Acta Astronautica 219 (2024) 678–692

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Challenges and progress in applying space technology in support of the sustainable development goals

Danielle Wood *, Minoo Rathnasabapathy, Keith Javier Stober, Pranav Menon

Space Enabled Research Group, Massachusetts Institute of Technology (MIT) Media Lab, 75 Amherst Street, Cambridge, MA, 02142, USA

ARTICLE INFO

Keywords:
Sustainable Development Goals (SDGs)
Space technology
2030 agenda for sustainable Development

ABSTRACT

The global community, with coordination from the United Nations, is energized to pursue the Sustainable Development Goals (SDGs), a list of 17 important aspirations that summarize the key challenges of our era. The SDGs apply to every nation and represent an international effort to eliminate extreme poverty, ensure access to safe drinking water, strengthen food security, and produce clean and reliable energy, among other pursuits. Space technology is already being used around the world to advance progress toward the SDGs and monitor their related Indicators. This paper explores how six technologies related to space—satellite Earth observation, satellite communication, satellite navigation and positioning, human spaceflight and microgravity research, space technology transfer, and basic scientific research—are being used to realize the vision that the SDGs represent. The paper also discusses the obstacles that limit the application of these technologies for the SDGs and provides an overview of potential paths to overcome these barriers. The paper finally studies the historical and potential roles that four distinct types of entities involved in global sustainable development—governments, non- and inter-governmental organizations, entrepreneurial companies, and universities— have played or may play in the application of space technologies towards the SDGs.

1. Introduction

Technology associated with human endeavors in outer space has the potential to support sustainable development on Earth. However, the realization of this potential depends upon international efforts to design space systems with sustainability in mind. One way to concretely define the areas in which space technology brings this benefit is to harness the concepts contained within the 2030 Agenda for Sustainable Development, facilitated by the United Nations [1]. This agenda delineates 17 Sustainable Development Goals (SDGs) that summarize the key aspirations of our generation, such as ending extreme poverty, ensuring everyone has access to food, clean water and health care, creating sustainable energy systems and cities, and maintaining a healthy balance with life on land and in the ocean [2]. Every member country of the United Nations has agreed to pursue the SDGs as part of their national development strategy. In this sense, the SDGs represent an international commitment to a sustainable future for life and civilization on Earth.

This paper is interested in how technologies derived from space exploration and research can and already do support the global effort to meet the SDGs, whether by delivering technical solutions to social and environmental challenges or by helping countries monitor their progress toward the various SDG Targets. In particular, this paper identifies six such technologies– satellite Earth observation, satellite communication, satellite navigation and positioning, human spaceflight and microgravity research, space spinoffs/technology transfer, and the infrastructure/inspiration arising from basic scientific research—and provides insights on how each of these technologies is already being used to support one or more SDG. In addition, the paper reviews barriers that make it difficult for some actors and communities to mobilize these space technologies for sustainable development, and surveys potential designs for overcoming these challenges.

A variety of actors shape the dynamic ecosystem of space policy and resources, including its relationship with the SDGs. National governments, non- and inter-governmental organizations, private firms, and universities are each involved in the space sector in distinct, formative ways and continue to direct the future of the development landscape. Recognizing this, the paper's final section will discuss the role each type of institution might play in the future application of space technologies for sustainable development, note the challenges they face, and review the technical and political progress each is making towards cultivating a

* Corresponding author.
E-mail address: drwood@mit.edu (D. Wood).

https://doi.org/10.1016/j.actaastro.2024.03.064
Received 22 June 2023; Received in revised form 16 January 2024; Accepted 31 March 2024
Available online 1 April 2024

more transformative space technology ecosystem.

1.1. The 2030 Agenda for Sustainable Development

As the effects of climate change and other environmental crises have continued to grow in visibility and exigency, the international community has produced three agreements that outline the changes it seeks to make to global economic, social, and environmental practices by 2030. These agreements are the 2030 Agenda for Sustainable Development, the Sendai Framework for Disaster Risk Reduction [3] and the Paris Agreement on Climate Change [4]. This paper focuses on the 2030 Agenda for Sustainable Development, while noting that all three international agreements work together to define objectives for the future.

