# Space Weather Goods, A Managerial Economics Perspective

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## Résumé :

La météorologie spatiale étudie l'activité du Soleil et son interaction avec la Terre.
Les éruptions solaires sont susceptibles d'affecter notre société moderne de plus en plus dépendante des technologies (télécommunication, électricité…).
Il est donc nécessaire de produire des biens pour se prémunir des colères du Soleil.
Dans ce mémoire de recherche, nous proposons une définition des biens de météorologie spatiale.
Puis, nous démontrons qu'ils respectent des caractéristiques bien précises et décrites dans la littérature d'économie managériale.
En effet, ils correspondent à des biens publics et plus précisément des biens tutélaires qui nécessitent l'intervention de l'État pour éviter une défaillance du marché.
Néanmoins, l'apparition de nouveaux acteurs privés pour fournir des biens de météorologie spatiale remet en cause la « gratuité » actuelle de leur distribution par les acteurs publics et pose la question de leur commercialisation et tarification.
Nous proposons à l'aide d'un modèle « *freemium* » supporté par une organisation en triade une solution qui pourrait concilier à la fois les intérêts publics mais aussi privés.

Mots-clés : Biens de météorologie spatiale ; Biens publics ; Biens tutélaires ; Commercialisation ; Tarification ; Disposition à payer ; Freemium ; Triade.

## Abstract:

Space weather studies the activity of the Sun and its interaction with the Earth.
Solar flares are likely to affect our modern society, which is increasingly dependent on technology (telecommunications, electricity…).
Hence the need to produce goods to protect us against the Sun's wrath.
In this research paper, we propose a definition of space weather goods.
Then, we show that they respect specific characteristics described in the managerial economics literature.
Indeed, they correspond to public goods and more precisely to merit goods which require the intervention of the State to avoid a market failure.
Nevertheless, the emergence of new private actors to provide space weather goods calls into question the current "free-of-charge" distribution by public actors and raises the question of their commercialisation and pricing.
We propose a "freemium" model supported by a triad organisation as a solution that could reconcile both public and private interests.

Keywords: Space Weather goods; Public goods; Merit goods; Commercialisation; Pricing; Willingness to pay; Freemium; Triad.

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# Space Weather Goods, A Managerial Economics Perspective

"*There are Ariosto's warriors in the sun*"

– Jean GIONO (Le hussard sur le toit, 1951, Folio p.15)

## 1. Introduction

The Organisation for Economic Cooperation and Development (OECD) published in 2011 a report where space weather events belong to the five most important future major shocks in terms of consequences. We can cite among the other global shocks the pandemics…

Space weather is a nascent research field that studies the activity of the Sun and its interaction with the Earth. The Sun is a big ball of gas and plasma that knows a cycle activity of more or less 11 years with ups and downs. When a strong eruption occurs on the surface of the Sun, it could hit the Earth and have detrimental effects.

In our economy today more and more dependent on technology, various sectors could be affected by space weather. For example, it could disrupt satellite navigation like GPS, Galileo with disturbances on the upper atmosphere.
This can affect activities that rely on precise positioning as aviation for take-off and landing, military guided missile, offshore drilling or autonomous car.
Space weather effects on ground could also damage or disrupt power distribution networks and degrade radio communication.
The main space weather effects are detailed in the annex A, with a short history of space weather events.

In the European context, PricewaterhousehouseCoopers (PwC, 2016) estimates that a single major space weather event could cost almost €15 billions of damages across several sectors.
To ensure sustainability, public and private stakeholders must provide coordinately and efficiently space weather goods to protect our society against the harmful effects of the Sun and mitigate the socio-economic costs.

Managerial economics defined as the application of economics concepts to solve managerial problems by Mansfield *et al.*, (2012) will help us to analyse space weather goods provision issue through a solid academic framework and draw from it, rational and concrete insights for managers.

Therefore, in this research paper, we investigate what can we learn from the managerial economics literature on an a priori scientific and technical subject that is space weather:

(1) We will define space weather goods,
(2) and then demonstrate that they respect specific characteristics described in the managerial economics literature that require the intervention of the State to avoid a market failure.
(3) Therefore, we need to raise the question of their commercialisation and pricing with emerging private space weather goods providers.

## 2. Defining space weather goods

### 2.1. Space weather data, product and service

Space weather goods are composed of data, product and service.
Data are measurements of any space weather parameter acquired by a satellite or instruments on the ground.
Then, a product describes a precise condition in the space environment.
Service is the interpretation of processed data that can be enhanced by other sources to enable an operator to take actions to mitigate space weather effects on its systems and/or customers.
Both, product and service are built from data.
For example, a product could give information on radiation risks associated to a solar storm whereas a service will enable airlines to modify their flight path to safeguard their passengers and crew from radiation due to the same solar storm (Aliberti and Wells, 2019).

In this research paper, a space weather good refers to both data, product and service due to their interdependency and the development capacity from data to service to deliver value to the end-users.

### 2.2. Space weather service categories

Space weather services could be compared to our tradtional weather service that we use every day and are divided in timeframe: Forecast, nowcast, postcast.
A description of each service is detailed in the figure 1, below.

