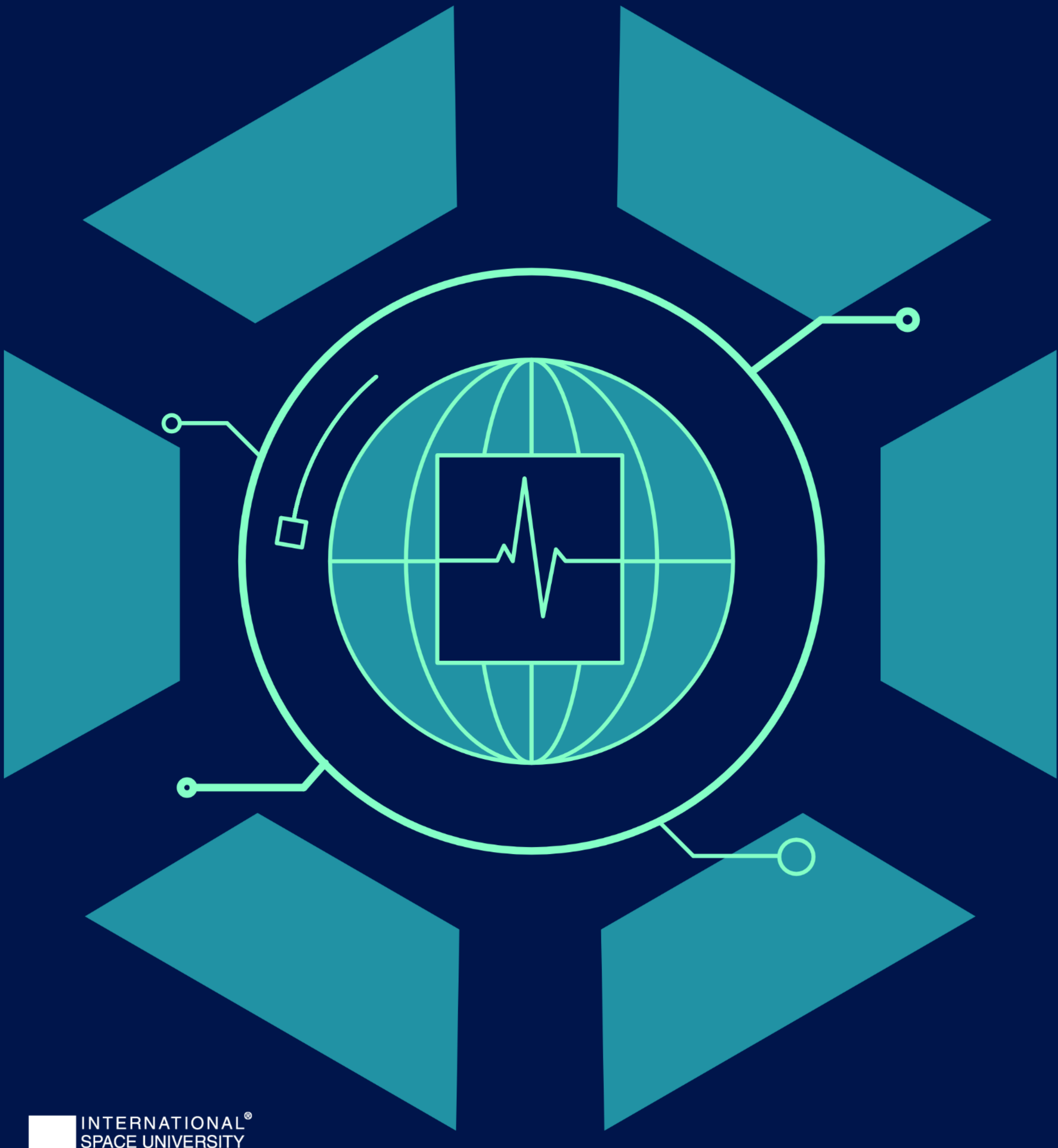
Report

Monitoring of Pandemics from Outer Space



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ISP2020

Monitoring of Pandemics from Outer Space

Final Report

International Space University Interactive Space Program 2020

The cover design shows a geometric stylization of earth as seen from space. Earth is overlaid by an ECG pattern as an icon for health monitoring and orbited by the depiction of a satellite. Earth is surrounded by a circle symbolizing a worldwide network both in an ecological and technological sense seeing how the COVID-19 pandemic is affecting the planet on a global scale as well as referring to the online format of ISU's Interactive Space Program 20. The four appendages around the circle stand for data and information as one of the tools available to us in the combat against pandemics. The six trapezoids are borrowed from the International Space Station's Cupola window architecture and evoke a personal and human connection to space and earth observation. The bottom left shows the logo of the International Space University.

The cover was designed by our very own Design Team. Our thanks go to Niels van der Pas, May-Li Uy and Elena Grashchenkova for their successful effort.

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Electronic copies of the Executive Summary and Team Mission Report may be found on the ISU website
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Abstract

Epidemiologists, health organizations, policymakers all around the world are working tirelessly towards a healthier future. The participants of the Interactive Space Program 2020 at the International Space University were tasked with a mission to investigate how space can help in the monitoring, mitigation, preparedness, and prevention of pandemics. The mission was a three-part study that looked into 1. monitoring, 2. mitigation, 3. prevention, and 4. preparedness by three separate subgroups. This paper, which constitutes a part of the complete research, briefly describes the monitoring of pandemics from space.

Section 1 introduces the vision and mission of the project. Section 2 briefly presents the research methodology to get the most effective results from the study. Section 3 presents the results and findings of the study.

We used an interdisciplinary approach to address the problem. Each section is divided into subsections, briefly describing the overview and addressing challenges and recommendations for each discipline. We started by identifying the stakeholders. Then, we presented a discussion on the monitoring parameters and systems. We then made an assessment of the available technologies, followed by the challenges in data processing and artificial intelligence for Earth observation. Finally, we outlined the economy, business, and regulations prospects with a reflection on international cooperation. Section 4, summarizes our findings and recommendations.

Faculty preface

In the past 9 months COVID-19 has affected over 21 million people and killed almost 1 million, making it the worst pandemic since the Spanish flu 100 years ago in 1918. While a vaccine is now seen as an essential part in resolving this crisis, it does not prevent or offer solutions to future virus outbreaks and epidemics which are inevitable.

Many studies have focused on vaccines whilst others have looked at optimal antibodies for convalescent serums, increasing mask filtering capabilities, reducing exposure risks, herd immunity thresholds and many more. However, one area which has yet to be focused on, is the use of space technology to monitor pandemics.

During the summer months of June and August 2020, the International Space University (ISU) held its first online program titled the Interactive Space Program (ISP). The participants / crew of the program stemmed from international, interdisciplinary, and intercultural backgrounds making for a truly collaborative, diverse, and effective project. The focus of this program was to mitigate, monitor and prevent pandemics using space resources of which three separate teams were constructed to provide recommendations focusing on either monitoring, mitigation or prevention. In keeping with the spirit of simulating the mission taking place in the year 2120, the three teams were given a habitat for their research operations: Near Earth Orbit, on a Mars base and on a Moon base.

Our team, Orbit, focused on the monitoring of pandemics using current space resources and technology and through this report have provided an in-depth analysis, exceptional identification of strategic gaps and practical recommendations for the monitoring of pandemics from space. The team worked over multiple time zones from 4 continents. Showcasing the truly international effort that space evokes, coming from diverse backgrounds of all ages and nationalities to communicating, working and developing an entire project online without anyone ever being in the same place. A mark of technological progress.

It has been a truly humbling experience to watch this professional team work closely together during exceptional circumstances. For the faculty, it has been a pleasure to learn from, communicate with and observe the Orbit crew, they have performed outstandingly. We invite the reader to review the practical information which this team has developed to further their own health systems, structures and capabilities.

Dr. Simon Pete Worden - Commander

Mr. Rishi Khan - Officer

Mr. Dillon O’Reilly - Officer

Crew preface

The year 2020 has been marked by the ongoing COVID-19 pandemic, as governments across the globe have been forced to put into place measures to contain the disease.

The consequences of this pandemic on public health, the economy, the environment, international traffic, and our social structure are apparent to us all.

In response to travel restrictions and social distancing measures, the International Space University (ISU) has established the Interactive Space Program, an international, interdisciplinary, and intercultural online program that has filled in the void left by the forced cancellation of the 2020 edition of the Space Studies Program It has been our pleasure to embark on this journey and inaugurate this new program together.

Our mission focused on identifying the contributions that the space industry can provide to the ongoing pandemic, and identify lessons learned that we can use to address similar threats to global health in the future.

The COVID19 pandemic has demonstrated how in times of globalization a disease can spread across the globe in only weeks, threatening lives, forcing the closure of international borders, stopping the economy, and disrupting supply chains. The ISP20 program, however, serves as a reminder that despite these constraints successful international, intercultural, and interdisciplinary collaboration can live up to these challenges, counter these issues and identify possible solutions.

This team report includes contributions from people across 17 countries in four continents spanning three life decades and coming from backgrounds as diverse as anthropology, biochemistry, immunology, veterinary medicine, geology, engineering, robotics, data sciences, medicine & public health, finance and law.