The 2030 Agenda for Sustainable Development is composed of 17 distinct Sustainable Development Goals (SDGs). The SDGs, also known as the Global Goals for Sustainable Development, address a wide array of topics regarding the environment, access to food, water and sanitation, gender equality, economic opportunity, government service, infrastructure and urban sustainability. They are further subdivided into 169 Targets, which are measured through numerous quantitative Indicators (which in turn are monitored by national statistics agencies in each country) [5]. These Targets and their Indicators facilitate technical and policy integration across numerous sectors, and therefore ensure the interconnectedness of the goals themselves. The SDGs cover every aspect of human life; thus, individuals and organizations can consider how their work and passions could contribute to some aspect of the goals. They were designed to be concise, easy to communicate, action-oriented and global in nature. Deemed as a 'universal call to action', every member country of the United Nations has agreed to pursue the SDGs as part of their national development strategy.

In many ways, the SDGs build upon the Millennium Development Goals (MDGs), which set ambitious Targets for developing countries between 2000 and 2015 [6]. While some criticized the MDGs as being too unrealistic or idealistic, it is now possible to show that their lofty ambitions have had an impact. The first MDG was to reduce global poverty by half between 2000 and 2015; this goal was met [7]. Thus, although not all of the MDGs were achieved, their overall positive effect evinces that setting ambitious targets for global progress encourages people from all sectors to collaborate toward development. However, there are key differences between the SDGs and the MDGs. First, while the MDGs set Targets for so-called "developing" countries (largely from the Global South), the SDGs apply to all countries. This shift eliminates the at-times pejorative distinction between "less developed" and "more developed" countries and reframes development as a shared global responsibility in which all countries have areas in which they need to improve. Further, it should be noted that the SDGs themselves were conceived and articulated through an inclusive process. The United Nations led a global dialogue prior to 2015 to define the SDGs, their Targets, and the quantitative Indicators that measure progress. This dialogue solicited input from many segments of society, including (but not limited to) governments, farmers, youth, and Indigenous peoples [8]. In this way, the SDGs represent a ground-up reimagining of global development along the lines of sustainability, democracy, and equity.

This paper explores how technologies used in or relating to space can play a role in the global pursuit of the SDGs, such as by improving the systems that help policymakers make important decisions, by enabling measurement of national progress on the 169 Targets, and much more. The next section will discuss salient examples of and general outlooks for six areas of space activity—satellite Earth observation, satellite communication, satellite navigation and positioning, human spaceflight and microgravity research, space technology transfer, and basic scientific research— as they relate to the SDGs.

2. Six space technologies that support the sustainable development goals

As noted in the introduction, six technologies from the space sector are already being used to support the monitoring of and progress toward the SDGs. These technologies include satellite Earth observation, satellite communication, satellite navigation and positioning, human spaceflight and microgravity research, technology transfer, and infrastructure arising from basic scientific research. The following section briefly discusses each area of space technology and highlights current examples of how these technologies are used in support of the SDGs. In order to provide an overview of diverse national space activity, examples are drawn from both established and emerging space nations based on the authors' previous work in space technology, policy analysis, and social science research [9–12]. The examples chosen showcase the relevance of space technologies to developmental needs, and in some cases illuminate the barriers that limit the application of satellite technology for the SDGs.

2.1. Satellite Earth Observation

Information derived from satellite Earth observation systems has high relevance to both the monitoring and achievement of the SDGs, as data gleaned from direct images of the Earth, measurements of environmental variables, and the outputs of Earth science models that have assimilated observations from space-based platforms are used around the world by remote sensing agencies, companies and non-profit organizations to inform environmental decision-making. Some of the first American satellites from the early space era signaled the utility of space technologies for Earth observation and remote sensing [13]. Following the launch of Sputnik-1 in 1957, for example, Vanguard-1 (1958) furnished the first density measurements of the upper atmosphere. Vanguard-2 (1959) was designed specifically to gather data on cloud cover, and was succeeded by TIROS-1 (1960), which created the first television footage of weather patterns. Since 1972, the "Landsat" series of satellites (built by the U.S. National Aeronautics and Space Administration (NASA) and operated by the United States Geological Survey or USGS) has collected continuous satellite imagery of the Earth's surface [14]. Modern Earth observation and remote sensing build upon the legacy that these early satellites established using new capabilities and points of emphasis. There is increasing participation by commercial companies in the operation and application of satellite Earth observation systems. These companies produce both visual imagery using optical sensors as well as providing additional types of sensing such as estimates of greenhouse gases via infrared observation.

