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Exploring The Intersection Between Space And Health

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Abstract

The paper explores the intersection between space and health, particularly within the One Health framework, which emphasizes the interconnectedness of human, animal and environmental health. It examines whether space technologies like Earth Observation (EO), Geographic Information Systems (GIS) and Global Navigation Satellite Systems (GNSS) can reinforce the holistic vision of health advocated by One Health. The paper details the institutional frameworks supporting the links between space and health, focusing on initiatives by the United Nations, the European Union and the United States. It identifies global trends in healthcare and space technology that could enhance the integration of space-based tools into health strategies. The paper discusses the role of space technologies in addressing some of the top health-related threats for humanity, such as (i) antimicrobial resistance (AMR), which refers to the ability of microorganisms to resist the effects of antimicrobial drugs, (ii) air pollution and (iii) potentially disruptive signals of change like new emerging zoonotic disease (shared between animals and humans) and unforeseen impacts of harmful chemicals and materials. The paper argues that space technologies offer unique, versatile and valuable tools for health-related purposes and applications, such as horizon scanning, conducting epidemiological research, responding to disease outbreaks, predicting, monitoring and mitigating vector and water-borne and communicable diseases, tracking drugs and vaccines, preventing drug counterfeiting, assessing environmental risks and supporting vaccination campaigns. The paper also review some notable case studies and communities of practice where space technologies have been effectively used, focusing on certain remarkable achievements such as significant savings during vaccination campaigns. The paper concludes by acknowledging the challenges and limitations of using space technologies for health, including that (i) all substances cannot be detected from space and (ii) many potential users, such as biopharma companies, are unaware of how to leverage space technologies for their needs. It makes recommendations for seeking to address these challenges, including the need for (i) supplementary ground-level data, sensors and observations, (ii) a more structured collaborative approach, combining experts from interdisciplinary fields, and (iii) uptake activities in terms of sharing best practices, capacity building, raising awareness and promoting the integration of the space sector with the healthcare/life sciences/biopharma sectors. However, it asserts that space technologies are essential for enhancing the effectiveness of the One Health approach and for identifying the factors that could determine the trajectory for planetary health and human wellbeing.

Acronyms/Abbreviations

Artificial intelligence (AI)
Centers for Disease Control and Prevention (CDC)
European Union Agency for the Space Programme (EUSPA)
Geographic Information System (GIS)
German Aerospace Center (DLR)
Heath Care Professionals (HCPs)
Internet-of-Things (IoT)
Low earth orbit (LEO)
Machine learning (ML)
National Oceanic and Atmospheric Administration (NOAA)
Non-communicable diseases (NCDs)
Platform for Space-based Information for Disaster Management and Emergency Response (UN-SPIDER)
Secretary of Health and Human Services (HHS)
Synthetic Aperture Radar (SAR)
Unmanned Aerial Vehicles (UAVs)
World Health Organization (WHO)

1. Introduction

Our planet is facing many challenges that do not stop at borders. We are confronted with a triple planetary crisis of climate change, nature and biodiverse loss and pollution and waste.[1] Whilst progress has been made in improving people's health, a number of significant health-related challenges remain ahead of us.

The need to follow a One Health, collaborative, multi-disciplinary approach, which emphasizes the interconnectedness of human, animal and environmental health, to address complex health-related challenges has gained traction during the 21st century.

The One Health approach is particularly relevant to look at, and beyond, the triple planetary crisis, to include other significant drivers of change.

This paper examines whether space technologies, including Earth Observation (EO), Geographic Information System (GIS) and Global Navigation Satellite System (GNSS), can offer valuable tools that can reinforce the holistic vision of health that One Health advocates. In other words, it seeks to answer the question whether public and private health-related entities and decision-makers could include space in their respective strategies?

2. Why space for One Health?

Pandemic, cross-border health threats and diseases are consistently ranked among the top global risks for the future of humanity. The healthcare and biophama industries are among the largest industries in the world, expected to growth at compound annual growth rates (CAGR) of respectively 5% to 11% and 7.5% to 9.5% during the next 5 years.[2]

Space technologies such as EO, GIS and GNSS can cover, in a versatile manner, a broad range of aspects relevant for several health-related purposes, stakeholders and users, including:

- help, at global, regional or local levels, predicting, monitoring and mitigating the effect of certain vector-borne, water-borne diseases and communicable diseases;
- monitoring of exposure to stressors (e.g., bad air or water quality), which in turn can help mitigating the effects of certain NCDs;
- drug and vaccine tracking and vaccination campaigns, including in remote areas and least developed countries;
- mapping the locations of reported counterfeit drug sales, distribution centers and hotspots for related counterfeiting activities;
- emissions and discharges of certain substances resulting from biopharma manufacturing as well as the use and disposal of such substances in waters, air and soils;
- help obtaining marketing authorizations for drugs by assisting for necessary Environmental risk assessments (ERA) ERA and Antimicrobial resistance (AMR)programs; and
- help estimating drugs and vaccines demand and doses, team sizes and demonstrate the value in investing in immunisation and vaccination coverage;
- generate savings during vaccination campaigns;
- help for conducting epidemiological research and responding to disease outbreaks and health-related treats and emergencies;
- supporting public communication and awareness (for instance by creating accessible and informative content for public dissemination such as visualizations and maps);
- mapping the distribution of health infrastructure such as hospitals and testing centers; and
- help achieve greater health equity.

