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How the upper atmosphere effects can influence European technological systems: a study of the socioeconomic quantification

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Abstract

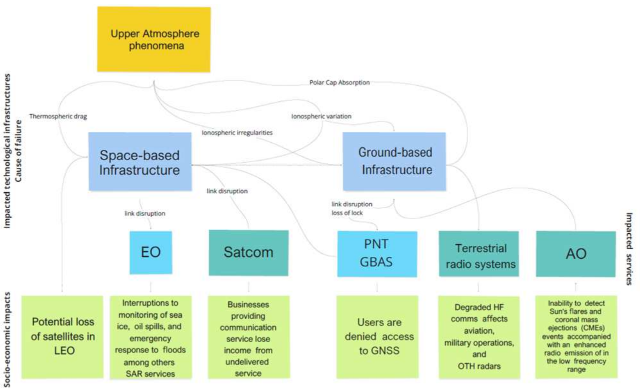
The new solar cycle and the increasing use of technological systems that make humans increasingly vulnerable to the effects of Space Weather have made the study of socio-economic impacts in the upper atmosphere useful and necessary. This paper therefore aims to raise awareness among as many people as possible of the importance of quantifying the socio-economic impacts of Space Weather to calculate the costs associated with mitigation actions in the sectors most affected.

1 Introduction

The PITHIA Network of Research Facilities (PITHIA-NRF) is a research infrastructure funded by the European Union's Horizon 2020 research and innovation program under Grant Agreement No. 101007599 that aims at building a European network integrating observing facilities, data collections, data processing tools, and prediction models for the study of the Earth's Ionosphere, Plasmasphere, and Thermosphere.

The project is expected to lead to research advances in data access and analysis and to the development of models with improved predictive power of those upper atmosphere phenomena (ionospheric variation, ionospheric irregularities, polar cap absorption, thermospheric drag, among others) which pose not only scientific but also societal challenges. For example, as shown in Table 1.

Table 1. Impacted technological infrastructures cause failure and their related socio-economic impacts



Space Weather effects in the Ionosphere and Thermosphere affect the performance and reliability of several essential space-borne and ground-based technological infrastructures, such as Earth observation systems (e.g., low-frequency Synthetic Aperture Radar (SAR), satellites (e.g., GNSS satellites), electricity grids, ground-based augmentation systems, astronomical observation systems (e.g., Low-Frequency Array (LOFAR), and terrestrial radio systems using high-frequency (HF) and very-low frequency (VHF) communications [1].

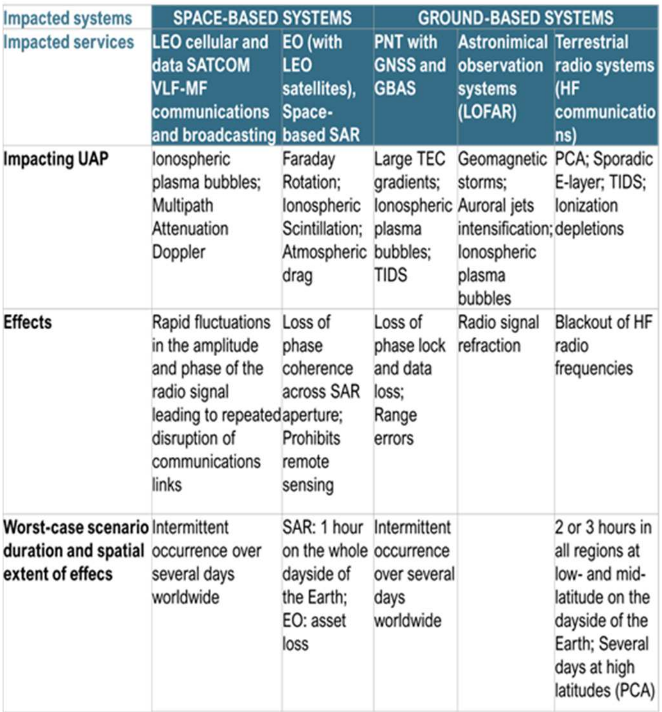
In turn, failures in any of these infrastructures may disrupt or render unavailable services of exceptional importance to society, such as power or those (nowadays ubiquitous) relying on accurate positioning, navigation, and timing information, such as transport, surveying, or banking.