It is our hope that our report will provide a little, yet meaningful, contribution towards the mitigation of the current pandemic, and the prevention of future health crises.

Team Orbit
ISP20, August 2020

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List of acronyms

AI	Artificial Intelligence
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
BDS	BeiDou Navigation Satellite System
CAMS	Copernicus Atmospheric Monitoring Services
COPUOS	Committee on the Peaceful Uses of Outer Space
CNES	Centre National d'Etudes Spatiales
COVID-19	Corona Virus Disease 2019
D-MOSS	Dengue MOdel forecasting Satellite-based System
eIDSR	Electronic Integrated Disease Surveillance and Response
EMS	Emergency Management Service
ENVISAT	Environment Satellite
EO	Earth Observation
ESA	European Space Agency
EWARS	Early Warning, Alert and Response System
GDPR	General Data Protection Regulation
GEO	Group on Earth Observations
GEO	Geosynchronous orbit
GEOSS	Global Earth Observation System of Systems
GIS	Geographic Information System
GLONASS	GLObal NAvigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HeRAMS	Health Resources Availability Monitoring Systems
IoT	Internet of Things
IRNSS	Indian Regional Satellite Navigation System
ISRO	Indian Space Research Organization
ITU	International Telecommunication Union
JAXA	Japan Aerospace Exploration Agency
LEO	Low-Earth-Orbiting
LIDAR	Light detection and ranging
ML	Machine Learning
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration

OMI	Ozone Monitoring Instrument
PAN	Panchromatic
SDG	Sustainable Development Goal
SAR	Synthetic Aperture Radar
SLAR	Side Looking Airborne Radar
SARS-CoV-2	Severe acute respiratory syndrome coronavirus
UN	United Nations
UNICEF	United Nations Children’s Fund
UNISPACE	UN Conference on the Exploration and Peaceful Uses of OuterSpace
UNITAR	United Nations Institute for Training and Research
UNOSAT	United Nations Operational Satellite Applications Program
UNOOSA	United Nations Office on Outer Space Affairs
UN-SPIDER	United Nations Platform for Space-based Information for Disaster Management and Emergency Response
VIIRS	Visible Infrared Imaging Radiometer Suite
VISNIR	VISible Near-InfraRed
WHO	World Health Organization

1. Introduction

Space has always been feeding our curiosity and imagination. Perhaps it can also expand our understanding of the 2020 COVID19 pandemic and help us to devise a strategy to get us through it. We believe it is possible, so we set this goal as our team's objective for the Interactive Space Program 2020 final report. Monitoring a pandemic from space can help to identify an optimal response and devise appropriate measures to mitigate its negative impact. There is already a multitude of organizations that monitor Earth in a variety of ways from space. This report highlights the existing systems, identify gaps that might have been overlooked, and present some recommendations based on our findings. We hope to provide stakeholders and decision-makers with an actionable document with suggestions about how to monitor pandemics from space.

Our vision statement, formulated around this objective, is:

'A future where effective use of space technologies for monitoring of epidemics supports informed policy decisions to improve quality of life and decrease health inequalities.'

In the quest of fulfilling this vision, the immediate mission we identified for ourselves is:

'To provide an interdisciplinary review on the use of space technology to identify opportunities for improvement in monitoring the predictive factors, spread, and consequences of epidemics, and provide recommendations for data fusion for the benefit of public health and enhance decision making for future epidemics.'

We have approached the topic from five different perspectives. First, we have investigated the subject from a health point of view, reviewing the parameters we can monitor and the systems available to do so. Second, we have discussed the available technologies to monitor these parameters from space. Third, we have analysed the challenges in data processing and the current use of Artificial Intelligence for Earth Observation. Fourth, we have presented an outline of the economic and financial impact and the international policies that can provide assistance. Finally, we have addressed the concerns regarding regulations and data privacy with respect to monitoring. We have identified the gaps and challenges concerning monitoring pandemics from outer space in all five of these areas and proposed specific recommendations.

We would like that this report supports decision makers to be better prepared for the next health crisis.

2. Methodology

We performed a state of the art of space-based monitoring capabilities with regards to pandemics and infectious diseases we have used the resources listed in the “Subject Guide on Space Technologies and Pandemics” that we found in the ISU Library’s Knowledge Portal (ISU Library, n.d.). We also consulted the official websites of space agencies and international organizations and their affiliates for pertinent material on the subject. The list of space agencies and organizations includes the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), the Japanese Aerospace Exploration Agency (JAXA), the Indian Space Research Organization (ISRO), the World Health Organization (WHO), the United Nations Office for Outer Space Affairs (UNOOSA), the United Nations Platform for Space-based Information for Disaster Management and Emergency Response (UN-SPIDER), and others. We also conducted a literature review of scientific papers across databases like PubMed, focusing on terms related to “space”, “earth observation”, “remote sensing”, “satellite”, “COVID19”, “epidemic”, “pandemic”, “infectious diseases”, “Ebola”, “vector”, etc. Finally, our report was enriched by the content of numerous webinars and talks given by experts and industry leaders we had the pleasure to follow during the ISP 20 program. Where we have borrowed ideas and quotes from these encounters, we have referenced them accordingly, although not all sessions were recorded or are publicly available.

We discussed the collected material in our team within several working groups focusing on public health, space technologies and data processing, international policy and collaboration, and law and business. Each working group investigated the state of art as of mid 2020, identified the gaps, and formulated recommendations to stakeholders and policymakers.

3. Findings

3.1. Stakeholders

3.1.1. United Nations (UN) and its Office on Outer Space Affairs (UNOOSA)

Many international space initiatives relating to global distribution of space data and knowledge are directly related to emergency and disaster management. In 2006, UNOOSA created the United Nations Platform for Space-based Information for Disaster Management and Emergency Response (UN-SPIDER), a knowledge portal for space-based information specifically related to emergency and disaster management. Their mission is to ensure that "all countries and regional organizations have access to and develop the capacity to use all types of space-based information to support the full disaster management cycle" (UN, 2006). (CDC, 2020)UN-SPIDER connects organizations that provide satellite data with nations hit by disaster, with a particular focus on developing countries (UN-SPIDER Knowledge Portal, 2006). UN-SPIDER lists the five main international initiatives relating to space disaster management as: (1) the Copernicus Emergency Management Service (Copernicus EMS); (2) the International Charter on Space and Major Disasters; (3) Sentinel Asia; (4) SERVIR (a joint venture between NASA and the US Agency for International Development); (5) the United Nations Institute for Training and Research (UNITAR) and its Operational Satellite Applications (UNOSAT) programme.

3.1.2. Stakeholder Gaps and Recommendations

As discussed by UNOOSA, many people around the world lack access to the basic benefits of satellite and space technologies. In a time of crisis, access to this data is integral to provide decision-makers with the resources they need for well-informed decisions. UNOOSA has started the "Access to Space for all" initiative to tackle this very issue (UNOOSA, 2020), which is in line with the United Nations Sustainable Development Goal (SDG) 10 ("To reduce inequality within and among countries"). This is also an issue that the NASA Earth and Science Division is actively addressing with educational outreach programs and live training webinars.

Data processing, artificial intelligence, and machine learning require specialized skills. We believe that a prevalent issue for non-space fairing nations is the inadequate availability of training for personnel interested in working with remote sensing data. For this reason, we recommend increasing public outreach, education and training programs, and the development of toolkits aimed specifically at developing countries.

One recommendation for the health policy sector could include the development of programs to raise awareness about the use of health-oriented geographic information systems (GIS) to monitor at-risk demographics and track the spreading of an outbreak within the general population. Dedicated GIS teams within the health-care sector could build, maintain, and use the tools needed to help decision-makers prevent and mitigate potential or on-going health issues. We will refer to other Team Mission Reports on these respective topics.

3.2. Monitoring Parameters

3.2.1. Health & Monitoring Systems

The use of satellite technology for predicting and monitoring epidemics is an established practice. However, remote sensing and Earth observation technologies do not allow the direct detection of disease spread. However, a range of environmental and economic parameters correlated to a health crisis can be measured directly. These parameters become proxies or surrogates for disease-related metrics.

Examples of indicators to track the onset or progress of a disease include the monitoring of habitats of pathogen-carrying vectors, and the monitoring of surface temperature to identify areas that present an increased risk to harbour diseases.

Health Resources Availability Monitoring Systems (HeRAMS)
The Health Resources Availability Monitoring Systems (HeRAMS) initiative launched by WHO aims to ensure that core information on essential health resources and services are readily available to decision makers at country, regional, and global levels. In particular, indicators about health facilities, resources for service delivery, availability of health services, and reasons for gaps in service availability are updated on a monthly basis, providing a clear picture of the health system strengths and weaknesses at country level (WHO, n.d.).