3. Space technologies

In practice, the use of space technologies for health-related purposes, from a One Health perspective, involves the following:

3.1 EO satellites

Since the 1970s, a number of missions, programs and satellites, either operated by public bodies, space agencies or by privately-held entities (which often provide data that complement public programs), have been effectively used for EO in health-related projects, using various instruments on board to measure a large number of parameters, ranging from land surface parameters, vegetation cover, clouds, precipitation, lightning, snow cover, to atmospheric trace gases, soil moisture and pollution.

The correlation between the measured parameters and the health-related issues at stake could be either direct or indirect, as illustrated by the following examples:

- direct: EO is used to measure, for instance, rainfall, temperature and vegetation, which are in direct correlation with mosquitoes, especially Anopheles species, which are vectors for Malaria.[3]
- indirect: high water turbidity levels can indicate suspended particles from pollution; the presence of colored dissolved organic matter in water can indicate organic pollution; thermal anomalies in water bodies can be linked to industrial discharge or sewage outflows; or changes in soil reflectance properties can indicate the presence of certain contaminants.[4]

Whist many, but not all, substances and compounds that could have an effect on (human or animal) health or the environment can be directly detected from space, many others, can be indirectly detected, as this table illustrates.

Table 1. Detection from space

Substance/ compound	Direct detection	Indirect detection
Methane (CH_4)	Yes	Yes (e.g. via vegetation stress)
Sulfur Dioxide (SO_2)	Yes	Yes (e.g., via acid rain indicators)
Oxides of Nitrogen (NO_2)	Yes	Yes (e.g., via ground ozone formation)
Carbon Monoxide (CO)	Yes	Yes (e.g., via effects on ozone concentration)
Aerosols	Yes	Yes (e.g., via reflectance or visibility changes)
Certain chlorine compounds	Yes	Yes (e.g., via impact on clouds)
Dust & fine particulate matter	Yes	Yes (e.g., via surface reflectance changes)
Specific hydrocarbons	Yes	Yes (e.g., via oil spills and surface slicks)
Complex hydrocarbons	No	Yes (e.g., via detection of environmental changes)
Toxic substances & pollutants*	No	Yes (e.g., via their effects on vegetation)
Nitrates & phosphates	No	Yes (e.g., via their effects such as algal blooms)

*For instance Cyanides, Arsenic, Cadmium, Lead, Mercury, Ammonium Chloride, Asbestos

For more information about health-related EO's missions, programs and satellites, please refer to Appendix A.

3.2 GIS and GNSS

GIS and GNSS have a complementary relationship, as GNSS provides the precise location data that GIS uses for mapping and spatial analysis.[5, 6] GNSS and GIS are powerful technologies that have been extensively used in various health-related applications, including early detection and containment of vector-borne and water-borne diseases such as Dengue,[7] West Nile fever,[8] Cholera,[9] assessing water quality and Diarrheal Disease monitoring,[10], monitoring communicable diseases such as Ebola[11] and Polio,[12] tracking exposure to environmental stressors such as air pollution to study Asthma prevalence[13], water pollution[14], drug and vaccine tracking and vaccination campaigns [15, 16], monitoring emissions from biopharma manufacturing[17] and environmental impact assessment of pharmaceutical industries.[18]

3.3 Other technologies

Many other space-based technologies and approaches have been effectively used for health-related purposes, including in combination with ground-based technologies and approaches:

- UAVs or drones, or high-altitude balloons, can be used for targeted monitoring and analysis;
- satellite communications, notably via constellations, can be used for health monitoring, emergency response and tracking the spread of diseases, especially in remote or hard-to-reach areas;[19]
- ground-based sensors: IoT-enabled sensors placed in the environment can continuously collect localized data on various parameters;
- data fusion: the approach of integrating and analyzing data from various sources to produce more accurate, consistent and useful information;
- AI and ML: data from the above-mentioned sources can be further enhanced using AI and ML, which can analyze vast amounts of data, detect patterns and anomalies in satellite images, predict trends and provide actionable insights;
- collaborative approaches to combine experts from interdisciplinary scientific fields;
- large data centers and Big Data analytics, supporting the storage and processing of massive datasets; and
- cloud computing, providing the infrastructure necessary for storing, managing and accessing EO data on a global scale.

4. Institutional framework

4.1 United Nations (UN)

The UN consider that space technology are not confined to the realms of astronomy and engineering but could rather help contributing to achieve the Sustainable Development Goals (SDGs), in particular SDG 3, on ensuring healthy lives and promoting well-being.