A variety of public and private entities use or provide services related to satellite Earth observation. Space agencies such as NASA, the European Space Agency (ESA), the Japanese Aerospace Exploration Agency (JAXA), and the Indian Space Research Organisation (ISRO), among others, participate in research and application projects to apply satellite Earth observation for sustainable development. Several United Nations agencies provide support to help national governments apply satellite Earth observation inputs as part of the monitoring and management of the SDGs [15]. Satellite Earth observation also offers many opportunities to update national statistical systems, playing a role in relation to most of the SDGs and around a quarter of the Targets [16], as analyzed by the United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM) and the Committee on Earth Observation Satellites. In addition, recent years have seen an increase in the number of commercial Earth observation companies– such as Maxar Technologies, Skywatch, Blue Sky Analytics, and Satelligence—that work across the fields of data acquisition/creation, dissemination, analytics, and intelligence [17]. Through the efforts of this diverse ecosystem, the applications of satellite Earth observation for sustainable development have become robust and variegated. Several salient examples are provided below.

SDG 2 (“No Hunger”), for example, seeks to ensure that everyone on Earth has access to safe, nutritious food. This goal is linked to the health and stability of global agricultural systems, as well as the planetary weather patterns that influence them. Satellite Earth observation technologies can provide data critical to evaluating the food security and crop health of regions around the world to identify locations that are at risk of drought or famine. Scientists may, for example, use satellite data to measure ocean temperatures and climate variations caused by El Niño and La Niña, which influence rainfall patterns in nearby continents [18,19]. These measurements are assimilated into global physics models that create a complete picture of the estimated ocean temperature, which is then used to make inferences about the movement of currents [20]. Global models like this are an input into atmospheric models that forecast rainfall (which can also be improved using historical rainfall measurements from satellites). Aside from oceanic and atmospheric patterns, scientists can also use satellites to estimate whether food-growing regions have adequate soil moisture to support crops using land data assimilation models [21]. For a given crop, scientists have historical data about how much moisture is needed at specific times of the growing season and how much photosynthetic activity is expected to indicate a healthy crop. Scientists can estimate photosynthesis by measuring evapotranspiration and the level of chlorophyll in plants using satellite observations. Thus, satellite Earth observation may promote food security at every stage of the environmental food production process, from keeping tabs on ocean temperatures and rainfall to estimating soil moisture and crop health.

Several international organizations are working to ensure that satellite Earth observation data is applied in support of SDG 2. For example, multiple international groups that have already created operational routines to consult satellite-based measurements and predict locations in the world that may face food insecurity based on satellite- and ground-based measurements. The United States Agency for International Development, along with NASA and the United States Geological Survey, operates the Famine Early Warning Systems Network (FEWS.net) to identify African countries that may be at risk for famine or drought [22]. In related work, NASA’s Harvest initiative [23] convenes multisectoral entities from diverse nations and promotes their adoption of satellite Earth observation data to improve results in agricultural land use, agricultural sustainability, and agricultural productivity. Research funded by the Harvest consortium addresses global [24], regional [25], and national [26] issues related to agriculture and food security.