Early Warning, Alert and Response System (EWARS)
The Early Warning, Alert and Response System (EWARS) was designed to help strengthen the emergency response by providing the infrastructure – mobile phones, laptops, solar-powered generators and chargers – required for setting up a mobile disease surveillance system. EWARS surveillance performance indicators are established by health service partners. Possible applications include event-based surveillance, surveillance of suspected outbreaks, active outbreaks, and public health events (Fall et al., 2019). An example of these applications is the Dengue Model forecasting Satellite-based System (D-MOSS) sponsored by the UK Space Agency's International Partnership Program. This system, which has been tested in Vietnam, incorporates Earth observation, seasonal climate data, and hydrological information (D-MOSS, 2019)

Corpernicus Atmosphere Monitoring Service (CAMS)
ESA's Corpernicus Atmosphere Monitoring Service (CAMS) provides a powerful tool for situational awareness and the assessment of the interactions between humans and the environment thanks to a geographic information system that couples locally generated data with satellite imagery. Eisen and Lozano-Fuentes (2009), for example, used GIS and remote sensing data combined with epidemiological and entomological information to better understand the spatiotemporal evolution and dynamics of dengue outbreaks.

COVID-19 Dashboard
Several dashboards on the COVID-19 pandemic exist. The Earth-Observation (EO) Dashboard is a joint initiative by ESA, NASA and JAXA, who are pooling resources to monitor environmental, agricultural and economic indicators (NASA, ESA, JAXA, n.d.). Appendix A gives an overview of the indicators listed on the dashboard.

Contact tracing Apps
End user devices calculate the user's location by combining signals coming from four or more navigation satellites, and then share the information through Internet. Contact-tracing apps use a unique key code, usually exchanged through Bluetooth, which enables the app to detect phones that are in close proximity for more than a few minutes. When users test positive for infection, they are required to update their status in the app, so the service provider can notify users that may have come into close contact with them.

3.2.2. Environmental proxies
The COVID-19 pandemics revealed the large-scale effect that health crises can have on the environment through their effects on human habits. To better understand this phenomenon,

we need to investigate both the immediate and the longer-term consequences. The environmental impact of pandemics is relevant because it affects several UN SDGs, like SDG 3 (“Good Health and Well Being,”) SDG 6 (“Clean Water and Sanitation,”) SDG 13 (“Climate Action,”) and SDG: 17 (“Partnerships") (UN, n.d.).

The near-global lockdown imposed at the beginning of 2020 caused a short-term drop in CO2 emissions. However, as time went on and lockdowns eased up, the emission values rose back to previous levels. This emission drop peaked at 26% average globally compared to 2019 values, with the largest factor being the reduction in surface transport. However, the drop on an annual level is not expected to be so significant with only a 4-7% range forecasted (Le Quéré et al., 2020).

While this measure suggests that the short-term drop in CO2 emissions will not have a lasting impact, there are other factors to take into account. As of mid-2020, a rising concern is that nations will sidestep their past commitments to climate change to ease the economic burden of the COVID pandemic, potentially inducing an overall net increase in CO2 emissions (Takenaka and Shimizu, 2020).

It is also important to highlight a two-way link between climate and pandemics because while a pandemic can be damaging to the environment in the long term, climate change can also increase the frequency of future pandemics by affecting the probability of vector borne diseases. Another factor is the largescale industrial meat industry, which not only affects the environment but is also increasing the risk of several disease groups. As of mid-2020, regions like tropical Africa and Southeast Asia have already seen an uptick in rate of diseases. Some of these predictive factors, like rainfall, temperature and animal livestock farming size, can, to various degrees, be monitored from space (Curseu et al., 2009).

The renewed global focus that emerged from COVID-19 has increased the awareness about how to adapt the ecosystem and the structure of our economies to be more in line with SDGs (UNFCCC, 2020).

Another effect of the lockdown was a significant decline in nitrogen dioxide emissions. ESA’s Copernicus Space Component consists of a group of space-borne missions called Sentinels, part of which support the Copernicus Atmospheric Monitoring Services (CAMS), which collects information on atmospheric variables like ozone, surface UV, air quality, and climate applications. SENTINEL-5, thanks to a high-resolution seven band spectrometer, is dedicated to monitoring atmosphere quality, aerosols and the concentration of atmospheric gases like ozone (O_3), nitrogen dioxide (NO_2), and sulphur dioxide (SO_2). MODIS-derived products can provide aid in detection and tracking of the migration of pollutants (NASA, n.d.).

Global issues such as the effects of climate change will keep providing justification for large multi-sensor satellites complemented by smaller and cheaper commercial satellites like Planet’s constellation of earth-imaging satellites.

3.2.3. Economic proxies

The monitoring of social and economic aspects of the COVID-19 threat is possible through proxies - environmental variables that can be correlated to other metrics. Thermal sensors installed on weather and remote sensing satellites provide crucial information on land surface temperature (LST) and nighttime light emissions can act as economic proxies to identify changes in industry-related activity. These proxies can include but are not limited to medical facilities, population demographics, landmarks, places of cultural/historic/religious significance, roads, public transport hubs, land use, and other social infrastructure. Time series analyses of thermal infrared images, which reflect the terrestrial thermal behavior of an area, denote patterns of energy consumption. The Visible Infrared Imaging Radiometer Suite (VIIRS) instrument from the National Oceanic and Atmospheric Administration (NOAA) and NASA reveal variations in light emission that are otherwise not detectable from other earth observation platforms with higher temporal resolution (Josh Blumenfeld, 2017). Daylight data from China's Liaoning province, for example, revealed that COVID-19 had an easily detectable effect on almost all major Chinese cities when compared to pre-pandemic patterns (Hudecheck, 2020).

Traffic management

One of the most immediate consequences of the pandemic has been a noticeable drop in traffic and related activities caused by the lockdown imposed by governments all around the world. Traffic data can be used as a proxy for social activity, revealing compliance to lockdown implementation. An effective lockdown is characterized by a dramatic decrease in traffic level for a given area, so it could be used as a reliable way to detect lockdown compliance. High-resolution optical panchromatic as well as visible, and near-infrared multispectral data sets with a good temporal resolution can be used to infer information about real-time traffic movements that can substantially help monitoring the pandemic.

Tracking supply chains

Supply chains equipped with tracking technologies enable companies to adjust rapidly to changes. Radiofrequency identification (RFID) tags are replacing traditional barcode scanning, reducing the time required to progress through the supply chain (Kewalram, 2020). In complement to EO tracking, the connection of transport systems through satellite communications could help increasing the automation of supply chains by providing not only precise positioning of trucks, vessels, and trains, but also by enabling communication between individual parts of the supply chain.

3.2.4. Gaps and challenges

The most obvious obstacle in pandemic monitoring is the technical inability to monitor the disease directly from space, forcing us to rely on surrogate parameters. The correlation between two parameters needs to be researched and established before formulating conclusions. An evidence-based approach requires an appropriate data set, so it is unrealistic to expect a robust assessment in the initial phase of a new disease outbreak.

Well-coordinated international research on the use of satellite data, however, may swiftly advance the understanding of proxies that are relevant to disease activity, which can be used to develop predictive models like a hierarchical risk model that integrates space-based, aerial, ground-based, and crowd sourced data.

A transparent communication in the uncertainty of the data is essential. Policy makers and the general public must be made aware of the limitations of the available data to promote confidence in its use.

3.2.5. Recommendations

For example, Dr Helena Chapman of the NASA Applied Sciences' Health and Air Quality Program (HAQ) highlights the "One Health" concept to promote cross-cutting scientific collaborations that use innovative data and technology (such as EO satellite data) to identify risk factors and develop approaches to complex global challenges that influence the ecosystem. "One Health" is defined as a collaborative, multisectoral, and transdisciplinary approach—working at the local, regional, national, and global levels—to achieve optimal health outcomes for all. (CDC, 2020). We believe this framework could be of significant benefit in space technology utilization if adopted globally. In 2004, NASA launched a partnership with the CDC. A primary driver for this partnership was to make greater use of remote sensing data in collaboration with NASA's HAQ program (Chapman and Haynes, 2020). The GeoHealth research group is another excellent example of this, their goal being to aid global health through the use of geospatial data in regional research hubs. Working in collaboration with WHO and organisation such as UNICEF, they offer the opensource AccessMod geospatial software in low/middle-income countries to aid health practitioners and Ministries of health in decision making. (Université De Genève, 2020). Through increased collaboration and joint-teaming initiatives, skilled professionals and decision-makers at all levels will have an opportunity to gain deeper understandings of existing technological capabilities, available resources, and identification of critical gaps.

Partnerships between policy makers, satellite providers and scientists like remote sensing experts, public health professionals, and researchers, benefit greatly from cross-domain shared knowledge and expertise. This approach should also identify the best use of available data elements to inform policy makers on key decision areas.

Remote sensing data can be especially useful in providing information about isolated areas and indigenous populations that are otherwise inaccessible. However, an adequate medical response requires an effective public health infrastructure and the capacity to use the data productively. (Piot, Soka and Spencer, 2019) highlighted the impact of inadequate funding and limited investment into the West African healthcare system regarding the management of the Ebola epidemics. Disease monitoring in areas of conflict is a hard and dangerous task for both humanitarian workers and domestic professionals because medical resources are often depleted, and medical centers can become military targets.