Beyond supporting the design of technologies mitigating the upper atmosphere effects, PITHIA-NRF, wishes to contribute to the ongoing effort of estimating the socioeconomic impacts of Space Weather, focusing on continental Europe. While no consensus has yet been reached among practitioners on the most suitable approach for tackling this challenging task [2], in recent years, a few studies have indeed advanced our understanding of the nature of impacts and put forth frameworks defining socioeconomic impacts indicators [2] and quantitative methodologies [3,4]. Our paper aims to contribute to such a framework. To the scope, our work moves from an assessment of how the upper atmosphere phenomena act on technological infrastructures and inhibit them, totally or partially, from providing their services. Then, a literature review on previous space weather socioeconomic impacts describes the consequences of "moderate" and "extreme" Space Weather events over Europe. In particular our work follows the approach in [2] to quantify the impacts of the upper atmosphere phenomena on power grids and satellites, therefore considering the repercussions on the use of GNSS and application fields such as aviation and railways In our view, the Abt Associates report [2] presents the most suitable framework for our work, computing lower and upper bound estimates for several economic sectors, and relying on stakeholders' perspectives on impacts. Our future step will be the refinement of our effort by eliciting stakeholders' inputs collected during the three Innovation Days organized during the PITHIA-NRF project.

2 Report Content

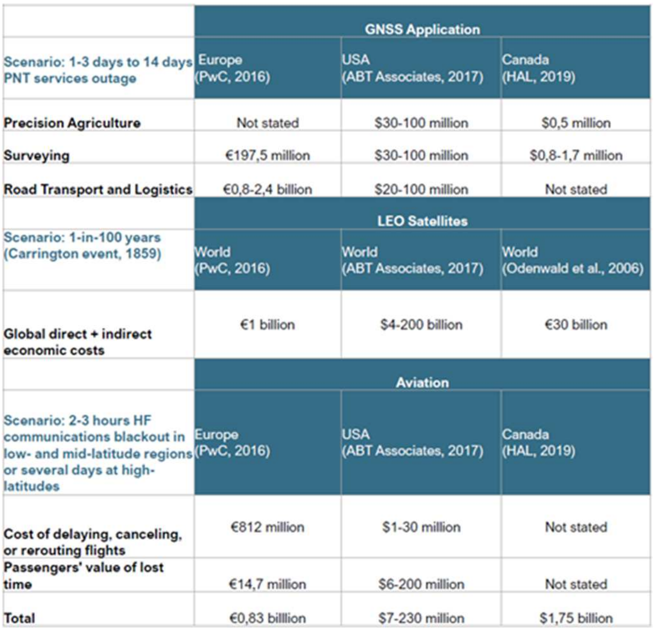
The near-Earth space environment undergoes daily changes driven by variable conditions of the Sun. Explosive eruptions of energy from the Sun causing minor solar storms on Earth are relatively common and of little consequence. On the contrary, rarely occurring superstorms generate physical changes in the Earth's upper atmosphere detrimental to satellites, signals from Global Navigation Satellite Systems (GNSS), and radio systems. While for these events the physical mechanisms and the technological consequences are extensively studied, this is not the case for the related socioeconomic ramifications, despite the growing dependence on these technologies by modern society. As previously said, failures in any of these infrastructures may disrupt or render unavailable services of exceptional importance. Therefore, our work identifies those infrastructures vulnerable to the upper atmosphere effects and quantifies how and to which extent they are impacted by exploiting the data provided by Earth Observations systems (e.g., low-frequency SAR), Low Earth Orbit (LEO) satellites (e.g., GNSS satellites), Astronomical Observation systems (e.g., LOFAR), systems offering PNT services, and radio systems using HF and VHF communications, through a systematic literature review. The summary of the effects of upper atmosphere space weather on technological systems and the estimated costs in three different scenarios (GNSS Application, LEO Satellites and Aviation) are presented in Table 2 and 3.