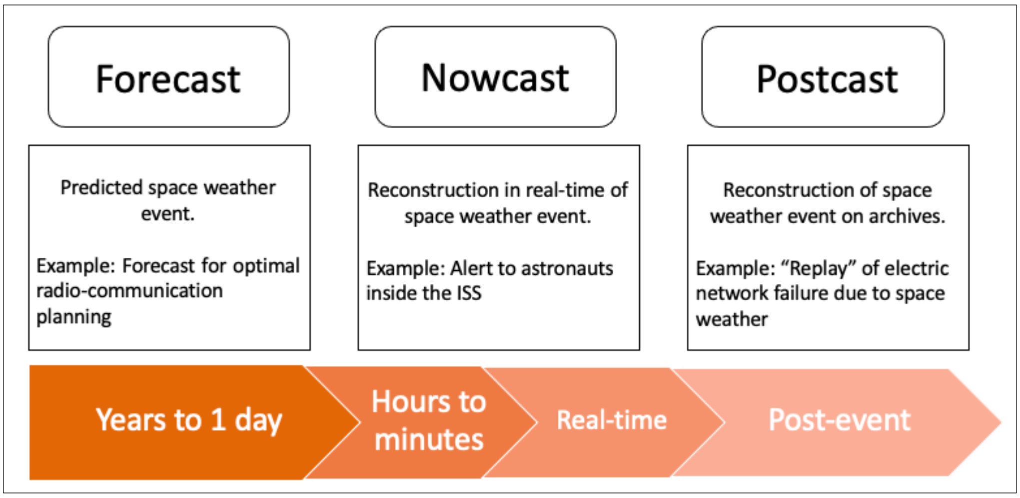


Figure 1: Space weather services categories, adapted from PwC, 2016

Space weather service market is still in its infancy and under development. Many end-users do not have a good knowledge of how they can benefit from services, so the demand still limited. Most of space weather services are still in the pre-operational and improvement phase.
In other words, for a vast majority of services, the technology readiness is still medium or not enough advanced to answer customers' need and the long-term sustainability is not yet reach with services that are not provided on a 24/7 basis and sometimes without end-users training.
For example, "real forecast" based on a scientific model as the one we use in the traditional weather will be available only in the next decades. Some can bridge the gap by using machining learning that recognise data patterns to predict space weather events but the accuracy still low today.

### 2.3. Space weather goods users

More and more sectors use space weather services with the increased awareness of space weather impacts on life and activities.

One of the most impacted sectors is space systems (e.g., satellites, rockets or human flight) because they are closest to the Sun and the Earth shield is less effective.
In this context, space weather services enable spacecraft manufacturers to avoid over-design to mitigate space weather events that can be costly and achieve a longer design life.
Spacecraft operators as flight control teams could reduce risk of satellite anomalies, provide more reliable service as telecommunications or broadcasting thanks to space weather services.

For non-space systems, we can quote airlines and aircraft manufacturers that use space weather services to optimise flight paths, to be compliant with legislation by monitoring and reducing the radiation exposure of aircrew and passengers.
A pioneering operational space weather project is currently lead by the International Civil Aviation Organisation (ICAO)[1] to provide a 24/7 nowcast service for commercial and general aviation.

Other users can be mentioned as electric power network manager, pipeline designers, rails operators, resource exploitation surveyors and extractors.
It is important to seize the cascading effect of space weather events. For example, spacecraft operations disruption can affect all the activities that use satellites like telecommunications, broadcasting, weather forecast, transport, logistics and finance for transaction. It is the same for power grid. A dramatic black-out of several weeks with no more internet, fridge, health services could even trigger in a catastrophic scenario to riots.
The figure below summarises the space weather service domains.

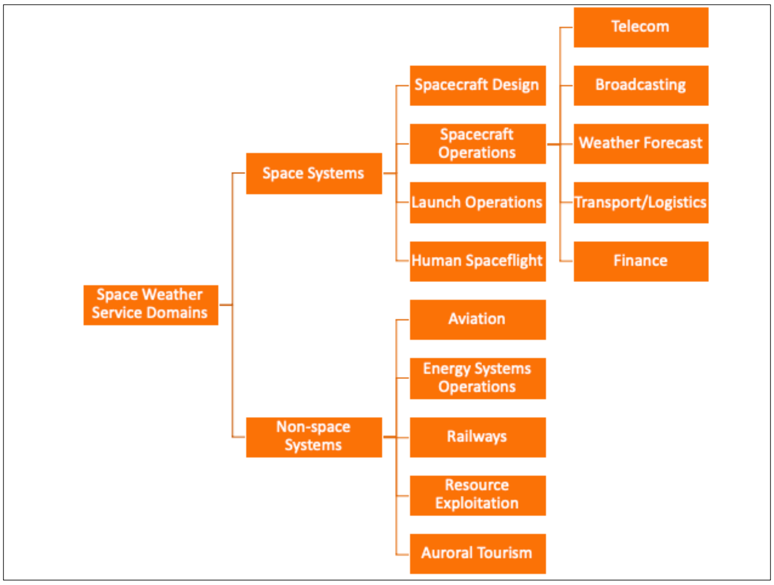


Figure 2: Space weather services domains, adapted from Aliberti and Wells, 2019

We have seen that space weather services could help to mitigate harmful effects.
It is worth noted that space weather services enable also entrepreneurs to create their own business with for example auroral tourism by predicting when and where aurora will happen.

[1] https://www.icao.int/Newsroom/Pages/New-global-aviation-space-weather-network-launched.aspx

### 2.4. Space weather goods enablers

Space weather goods create societal benefits by protecting critical infrastructure against the Sun. For example, The European Space Agency (ESA) federates assets and capabilities of European scientific institutes into a virtual network to provide space weather goods[2]. This is part of the Space Situational Awareness (SSA) programme of ESA to acquire the independent capability to track space objects and natural phenomenon that could have detrimental effects on European sensitive infrastructure as satellites or power grids.

We assess that three space weather goods provision could exist.
A public one that answers a societal or public demand. This model is used in Europe.
A private one where demand could return profit, it has not yet really been implemented.
And a public-private model where cohabits a social desirability with the potential to create revenue. This last model is used in the United States where taxpayers' projects lead by the National Oceanic and Atmospheric Administration (NOAA) provide freely data and products. On the other side, the NOAA's specialised space weather forecast called Space Weather Prediction Center (SWPC) provides tailored services with a subscription launched in 2005 which today knows a rapid increase in customers due to a better understanding of the sectorial space weather impacts.

For now, public source funding and operating organisation of space weather goods are mainly in the world managed and provided by public models because they are considered as a public good.

## 3. Publicness mapping of space weather goods

The term "public good" is often used to describe a good that is in the public interest.
Nevertheless, "public good" has a more precise meaning in the managerial economics literature with assumptions and implications about how the market works.