As an example, another approach towards the further development of proxies could be to merge data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) found on NASA's Terra satellite and the Ozone Monitoring Instrument (OMI) onboard NASA's Aura satellite. This data set could provide additional information that can be used as an environmental proxy to monitor COVID-19.

Tracking systems can automatically re-route users to avoid contagious areas (UN iLibrary, 2019). This form of dynamic re-routing should also be considered for delivering medical supplies and first-need goods while avoiding transport bottlenecks and restrictions. However, tracing of suspected COVID-19 carriers and related contacts using mobile location data has sparked privacy concerns that need to be properly addressed at policy level.

3.3. **Technology Assets**

3.3.1. Overview

Satellite-based EO (Earth Observation) offers the ability to monitor extremely wide areas, taking multiple image samples over time, and storing image related data to perform time series analysis.

Remote sensing, GIS, (Geographic Information System), communications satellite constellations, and global navigation systems are all space technologies that have been used to address the COVID-19 crisis. Satellite data is sensitive to behavioral changes on the environment, so by tracking observable parameters we can infer correlated phenomena.

Geospatial anomalies can reveal the expansion of the COVID-19 virus by providing information on the number of people affected, and by updating real-time data collected on the ground with those coming from GIS platforms. For an overview on the remote sensing technologies, please see Appendix B, Remote Sensing Technologies.

While **telecommunication satellites** don't have actual monitoring capability, information can be extrapolated from data users. As an example, Telecom satellite operators collect information on current subscribers. This data collection strategy has been put at the service of some governments to support strategies aiming at understanding virus spreading. In particular by figuring out the dynamic structure of population movements. The key lies in understanding large movements of population across countries, with up-to-date information. By developing statistical frameworks respecting privacy, telecom operators can offer decision-making to planners complaint with stringent privacy regulations (Orange Group, 2020). For an overview on the existing satellite telecommunication systems, please see Appendix C, Satellite Communication Constellation.

A **global navigation satellite system (GNSS)** is a satellite application that enables users to identify their global coordinates on land, water, and air. Traffic data analysis, often in real-time, are supported by GNSS. The widespread use of GNSS-capable mobile devices, through tele-consultation, offers an alternative to the traditional face-to-face medical follow-up of patients, an approach that is particularly relevant to tackle global public health emergencies, while localizing patients. However, tracing of suspected COVID-19 carriers and related contacts using mobile location data has sparked privacy concerns. Tracking systems can automatically adapt the travel route for users to avoid contagious areas (UN iLibrary, 2019). Please see appendix B for more references on GNSS and available systems.

3.3.2. Gaps and Challenges

Monitoring hard-to-reach areas without global communications

Satellite communication is an essential tool to monitor infectious diseases in remote and underdeveloped locations where ground-based telecommunications infrastructures are missing, and mobile network coverage is limited. Health professionals use satellite equipment to interchange voice and data with medical points and hospitals, identify hotspots, track the spread of the disease, and death/recovery rates (MnINa12, 2020); COVID-19, 2020 (Telecoms Sans Frontieres, 2020). Additionally, several e-health platforms and telemedicine solutions employ satellite connectivity to assist health professionals (Satmed, 2020); (MnINa12, 2020) in regions where telecommunications infrastructure is likely to be weak or unavailable.

Disease monitoring in areas of conflict is a hard and dangerous task for both humanitarian workers and domestic professionals because medical resources are often depleted and medical centers can become military targets (as an example, the internet connections to protect the Syrian population from COVID-19, 2020) (Telecoms Sans Frontieres, 2020).Global Positioning System (GPS) is the most used GNSS. However, Galileo and GLONASS have better positioning accuracy than GPS. Continuous, unobstructed global coverage is not possible with GPS-only positioning because a natural or an artificial obstacle can break the line of sight with one or more satellites over certain areas (Telit, 2018), A research has shown how to combine multiple GNSS signals for precise positioning (Li et al., 2015).

A multi-GNSS receiver has several advantages over GPS-only positioning because it improves the availability of a navigation signal, increases security, and ensures better data integrity that is crucial for industries like rail and automotive, using satellite navigation (Telit, 2018).

3.3.3. Recommendations on GNSS and telecommunications satellites

An optimized and reliable positioning system is required to provide coverage in areas with inadequate telecommunications infrastructure. Global coverage by the Galileo and BeiDou system was completed in 2019 and 2020 respectively. While research on the development of multi-GNSS receiver has been under way for a long time now, the availability of such receivers to end-users is still lacking. We recommend accelerating the development and manufacturing of multi-GNSS receivers to address the challenge of reliable global coverage in remote areas. The above recommendations support and promote achieving of several SDGs, namely SDG 2: Zero Hunger, SDG 3: Good Health and Wellbeing, SDG 9: Industry, Innovation and Infrastructure, SDG 10: Reduce Inequality within and among countries, SDG 17: Partnerships to achieve the Goal. The proposed measures like multi-GNSS receivers, multi-system satellite communication phone, and providing satellite connectivity to medical professionals in hard-to-reach and conflict areas are aimed to improve the response to epidemics in developing countries and countries where no other connectivity is available. Since epidemics are one of the hardest health-related challenges, these measures strongly align with the SDG 3 (target “Strengthen the capacity of all countries, in particular developing countries, for early warning, risk reduction and management of national and global health risks”).

The development of a multi-satellite system communication phone with the technical capability to connect to various systems is also advisable. An application that displays the locally available communication satellites from various constellations would also ease and accelerate the access to a satellite communication system, as current apps are limited to specific satellite system. The application should enable the user to filter the systems by latency, costs, duration of availability, and so on. The application should also clearly explain how to connect the end user’s device to the selected system.

A reliable communication channel is essential to further improve the resilience of supply chains and ensure reliable supply during epidemics or other disasters, especially in remote areas.A Global effort in providing satellite connectivity to medical professionals in hard- to-reach and conflict areas in terms of hardware equipment and organization of support is recommended

3.4. Data processing and artificial intelligence for earth observation

3.4.1. Overview

As of 2020, the use of artificial intelligence (AI) for Earth observation is experiencing significant growth. AI tools and methodologies enable deep exploration of large data sets while providing meaningful insights and enhanced prediction capabilities.

The field of computer vision applied to high-resolution satellite images, in particular automated feature extraction, is essential. The main processes include detection, classification, recognition, and indexing of the images within its context

These large data sets –in the order of magnitude of petabytes– needs to be fragmented, cleaned, and prepared before use. Typical machine learning tasks performed on the image are classification, feature detection extraction, and automatic recognition and identification to detect changes at the global scale. Large data archives must also be indexed to make them accessible through text mining.

Feature extraction and classification, when automated, can help high-level processing of thousands of images, comparison with other datasets, and produce data visualization for decision making. As an example, advanced developments supporting the automation of target recognition to detect proxies for COVID-19 (see Appendix D, COVID-19 Data Sets) have proven effectiveness. The machine learning techniques used in this example were based on convolutional neural networks (CNN) with multi-sampling and location positioning on images. The inductive learning is not limited to clustering techniques: depending on the class of problems to address, reinforcement learning, and random forest techniques can be more effective. CNN and deep neural networks require an important quantity of labeled data for training datasets. Just as an example, the BigEarthNet dataset contains 590,326 Sentinel2 image patches (BigEarthNet, 2020). Unfortunately, this data is often unlabeled. Data labeling is a necessary step that creates an additional workload to data scientists working on feature extraction automation.

3.4.2. Challenges on Data

We identified significant challenges affecting the ability of satellite data analysts to deliver answers in an effective and timely manner. While there are established satellite technologies and facilities for the monitoring of the COVID pandemic, many challenges and gaps are still in the way of effective data usage.

EO data processing is currently limited by several factors. Satellite data is gathered from various sources like multispectral, hyperspectral, infrared, microwave, SAR (Synthetic Aperture Radar), LiDAR (light detection and ranging). The diversity of data derived from multispectral optical sensors acquiring several images in different spectral channels and radar sensors delivering information on amplitude, frequency, phase/polarization, from new generation of SAR satellites complicates data fusion. Satellite data processing needs specialized image processing software like Erdas, ENVI, PCI and so on, whose licenses are extremely expensive. Moreover, these software packages require highly specialized skills. AI and machine learning systems, which are significantly simplifying data labelling and structuring, require specialized hardware. For example, both Airbus' Pixel Factory and PCI Geomatics' GXL require expensive GPU based hardware, while the kind of atmospheric data processing required in weather forecasting needs a powerful super-computer and customized software.

The remote sensing estimated geophysical parameters require a significant work in terms of data cleaning, formatting, normalization which is one of the major tasks for AI applications. A considerable task to be considered prior to any AI application, is data preparation, which includes data cleaning, curation, formatting, co-gridding, and normalization. Diversity and scale of the data adds to the complexity of preparation. The very high dimensional data from remote sensing problems (multispectral, hyperspectral, multiangular, multisensory, and multitemporal), slows direct adoption of standard deep learning strategies that use pretrained models.