In addition to examining the use of satellite-related technology to support global agriculture, consider the space to support sustainable fishing and aquaculture. Multiple authors have highlighted that nutrition from fishing and aquaculture is already key to meeting human needs and that the role of these sources of food will increase in the future [27–29]. Some authors specifically highlight the importance of fishing and aquaculture for providing food for low-income groups and nations [30,31]. Other authors highlight the unique needs of Small Island Developing States with regard to food security as climate change advances and fisheries are strained [32]. The Sustainable Development Goals calls for both harnessing and managing fisheries and aquaculture under SDG14. Target 14.4 reads “By 2020, effectively regulate harvesting and end overfishing, illegal, unreported and unregulated fishing and destructive fishing practices and implement science-based management plans, in order to restore fish stocks in the shortest time feasible, at least to levels that can produce maximum sustainable yield as determined by their biological characteristics” [33]. The need to avoid over exploiting fishing stock is balanced with the need to ensure that fishing and aquaculture play a role to address food security. Specifically Target 14.7 reads, “By 2030, increase the economic benefits to Small Island developing States and least developed countries from the sustainable use of marine resources, including through sustainable management of fisheries, aquaculture and tourism.” Finally, Target 14. b calls for “[providing] access for small-scale artisanal fishers to marine resources and markets.” Satellite Earth Observation has been used to support the integrated goal of accessing the benefits of fisheries and aquaculture to support nutrition while consider sustainable management approaches. Looking historically, the potential to use satellite data to identify “Potential Fishing Zones” where fish would be likely to congregate envisioned early in the satellite era [34]. India was an early leader in operationalizing methods to use satellite-based Sea Surface Temperature and Ocean Color Measurements to provide fishers with maps of Potential Fishing Zones [35]. Reports show methods used by the Government of India to validate satellite-based Potential Fishing Zone maps using in-situ data collection. The methods to estimate Potential Fishing Zones have continued to mature, have incorporated advanced technology such as machine learning, and have been deployed in multiple regions [36–39]. More recent authors emphasize the need to use the satellite based information to support sustainable management of fisheries [40]. In parallel, aquaculture is the practice of farming fish and also needs to be carefully management and monitored to balance the benefits with environmental impacts. The United Nations Food and Agriculture Organization published a guide to apply satellite data and Geographic Information Systems to support fishes and aquaculture [41]. Authors continue to develop applications showing mapping of aquaculture locations, measurement of parameters to inform fish health, and monitoring for potential environmental concerns such as algal blooms caused by the nutrient rich farms [42,43]. Innovation in the use of satellite Earth Observation for SDG14 is active and continues to expand. Ongoing work is improving methods to monitor illegal fishing through a combination of remote sensed parameters such as ocean color, high resolution imagery of boats and the data from the Automated Ship Identification System [44,45]. More work is needed to ensure that low-income coastal nations and Small Island Developing States can harness these emerging technologies to manage their own fragile fisheries.

In another vein, the Group on Earth Observations (GEO)—a multilateral association of national governments and non-governmental organizations– focuses on increasing free access to and use of environmental monitoring data (including that from satellites) for the benefit of agriculture, biodiversity, forest management, mercury monitoring and other societal needs [46,47]. The GEO maintains the Earth Observations for the Sustainable Development Goals (EO4SDG) website and project database [48]; GEO also hosts the Crop Monitor, which provides regular reports on food security based on satellite data focused on the primary international staple foods, such as wheat, maize, rice, and soy [49]. Similarly, its Global Agricultural Monitoring (GEOGLAM) Initiative—the result of a 2011 G20 mandate to coordinate satellite-based monitoring of global croplands— aims to strengthen global agricultural monitoring by improving the use of remote sensing tools for crop production projections and weather forecasting. By providing coordinated Earth observations from satellites and integrating them with ground-based and other in-situ measurements, the initiative will contribute to generating reliable, accurate, timely, and sustained crop monitoring information and yield forecasts [50–52].

Earth observation satellites also possess a unique ability to monitor and produce data on global land cover. They can be used along with ground and air-based observation to identify deforestation and show the benefits of regulations or community policies to protect inland and coastal forests; they may thus support SDG 15 (“Life on Land”) [53]. We see an example of this support in recent research on mangrove forests. Mangroves play a vital role in their home ecosystems; their many positive impacts include erosion and flood control, fisheries support, carbon sequestration, biodiversity conservation, and nutrient cycling. Furthermore, because mangrove forests exist in densely-populated tropical regions, many coastal communities depend on them for food, forest products, and tourism revenue, as well as for natural defense against storm surges and coastal erosion. Given the various benefits mangrove forests provide, Global Land Survey (GLS) data and the Landsat archive is being used to improve the scientific understanding of the extent and distribution of mangrove forests of the world [54,55]. Recently, research was conducted using a novel map-to-image change method to detect annual and decadal changes of mangrove forests to an accuracy of over 90% [56]. The research concluded that the changes in mangrove extent were the consequence of natural and anthropogenic drivers, resulting in net increases or decreases in extent dependent upon the study site. Some teams use satellite Earth observation, in conjunction with ground- and air-based observation, provides consistent monitoring of mangrove baselines on at least a 5-year interval or more frequently to suit the requirements of policymakers. In a similar vein, Global Forest Watch (GFW)– established by the World Resources Institute (WRI) as an initiative of the Forest Frontiers Initiative– develops data on global tree cover change based on Landsat satellite imagery. GFW cultivates transparency and supports sustainable forest conservation and management by publishing its data freely online [57].