### 3.1. Non-rivalry

Mas-Colell *et al.* (1995) explain that a good is said to be public if the consumption of this good by one user does not prevent its consumption by another user.
Indeed, there is no destruction by use (non-rivalry assumption).
Whatever the quantity is produced, the cost of supply to an additional consumer is zero.
For example, a television show is a non-rivalrous good. When you watch television, it is not preventing other household to watch the same television show as you.

Non-rivalry assumption applies to space weather goods because they are distributed in a digital format. On internet, any users can download or use space weather goods by joining the existing delivery platform. A pure digital duplicate of the goods is available for any users.
In fact, "architecturally" speaking, the servers that deliver space weather goods, designed to host thousands of people at the same time, can supply a new user with a cost equal to zero.
No network congestion is to be reported yet that could challenge this non-rivalry assumption.

[2] https://swe.ssa.esa.int/current-space-weather

### 3.2. Non-excludability

Samuelson (1954, 1955) keeps the non-rivalry assumptions to define a public good and adds another one: Non-excludability.
A good is non-excludable if no one can be excluded from its consumption, especially those who have not paid for it.
Public lights are an example of a non-excludable good, it is impossible to prevent a person in the street from being illuminated by the public lights.

Non-excludability applies to space weather goods because data policy ensures it.
It is clearly mentioned in the data policies that we have consulted (Royal Observatory of Belgium[3], World Data System[4]) that space weather data are free-of-charge or at minimum cost and fully and openly shared because satellite programmes are taxpayer funded.
Commercialisation of service from available data is possible if they have an "obvious added-value" compared to existing public service and with the express written prior consent of the provider. There is no price-exclusion for space weather goods.
It is interesting on this point to note that most of the entities interviewed for this research paper, have not yet defined what is "obvious added-value" because no private company has yet asked them for the permission to use their data.

We have demonstrated that space weather goods could be considered as a public good because they respect non-rivalry and non-excludability assumptions about how the market works.
But we need now to investigate for non-market values (externalities) of these goods.

### 3.3. Positive externalities

Marciano and Medema (2015) underline that a positive externality occurs when the action of one firm or consumer benefits other firms or consumers without being taken into account by the market.
As an example, education provides positive externalities. A better-educated population is more creative, more enterprising and will bring more value to the society. This is not taken into account directly by the market.

As we have seen, space weather goods create societal benefits by shielding our society against the harmful effects of the Sun and provides positive externalities.
Indeed, space weather goods support the sustainable development goals of the United Nations sustainable goals[5] and more precisely the goals on good health and well-being, climate action and life on land.

Aliberti and Wells, 2019 give some examples of positive externalities of space weather goods.
In case of an extreme space weather event, damages could occur to the high voltage networks transformers with blackout lasting weeks to months. Hospitals dependent on electricity cannot more use their ventilators for example. A space weather service that can predict this extreme event and give the capacity to hospitals to switch quickly from electric to fuel powered energy generators will reduce the morbidity and mortality due to prolonged electrical blackouts.
Oil drilling industry uses global Navigation Satellite System (GNSS) signals for a precise directional drilling on offshore oil platform. A space weather event could occur and degrade

[3] https://www.astro.oma.be/common/internet/en/data-policy-en.pdf
[4] https://www.icsu-wds.org/services/data-sharing-principles
[5] https://sdg.esa.int/activity/esa-space-weather-coordination-centre-4295

the GNSS signal in the upper atmosphere. Consequently the precision drilling positioning is no more in the range of millimetres but in meters. An unprecise drilling may lead to a blowout with a large volume of oil leaked and dramatic consequences on environment and commercial activities as fisheries. A service that can alert oil drillers when the GNSS signal is degraded could reduce risk from spill-over of under water oil wells.

### 3.4. Merit goods

Musgrave (1959) depicts merit goods as goods that are under-provided by the market due to two reasons:

- These goods create positive externalities that are not captured by the market (under-produced),
- Consumers are myopic, that is to say, they only see their choices in a short-term utility. So, they don't take into account long-term benefits of merit goods (under-consumed)

Space weather goods validate the two reasons given by Musgrave. As we have seen before in part 3.3, space weather goods generate positive externalities. And it is difficult for people to cope with space weather risks that are centennial. Indeed, the last extreme space weather event occurred 162 years ago. On a daily basis, space weather often has little or no impact for us. Therefore, the benefits of space weather goods are considered by consumers as too intangible or too distant in time.

In this situation, according to Musgrave (1959), the State needs to intervene to avoid a market failure defines by Ostrom (2010) when resources are not efficiently allocated to provide a good. If the consumers on the market follow their individual choice, they will not tend to invest and develop space weather goods because it is useless for them in the short-term. It is therefore necessary for public authorities on behalf of sustainability and long-term perspective not to follow the individual utility and deviate from the consumer sovereignty.
In our case, the State intervenes to fund research, to implement a solid infrastructure (satellite, on-ground station) and to support free-of-charge space weather goods dissemination.
The satisfaction of space weather goods is mainly provided through public budget.
Otherwise, nobody will ensure the provision.

All in all, we demonstrate that space weather goods could be considered as a public good and more precisely as a merit good due to positive externalities and the utilitarian myopic of consumers.

Nevertheless, on the emerging space weather market, we observe new private players as Spire[6] or Mission Space[7] that provide space weather goods with their own private satellite constellation. In fact, thanks to the New Space trend, innovation like the miniaturisation of satellites (e.g., smallsatellite) and new funding sources provided by capital risk venture or business angels enable private companies to enter in the taxpayer market of space weather goods. It seems that it is now possible to provide space weather goods with a private space-based infrastructure (e.g., smallsat constellations) and machine learning with artificial intelligence to ensure services. The postulate that guides these actors is that there is room for an untapped potential in commercial space weather activities.

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[6] https://spire.com
[7] https://www.mission.space

Then, it poses the pricing question of space weather goods that are mainly provided for free today and how to conciliate public and private interests.

## 4. Pricing and commercialisation of space weather goods

In the two following parts, we will assess the pricing of space weather goods in a classical approach: By confronting the cost to deliver space weather goods (supply side) and the willingness to pay of customers (demand side).