Data of quality availability is also a key challenge. Several EO open sources do not meet the quality standards required for research. Spatial and temporal resolution are critical factors. For example, the spatial resolution of Copernicus' open imagery may not be enough to detect the level of detail required by an application like transportation monitoring, where the spatial resolution needs to be high enough to enable proper vehicle identification within the limits set by country-specific remote sensing policies.

Data storage is a critical aspect of Earth Observation because of the sheer volume of satellite images. Data grows exponentially, and with it the need for data mining on distributed large data sets obtained from new constellations (for instance, Copernicus' combined capabilities is of 250TB/day). Land monitoring of a country or continent requires proper categorization, storage and data management, trained personnel, and appropriate policies. Current datasets generated by EO from private and institutional constellations can also be complemented by data derived from smart sensors, Internet of things (IoT) connected objects, unmanned platforms, high-altitude pseudo-satellites (HAPS), social media, and other crowdsourced sources, further increasing the volume of data. While online cloud storage can be a valid storage solution, it also presents other issues around privacy and classified data protection policies.

3.4.3. Gap analysis

There is an exponential growth of data from the rising number of space assets, with insufficient growth of storage and data processing capacity on the ground. As highlighted by Dr. Nicolaus Hanowski, department head of ESA's ground segments and operations, during a lecture at ISP20, "Copernicus satellites deliver six operational services and generate 250TB of data per day. Europe still lags behind in capability to process all this new big data" (ESA, 2020).

Quantum computing could form a part of the solution to this problem in the long term; however, the technology is in its early stages and it could require years before to reach maturity.

Proper image analysis requires significant skills. A multi-level processing is often needed to extract the useful information from raw data. While in some cases the data is geographically tagged, too often it is only georeferenced.

We couldn't identify a global framework for the integration of multiple data sources, with the exception of the Sendai Framework by the United Nations disaster risk reduction.

3.4.4. Recommendations

The availability of real-time satellite data, which is critical in the assessment of an ever-evolving pandemic, is still inadequate. The combination of this data with other reliable data sets, needs to meet appropriate reliability standards if used for decision-making. While the WHO, governmental organizations, and hospitals can provide vast quantities of data during pandemic and epidemics, it can be difficult to integrate them in time to affect decision making during the crisis (Zhou et al., 2020).

We recommend to expand the use of AI and in particular machine learning and invest in state-of-the-art IT infrastructures to enable scalable automation to effectively track, monitor, forecast, and model the spread of a pandemic.

A general issue with AI as of 2020 is the fact that its internal decision-making model is can be opaque. We need to move towards a more transparent and explainable AI, especially in all applications that affect individuals, to be able to trace back decisions.

Satellite sensing also needs to be integrated with ground-based and crowdsourced data, building trust with health care workers and local communities.

3.5. Economic Outlook, Regulations and International Collaboration

3.5.1. International Collaboration

This section explores potential opportunities and challenges of international collaboration for the monitoring of pandemics. We use the United Nations Sustainable Development Goals as a benchmark to ensure that our recommendations are in line with the 2030 Agenda for Sustainable Development as adopted by all the United Nations member states in 2015 (UN DESA, 2020).

General Overview and Challenges

The WHO International Health Regulations (2005) set a goal to prevent pandemics without further harm international traffic and trade. These regulations state that every nation shall develop the capacity to detect relevant public health events, with the assistance of the WHO if needed (ibid, art.5). States shall notify the WHO if these events occur within their own country (ibid, art. 6), or when imported (ibid, art. 9). The WHO analyzes this information and, when relevant, share it with other countries (ibid, art. 10 and 11).

Associated challenge:

A potential gap is that the WHO does not have to be informed if and when information pointing to an infectious disease in another country is received through remote means like space-based assets.

Companies and organizations providing satellite data are not uniformly distributed. In 2018, 49% of the satellites in orbit were operated by US-based organizations, 13% by China, 7% by multinational corporations, and 6% by Russia (Satellite Database | Union of Concerned Scientists, 2020) (Infographic: The Countries with the Most Satellites in Space, 2020). However, data collected from space is also beneficial to countries without significant presence in space, especially during pandemics. These nations face additional obstacles, like the lack of expertise in remote sensing image processing. Currently, aid is not given based on objective parameters, but rather on state and media attention (Zannoni, 2019).

Associated challenge:

International organizations and initiatives are required to ensure that health-related data and information are distributed globally wherever they are needed, so all countries can effectively monitor a local pandemic.

Within the existing space and disaster management framework there is no international initiative focused exclusively on pandemics. The International Charter on Space and Major Disasters defines “natural or technological disaster” as “a situation of great distress involving loss of human life or large-scale damage to property, caused by a natural phenomenon […], or by a technological accident […]” (Article 1 - Text of the Charter - International Disasters Charter, 2020)(article 1). While this definition does not include outbreaks of infectious diseases, epidemics, or pandemics, the charter has been activated during the 2014 Ebola outbreak in West Africa (Activations - International Disasters Charter, 2020). The WHO used the high-resolution imagery from the International Charter as part of their Global Ebola Response Mapping and Monitoring System (Asrar et al., 2015).

Another initiative listed by UN-SPIDER is the Copernicus Emergency Management Service (EMS). The EMS has been activated four times for the monitoring of epidemics. Three of these activations were for an outbreak of Ebola: in 2018 in the Democratic Republic of Congo; the Ebola crisis in West-Africa in 2014; and the Ebola epidemic in Guinea [CEMS source on activations]. The satellite data was used to find out where the virus originated and to produce maps for coordinating medical responses (Extance, 2014). Most recently, the Copernicus EMS was activated for the outbreak and spread of COVID-19 in Italy (List of EMS Rapid Mapping Activations, 2020). The data was used to create dynamic satellite maps, continuous census and actual usage (vs. Expected) of mobile and temporary hospital infrastructure [UNOOSA webinar].

Associated challenge:

These activation examples show that these initiatives can be useful in dealing with a pandemic, but the activation criteria of the various initiatives remain unclear and inconsistent.

Recommendations

We propose to the members and partners of the international charter for space and major disasters to EITHER amend the charter to include a new section focused on epidemics/ pandemics OR the creation of a similar charter specifically targeting international collaboration on sharing information on monitoring of epidemics/ pandemics. The decision to amend or create should be based on minimal impact to the members and partners as well as to the effectiveness of the existing charter. If a new charter is to be created, it should mimic the existing charter in its members, partners, and framework for activating the charter.

a) We urge continuing the inclusion of commercial partners to the charter, such as the current inclusion of Planet in 2018 (Zolli, 2018).
b) We suggest the WHO as a potential member of the charter, who can assist in identifying the appropriate parameters to monitor depending on the specifications of relevant epidemics/pandemics.
c) Based on the topics covered in previous sections of the report, we suggest the intent of activation of this charter be to aid in the monitoring of relevant factors, including but not limited to:
    i) Medical infrastructure
    ii) Environmental proxies
    iii) Economic impacts

Potential Conflicts of recommendation

We acknowledge the potential political implications of a request of activation requested by a country on another country based on data monitoring. It is important to recognize that the information shared under such a charter needs to be contextualized appropriately for the local situation and should only be used for the purposes of monitoring pandemics. We rely on the ethical standards of the participating actors to adhere to the specifications of the charter.

Link to Sustainable Development Goals

This recommendation meets the intent of SDG3 (“Good Health and Wellbeing”). SDG16 (“Peace, Justice and Strong Institutions”) and SDG17 (“Partnership”) will also be positively impacted by a stronger international collaboration on sharing remote sensing and Earth observation information for the monitoring of pandemics. Additionally, SDG10 (“Reduce Inequalities”) is also addressed because we promote the sharing of information between space-faring and non-space faring nations, closing the gap of inequal access to outer space data. This is in line with the first article of the Outer Space Treaty, which states that the use of space “shall be carried out for the benefit and in the interest of all countries, irrespective of their degree of economic or scientific development” [Outer space Treaty].

3.5.2. Business and Market outlook:

The global space economy was an estimated USD 423billion in 2019, with around 79.5% coming from commercial revenues and 20.5% from government budget.[1] The sector grew 6.7% on average in the years 2005-2017, outgrowing the overall global economy (2). According to BofAML (Bank of America ML) and Morgan Stanley, the industry will triple to octuple its size by 2040 (3).

Of the 423bn$ overall economy size, around 80% is represented by the satellite industry. In the case of Earth observation, global revenues have been increasing double digits since 2013 with an expected CAGR of 8.5% to 2025. This result was mainly caused by the decreasing launching and operating costs of smallsat technologies and by an increased demand for data analytics by industries like agriculture, insurance, and health as the indispensable basis for nowcasting, impacts mitigation and recovery. Please see full findings in Appendix E.

Despite the economic downturn caused by COVID19, the space sector maintains its momentum. In Q1 2020, COVD19 caused a decrease in space infrastructure investments of 33% but an increase of 39% in space applications investments, as demand for online platforms/services and remote working increase. In general, governmental agencies stepped in with contracts to support the sector, which is expected to play an enhanced role (especially in the monitoring applications) in the post-COVID world. Contrary to expectations, venture capital investments increased 4%, on the wave of space application investments (5).