Satellite Earth observation data and models also allow for the measurement of air quality, such that air quality standards, policy, and regulations can be implemented [58,59]. NASA's Health and Air Quality Applied Science Team (HAQAST) projects, for example, use satellite data to identify and respond to air quality challenges around the world in support of SDG 3 ("Good Health and Well-Being") [60]. They routinely produce in-depth studies of issues related to air quality and pollution [61], and their Rapid Response teams in particular deploy expertise to solve urgent local and/or regional problems in one year or less [62]. Indeed, satellite Earth observation measurements and Earth science model outputs are used around the world by remote sensing agencies, companies and non-profit organizations to inform environmental decision making.

While much progress has been made to apply satellite Earth observation measurements and model output to the SDGs, barriers remain that create a challenge for novices to use this technology and the data it produces. Firstly, when organizations such as NASA and ESA provide large amounts of satellite Earth observation data freely on their websites, there is often such a large amount of data available that those who are new to data applications often struggle to decide what data they need and where to find it. Secondly, application of satellite data to build decision support maps require specialized knowledge of the specific category of data. Such situations demonstrate that it is not enough to simply provide access to data; more must be done to facilitate its effective use by those who would stand to benefit from it.

There are, too, ongoing international debates about the ethics and policies related to the cost of data, which Mariel Borowitz explores in her book *Open Space* [63]. When satellite Earth observation data is first downloaded from a satellite, several software processes are required to convert the raw data into useful information. As an illustration, NASA provides a standard set of Earth observation data analysis levels [64]. Some advocates of open data sharing argue that satellite Earth observation data that is unprocessed or still at a lower level of processing should be freely shared for further use and analysis by government, non-profit and academic users. Some argue that government-owned satellite systems should share data freely while commercially-owned satellite operators may charge in order to recover their costs. A third argument is that the fees should depend on the type of user. Under such a model, government or academic users conducting research for the public good would receive free data, while commercial users would pay fees. It is indeed that commercial entities who operate satellites as a business model need to identify customers and seek to earn back their investment and seek profit. Several examples show a compromise between the commercially sold and publicly shared models of data access. Government agencies in the United States sometimes buy data from commercial Earth Observation satellite operators and provide the data freely to government employees and government funded researchers [65]. In other cases, commercial satellite operators allow the public to access a subset of their data to increase familiarity with the data and its capabilities [66]. There is no universal consensus on what payment structure is equitable or appropriate, and all of these examples of data sharing and costing policies are used within the global marketplace of satellite Earth observation data. However, there is more general agreement that it is appropriate to charge for value-added services that start with satellite-based Earth observation as an input and create a software-based tool combining several types of data and algorithms to produce a report or recommendation.

In sum, Earth observation has historically been and continues to be one of the primary areas in which space technology supports humanity's pursuit of the SDGs. The data and knowledge created by Earth observation satellites and their supporting infrastructure makes it possible to maintain detailed measurements of the SDG Targets and make progress toward achieving multiple Global Goals.

2.2. Satellite communication

As the internet has become a core utility for global social and economic life, communications infrastructure has become increasingly important to economic and social development. Access to the internet and other forms of broadcast media may support progress toward a number of SDGs, including SDG 9 ("Industry, Innovation and Infrastructure") and, by promoting information sharing and mass communication, SDG 4 ("Quality Education"). However, many peoples and parts of the world are yet to be fully integrated into the network of global communications, and thus cannot enjoy the developmental benefits that connectivity confers. In its Global Connectivity Report 2022, the International Telecommunication Union (ITU) noted that while rates of connectivity are improving around the world, 2.9 billion people still lack internet access, and many more have only slow-speed, unreliable connections. Furthermore, the unevenness of access tends to reflect the axes of social and economic inequality: those who cannot or do not use the internet tend to live in rural areas of lower-income countries; be women; be elderly; and have less education than those who do use the internet [67]. There is, in this sense, work to be done before contemporary communications can maximally contribute to the pursuit of the SDGs.