In 2021, the UN Committee on the Peaceful Uses of Outer Space (COPUOS) developed the following thematic priority: "*strengthened space cooperation for global health*". It recommended to facilitate and promote the integration of the space sector with other sectors such as public health.[20]

In 2022, the UN General Assembly adopted a resolution entitled "Space and global health", which acknowledges the contribution of space science and technology to efforts towards the achievement of SDG3 and encourages UN entities, intergovernmental organizations, governments and the private sector to coordinate all key space activities relevant to global health.[21]

In 2023, the UN noted that, whilst progresses have been made in improving people's health, (i) inequalities in health care access still persist, (ii) health-related crises have impeded progress towards SDG3, (iii) the "*alarming decline in childhood vaccination is leaving millions of children at risk from devastating but preventable diseases*" and (iv) tuberculosis and malaria deaths have increased compared with pre-pandemic levels.[22]

Also, the UN, and in particular COPUOS, the United Nations Office for Outer Space Affairs (UNOOSA), in cooperation with the WHO, and other entities, has:

- initiated UN-SPIDER to provide universal access to space-based information and services relevant to disaster management. Whilst UN-SPIDER's primary focus is on natural and technological disasters, it has expanded its remit to include pandemics and health-related emergencies, particularly in the context of disaster management.
- been actively engaged in several activities in terms of capacity building, raising awareness and increasing collaboration efforts on space and global health issues.[23]

The UN "Summit of the Future", which will be held in September 2024, has been framed as a "once-in-a-generation" opportunity to address the complexities of modern challenges, reinvigorate multilateralism and ensure that institutions are equipped to serve the needs of all people. In the "Our Common Agenda" report, which serves as the foundational blueprint for the Summit, the UN Secretary-General highlighted that failure to deliver what people need most, including "*health* […] *and a vaccination against disease* […]", drives mistrust.[24] Accordingly, in terms of health governance, there is a need to focus on "*prevention, preparedness and equity*" and "*accelerate access to health technologies to address neglected, emerging infectious diseases*" and other health threats such as AMR, which refers to the ability of microorganisms to resist the effects of antimicrobial drugs.[24]

The following relevant health-related issues have been listed by the WHO among the top threats for global health: (i) AMR, (ii) air pollution, (iii) dengue, a mosquito-borne disease that causes flu-like symptoms and can be lethal, (iv) the need for better preparedness for future pandemics, including to address future treats such as emerging infectious diseases, (v) universal health coverage and the need to provide equitable, affordable and high-quality care to all, (vi) to reduce NCDs' risks, (vi) to decrease health inequities and (vii) to increase health system resilience.[25]

In the draft Declaration on Future Generations, which could be adopted during the Summit of the Future, it is indicated that SDG3 should be achieved, in particular, through "*digital and space innovations for vaccine production and delivery, disease monitoring and health advancement research*".[26]

The UN and in particular, the United Nations Development Programme (UNDP) agency, has also been involved in identifying the factors that could determine the trajectory for planetary health and human wellbeing. According to the UNDP report entitled "Navigating New Horizons - A global foresight report on planetary health and human wellbeing":

- the issue of "*humans and the environment*" is a critical shift and a potential threat, that needs to be closely watched due to its potential to significantly affect planetary health and human wellbeing;
- 4 out of 18 "signals of change", that points to a future possibility, different to today's norm or that could potentially disrupt, are related to the One Health approach: (i) ancient microbes hidden in thawing Arctic permafrost, which raises concerns about the potential introduction of ancient microorganisms into the environment; (ii) new emerging zoonotic disease (shared between animals and humans), which may pose global public health risks due to their potential to spread rapidly and unpredictably; (iii) AMR - currently considered by the WHO as one of the top ten global health threats - approaching critical levels; and (iv) unforeseen impacts of harmful chemicals and materials.[1]

It is thus essential to monitor and prepare for these potential critical shifts and changes as well as to better understand the convergence and numerous interactions between them. Clearly, space technologies have an important role to play in this respect.

4.2 European Union (EU)

Whilst we are not aware of any legislation adopted at EU level that explicitly mandates using space technologies such as EO for health-related purposes, the following highlight the links between space and health:

- the EU Space Programme Regulation[27] and the Regulation which establishes the Copernicus EO program[28] set out that Copernicus can be used for environmental monitoring and emergency management, which include to monitor and manage diseases, to assess exposure to environmental stressors that impact public health and to respond to health crises;
- space agencies such as ESA and EUSPA and R&D programs such as Horizon 2020 and Horizon Europe have been involved in, or have funded, projects related to various societal challenges, including public health and the environment;
- EO has been used in support of the EU institutional framework designed to address cross-border health emergencies and threats. This framework has been strengthened in recent years, especially in response to the COVID-19 pandemic[29]; and
- when submitting an application to obtain a marketing authorization for placing a new medicinal product on the EU market, a prospective Environmental Risk Assessment (ERA) is required since 2006.[30]