In order to support our arguments, we will rely on two forms that we addressed to the supply and demand sides and with additional interviews. The forms could be found in annex B and C. Form-1 which addressed the scientific institution that supply weather goods received 12 responses. The profile of the respondents is mainly space weather scientific of European Space Agency (ESA), Science and Technology Facilities Council (STFC), Royal Observatory of Belgium (ROB), NOAA (National Oceanic and Atmospheric Administration) involved in space weather goods design and provision.
Form-2 which addressed private companies that could buy these goods received 4 responses. 3 belongs to the space system industry and one from energy systems operation.
The two forms in about fifteen questions ask to the respondents, how they see today space weather goods market, the gaps to meet, the added-value of the private sector and how they foresee the whole ecosystem in 20 years.

### 4.1. Cost to deliver space weather goods (supply side)

It is quite difficult to estimate with precision how it costs to deliver space weather goods. Because sometimes the information is non-public, and many stakeholders are involved.
Furthermore, the satellites and on-ground infrastructures are not only dedicated to space weather mission, so we face mutualised costs. As an example, the satellite Deep Space Climate Observatory (DSCOVR) is use by NOAA for space weather missions but also for earth observation ones. Its total cost that includes launch is $340 million[8] (€283 million).
But, how to split the cost between space weather and earth observation missions?

However, we can draw some figures on the costs to deliver space weather goods.
The ESA Ministerial Council of 2016 dedicated €127 million to space weather activities.
Since 2007, €63.6 million are invested by the European Union in space weather activities through the EU's Framework Programmes for Research and innovation that involves universities, research institutes and private companies (Aliberti and Wells, 2019).
Moreover, the total cost for ESA to implement its space weather program to provide goods is estimated by PwC, 2016 at €502 million.
On the American side, Lipiec and Humpreys (2020) estimate that nearly $350 million are allocated to space weather for only the year 2019.
In other words, the costs to deliver space weather are expensive, and a long-term investment is needed to set-up and to maintain the infrastructure to provide space weather goods. It is impossible for a single actor to have a reliable and robust space weather system as for the traditional weather. Space weather is at the crossroads of different scientific disciplines as fluid mechanics or plasma studies. A broad and advanced scientific and technological knowledge has to be reached. This is why space weather strength in numbers.

[8] https://www.nasa.gov/content/goddard/qa-on-noaas-dscovr-mission/

International cooperation is decisive in the area of space weather and takes its roots in 1928. The UN bodies as the Committee on the Peaceful Uses of Outer Space (UNCOPUOS) puts the stress on the development of a space weather road map (policy) for international coordination and information exchange.
The International Space Environment Services (ISES) is engaged in the coordination of space weather services on operational matters. And research and education collaboration are assured by the Committee on Space Research (COSPAR).
Reliable space weather goods have to be reached in an international coordinated way.

### 4.2. Willingness to pay (demand side)

We will now qualify the willingness to pay of space weather goods. It is the amount the user is willing to pay for a determined quantity of goods.

From our forms, 55% of the supply side characterise the willingness today of users to pay for space weather services as low because reliable products are already available for free on the internet. 36% believe that the willingness is medium and only 18% that the willingness is strong notably for mid-term planning and localised geographical for short-term.

We have seen that power grid operations, aviation and logistics & road transport are sensitive sectors to space weather events.
According to PwC, 2016, in case of one single space weather event, the ESA space weather program that provides services allows to power grid sector to save €1,225 millions of damages, €544 million for logistics and road transport and €246 million for aviation (see annex D).
To be more precise on the aviation sector, NOAA assesses that the cost to de-route polar flights due to a space weather event is equal to $100k (€84k) per flight[9].
We can simply infer that the more a sector is sensitive to space weather events, the more it should want to pay space weather goods to save money.

Moreover, through our interviews, we notify that even if the majority today of space weather goods are free, users could pay for added-value space weather goods.
Added-value could be characterised by tailored services that meet specific individual customers' needs. In other words, systems centric services that are quicky available and propose a set of actions to take to mitigate space weather events.
Some respondents highlight that the real added-value is to ensure a 24/7 operational infrastructure to provide continuously goods with assistance in case of an issue. Something that is not in the core mission of scientific institute and only feasible by actor that have the ability to create revenue thanks to fee-based services in order to maitain the infrastructure.
All demand-side respondents use in-house solution to protect their activities against space weather. Two main reasons can explain this position. Space weather effects is a sensitive issue for these companies and they prefer to find solution with their own workers so as not to take outsiders into confidence. And/or added-value provided by the public entitiy is not enough for them to overtake in-house solution. However, they are eager to see what will offer private company and ready to pay more is the service meets their needs with high confidentiality.
All in all, we deduce that the more tailored is the service, the more customers' willingness to pay should increase.

[9] https://www.swpc.noaa.gov/sites/default/files/images/u33/swx_booklet.pdf

83% of interviewed people from the supply side designed private sector to provide this added-value. So, private players will build their customer-focused products on baseline service provided by public entities. As a matter of fact, free rider and bundling risks may appear.
Free rider understood as a consumer that benefits from a good without paying for it, is not a real issue for space weather. Public authorities even encourage a certain degree of free riding because it doesn't increase costs and could lead to societal benefits because as we have seen in part 2.4, space weather goods are merit goods.
On the other side, bundling is illustrated by Candela and Geloso (2019) by entrepreneurs that sell complementary fee services as ship pilotage by using a free public good: The lighthouse.
In our case, we can imagine a private company that provides a dedicated software for spacecraft orbit operations that use public space weather goods to refine its manoeuvres proposals.
The software is fee-based and bundling with free public space weather goods.
However, are private company free to charge added-value services if part of their data is public or have to follow a regulated rate?
To answer this question, we can make a connection with the traditional weather satellites data sharing system. Cirac-Claveras (2018) describes a "data-war" between private (GeoOptics, PlanetIQ…) and public actors (NOAA) on weather data sharing in the United-States.
Private sector claims that the public sector provides non-necessary free data that destroy the market. These free data lower the willingness to pay of users.
Public entities defend themselves by arguing that weather data are a governmental market that respects an unrestricted data sharing principle.
In an attempt to solve the conflict, the Resolution 40 of the World Meteorological Organisation (WMO) has been appealed. Adopted in 1995, this policy document distinguishes "essential" data to protect life and property that must be freely shared and "additional" data that could be charged with fees. The resolution of the dispute is still ongoing with different interpretations of the words "essential" and "additional" by both parties.
Nevertheless, this example validates the confrontation between a customer model and a taxpayer model. How to overcome this opposition?
Thus, we investigate an efficient and coordinated way to commercialise space weather goods and to conciliate both the public and private sides.