Satellite communication systems may help to close the global internet coverage and usage gaps, and thus help a greater number of communities make progress toward the SDGs. They offer robust connectivity for broadcasting radio and television signals, establishing internet connections, or enabling phone or video-based calls. They are useful in rural or remote communities where traditional communication infrastructure is expensive to implement and may also be used in emergency contexts after disasters have destroyed local infrastructure. Cubic's Ground Air Transmit Receive (GATR) satellite communication terminal, for example, consists of an inflatable antenna that can be easily transported in a carry-on suitcase while deflated but may be quickly deployed to provide critical connectivity. The GATR system was used in the Philippines during the recovery from Typhoon Haiyan in 2013 [68]. Satellite-based communications systems like the GATR technology may support recovery efforts around the world in the wake of future disasters.

Arguably from its inception, satellite communications technology has maintained a commitment to extending access to new peoples, geographies, and use cases. Although the British writer Arthur C. Clarke theorized global satellite communications in a 1945 article [69], the combined efforts of public and private entities—including NASA, RCA, AT&T, and the Hughes Aircraft Company—in the mid-20th century helped bring this technology to life [70]. Building upon their successes, Congress passed the Communications Satellite Act of 1962, which eventually led to the establishment of the International Telecommunications Satellite Consortium (Intelsat) in 1964 [71]. With the launch of the *Early Bird* satellite in 1965, global satellite communications became a reality. The related Inmarsat emerged in England in 1979 to provide service to mobile (esp. maritime) systems. Both Intelsat and Inmarsat have historically operated their satellites in geosynchronous (GEO) orbits, which enabled them to provide global coverage with fewer satellites. Both organizations were also ultimately made private companies—the latter in 1999, the former in 2001— and have been managed by separate international organizations, each with more than 100 member states [72,73]. As of the time of writing, a proposed merger between Inmarsat and commercial communication satellite operator ViaSat is under development.

The contemporary satellite communication landscape reflects encouraging developments for improving global connectivity, but there remain questions about how public policy and business strategy will determine the extent of this improvement. There are, for example, divergent philosophies on how public policy should shape the satellite communication marketplace. Previous studies have explored the role of public policy in obstructing entrants into the satellite broadband market, as governments in developing countries have often sought to protect nationalized telecommunications providers from market competition, thus driving up costs for the end user [74–76]]. These studies have consistently highlighted the importance of liberalized trade, deregulation, streamlined licensing procedures and fees, and open competition to reduce end-user costs and quality of service. However, this perspective does not acknowledge that liberalization sometimes favors developed economies more than developing ones, and that in some cases, the governments of developing countries may elect to guard their local industries and companies from an influx of multinational capital that tends to take ownership of those industries away from local populations [77]. In this sense, it is not yet clear what combination of policies and approaches will create the ideal conditions for the equitable, beneficial growth of the global satellite communications industry.

On the technological side, the costs of producing, launching, and maintaining satellites for broadband service have historically prevented many countries from launching their own communication satellites. However, in each region, national governments and their private sector designates have prioritized the opportunity to create domestically operated satellites, both to provide services and to generate revenue [78]. In 2022, for example, Angola successfully launched ANGOSAT-2, which provides satellite-based communications to the entire African continent (though primarily to Southern Africa) [79]. Much like Angola, Thailand (Thaicom) [80], Egypt (NileSat) [81], and Malaysia (MEASAT) [82] also have national satellite operators.

In addition, technological advances—coupled with an increased demand for high-speed, low-latency internet service worldwide—have spurred a resurgence in the commercial satellite broadband market. The technology for providing communications using satellite constellations in Low Earth Orbit was developed in the 1990s by Iridium, which began providing service in 1998. Although Iridium's satellite phone offerings did not achieve mass adoption, the company continues to operate its constellations for clients that required service in remote operations such as the United States Department of Defense [83]. New players like OneWeb, ViaSat, and SpaceX (Starlink) have reentered a market that failed to get off the ground in the '90s [84,85]. The satellites designed and manufactured by these providers—which operate a large number of satellites within constellations in Low Earth Orbit and Medium Earth Orbit—are cheaper to produce and offer lower latency than the previous generation of communications satellites built by Iridium, Teledesic and Globalstar. As business analysts have suggested, however, the financial viability of large LEO constellations may require as much as a 75-percent reduction in production costs and may still present high hardware costs for consumers [86,87]. Furthermore, as more private operators launch their fleets, there are concerns that heavy traffic in LEO and MEO will increase the risk of space debris formation, and thus increase the likelihood of destructive collisions like that of Iridium 33 and Kosmos 2251 in 2009 [88].