4.3 United States

Similarly to the situation in the EU, we are not aware of any U.S. law that mandates the use of space technologies such as EO for health-related purposes. The U.S. has, nevertheless, adopted the following that underscores the relevance of space technologies for health-related purposes:

- the National Aeronautics and Space Act 1958 (as amended), which is the foundational law that established NASA, sets out: (i) NASA's Earth science and applications program shall contribute significantly to supporting the health of the people of the United States and the citizens of the world; (ii) the general welfare of the United States require that adequate provision be made for space activities, under NASA's responsibility, and that NASA seek and encourage, to the maximum extent possible, the fullest commercial use of space; (iii) the space domain is important to the function of critical infrastructure vital to public health; and (iv) the space program can make substantial contributions to health-related research and should be an integral part of the Nation's health research and development program;[31]
- pursuant to U.S. law and FDA guidance, there is a need to assess the environmental impact of certain (not all) drugs, including its manufacture, use and disposal.[31] If the assessment identifies significant environmental risks, a detailed ERA may be required;[31]
- U.S. law mandates the CDC to use various technologies, including EO, for monitoring and managing diseases (especially vector-borne diseases), conducting epidemiological research and responding to disease outbreaks (including pandemics, epidemics, and other public health emergencies) and monitoring environmental risks[32]; and
- under US law, the HHS is responsible for setting up an Antimicrobial Task Force and encouraging reporting on antimicrobial drug use and antimicrobial resistance.[32]

5. Global trends

5.1 Health-related trends

The following health-related trends could have a positive impact on the use of space technologies from a One Health perspective and, in particular, of EO to monitor and predict health treats such as zoonotic diseases and AMR, manage vaccination campaigns, assess the environmental exposure of medicinal products (ERA) and monitor pollution in water bodies, soil and air:

- Our resilience, wellbeing and ability to navigate crises is now fully connected to the food we eat, the water we drink, the air we breathe and our relationship with the Earth.[1]
- Global health spending reached unprecedented levels. In 2021, global health expenditure peaked at approximately $9.8 trillion, accounting for 10.3% of global GDP.[32] The WHO considers that the cost of vaccination is one of the main factor of growth.[32]
- There is a noticeable shift towards more sustainable and preventive healthcare models.[33]
- Governments and private entities are increasingly investing in preventive care to curb rising costs associated with treating chronic conditions.[33]
- Approximately 60% of all known infectious diseases in humans are zoonotic,[34] and about 75% of all emerging infectious diseases that have affected people over the past three decades originated from animals.[34]
- Environmental risk factors for health cause about 23% of all global deaths and about two thirds of these are attributable to NCDs.[35]
- Strengthened ERA, requiring the biopharma industry to limit the impact of its products and

processes on the environment and biodiversity. For instance, in the EU, it is proposed to extend the scope of the ERA to cover products already on the market and, for antimicrobials, the entire manufacturing supply chain (inside and outside the EU). If the ERA is incomplete or insufficiently substantiated or if the risks have not been sufficiently addressed, this could be a ground to refuse to grant certain marketing authorizations for medicinal products.[36]

5.2 Space-related trends

The following space-related trends could have a positive impact on the widespread use of space-related technologies and the speed of their adoption, including within the One Health framework:

- the cost of access to space, which is a critical factor, has significantly decreased during the 21st century, in particular due to advancements in technology, increased competition, the rise of private companies, economies of scale and the development of reusable launch vehicles, as this table illustrates:

Table 1. Decreasing costs to access space[1]

Period	Launcher programs	Cost per launch	Cost per kilogram
Early 2000s	Space Shuttle (NASA)	$500m to $1.5b	$10K to $25K
	Arianespace's Ariane 5	$165m	$10K to $25K
Mid-2010s	SpaceX Falcon 9	$50-55m	$2,5K to $4K
	SpaceX Falcon Heavy	$90m	$2,5K to $4K[2]
Mid-2010s	Small launchers[3]	$7.5m	Not specified
2020s	SpaceX Starship	Not specified	Potential <$100

1 to LEO
2 assumed similar to Falcon 9
3 e.g., Rocket Lab's Electron

- EO is gradually perceived as an engine for economic development, that can benefit a wide range of business interests, with significant potential value-added, estimated at $266 billion in 2023, and which could exceed $700 billion globally in 2030;[37]
- (i) promising advancements in Earth Observation (for instance, hyperspectral imaging, LIDAR, SAR and increased temporal and spatial resolution), (ii) enhancement of the capabilities of GIS and GNSS (for instance, multi-GNSS systems, advanced signal processing, enhanced 3D mapping and enhanced data sharing and cross-platform integration), (iii) improvements in GIS interoperability and the adoption of open data standards; (vii) more powerful integration with emerging technologies such as AI and ML, Big Data and cloud computing, enabling multi-user, global collaboration across different geographic locations.