At the same time, Space agencies budgets might face pressures for reduction, as governments need to fund short term losses of the economy. An alternative to staff cuts, in this respect, could be to outsource or to subcontract (as an example, agencies have started giving money to private entities for micro-launchers) and to focus activities on high-ROI applications programs involving New Space players.

Another barrier to resilience, ROI efficiency and growth of the sector are the relatively small space-specific expert knowledge in private industries, especially in non-tech and non-electronics focused sectors. For this reason, potential of space monitoring for sectors such as health remain relatively unexplored. Lack of cross-industry expertise also keep the space customer base largely limited and dominated by governmental players and few billionaires. Finally, the downstream sector, especially in Europe, would benefit from further specialization, a stronger downstream-upstream interlink and a financing system that supports scale-ups (high-risk, medium term financing system).

Recommendations

(For the full list of recommendations, see Appendix E)

While we see an immense social and economic benefit from EO monitoring of pandemics, we recommend, in these times of downturn, that space agencies join efforts with private companies in developing disruptive space technologies with a high ROI.

<u>In particular:</u>

To support resilience and growth of the space sector, especially New Space players and SMEs, we recommend:

a. Devise a technical/policy/financial advisory portal dedicated to connect space-focused SMEs.

b. Link any investment from agencies or from governments to spin-offs, and suggest governments to invest in activities with high return factors.

To improve economic traceability of the overall sector and facilitate its financing, we recommend:

a. Compare EO technologies with existing solutions to perform cost benefit analysis that can be used to convince public decision makers to invest.

To increase cross-industry fertilization, we recommend:

a. Explore business models based on joint ventures between space and traditional industry, between traditional and New Space and between established and new players (like OneWeb and Airbus, Alenia Space and Spaceflight industries). This kind of partnership would shorten the S-curve, likening space investments to those in tech and creating an ecosystem of potential startup acquirers, forming expertise outside the space industrymajd developing an increased customer base.

b. Insert anchor tenancy within PPPs, establishing long term, KPI-based commitment from a public entity to buy data/services/products from the private sector, like what NASA did to 'grow' SpaceX. A similar strategy could be also pursued by non-space public actors, like the WHO or national health services, in combination with grants/co-finance to cover procurement costs, acting as the first customer of innovative commercial solutions like an AI-enabled service deriving pandemic-related analytics from the intersection of publicly available satellite data and geo-localized IoT on a population sample.

3.5.3. Regulations and Data Privacy

Monitoring pandemics from Space: legal framework

Five international agreements (UNOOSA, 2020b), drafted and adopted in the sixties and seventies of the 20th century, form the core of the outer space law. The Outer Space Treaty outlines guiding principles related to the use and exploration of outer space that may apply to space monitoring in general. Article 1 states that the use of outer space shall be carried out for the benefit and in the interests of all countries, and it shall be the province of all humankind. Space shall be free for exploration and use by all states without discrimination of any kind and on a basis of equality. States shall carry activities promoting international cooperation and understanding. However, the OST does not specify health protection as the objective of space activities, and do not contain any reference to pandemics.

When public health became a more relevant topic, the United Nations recognized the immense potential of space technologies for global health. The UN Conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE III) of 1999 recommended to "improve public health services by expanding and coordinating space-based services for telemedicine and for controlling infectious diseases." The UNISPACE +50 report further confirmed the intention to strengthen space cooperation for global health.

In its resolutions (UNOOSA, 2020a), the UN Committee on the Peaceful Uses of Outer Space (COPUOS) remarked the importance of space in combating infectious diseases and reminded that "space science and technology and their applications have and will continue to have a significant role in achieving the comprehensive 2030 Agenda for Sustainable

Development and the Sustainable Development Goals" that include good health and well-being.

Remote sensing and satellite navigation are the main space technologies used to monitor pandemics from space. The only international act specifically regulating remote sensing activities is the UN General Assembly Resolution 41/65 of 9 December 1986 on Principles Relating to Remote Sensing of the Earth from Outer Space (UNOOSA, n.d.). This non-binding act establishes freedom of remote sensing from anywhere, at any time, and by anyone, underlining that these activities shall be conducted in accordance with the Charter of the United Nations, the Outer Space Treaty, and the relevant instruments of the International Telecommunication Union (UNOOSA, n.d.). Because of the lack of adequate legal regulation at the international level, some national laws governing licensing and very high-resolution systems were adopted at the national level, making remote sensing regulations non-uniform across countries.

GNSS which can be used to determine users' locations and track movements, is another space technology that can be used to monitor pandemics. Like other space activities, satellite navigation is subjected to the principles of the Outer Space Treaty and must be conducted in accordance with international laws and ITU regulations.

The rapid development of space technologies has led to the regulations through legal instruments that are not directly related to the outer space law. Examples are information technology law, intellectual property law, environmental law, and regulations of numerous international organizations. To reduce and manage disaster risks, under the auspices of the International Telecommunication Union, states have signed the Tampere Convention that governs the provision and availability of telecommunication during disasters (Tampere convention, n.d.). The Convention, which defines outbreaks of infectious diseases as health hazards, may therefore be applicable to pandemics too.

Rights to privacy and its relevance to space monitoring

Remote sensing imagery and navigation provide unique opportunities for collecting and transmitting information on the location and movement of populations. While these activities are allowed by international laws, they raise legitimate legal and ethical concerns, especially in the context of possible privacy violation.

International human rights belong to a separate branch of international law that is not reflected in outer space law. The Universal Declaration of Human Rights (United Nations et al., 2002), the International Covenant on Civil and Political Rights, the European Convention on Human Rights are adopted by many countries. The right to privacy includes the prohibition of arbitrary interference with the subject's privacy, family, home and/or correspondence.

Current space technologies provide extensive monitoring capabilities. While satellite imagery is generally used to observe relatively wide areas, geospatial data is accurate and personal, and therefore, more sensitive. The 2020 outbreak of the Covid-19 pandemic has demonstrated the widespread use of navigation services to track people's location and movement. The government of South Korea, for example, used geospatial data to track the location of new airport arrivals and to support existing testing networks and contact tracing (Business Insider, 2020). Another example is Israel, whose government authorized the collection of location data of people who were sick and those who should be quarantine (The

New York Times, 2020). These measures, while justified for the purpose of public health protection, may still constitute a privacy right violation.

In the late 2010s, Europe has begun introducing stricter rules to discipline the collection, processing, and transfer of personal data. The General Data Protection Regulation (GDPR), introduced in May 2018, puts strong requirements on governmental and private controllers and processors of personal data to establish appropriate technical and organizational measures to implement data protection principles that include lawfulness, transparency, and purpose limitation For the processing of personal data, the consent of the data subject is essential.

While geolocation data from mobile devices doesn’t contain any information about the owner, it can be considered personal according to the GDPR if the location data leads to the identification of an individual. This data is usually collected and processed not specifically for health-related purposes. It is debatable whether this kind of data collection is compliant with the GDPR because any change to the purpose would require the explicit consent of the data subject.

Conclusions

The issues of personal data collection, ownership, and access may raise legitimate concerns about the legitimacy of space monitoring. To which extent are state authorities allowed to interfere with privacy? Is public interest a sufficient justification to violate personal rights? Are the same concerns valid when data is collected by a private company? What is privacy in the age of rapid development of space and computing technologies? The answers to all these questions are not obvious, and they may depend on the legislation of each particular country. Comprehensive research involving experts in science and technology, law, ethics and philosophy, can also be helpful in analyzing the underlying issues.

As of 2020, many areas of space activities remain unregulated. The need for an international instrument to regulate remote sensing and navigation becomes increasingly important as the space industry continues to grow. A clear and effective international regime could sort up the use of space technologies and give certainties to governments and private companies entering space domain in the New Space age. An international legal framework similar to the European air traffic control may be required to establish a unique global space-based satellite system that will regulate data management and determine principles on personal data protection worldwide.

4. Conclusion

The main finding of this joint research is the need to establish interdisciplinary partnerships between policy makers, space-service providers, and pandemics specialists. Scientists could involve remote sensing experts, public health professionals, and researchers in the Geo Health Community of Practice. This partnership could benefit greatly from shared knowledge and domain expertise from each respective area of practice. This combined multi-disciplinary knowledge would enable a better understanding of health issues, resource availability, space technology capabilities, gaps with current solutions, and reasonable expectations for success. This approach should also identify the best use of currently available data set to inform policy makers on key decision areas. Interdisciplinary data sandboxes might help practitioners of remote sensing data and pandemics specialists to create innovation. It is worth noting that the cost of certain remote sensing data sources could limit its accessibility, therefore constraining the full impact of an identified solution. Another key aspect of these partnerships is the dissemination of skills and through public outreach, specific interdisciplinary education programs, and training sessions aimed specifically at developing countries, including toolkits in the local languages when necessary.

