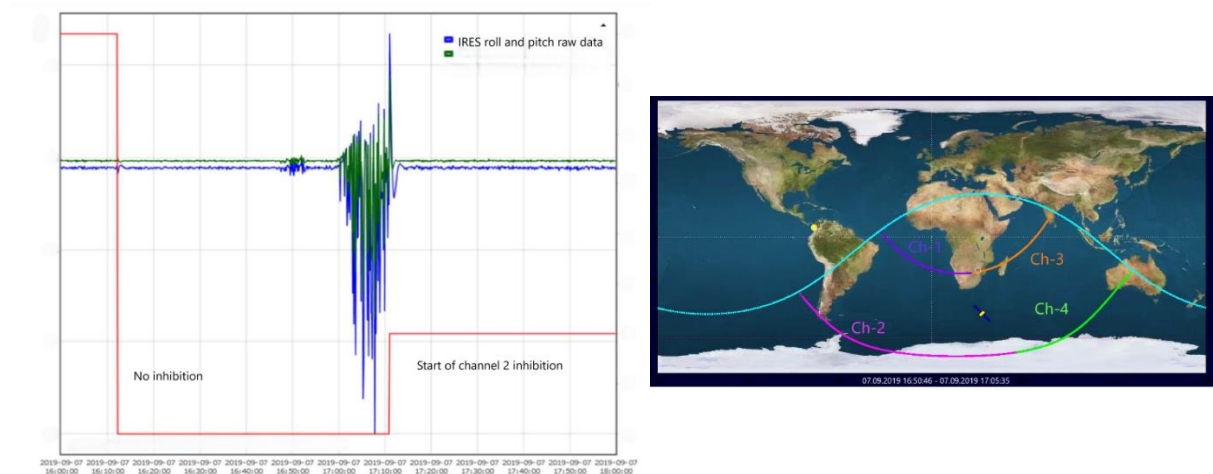


Fig. 13: Antarctic perturbations on the IRES raw data and IRES scan path termination on the Earth surface from one of the spacecraft in the non-nominal orbital plane due to the Soyuz launcher failure

Given the impact of atmospheric phenomena like SSW on satellite sensors, Galileo’s ability to detect and analyze such events presents an opportunity for environmental monitoring beyond its primary navigation function.

4. Use of Galileo constellation as a tool for environmental monitoring

In 2019, Galileo's IRES detected an exceptional stratospheric warming event in the Southern Hemisphere, a rare occurrence in this region. These findings reinforce the importance of integrating space weather and atmospheric monitoring into the Galileo system's operational framework. By monitoring and analyzing space weather conditions, such as solar flares and geomagnetic storms, operators can anticipate and mitigate potential disruptions to satellite functions. The 2019 stratospheric warming event underscored the importance of not only tracking terrestrial/atmospheric weather patterns but also understanding the dynamic space environment that directly influences spacecraft operations. Integrating space weather data into Galileo’s operations is crucial for ensuring system resilience. Space weather phenomena, such as geomagnetic storms and solar flares, can significantly impact spacecraft performance. Space weather events pose significant challenges to spacecraft operations, potentially resulting in total or partial loss of functionality or temporary outages. Space weather refers to the environmental conditions in space as

influenced by the Sun and the solar wind. The primary space weather events that can impact spacecraft operations include:

- Solar Flares: Powerful solar radiation bursts disrupting communication and navigation, affecting Earth's Radiation Belts by altering electron levels and causing charging issues in satellites.
- Geomagnetic Storms: Solar wind disturbances impacting Earth's magnetic field, leading to satellite drag and navigation errors.
- Cosmic Rays: High-energy particles from space damaging spacecraft electronics and increasing radiation exposure.

Each Galileo satellite will pass through the Earth's outer radiation belt twice every orbit (see Fig. 14). The outer belt is populated with very high energy electrons (~100 keV to 10 MeV) which are readily able to pass through even moderate levels of shielding: for this reason, Galileo has been designed to cope with a severe total ionising dose requirement and with elevated levels of electrostatic charging.

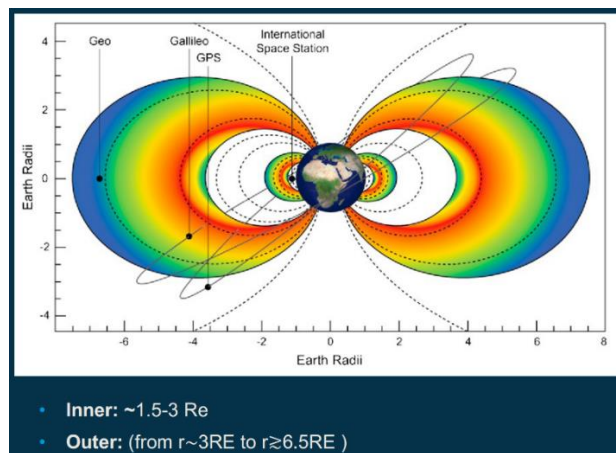


Fig. 14: Radiation Belt and Galileo orbit

The outer belt is not constant: on the contrary it is highly dynamic, varying strongly in response to buffeting by the solar wind. This leads to 'electron enhancement' events which pose a significant charging threat, and which are the periods when the majority of total dose is delivered to the satellite equipment and components. Sporadic solar particle events may elevate fluxes of protons and heavier ions by many orders of magnitude for periods ranging from hours to days.