6. Case studies and communities of practices

Space-related technologies, including EO, GIS and GNSS, have increasingly been deployed for several health-related purposes. Below are some notable case studies and communities of practice where space technologies have been effectively used across selected diseases and risk areas, focusing on certain remarkable achievements:

6.1 Efforts to eradicate Polio in Nigeria

In Nigeria, EO, GIS and GNSS have been used during a vaccination campaign in 2014, which resulted in stopping the transmission of Polio, a communicable disease, for the first time in the country history. EO and GIS data were used to produce maps and population estimates used in planning and implementing the campaign. In this context, the net socioeconomic benefits associated with the use of space technologies have been estimated at between *"$46.0 million and $153.9 million*" in one year.[12]

6.2 The Malaria Atlas Project (MAP)

MAP is an ongoing initiative that leverages EO data to monitor in real-time and globally map malaria, a vector-borne disease. By correlating certain environmental conditions with malaria transmission data, MAP can predict seasonal and long-term changes in malaria risk. This helps health agencies anticipate and respond to outbreaks more effectively, especially in resource-limited settings. MAP has provided tools for understanding and combating one of the world's most persistent health challenges.[38]

6.3 The Global Mosquito Alert Consortium (GMAC)

GMAC is a global community of practice to monitor and control mosquito populations, which are the primary vectors of diseases like malaria, dengue, zika, and chikungunya. GMAC follows a citizen science approach to contribute to mosquito surveillance by reporting sightings of mosquitoes, breeding sites and bites. GMAC combines data from various sources, including EO data, geographic information systems (GIS) and ground-based observations, to facilitate the collection, visualization and analysis of mosquito-related data, which are disseminated via mobile applications and online platforms.[39]

6.4 Assessing water quality and monitoring diarrheal disease

Case studies have demonstrated that EO and GIS could be effectively used to monitor environmental factors like rainfall, river discharge and water salinity that contribute to the spread of cholera, to monitor water quality and for improving related early warning systems and public health responses in countries such as Bangladesh, Kenya, Peru and Uganda. The Community of Practice: GEO AquaWatch Initiative focuses on using EO data for global water quality monitoring, which could be linked to diarrheal diseases, especially in developing countries.[40]

6.5 Assessing air quality and monitoring related diseases

Case studies have demonstrated that EO, GIS and GNSS could be effectively used to monitor air quality, the correlation between pollutants like nitrogen dioxide (NO2) and particulate matter with respiratory diseases such as asthma and its impact on public health in certain cities such as New York (USA), Cairo (Egypt), Beijing (China) and several major cities in South Asia, particularly in India and the Ruhr valley in Germany.[41]

6.6 Drug and vaccine tracking and anticounterfeiting activities

Case studies have demonstrated that EO, GIS and GNSS could be effectively used to monitor supply chains, (often cold chain) distribution networks and ensure the safety and efficacy of drugs, such as vaccine distribution during the COVID-19 pandemic, Antiretroviral Drugs (ARVs) in Kenya, anti-malarial drug distribution in Myanmar as well as for mapping of counterfeiting incidents in Nigeria.[42]

6.7 Detection of pharmaceutical contaminants in waters and soils

Case studies have demonstrated that EO (including by using multispectral imaging from satellites), GIS and GNSS have been effectively deployed for monitoring and tracking, using an indirect approach, the presence of pharmaceutical contaminants such as antibiotics and hormones and residues in water bodies such as the Rhine river and Danube river basins, in Italian lakes such as Lake Garda and Lake Maggiore, in the Ganges river in India, in the Mekong river in Southeast Asia, in the Mississippi river, USA, as well as for related monitoring of soils in the Netherlands.[43]

6.8 Use of space technologies during the COVID-19 Pandemic

During the COVID-19 pandemic, space technologies have been extensively used, often under the leadership of space agencies such as NASA, ESA and JAXA, in a versatile manner, including (i) to monitor changes in air quality due to the required lockdowns, (ii) tracking changes in human mobility (train, air, road & ship) and supply chains, (iii) monitor agricultural productivity and food supply chains, (iv) monitor and predict the spread of COVID-19, particularly in relation to environmental factors, (v) support epidemiological models, helping to predict hotspots and the potential spread of the virus under different conditions, (vi) supporting public communication and awareness by creating accessible and informative content for public dissemination such as visualizations and maps; (vii) mapping the distribution of health infrastructure such as hospitals and testing centers, and (viii) assess the socioeconomic impacts of the pandemic, including changes in economic activity, land use and infrastructure.[44]

For more information about case studies and communities of practice, please refer to Appendix B.