Table 2. Summary of the effects of upper atmosphere space weather on the systems presented in the report



Impacted systems	SPACE-BASED SYSTEMS		GROUND-BASED SYSTEMS		
Impacted services	LEO cellular and data SATCOM VLF-MF communications and broadcasting	EO (with LEO satellites), Space-based SAR	PNT with GNSS and GBAS	Astronimical observation systems (LOFAR)	Terrestrial radio systems (HF communications)
Impacting UAP	Ionospheric plasma bubbles; Multipath Attenuation Doppler	Faraday Rotation; Ionospheric Scintillation; Atmospheric drag	Large TEC gradients; Ionospheric plasma bubbles; TIDS	Geomagnetic storms; Auroral jets intensification; Ionospheric plasma bubbles	PCA; Sporadic E-layer; TIDS; Ionization depletions
Effects	Rapid fluctuations in the amplitude and phase of the radio signal leading to repeated disruption of communications links	Loss of phase coherence across SAR aperture; Prohibits remote sensing	Loss of phase lock and data loss; Range errors	Radio signal refraction	Blackout of HF radio frequencies
Worst-case scenario duration and spatial extent of effecs	Intermittent occurrence over several days worldwide	SAR: 1 hour on the whole dayside of the Earth; EO: asset loss	Intermittent occurrence over several days worldwide		2 or 3 hours in all regions at low- and mid-latitude on the dayside of the Earth; Several days at high latitudes (PCA)

Table 3. Estimated costs in three different scenarios on GNSS Application, LEO Satellites and Aviation



	GNSS Application		
Scenario: 1-3 days to 14 days PNT services outage	Europe (PwC, 2016)	USA (ABT Associates, 2017)	Canada (HAL, 2019)
Precision Agriculture	Not stated	$30-100 million	$0,5 million
Surveying	€197,5 million	$30-100 million	$0,8-1,7 million
Road Transport and Logistics	€0,8-2,4 billion	$20-100 million	Not stated
	LEO Satellites		
Scenario: 1-in-100 years (Carrington event, 1859)	World (PwC, 2016)	World (ABT Associates, 2017)	World (Odenwald et al., 2006)
Global direct + indirect economic costs	€1 billion	$4-200 billion	€30 billion
	Aviation		
Scenario: 2-3 hours HF communications blackout in low- and mid-latitude regions or several days at high-latitudes	Europe (PwC, 2016)	USA (ABT Associates, 2017)	Canada (HAL, 2019)
Cost of delaying, canceling, or rerouting flights	€812 million	$1-30 million	Not stated
Passengers' value of lost time	€14,7 million	$6-200 million	Not stated
Total	€0,83 billlion	$7-230 million	$1,75 billion

A literature review on previous Space Weather socioeconomic impacts was used to assess the costs associated with the risks posed to critical space-borne and ground-based technologies by upper atmosphere disturbances. These costs are high and comparable to those caused by natural hazards like tsunamis, earthquakes, or floods. Nevertheless, our work highlights how the quantification of the socioeconomic impacts is not yet mature because of the lack of important modeling information and modern society's lack of experience with extremely large events. Nonetheless, governments, asset owners, and business managers need advances in this area to realize and operate countermeasures aiming at mitigating the risks posed by the upper atmosphere disturbances due to space weather [1].

2.1 GNSS Application

GNSS and GBAS are sensitive to upper atmosphere perturbations that, in the worst-case scenario, could make PNT services unavailable to commercial and non-commercial users for several days: from 1-3 days to 14 days of GNSS outage.

Considering the increasing global demand for GNSS-based services, it is very timely to analyze the impacts from a social and economic point of view.

2.2 LEO Satellites

The quantification of the impacts of upper atmosphere phenomena on satellite operations may vary depending on assumptions (e.g., one or more asset losses) and the severity of the space weather events considered.

While LEO satellites are less vulnerable to cumulative dosage or anomalies caused by Solar Particle Events (SPEs) than those in Geostationary Orbit (GEO) and

Medium Earth Orbit (MEO), reducing costs associated with defensive investments, their most significant risk comes from atmospheric friction and orbit decay caused by variable drag forces in the thermosphere (atmospheric drag). The launch of SpaceX's 49 Starlink satellites in February 2022 can be seen as an example of how even a modest space storm can have significant practical and financial consequences. The increased atmospheric drag associated with a small geomagnetic storm caused the loss of most of the 49 satellites launched.[5]

2.3 Aviation

In aviation, HF communications remain the primary means of communication between poles (ICAO, 2015). From an economic point of view, the results regarding the costs of delay, cancellation, or diversion of flights in the event of a total blackout of HF radio frequencies in Europe, the United States and Canada are relevant.

Depending on the intensity and type of upper-atmosphere phenomena, the time extension and the areas affected by the disruption may vary (from a few hours to several days when considering low and mid-latitude regions and high-latitude regions).