4.1 Tools for Estimating Space Environment and Effects

To mitigate these risks and support the investigation of anomalies, various tools and resources are today available to estimate the space environment and its effects on spacecraft.

Spacecraft operators, Flight Controllers, Science Operators have access to multiple resources on the ESA space weather portal [12] to handle space weather-related risks:

- Environmental Estimation Tools: These tools help estimate the radiation levels and particle fluxes around a spacecraft.
- Risk Assessment Tools: These tools assess the potential impacts on spacecraft systems.
- Anomaly Investigation Support: These tools assist in investigating anomalies caused by space weather events.

The space operations domain is served by a range of alerts and risk forecasts, data, and tools for environmental conditions. These include:

- Space Weather Alerts: Real-time alerts for solar flares, geomagnetic storms, and other space weather events that could impact spacecraft.

- Risk Forecasts: Projections of potential space weather risks over short and long-term periods, aiding in operational planning and decision-making.
- Data and Tools: Access to historical and real-time data on space weather conditions, along with analytical tools to evaluate their impact on spacecraft systems.

4.2 Galileo Operations and Space Weather Data

Space weather events and conditions could significantly impact spacecraft operations, but with the right tools and resources, these risks can be managed effectively. By leveraging environmental estimation tools, risk assessment tools, and real-time alerts and forecasts, spacecraft operators can better understand and mitigate the effects of space weather, ensuring the continued success and safety of the Program.

The possibility of using space weather data in Galileo operations as a warning system is an important consideration for enhancing the reliability and safety of this global navigation satellite system. By integrating space weather data into operational protocols, potential risks can be anticipated and mitigated, ensuring the continued service and accuracy of the Galileo system.

This integration of space weather data into Galileo operations is a practical necessity in the face of increasing space activities and reliance on satellite-based systems. The use of environmental monitoring and real-time data analysis enhances the operational resilience of the Galileo constellation, ensuring that it can withstand and adapt to the dynamic space environment.

5. Conclusion

The 2019 stratospheric warming event underscored the importance of not only tracking terrestrial/atmospheric weather patterns but also understanding the dynamic space environment that directly influences spacecraft operations. Recognizing the significance of this event, efforts were made to integrate space weather information into the Galileo system's operational framework.

By proactively monitoring and responding to space weather conditions, Galileo can maintain its high standards of accuracy and reliability, providing uninterrupted services to users worldwide. This ongoing effort to incorporate space weather data and tools represents a significant advancement in satellite operations, showcasing the commitment to leveraging technology for the protection and enhancement of critical European infrastructure.

As we continue to advance our understanding of space weather and its impacts, the implementation of these tools and protocols will play a crucial role in safeguarding the Galileo system and similar satellite constellations. The future of satellite operations depends on our ability to predict, mitigate, and respond to the ever-changing conditions of space.

Galileo is not only the most precise satellite navigation system, but it can also provide valuable information on space weather data through its IRES and onboard Environmental Monitoring Unit (EMU). In fact, already in the frame of the design of the Galileo spacecraft it was decided to equip two of the 32 Galileo spacecraft in-flight with an Environmental Monitoring Unit to characterize better the radiation environments in the MEO orbits. By utilizing the Environmental Monitoring Unit onboard, the Galileo satellites measure various parameters like internal charging currents, energetic proton fluxes, and internal doses, which are essential for gauging the space weather threat. The data collected from these sensors will help in predicting electron enhancement events and solar particle events, thereby ensuring the resilience and reliability of the satellite system.

This paper explored the possibility of an innovative use of the Galileo constellation as a tool for environmental monitoring, presenting key findings and future research directions. In fact, the raw data provided by the IRES and currently used to keep the nadir pointing, required for the dissemination of the navigation data, could also be used to monitor the CO₂, determined at the 15 μm CO₂ absorption band, and even relate it to the ozone profile [11]. Additionally, these data could be used to monitor future Sudden Stratospheric Warming in the southern hemisphere and the evolutions of the temperature gradient in the stratosphere.

As a project of the European Union, Galileo not only provides precise satellite navigation but also it might serve as instrument in understanding atmospheric and space weather condition from on-board data, as well as in analysing surface properties by using the reflected signals from the satellites (GNSS-Reflectometry). Since the reference Galileo

Constellation is composed by 24 spacecraft in Walker configuration (24/3/1) plus spares, an instantaneous global coverage could be provided.

The integration of this space weather data into Galileo's operations represents a significant technological advancement. It demonstrates the commitment to maintaining the highest standards of accuracy while protecting the European infrastructure from the adverse effects of space weather. Future efforts will focus on refining these tools and protocols, further enhancing Galileo's ability to mitigate and respond to space environment dynamics..

Acknowledgements

Galileo is a European project that involves the cooperation of different stakeholders. It is a joint initiative of European Commission, ESA and EUSPA. Since 2016 EUSPA is responsible for the management of Galileo operation under GSOp contract while ESA is Galileo's design authority and system development prime.

The documentation provided in the frame of the design of the Galileo spacecraft has been used as supporting materials for the preparation of the paper. In particular, the IRES mounted on Galileo S/C are manufacturer by Leonardo (former Selex), while OHB is the spacecraft Prime contractor.

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