7. Challenges and limitations

Whilst, as examined above, space technologies can help addressing several global health-related issues and drivers of changes, there are a number of technological, economic and societal challenges and limitations in using a space approach from a One Health perspective, including the following:

- The space technology development and launch costs.
- It is not possible to detect, directly or indirectly, all substances and compounds that could have an effect .[38]
- Lack of direct health-related data: it is often challenging to provide direct health data (for instance, data about the number of people already vaccinated/or in need of vaccines, the prevalence of

specific diseases or the immunity levels within a population).[44]

- Inadequate resolution: although EO data can, for instance, estimate population sizes, many satellites often lacks the granularity required to determine the specific needs of sub-populations, such as vulnerable groups (e.g., children, elderly, immunocompromised individuals) or to detect small-scale events.[44]
- Infrastructure limitations: EO data might, for instance, indicate where populations are, but it could be difficult to provide detailed information on local infrastructure (for instance, on the availability of cold storage facilities necessary for certain vaccines or logistical variables such as transportation, storage and the availability of healthcare personnel).[44]
- Data timeliness: the timeliness of EO data can be a limitation. If EO data is outdated or not updated in real-time, it may lead to inaccurate estimates. For instance, in areas with significant migration or displacement (e.g., due to conflict, natural disasters, or economic reasons), EO data can struggle to keep up with rapid changes in population distribution.
- Need for quality GIS data: there is a lack of availability and accessibility of quality geospatial data and it is often necessary to improve the already existing GIS technical capacity in certain countries. Often, there is no supportive institutional framework (strategy and plan, governance, policies, resources).[44]
- Finding business models: it can be challenging to find appropriate business models for health-related EO data, especially when much of it is freely available and considered a public good.
- High costs for value-added services: while basic EO data may be freely available, advanced services such as high-resolution imagery, customized data processing, predictive analytics, AI and ML, often come at a high cost, which may limit accessibility.
- Public-private partnerships (PPPs): collaboration with governments still represent one of the largest clients for EO health-related data and it may be necessary for private entities to find appropriate PPPs and for public entities to promote them.
- Low market readiness: a very small number of persons, often coming from the academic world, are aware of the potential of the use of space for health-related purposes. Many potential users, such as biopharma companies, are simply unaware of how to leverage space technologies for their needs.
- Lack of specialized expertise: interpreting EO data often requires specialized technical expertise and understanding of GIS.
- Interoperability and standards: there is a need for improvements in interoperability of space-related data and related technologies and for the development of relevant standards.
- (Cyber)security: the protection of space systems, data transmission and related technologies and infrastructure from cyber threats is essential for maintaining integrity and reliability, but could be costly;
- Integration: the integration of the above-mentioned other technologies with EO and GIS & GNSS has its own challenges and limitations. For instance, IoT-enabled sensors, especially in remote locations, need reliable power supply and robust data management systems to handle storage, processing, and analysis efficiently.
- Developing country challenges, limited budgets and lack of infrastructure.
- Policy and regulatory constraints, including the need to navigate a complex regulatory landscape and most often the need to obtain authority approval for instance to conduct vaccination campaigns.
- The environmental risk assessment (ERA), for which space can provide assistance, also has its own limitations. For instance, ERA is often based on the use of an individual medicinal product (MP) and thus does not account for multiple MPs containing the same active pharmaceutical ingredient, all of which contribute to the overall environmental burden. The level of environmental data associated with a MP can be quite variable and transparency and accessibility of environmental data in the public domain is inconsistent and/or could raise bioethical issues.[4]
- Lack of awareness and need for supporting activities: there is limited awareness and understanding of the advantages of using space in the health sector and hence uptake activities in terms of raising awareness, sharing of best practices, lessons learned, capacity building, global experts, centers of excellence and increasing collaboration efforts on space and global health initiatives are needed.

8. Recommendations

In view of the above, the space and the healthcare/life sciences/biopharma sectors could benefit from the following approaches, that could address certain of the above-mentioned challenges and limitations, such as:

- To complement space technologies with UAVs or drones or high-altitude balloons or ground-based sensors and observations. For instance, IoT-enabled sensors can be placed in the environment and used to continuously collect localized data on various parameters and transmit them in real-time to satellites.

- Data fusion approach: for instance, EO data could be integrated with socioeconomic data, such as population statistics, to help assess climate impacts on human populations.
- To supplement the large-scale monitoring provided by EO with more specific and direct ground-based data or measurements or on-site sampling and laboratory analysis. For instance, during a vaccination campaign, EO data and GIS& GNSS could be combined with: (i) data collected at the health facility level (e.g., tally sheets recording every dose of vaccine given, the number of vaccinated children or the target population in the facility catchment area) and/or (ii) demographic data from local health authorities and healthcare professionals.[44]
- To enhance data using AI and ML: for instance, ML algorithms, including deep learning and traditional models, are essential for detecting subtle spectral differences indiscernible to the human eye, allowing for precise bacterial strain discrimination.
- To follow a structured collaborative approach, combining experts from interdisciplinary fields such as epidemiology, ecology, EO, Big Data Analytics and AI/ML.
- Interoperability and standards: systems and technologies can be designed to work in a standardized manner with various types of satellites, constellations, networks, making them adaptable to different needs.

The following actions are also recommended:

- To consider appropriate policies, governance and cooperation frameworks to capture this opportunity. For instance, it would be useful to demonstrate, in practical terms, to selected biopharma companies (i) how space can help to fulfill unmet needs (for instance, in terms of managing vaccination campaigns, tracking drugs or fighting counterfeiting) and (ii) help them to comply with regulatory requirements such as ERA and AMR. Similarly, it would be useful to highlight the significant savings that the use of EO can provide during vaccination campaigns.[44]
- To support and promote the links between space and health and the integration of the space sector with the healthcare/life sciences/biopharma sectors, including by way of sharing of best practices, capacity building, raising awareness and other uptake measures.