A way to create more access and awareness is an open data policy for EO, which is thoroughly discussed by institutional bodies, as an example by the European Commission. The majority of the current data delivery models lies on governmental organizations leading significant size programs, while making the EO results available at no cost. One potential evolution could be to open the commercialization of images at fixed cost, enabling the emergence of an ecosystem of commercial operators. For resilience and availability, a hybrid model including both private and public entities would guarantee access to the service. Governments should add consistency by issuing proper regulation mechanisms for commercial operators. In this sense, while space agencies NASA, ESA, and JAXA will gradually become just like other customers for New Space companies, the presence of open data, such as EOSDIS from the US and Copernicus from Europe, is likely to act as a strong challenge to market growth and eco-system emergence. Therefore, the support to create funds and initiatives for the purpose of growth of interdisciplinary new ventures on geo health would be beneficial as a whole for the eco-system.

The global space economy has been outgrowing the overall global economy due to increased privatization, in the case of New Space, and business model innovations. Returns on EO and monitoring (ROI) are already high and they have a potential for further increase. While the presence of open data and the lack of effective growth finance are strong barriers, especially in times of economic downturn when impact on the start-up ecosystem is expected to be substantial, the EO segment is expected to significantly grow. Further incorporation of technology and business model innovations will lead to an increased outsourcing of current institutional internal activities and a wider use of PPPs and joint ventures will provide additional resilience.

This emerging eco-system will stimulate the exponential growth of data from the rising number of space assets, with insufficient growth of storage and data processing capacity on the ground. While new technologies like quantum computing could provide a solution to this problem in the long term. In the meantime, the expanded use of machine learning and related AI techniques, paying attention to explainable AI for decision-making, and greater investment in supporting computing infrastructure can enable the automation at scale for monitoring solutions to screen, track and model the spread of pandemics in a safe way.

These objectives can only be achieved with international cooperation. As of 2020, many areas of space activities remain unregulated. The need for an international instrument to regulate remote sensing and navigation becomes increasingly important as the space industry continues to grow. An evolution of the international charter for space and major disasters, a major instrument in the solving crisis around the planet, would support better policy understanding pandemics outbreak and its evolution. We believe that amending the charter to include a new section focused on outbreaks of infectious disease, pandemics and epidemics or the creation of a similar charter specifically targeting international collaboration on sharing pandemic monitoring data would lead to improved international cooperation to identify better joint solutions.

Privacy and ethics are central concern at the heart to ensure the respect of personal rights and the legitimacy of space monitoring. Boundaries and proper regulations on governmental authorities and commercial operators needs to be properly to ensure proper use of space assets and data processing. While this issue is certainly complex, we believe that the rapid technology development calls for an urgent answer to ensure that these essential rights are respected.

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Appendix A

EO Dashboard indicators JAXA NASA ESA

Table 1: Indicators as shown on the EO Dashboard provided by ESA, NASA and JAXA

Economic	Agriculture	Environment
• Import/production sites: status of metallic ores • Airports: throughput • Import/production sites: status of non-metallic ores • Finished goods production; output inventory level • Activity (cars/containers) • Nightlights • Population	• Productive areas • Activity indicator • Productive area change • Harvested parcels evolution over time • Harvested area evolution over tile • Harvesting activity: cumulative harvested area • Planting activity	• Air Quality • Greenhouse gases • Water Quality Regional Maps • Water Quality Time Series

Appendix B

Remote Sensing technologies
The main families of sensors include:

- Optical/Multispectral (Pleiades, World dView, IKONOS, Cartosat): These PAN/MX (panchromatic images) sharpened imagery deliver high spatial and temporal resolution data about crowds/cars/population density in places with public interest. This enables visual estimation and allow for further processing with feature extraction and a AI-based classification methods.
- Hyperspectral and spectro-radiometers: These sensors monitor the spectral properties of the ground and air quality data, which can be used for the detection of greenhouse gases. Future missions could plan a combination of hyperspectral sensors and atmospheric sensors to detect traffic (related gaseous anomalies in real-time.
- Thermal and infrared : These sensors can measure nighttime light emissions data.
- SAR/SLAR technology: These are a high-spatial resolution sensors using a radar antenna. Resolution depends on aperture and band Multi-frequency radar can bring improvements in monitoring. As an example, Israel and NASA are developing the dual-frequency radar: C-band and L-band, while Japan has the only real L-band that is reliable.

Geographic Information Systems (GIS)
Geographic Information Systems (GIS) use a combination of computer hardware or storage, software or processing tools, data products, and experts dedicated to sense, gather, and process geospatial information efficiently. A GIS allows the user to visualize spatial data, combining multiple data sets in ‘layers’ over a geographical area, enabling decision-makers to recognize patterns that are not apparent in the individual layers.

The use of GIS data as a reactive measure for isolated incidents in a time-limited matter is less effective than as a proactive on-going program tackling multiple issues (Boulos, 2004). Additionally, some data is underutilized and is not contributing to the decision-making process (Krisifoe, 2018). For an overview on GIS, see Appendix B, Geographic Information System (GIS).

GNSS
Existing constellations include US’ Global Positioning System (GPS), Europe’s Galileo, Russia’s GLObal NAvigation Satellite System (GLONASS), Indian Regional Satellite Navigation System (IRNSS), and China’s BeiDou Navigation Satellite System (BDS).

Appendix C

Satellite Communication constellations

Table 2: Overview of existing satcom systems and coverage

MSS (Mobile Satellite Systems)	Coverage	Latency	Frequencies	Provided Service
Geostationary				
(Inmarsat, n.d.)	Global (except polar regions 80° S/N)	900-1100 ms	L-Band	Phone connection, email, SMS
(MnINa12, 2020)	Europa, Africa, Asia	< 800 ms	L-Band	Internet, Phone and SMS
(Viasat, 2020)	America, Europe, North Atlantic	Ca. 638 ms	Ku-/Ka-Band	
(Intelsat, Intelsat Satellite Network, 2016)	Global	?	C-, Ku-, Ka-Band	Broadcast and VSAT services, mainly Internet & TV
(Eutelsat, n.d.)	Global	?	C-, Ku-, Ka-Band	Mobile and stationary internet
Non-Geostationary				
(Ground Control, 2020)	Global	700 to 900 ms (expected to be 40 to 50 ms in future)	L-Band	Phone connection, mobile & stationary internet
(Globalstar, 2020)	Global (except polar regions)	?	L-Band	

Appendix D

COVID-19 Data Sets

These developments are moving forward thanks to the rise of deep learning and reinforced learning for object recognition.

A complete satellite data tool chain includes visualization, user interaction, analytics, processing architectures, security and data management, cloud and high-performance computing (HPC), and sensors. The data processed within a network infrastructure needs to go through an assessment in terms of cybersecurity

The recent COVID-19 has made available an important and massive number of data-sets to help data scientists and experts have access and to be able to propose solutions. In particular, the following data sets have been comprehensive

Table 3: COVID-19 studied open data-sets for data scientists

NOAA COVID-19 Open data	Environmental Data for Infectious Disease Research
European Data Portal	Related to several data challenges regarding, work, transportations, statistics of mortality, location.
ESA	EuroDataCube
John Hopkins University	Covid -19 data sets for USA
Kaggle	COVID-19 Open Research Dataset Challenge (CORD-19) An AI challenge with AI2, CZI, MSR, Georgetown, NIH & The White House
Azure data sets	COVID-19 Data Lake
French gov	COVID-19 Worldwide Data
OpenDataSoft	COVID-19 Data catalog
CDC	Pandemic resources
ECDC	COVID-19 pandemic
Allen AI Inst	CORD-19: COVID-19 Open Research Dataset

Appendix E

Economic, Markets and Financial Outlook

The global space economy was an estimated USD 423.8 billion in 2019, more than three quarters coming from commercial revenues and the rest coming from government budget.[1] The sector grew 6.7% on average in the years 2005-2017, outgrowing the overall global economy (MnINa12, 2020). The expectation is, according to BofAML and Morgan Stanley, for the industry reach triple to octuple the size by 2040 (Viasat, 2020). – Before the commercialization of the space industry, only states were investing in the sector. Its increased privatization has a substantial role in the development of space applications and has revealed several opportunities for agility and innovation which, in turn, generates affordability for our daily services.

Similarly, to Uber and Airbnb disrupting the traditional business models of the hotel and transportation industries, decreasing users' transportation and accommodation costs substantially, newspace startups are bringing cost-effective solutions and lower risk business models broadening access to space. As a consequence, space agencies such as NASA will become one of many customers for these newcomers.

Of the 423.8bn$ overall space economy size, around 80% is represented by the satellite industry. In the case of Earth Observation (EO), global revenues have been increasing double digits since 2013 (Inmarsat, n.d.), exactly due to the increased number of affordable SmallSat technologies, agile business models, and decreasing launching and operating costs. EO data is used to support different industries such as Agriculture, Insurance, Commercial, Infrastructure, Health, and Defense. Monitoring assets in these sectors can contribute to significant savings in loss in case of a pandemic such as COVID19. Moreover, predicting and monitoring disasters and diseases will mitigate economic losses and support rescue operations. The EO market is highly competitive and soon to be fragmented due to the presence of many players in the market (e.g. Planet, Earth, Eagle View Airbus Defense and Space with OneAtlas, MAXAR, UrtheCast Corp., Harris Corporation) and new and innovative satellite operators entering it (especially in the US). The increasing demand for data analytics to provide accurate insights of the earth observation across various industries demands a large amount of data (organizations believe that the larger the amount of data, the more accurate insights could be generated), which has significantly driven the demand for EO services. As a consequence, the segment is growing rapidly, being valued at USD 2,743.6 min 2019, and expected to reach USD 4,427.2 m by 2025 (a CAGR of 8.5%) However, the presence of open data, such as EOSDIS from the US and Copernicus from Europe, is likely to act as a strong challenge to the market growth (Mordor Intellignce, 2020).