### 4.3. Freemium model…

Freemium model is one of the most effective ways to grow interest in a good and reveal the willingness to pay of consumers (Sato, 2019). It is a pricing strategy that enables to offer a basic good freely and to charge for additional features.

We could imagine a space weather goods freemium model composed of 2 layers:

- Free public baseline products,
- Premium (fee-based) added-value services of private companies.

This first layer made of public products will make consumers to cope with space weather's utility. We propose this graduated scale to assess the user's utility of space weather goods (from lowest to highest utility):

1- No understanding at all of space weather
2- Aware of overall space weather impacts
3- Already experienced space weather issues
4- Take measures to monitor space weather impacts on their system
5- Precise mapping with a corporate risk scenario to mitigate space weather impacts

The aim of this freemium model is to smoothly accompany the user from step 1 to step 5.

The users can download an application on his phone or a software on its computer. Then, after a quick registration, it will have access for free to a product dashboard with key indicators corresponding to its activity provided by public entities. For example, NOAA is already doing dashboard for industry like aviation[10]. Users will improve their understanding level of space weather impacts on their activities. As an example, a military radioman suffers from discrepancies while talking to the headquarters to take orders. Indeed, his radio suddenly beams pop music. The radioman does not know that this frequency shift is an effect of current space weather event. But by monitoring space weather through a dashboard indicator dedicated to radio broadcast, he could have made the link.
Thanks to this first layer, the consumers will have a well-informed and a rational view (Hoberg and Strunz, 2017) on space weather goods.

The second layer with fee-based added-value services will reveal the willingness to pay.
Users will become customers because at some point, in order to minimise as much as possible, the damages that can be generated by space weather, you have to tailor general dashboard indicators on individual basis and this as a price. As we have seen in part 4.2, users will pay for services targeted on their needs. Back to our previous example, the military radioman must take actions to mitigate radio frequency shifting on the battlefield. For this, private companies will aggregate other sources of data like the relay antennas in the sector, the current military satellite coverage, the knowledge of radioman regarding space weather and will develop tailored algorithm to provide actions with Key Performance Indicators (KPI) in order to dramatically reduce space weather effects. Moreover, fee-based services could offer a 24/7 service availability and courses to train operators to be familiar with space weather.
All these "à la carte" features is a way to reveal the willingess to pay of the customer.
For example, we can imagine a customer that only pay to have access to a service for 8 hours a day that corresponds to the working time of the society. After, the company can pay to train some of its operators and if the return of experience shows clear benefits, the society can opt for a 24/7 service availbility with support.

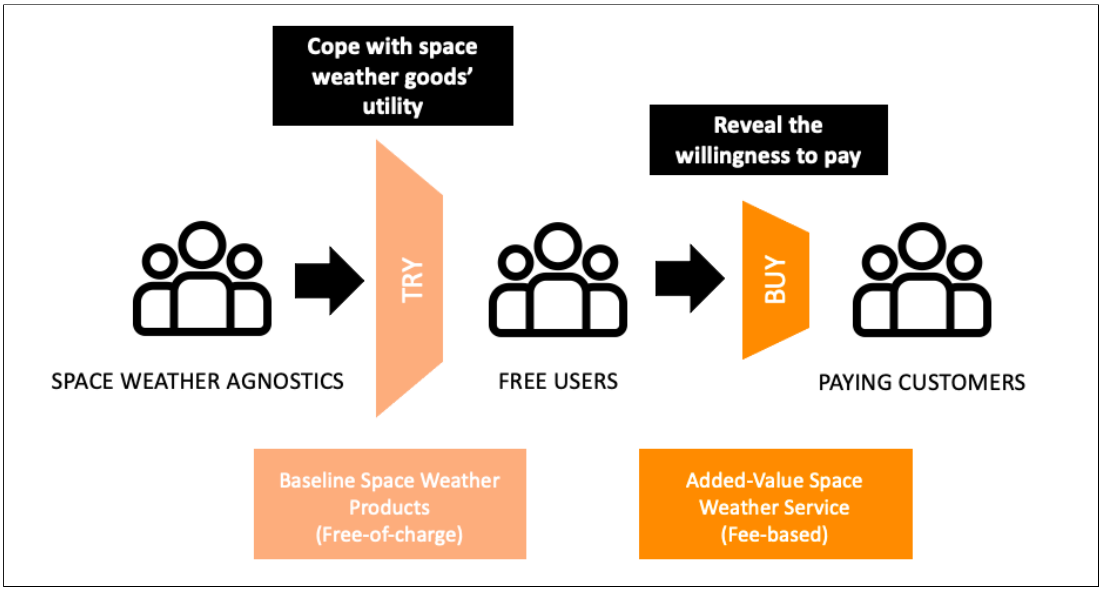


Figure 3: Space Weather Goods Freemium Model

[10] https://www.swpc.noaa.gov/communities/aviation-community-dashboard

This freemium model should be an optimal menu pricing for space weather goods where basic products are free-of-charge to grow users' utility in the space weather goods and additional fee-based features is available to tailor the services according to the needs and the willigness to pay of the customers.
However, a robust and coherent organisational framework has to be implemented to support this model.

### 4.4. …supported by an organisational framework: A service triad

63.6% of the respondents of our survey indicate that a public-private model is the most suitable to provide operational space weather services.
Hence, in this part, we examinate organisational framework called service triad to support the previous freemium model.