9. Conclusions

In essence, space is creating the opportunity for more capabilities to be deployed above Earth for the benefit of those on Earth. This paper has explored the intersection between space and health, particularly within the One Health framework. The space-related technologies, the institutional framework, the global trends and the case studies and communities of practice examined in this paper, all support the view that space can indeed offer unique, versatile and valuable tools that can enhance the effectiveness of a global One Health approach and help addressing some of the most pressing health issues being faced today by humanity.

Space can detect early signs of global developments, monitor changes as they mature into trends, offer critical insights, and hence be used by a wide range of private and public users, stakeholders and decision-makers. Therefore, space may arguably be the missing element in an effective health-related strategy.

That said, this paper has identified significant challenges and limitations in using a space-only approach. Whilst the intersection of space technology and One Health inherently demands cross-disciplinary collaboration, it seems indeed that bringing together experts from various fields such as public health, life sciences and space engineering, can foster innovative solutions that are more effective in addressing the complex challenges at the nexus of human, animal and environmental health. Also, there are opportunities for space-technologies to continue to evolve, to better integrate space with other sectors and for policies to anticipate future developments, manage risks and take anticipatory actions that can rebalance planetary health and human wellbeing.

The period from 2024 to 2030 is an important opportunity window to continue to explore the intersection between space and health, given (i) the above-mentioned favorable trends, (ii) international commitments during such period linked to the UN SDGs, and (iii) the likely reinforcement of environmental disclosure requirements and emissions regulations during such period.

Appendix A: Examples of health-related EO's missions

These are the missions, programs and EO satellites that have already been effectively used for healthcare-related purposes, with an indication of relevant instruments and the parameters measured:

Mission/program/satellite	Instrument	What has been measured?
NASA's Terra and Aqua	MODIS; MISR	Land surface parameters; vegetation cover; precipitation…(MODIS); Earth's atmosphere, surface and clouds (MISR)
NASA/JAXA TRMM	PR; TMI, VIRS…	Rainfall and associated weather phenomena
US DoD DMSP	Operational Linescan System for imaging	Indicators of human mobility
ESA's Copernicus program/Sentinel satellites	SLSTR/Sentinel-3; MSI/Sentinel-2; SAR/Sentinel-1	Land surface temperature; vegetation index; surface soil moisture
ESA's Copernicus program/Sentinel-5P satellite	TROPOMI	Air quality monitoring (pollutants such as ozone, carbon monoxide, nitrogen dioxide and aerosols)
NASA's Landsat program	OLI; TIRS	Land cover; vegetation health; water bodies; surface temperature; soil moisture…
NOAA' satellites	AVHRR; ABI & GLM	Cloud cover, sea surface temperature; vegetation, ice, snow cover…(AVHRR); weather monitoring, storm tracking, cloud cover and lightning detection **(**ABI & GLM)
NASA's ozone mapping satellites	TOMS; OMI	Ozone data (TOMS); ozone levels, nitrogen dioxide (NO_2), sulfur dioxide (SO_2) and other pollutants (OMI)
Suomi National Polar-orbiting Partnership (Suomi NPP)	VIIRS; ATMS; CrIS; OMPS and CERES	Composite image of the Earth at night to quantify the fluctuations in population size and distribution
NASA/JAXA GPM Mission	GPM Microwave Imager (GMI); Dual-Frequency Precipitation Radar (DPR)	Intensity and distribution of precipitation; size distribution of raindrops, structure of storm systems and intensity of rainfall
NASA's SMAP satellite	Radar; radiometer	Soil moisture
Privately operated EO satellites	Imagery ; small synthetic aperture radar (SAR) satellites	Imagery; weather and climate data; Urban health assessments