Whilst the direct lifetime public rate of return for Earth Observation initiatives is between 2.2 and 4.4 EUR for each EUR spent, and between 4.4 and 13.0 EUR when spillover (Intelsat, Intelsat Satellite Network, 2016) effects are considered, it is worth noticing that, especially for EO and remote sensing, the majority of benefits remains non-quantifiable and not-immediately-monetisable in nature. Estimating the ROI of space monitoring of spread and impacts of pandemics implies the preliminary establishment of, at least, uniform and widely recognised qualitative factors and social and environmental KPIs (e.g. percentage of early detected cases/hotspots, efficiencies in critical supply chains, efficiency of containment measures, measures of economic recovery). As such, that public ROI is expected to be larger. Additionally, since leveraged investments as a percentage of initial investment range between 12% and 312% factor for the space (Intelsat, Intelsat Satellite Network, 2016), the overall rate of return is bigger than the purely public ROI.

Incorporation, by newspace startups, of new technology trends such as miniaturization (further reducing costs and time to market), cloud computing, AI embedded within satellites and automatically integrating ground and space-based data, optical and laser communications, reusable launchers, will not only increase spillover effects on private industries (due to a broadening of the customer base), hence increasing the ROI of space investments, but also pave the way for furthering disruption in business models. On one side it will increase the outsourcing of institutional initiatives (e.g. the launch of an individual satellite/constellation being broken down and each subcomponent, including final aggregation, being subcontracted to a different specialized private actor), and PPPs (such as the ones used for TERRASAR, Geoeye and COSMO SKymed), on the other side it might promote the birth of JVs between space and industry partners (e.g. a JV amongst an AI and provider, a CubeSats manufacturer, and an IoT/wearable company to produce advanced data fusion and analytics to detect areas with high risk of contagion). This outlook is already underway: according to Airbus, “Since 2010 NASA has increased its expenditures to private firms in an effort to save money on systems and services, such as maintenance of ISS. SpaceX alone received about $2.6 billion in 2014 from NASA” (Airbus, 2020).

Financing of space companies

Currently, 80% of companies utilize financing for R&D and product development (MnINa12, 2020), mostly in the form of VC/Private equity mixed with institutional grants (non-dilutive nature and a precondition to obtain private financing) and a minimum input from crowdfunding (such as SpaceStarters).

However, institutional funding, especially in Europe, is mostly limited to technology readiness levels that rarely go beyond the business plan and other equity/debt instruments are limited and intermediated, lengthening times for access to finance. Even grants tend to finance ‘established’ innovators (e.g. those with a track-record in patent-filing) rather than disruptors or young entrants (e.g. unicorns). Whilst companies’ growth in the US is supported by a vibrant VC market and a private financing ecosystem of wealthy tech/space players, Europe only has 3 space-focused VC funds (OpenSkyTechnology, Airbus Ventures and Seraphim) and a few countries launching national thematic VCs for space, against the over 120 focused funds in the US.

Additionally, access to scale-up private finance (I.e. business loans, project finance, bonds issuance and a handful of guarantees) remain the biggest hurdle at the company and sector level. This is not only due to bureaucracy and cost of compliance, but also to strict credit requirements determined by a lack of knowledge and lack of predictable revenue streams/exits.

As a consequence, in crisis times such as these, start-ups are faced with the choice among stagnation, early IPO/acquisition or VC funding. But whilst vying for an early IPOs on regional stock exchanges comes at the expense of resilience (as the higher volatility of small cap stocks is enhanced by the overall declining stock market), VC funding prevents from accessing public grants and is exposed to long term, crisis-related reduction in VC investments.

At the same time, whilst pure-play commercial upstream space companies (e.g. SES and Eutelsat) and established newspace players (e.g. Spire and Planet) may appear more resilient due to the more defined market segments/regulatory environments and the relatively lower capital intensity, they will be also long-term-impacted by a contraction in private investments and will have limited startup acquisition power to compensate for startup mortality.

COVID-19 impact on Space Sector

Depending on whether there will be other outspreads and lockdowns, speed and extent of sector recovery may vary and it's anyway expected to be slower for space infrastructure, for non-US actors (which cannot count on the same level of private financing support), and for less established New Space companies heavily dependent on future financing, future contracts and major launches, all of which is currently uncertain/on hold. A medium-term consolidation, much like what happened to OneWeb, is expected; however, there is a risk is that this situation would eliminate an entire small-medium ecosystem of innovation. This uncertainty in employment and economic growth could be re-absorbed by more established commercial players.

Full Recommendations Business outlook

Nowadays, the new era of space emphasizes the preponderant role that space activities and assets play to serve the world needs regarding the health crisis of COVID 19. We see an immense social and economic benefit from Earth Observation satellites into monitoring Pandemics. In this era of financial and economic downturn, we recommend space agencies to join efforts with private companies in investing in space disruptive monitoring technologies due to the high values of expected ROI of this sector.

<u>In particular:</u>

To support resilience and growth of the space sector, especially newspace players and SMEs, we recommend:

- Devise a portal dedicated to space-focused SMEs facilitating their access to finance (and government allocation of public funds), aggregating demand for LEO launches, providing technical/regulatory/financial advice and acting as a financial intermediary for pre-funding, insurance and co-financing solutions.
- Increase blended products (e.g. grants+loans, loans+guarantees) and co-invest with the VC arms of established aerospace players (which could also provide technology validation) focusing new financial products on risks coverage. For example, devising space-focused project finance risk-sharing solutions (e.g. bilateral loss-sharing agreement for project development, satellite insurance for companies with no flight record or access to testing facilities), risk-mitigating instruments (e.g. governmental or multilateral guarantees on bank loans, space-focused export credit finance, revolving fund-of-funds where private VC investments are 'downside-protected' by the presence of a multilateral lender) or bridge finance (e.g. loans covering the launch costs of a portfolio of companies, loans supporting the operations of traditional space companies' supply chain).
- Link any investment from agencies or from governments to spin-off factors, and suggest governments to invest in activities with high return factors.

To improve economic traceability of the overall sector and facilitate its financing, we recommend:

- A robust cost benefit analysis comparing Earth Observation technologies with existing solutions in order to convince government decision makers to make such investments with government funding.

- Standardise regulation, ROI/ KPI calculations and T&Cs for investment via coordinated global and regional space investment forums. These forums would serve as a centre of interdisciplinary dialogue and information on market potential, risk assessment, case studies and best practices (to be shared in an anonymized/aggregated format) so as to facilitate investments from pension funds and other institutional investors. Investment forums could also be utilised as/built upon existing matching platforms, such as Japan's Space Business and Investment matching platform or the Space New Economy Creation Network. Investment forums could also be a reference point to national/regional business angel networks (strengthening of which is particularly important in Europe) and coordinate capacity building initiatives involving financial professionals, policymakers, academia and non-space industries.
- Simplify (administratively) and coordinate grant funding for the space sector, so as to facilitate access. In this respect, space investment forums could also offer orientation services, to help identify and access the right financing instrument and to help synchronization of public and private funding.

To increase sector agility and resilience, facilitating cross-industry fertilisation, we recommend:

- Explore business models based on JVs between space and traditional industry, between traditional space and new space and between established and newer newspace players (e.g. OneWeb and Airbus, Alenia Space and Spaceflight industries): this would shorten the S-curve, likening space investments to those in tech, create an ecosystem of potential start-up acquirers facilitating space-focused M&A activity, facilitate cross-fertilisation and formation of expertise across and outside the space industry, planting the seeds for an increase in the customer base.
- Insert anchor tenancy (i.e. long-term commitment from public entities to buy data/services/products from the private sector) within PPPs (MnINa12, 2020). In the US, NASA shaped KPI-based, multi-year fixed-price contracts as anchor tenant to SpaceX, helping the company grow-up stage with mutual benefits whilst introducing more flexibility in the design specifications and leaving the possibility to use the spacecraft for private purposes. A similar strategy could be pursued by more established non-space industry sectors and public actors (e.g. health companies or national/international health organisations) increasing resilience of the space sector by further developing a customer base. In so doing, these could be helped by grants or co-finance to cover procurement cost. Similarly, a public actor can act as the first customer of innovative commercial solutions (e.g. a national health service acting as the first customer of an AI-enabled service that derives pandemic-related analytics from the intersection of publicly available satellite data and geolocalised IoT on a population sample).

To further develop downstream services and newspace, particularly important will be to multiply platforms (and related agreements) for the sharing of publicly available space data (such as the Copernicus Data and Information Access Service) whilst increasing IPR protection.

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