Several business models have been proposed to solve the problems created by the manufacturing and operating costs of LEO constellation-based internet services, although they each have certain limitations. Consultants and analysts at McKinsey and Company have suggested that firms might opt to build a subscriber base and ecosystem control by offering service and ground-based hardware below cost before seeking to generate profits through advertising revenue and content creation [89]. Firms with significant cash reserves— like SpaceX and Amazon—may be able to prioritize market control over profit for some time, but it is unclear what will drive revenue generation. It has also been suggested that higher prices in developed countries could help subsidize the cost of service in the developing world [90]. Such a plan is limited by competition from fiber optic and cable internet service in the developed world. With cheaper and more convenient solutions available to customers in much of the Global North, it is unclear that satellite broadband providers would be able to generate enough revenue from the developed world to effectively subsidize access in developing countries. Lastly, companies like Hughes/Express Wi-Fi have previously implemented community-based models that provide a single subscription that supports hundreds of users in a given area with a public Wi-Fi access point [91]. This strategy dramatically improves the affordability of service but may not adequately meet demand in the long term, as individual users would be limited to very small data bundles (in the megabytes) to maintain usability and profitability even as development brings the need for greater data consumption. It may present the greatest value in the early days of infrastructure construction and development but will need to be replaced as developmental needs grow over time.

Taken as a whole, developments in both publicly- and privately-managed satellite communication ventures offer encouragement that global rates of connectivity will continue to grow, although the business models that create sustainable supply and demand are still evolving.

2.3. Satellite navigation and positioning

Global Navigation Satellite Systems (GNSS) are operated by several national or multi-lateral space agencies to provide services in the areas of positioning, navigation and timing [92]. Current systems building upon several generations of positioning technology– including Transit, the world's first satellite navigation system, which operated between 1968 and 1996. The United States launched the first of 24 original satellites for the "Navstar GPS" service in 1989 [93], and the system became fully operational in 1995 [94]. The United States continues to operate the Global Positioning System (GPS) and a supporting augmentation system called the Wide Area Augmentation System (WAAS) [95], while the European Union operates the Galileo system and a supporting augmentation system called the European Geostationary Navigation Overlay Service (EGNOS) [96]. Similarly, Russia's global system is called GLONASS [97]; and China's BeiDou/COMPASS system—now in its third generation—has been providing global service since June 2020 [98]. Japan and India, too, operate regional systems: Japan's Quasi-Zenith Satellite System (QZSS) is a four-satellite constellation that offers an Asia-Oceania regional complement to American GPS infrastructure [99] with a focus on Japan. Meanwhile, India has been pushing smartphone manufacturers to ensure compatibility with its Navigation with Indian Constellation (NavIC) service from 2023 onwards [100]. All of these GNSS operators coordinate on topics related to interoperability via the International Committee on GNSS hosted by the United Nations Office of Outer Space Affairs (UNOOSA) [101,102].

GNSS services may support the SDGs in myriad ways. Christina Giannopapa identifies opportunities for further investment in the EU's Galileo system and Global Monitoring for Environment and Security (GMES) program because of their potential to further numerous policy areas in the Europe 2020 development initiative [103]. In the area of transport policy, for example, Giannopapa highlights that GNSS service can alleviate traffic bottlenecks and ensure the smooth movement of people and goods, in support of SDG 9 ("Industry, Innovation, and Infrastructure"). Similarly, in the area of environmental action, Galileo's infrastructure can help track the movements of endangered animals for the purposes of scientific study and wildlife preservation. In this area, some scientists have tracked endangered turtles by placing a system on their backs that receives GNSS signals, calculates the location and transmits the location data back to researchers using satellite-based communication systems [104]. This use of GNSS technology directly promotes SDGs 14 and 15 ("Life Below Water" and "Life on Land," respectively).