3 Considerations and future steps

According to NASA and NOAA Space Weather reports, Solar Cycle 25 has begun, and the last forecast of the Prediction Panel identifies the solar maximum to occur in 2025. Considering the direct and indirect economic costs associated with upper-atmosphere phenomena, as shown in Table 4, an accurate study is needed in relation to the quantification of these types of impacts, which may occur more frequently as moderate events, but extreme events cannot be excluded.

Our literature review was conducted in relation to predicting the socio-economic impacts of an extreme event (e.g., Carrington event, 1859), as shown in Table 3, in LEO satellites. However, we are receiving inputs that invite us to extend our research towards a more in-depth study of moderate events, likely less dangerous but occurring more frequently.

The objective is therefore to calculate the associated costs with mitigation actions in a given sector, considering the risks posed by Space Weather in the upper atmosphere as shown in Table 5.

Together with the Space Weather forecasting and real-time Space Weather monitoring satellites, for which NOAA already provides all the necessary information, it is the economic point of view to support governments, asset owners and commercial operators who are increasingly vulnerable to technologies that could suffer losses, especially during the future solar maximum.

Table 4. Economic costs associated with upper atmosphere phenomena

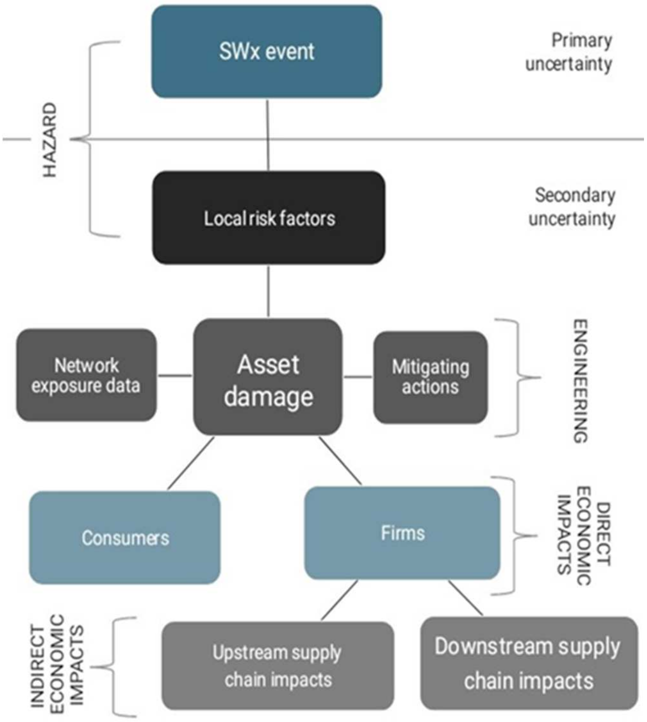
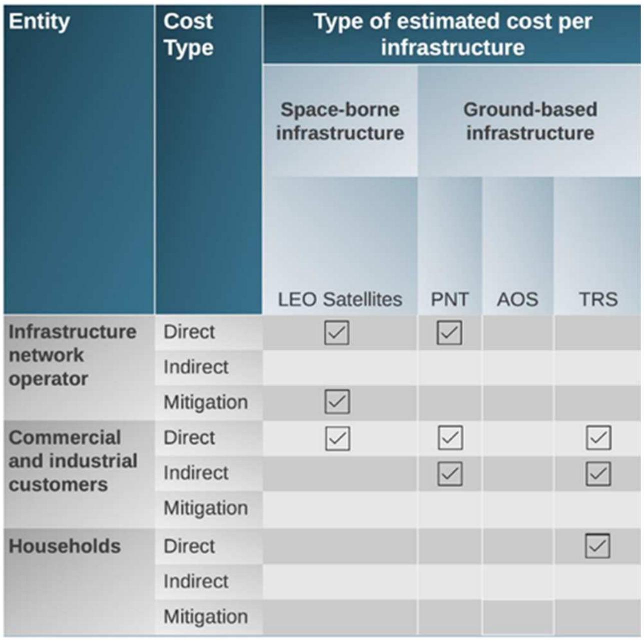


Table 5. Type of estimated cost for infrastructure



Entity	Cost Type	Type of estimated cost per infrastructure			
		Space-borne infrastructure	Ground-based infrastructure		
		LEO Satellites	PNT	AOS	TRS
Infrastructure network operator	Direct	☑	☑		
	Indirect				
	Mitigation	☑			
Commercial and industrial customers	Direct	☑	☑		☑
	Indirect		☑		☑
	Mitigation				
Households	Direct				☑
	Indirect				
	Mitigation				

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