ABI means Advanced Baseline Imager
Aerosol properties include quantities of aerosols (small particles like dust, smoke, and pollution), aerosol size and type
Atmospheric trace gases and aerosols include Ozone (O_3); Nitrogen Dioxide (NO_2);Sulfur Dioxide (SO_2); Carbon Monoxide (CO); Methane (CH_4); Formaldehyde (HCHO); Aerosol Optical Depth (AOD); Cloud Properties and Tropospheric Ozone
ATMS means Advanced Technology Microwave Sounder to measure temperature, humidity and precipitation
AVHRR means Advanced Very High Resolution Radiometer
CERES means Clouds and the Earth's Radiant Energy System
CrIS means Cross-track Infrared Sounder to measure atmospheric temperature and moisture profiles
DMSP means US DoD Defense Meteorological Satellite Program
GLM means Geostationary Lightning Mapper
GPM means Global Precipitation Measurement
Land surface parameters include land cover, reflectance, vegetation indices, temperature…
MISR means Multi-angle Imaging SpectroRadiometer
MODIS means Moderate Resolution Imaging Spectroradiometer
OLI means Operational Land Imager
OMPS means Ozone Mapping and Profiler Suite
Ozone mapping satellites include Nimbus-7, Meteor-3, Earth Probe (TOMS-EP), Advanced Earth Observing Satellite and Aura
PR means Precipitation Radar
Privately operated EO satellites include WorldView Satellites (Maxar Technologies), Planet Labs Satellites (Dove, RapidEye, SkySat), Spire Global's satellites, ICEYE, BlackSky, Capella Space…
SLSTR means Sea and Land Surface Temperature Radiometer
SMAP means Soil Moisture Active Passive
TIRS means Thermal Infrared Sensor
TMI means TRMM Microwave Imager
TOMS means Total Ozone Mapping Spectrometer
TRMM means Tropical Rainfall Measuring Mission
TROPOMI means Tropospheric Monitoring Instrument
VIIRS means Visible Infrared Imaging Radiometer Suite
VIRS means Visible and Infrared Scanner

Appendix B: Space for health case studies and communities of practices

This table provided additional information about case studies and communities of practices relating to the links between space and health:

Disease/risk areas	Outcome	Sponsors/Location/Stakeholders
Dengue fever	Model to predict the patterns of outbreaks; targeted interventions	University of California, Irvine; Peru; Public health officials and policymakers; NGOs
Malaria	Prediction of the patterns of malaria transmission; targeted interventions	Academic researchers of Maryland, Duke, NASA; Amazon region of Brazil, Peru; public health officials and policymakers; NGOs
Cholera	Improve and enhance global predictive ability of forecasting risk of cholera outbreaks	NASA project; global (including Yemen, Pakistan, Ghana, Malawi, Ethiopia, Afghanistan); public health officials and policymakers; NGOs
Zika virus (and similar arboviruses)	Zika modelling studies, including frequency and risk of ZIKV infection	University of Oxford; global, regional and local levels; public health officials and policymakers; NGOs
Respiratory diseases such as asthma and chronic obstructive pulmonary disease (COPD)	Better prediction of the incidence of outbreaks; targeted interventions; strategies for air pollution control	Journal of the American Medical Association (JAMA); USA; public health officials and policymakers
Ebola (could be used for other diseases such as Lassa fever, Rift Valley fever and Crimean-Congo hemorrhagic fever	Early warning system for Ebola outbreaks; prevent the spread of the disease	University of Oxford; 2014-2016 Ebola outbreak in West Africa; public health officials and policymakers
COVID-19 (and possibly other infectious diseases)	Prediction of COVID-19 outbreaks; strategies for the prevention and control of diseases	Space agencies; many countries, including Italy, Spain, and the United States; public health officials and policymakers
Cyanobacteria (e.g., algal blooms); increased health risks for humans and wildlife in contact with water	Cost-effective way to monitor algae risk in real-time; improved ability to mitigate the harmful effects	EONEMP project in South Africa (2015-2018); EPA, NASA, NOAA…; freshwater lakes and coastal regions effected by algal blooms; health and environmental authorities
Measles disease	Estimation of coverage for a measles vaccination campaign; help with disease surveillance; immunization campaigns; seasonal shifts in populations	Penn State University, NIH's Fogarty International Center (FIC); Niamey, a city located in Niger (Africa); public health officials and policymakers
Polio (Vaccination)	Cost-savings to the health system (estimated at between $46 million and $153 million in net socioeconomic benefits); accurate, standardized and geo-referenced maps and population estimates	December 2011, the National Primary Health Care Development Agency of Nigeria, along with GPEI partners and the Bill and Melinda Gates Foundation; Nigeria; Satellite imagery collected by DigitalGlobe (Maxar)
West Nile Disease (WND)	Mitigating the effects of vector-based diseases such as WND	ESA project AIDEO; Italy; health and environmental authorities
Foot-and-Mouth disease (FMD)	Decision-support tool to estimate current and future vaccine dose demand for FMD	European Commission, FAO, WOAH; Endemic countries; health and environmental authorities

NCDs such as cardiovascular and respiratory diseases, cancer, diabetes & mental health disturbances	Mitigating the effects of NCDs	DLR, University of Wuerzburg…; Germany; Outpatient Clinic for Environmental Medicine
Vaccinations campaigns including coverage recommendations (for vaccine preventable diseases)	Satellite-based data-maps to help vaccinators and healthcare workers	Acasus (consultancy), Bill & Melinda Gates Foundation, Columbia University, University of Southampton (UK), Flowminder; Democratic Republic of the Congo (DRC); health authorities, biopharma industries, HCPs
Immunisation programing and vaccination coverage	Disease surveillance, vaccination coverage modelling and vaccinator tracking, delivery in vaccine coverage; more equity in health	UNICEF, Gavi, the Vaccine Alliance; experiences in Nigeria, Myanmar and Cameroon; health authorities, biopharma industries and HCPs

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