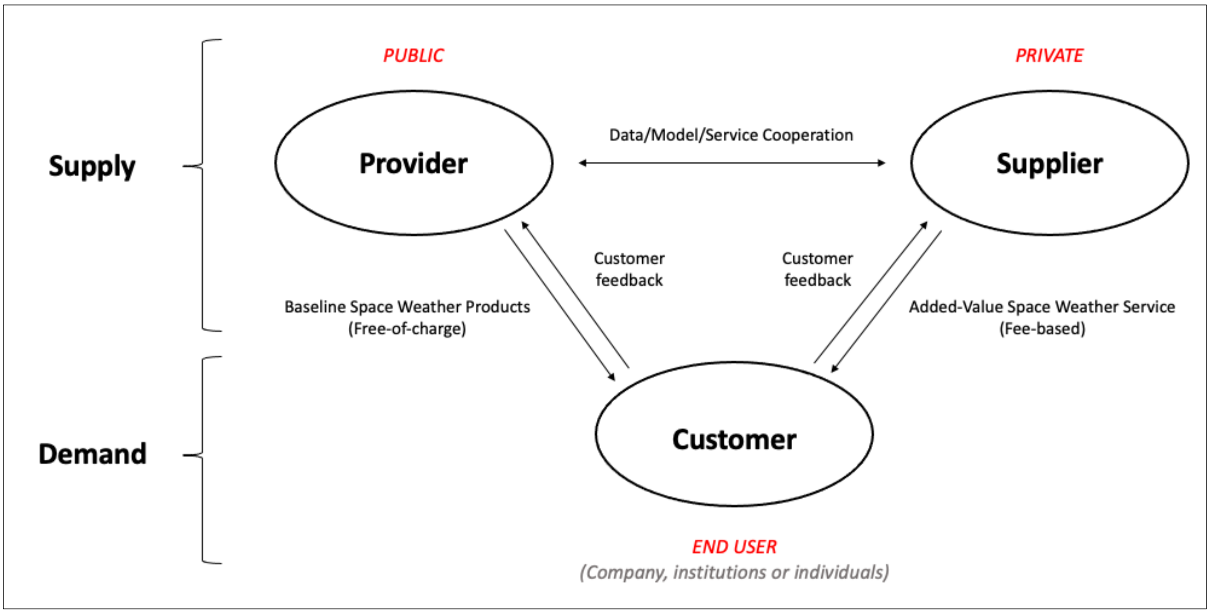


Figure 4: Space Weather Goods Service Triad

On the contrary of daily life exchange between two entities (a seller and a buyer), the service triad is composed of three actors: Provider, supplier and the customer (Wynstra *et al*, 2015).
This service triad organisation is already used for traditional weather goods provision.
Adapted to our case, a service triad is based on a contract between a provider (public entity) and a supplier (private entity) to collaborate on data, models, products and services together to provide goods to the consumer.The benefits are manifold: A better and global coverage is possible thanks to public and private satellites and on-ground instruments, costs are mutualised, more streams of funding are available with private sponsorships. The aim is with a public-private cooperation to build a robust and operational infrastructure.
Nevertheless, the prerequisite of a service triad is to know exactly which data could be charged or not, to avoid a "data war" as seen in part 3.2. An updated Resolution 40 has to be discussed and adopted by the different stakeholders.

Then, the supply meets the demand through the freemium model where provider delivers baseline space weather products and supplier sells its added-value services (see part 3.3).

The advantages are to offer a unique user experience and have a customer feedback that is now rather difficult to get. This feedback is then analysing and re-use through the provider and supplier agile cooperation to design or improve the goods.
However, the providers and suppliers' prerogatives have to be defined through a bill of specification to avoid any confusion with the customer or duplicate work. Coordination is key. To achieve this, at the beginning, the number of providers and suppliers should be minimal: One or two providers with two or three suppliers. Their number may increase with the rise of customers.

## 5. Conclusion

We demonstrate that space weather goods provision could be considered as a "grand challenge" defined by George *et al.* (2016) as a global problem with possible detrimental effects on our society that can be addressed by coordinated and sustained effort by different stakeholders.
The tackling of "grand challenge" is both a scientific and also a managerial problem.
Indeed, the originality of this research paper is to analyse space weather and the goods associated through a managerial economic point view and not in the classical scientific way.
Therefore, we can learn that space weather goods could be considered as merit goods and require a State intervention to avoid a market failure.
Nevertheless, new private comers raise the question of pricing and commercialisation of space weather goods. To answer it, we confront the cost to deliver space weather goods (supply side) and the willingness to pay of customers (demand side).
The cost to deliver is quite expensive due to heavy space and ground-based infrastructure and intensive research in various scientific and technical fields.
So, space weather goods provision strength in numbers. Cooperation between private and public actors at an international level is preponderant to achieve robust and operational services.
As with traditional weather forecasts, users expect generic and essential services to be free but will pay for services targeted on their needs to mitigate space weather effects on their activities in order to save money or set a business as auroral tourism.
We assess that a "freemium" model implemented through a service triad organisation could be a solution to efficiently provide space weather goods in a coordinated and sustained effort between public and private actors.
The next step of this research paper could be to quantify with precise metrics the willingness to pay of space weather goods users and define how to allocate customer's payment between public and private actors in the triad organisation.

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Errors are mine.
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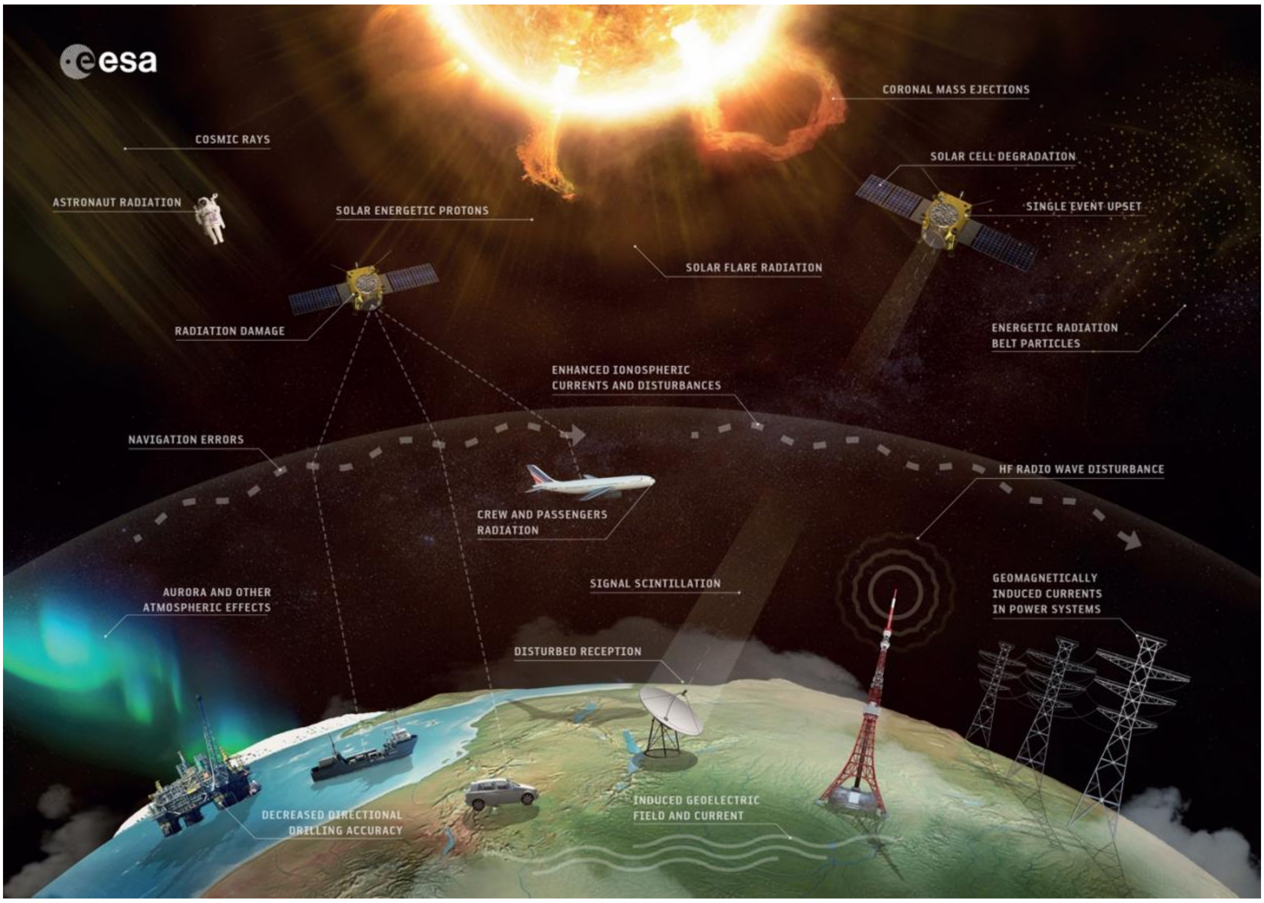
# 8. Annexes

Annex A: Space weather effects and history of major space weather events




Space weather effects, (source: ESA)

Short history of major space weather events:

1859: The largest documented solar flare. It is called the Carrington event named after the astronomer who discovered it. The telegraph network was affected.

1989: In winter, in the province of Quebec, 6 million inhabitants were without electricity for almost nine hours because of transformers failures.

2003: On 4 November, the so-called Halloween solar flare occurs, the most powerful flare recorded in 40 years. Many satellites experienced anomalies. The estimated cost in excess of $10 billion.

2005: A Swedish airport is forced to ground its planes because its control towers were suddenly out of order.

2012: A solar event of the same magnitude as that of 1859 occurred on the far side of the sun. The earth was spared because the flare was not directed towards it.

2017: A French plane flying over the Atlantic disappeared from radar screens before reappearing one hour and a half later.

Annex B: Form-1 (Supply side)

# Form-1 (Supply side)

Do you think Space Weather service is a public good (= consumption of a good by one user does not dimmish the capability of another user to use the good)?

- [ ] Yes
- [ ] No

How do you describe the Space Weather service market today? (e.g. maturity, efficiency, demand...)

Your answer

Classify these requirements (from most to least important) for a successful Space Weather service provision:

| | Structured and active demand | Reliable and affordable technology that is adapted to user needs | Organisational framework | Political willingness |
|---|---|---|---|---|
| Requirement 1 | ○ | ○ | ○ | ○ |
| Requirement 2 | ○ | ○ | ○ | ○ |
| Requirement 3 | ○ | ○ | ○ | ○ |
| Requirement 4 | ○ | ○ | ○ | ○ |

Continued Annex B: Form-1 (Supply side)

Do you think that actual Space Weather Service market captures all the value of Space Weather Data? (e.g. externalities; non-market value)

Your answer

Where do you place your understanding degree of customer needs by Space Weather?

| | 1 | 2 | 3 | 4 | |
|---|---|---|---|---|---|
| No understanding at all | ○ | ○ | ○ | ○ | Precise understanding |

For you, which model is the best suitable to provide operational Space Weather services?

- ○ Public model
- ○ Private model
- ○ Public-private model

How do you characterise today the willingness of customers to pay for Space Weather services?

- ☐ Low
- ☐ Medium
- ☐ Strong
- ☐ Other:

Continued Annex B: Form-1 (Supply side)

In how long do you see the uptake of commercial market solutions?

- ○ Today
- ○ 5 years
- ○ 10-15 years
- ○ 20-25 years

According to you, what is the value-added that could bring the private sector in providing Space Weather services?

Your answer

Does space weather as a service as the same business potential as atmospheric weather applications?

- ○ Yes
- ○ No
- ○ Don't know

In your opinion, where and how will be the Space Weather services market in 20 years? (e.g. maturity, new players, framework, demand, products available...)

Your answer

Annex C: Form-2 (Demand side)

# Form-2 (Demand side)

Company sector:

- ◯ Space Systems
- ◯ Aviation
- ◯ Railways
- ◯ Energy Systems Operation
- ◯ Other: ________

"Resilience becomes an additional pillar of business performance (e.g. COVID-19)" :

- ◯ 1. Not agree
- ◯ 2. Rather agree
- ◯ 3. Fully agree

Do you know what is Space Weather?

| | 1 | 2 | 3 | |
|---|---|---|---|---|
| Not at all | ◯ | ◯ | ◯ | Yes, precise knowledge |

Continued Annex C: Form-2 (Demand side)

On a scale of 1 to 5, where do you place your understanding level of Space Weather impacts on your business?

- ○ 1. Not at all
- ○ 2. Aware of overall Space Weather impacts
- ○ 3. Already experienced Space Weather issues
- ○ 4. Take measures to monitor Space Weather impacts on my system
- ○ 5. Precise mapping with a corporate risk scenario

What are your needs regarding Space Weather?

Your answer

Which Space Weather services do you already use or plan to use ?

- ○ Forecast
- ○ Nowcast
- ○ Postcast
- ○ None of them

Could you name the products you have used and the providers (ESA, NOAA...)?

Your answer

Continued Annex C: Form-2 (Demand side)

Do you need a training/education track to use these Space Weather services?

- ◯ Yes
- ◯ Internal training is enough
- ◯ Not at all

Sort by order the Space Weather service feature you are looking for (from the most wanted to the least wanted):

| | Intuitivity | Visualisation | Quickly available (within minutes) | Actionable (systems centric) | Integration (API) | Education / Training |
|---|---|---|---|---|---|---|
| Feature 1 | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |
| Feature 2 | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |
| Feature 3 | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |
| Feature 4 | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |
| Feature 5 | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |
| Feature 6 | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |

How do you characterise today your willingness to pay for tailored-made Space Weather services that provide more value-adding information as compared to those provided by the government and openly accessible on the internet?

- ◯ 1. Low
- ◯ 2. Medium
- ◯ 3. Strong

Continued Annex C: Form-2 (Demand side)

Do you prefer to work on a tailored-made Space Weather service with?

- A Scientific Organisation
- A Space Weather Commercial Entity
- Both

Do you use in-house solution to mitigate Space Weather impacts?

- Yes
- No

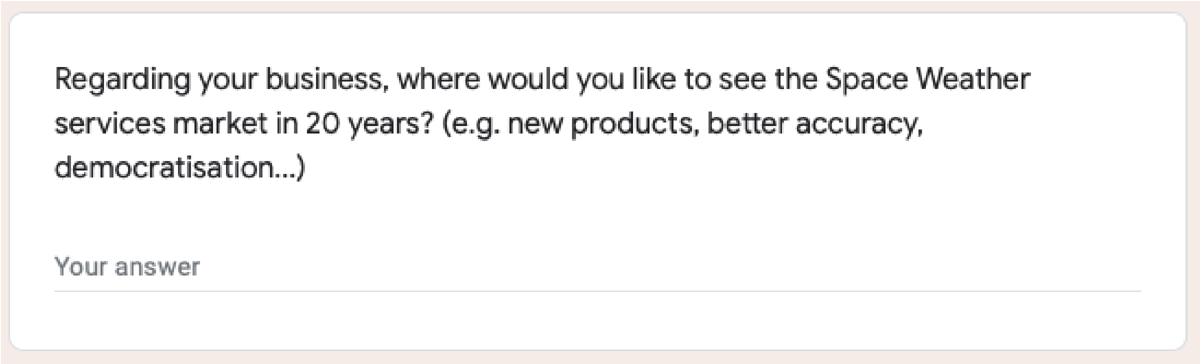
If not, why do you not use Space Weather services available on the market?

Your answer

Class in priority, the barriers that prevent you to invest in Space Weather service

| | 1. Benefits too distant and too intangible | 2. Sensitive and proprietary subject | 3. Not a clear view of Space Weather providers' landscape | 4. Accuracy of services | 5. Not aware of Space Weather impacts on my business |
|---|---|---|---|---|---|
| Barrier 1 | ○ | ○ | ○ | ○ | ○ |
| Barrier 2 | ○ | ○ | ○ | ○ | ○ |
| Barrier 3 | ○ | ○ | ○ | ○ | ○ |
| Barrier 4 | ○ | ○ | ○ | ○ | ○ |
| Barrier 5 | ○ | ○ | ○ | ○ | ○ |

Continued Annex C: Form-2 (Demand side)



Regarding your business, where would you like to see the Space Weather services market in 20 years? (e.g. new products, better accuracy, democratisation...)

Your answer

Annex D: Cost/Benefits of ESA program to provide space weather services

| Cost/Benefit | Do nothing scenario | Do ESA scenario | Value added of ESA Services |
|---|---|---|---|
| **User domain benefits** | | | |
| *Satellite operations* | - €283 M | - €267 M | €26 M |
| *Launch operations* | - €0.3 M | - €0.1 M | €0.2 M |
| *Resource exploitation* | - €327 M | - €135 M | €192 M |
| *Power grid operations* | - €5,771 M | - €4,546 M | €1,225 M |
| *Aviation* | - €3,312 M | - €3,066 M | €246 M |
| *Logistics/Road transport* | - €3,432 M | - €2,888 M | €544 M |
| **Investment benefits** | | | |
| *GDP impact* | None | €952 M | €952 M |
| **Total Benefits (b)** | - €13,135 M | - €9,950 M | **€3,185 M** |
| **Programme Costs (c)** | None | - €529 M | **- €529 M** |
| **Total Net Benefits** | - €13,135 M | - €10,479 M | **€2,656 M** |
| | | Benefit / Cost ratio (b/c) | 6 |

Cost/Benefits of ESA program to provide space weather services
(Sources: PwC, 2016 and ESPI, 2019)

How to read this tab?

For example, a single space weather event is assessed to cost to aviation sector € 3,312 million without using ESA's space weather services.
With them, the cost is only assessed at € 3,066 million, this is a net saving of € 246 million.