In the fight against vector-borne diseases, too, there are applications for GNSS services, which may work in conjunction with other satellite technologies to maximize the efficacy of response. Diseases such as malaria, chikungunya, dengue, and zika are spread by mosquitoes; satellite navigation and positioning systems may work together with other satellite technologies to forecast exposure and transmission within regions. After satellite Earth observation data and images provide information about favorable conditions for mosquito activity and disease transmission (including human-human transmission), GNSS services can support response efforts by mapping the location of recent cases and routes to areas that can be treated to reduce vector activity. Organizations in southern Africa are applying all of these techniques to reduce malaria transmission in support of SDG 3 ("Good Health and Well-Being") [105]. Since 2009, for example, the Southern African Development Community's Elimination Eight Initiative (E8) has facilitated collaboration and data-sharing across eight southern African countries working to reduce transmission and achieve subnational elimination of malaria [106], and as of 2021, several frontline countries—including Botswana, Eswatini, Namibia, and South Africa—are maintaining low caseloads of 0–29 incidences per 1000 people [107].

2.4. Human space flight and microgravity research

Research and design pursued in the context of human space flight creates knowledge about the human body, plants, animals, and materials in support of SDG 3 ("Good Health and Well-Being") and SDG 9 ("Innovation, Industry, and Infrastructure"). One aspect of human space flight that creates new knowledge is studying the changes caused by exposure to altered gravitation effects; thus the category of Microgravity Research bears consideration. Many techniques are used to create economical simulations of microgravity conditions within the Earth environment. Drop towers—such as NASA's Glenn 2.2 Second Drop Tower in Ohio [108]— utilize free-fall physics to offer industrial, government, and academic users accessible—if brief—time to experiment in microgravity. In a different vein, clinostats [109] and human bed rest studies [110,111]] allow researchers on Earth to study the effects of microgravity on living tissue and whole organisms. Parabolic plane flights can create microgravity conditions for approximately 20 s [112] while suborbital rocket flights typically provide about 5 min of exposure to reduced gravity. These microgravity platforms have a continued importance in the current research landscape, as their relative affordability and accessibility ensures that diverse actors, not all of whom may be able to research using the International Space Station, can still experiment with and learn about the implications of microgravity exposure.

Currently, however, the primary platform available for routine human space flight and microgravity research is the International Space Station (ISS). The ISS was built largely between 1998 and 2011 and owned in parts by NASA, ESA, JAXA, the Canadian Space Agency (CSA), and the Russian space agency Roscosmos, who all operate via a treaty agreement. The ISS has helped humanity maintain a continuous presence in outer space since 2000 [113]. The U.S. portion of the ISS was designated a U.S. National Laboratory in 2005; its non-NASA research portfolio has been managed by the Center for the Advancement of Science in Space, Inc. (CASIS) since 2011 [114]. CASIS selects projects from governments, universities, non-governmental organizations, and private partners to facilitate the use of the ISS's unique resources (such as exposure to microgravity, radiation, extreme temperatures, vacuum conditions, etc.) for scientific research and commercial product development.

Recent projects at the ISS National Laboratory highlight the potential of microgravity research to support the SDGs. Massachusetts-based biotechnology firms Qlibrium and 1Drop Diagnostics each leveraged the ISS National Lab to conduct microfluidic research for new medical devices: Qlibrium's device is an ultra-thin pump for delivering medications through the skin, while 1Drop Diagnostic's device is a portable tool for running a suite of diagnostic tests from only a drop of human blood [115]. Similarly, nScrypt has collaborated with Techshot, Inc.— one of the ISS National Laboratory's commercial facility partners— to begin testing its 3D BioFabrication Facility (BFF) in microgravity. The BFF will use adult stem or pluripotent cells to fabricate cardiac-like tissue of varying thickness. Such tissue cannot be produced under Earth gravity; this line of research could potentially revolutionize organ replacement procedures, which are plagued by long waitlists [116]. All three endeavors may impact health outcomes on Earth, and each testify to the potential of microgravity research to advance SDG 3 ("Good Health and Well-Being"). More generally, the R&D activities of commercial entities using the ISS supports SDG 9 ("Innovation, Industry, and Infrastructure") as does CASIS's commitment to developing a commercial economy in low-Earth orbit.

While many experiments in the orbital environment continue to operate on the ISS, the looming retirement of the ISS raises questions about the future of the microgravity research ecosystem. In early 2022, NASA announced plans to de-orbit the station around 2030. In preparation for this transition, there is a move toward commercial stations and orbital platforms preparing to operate in the low-Earth orbit (LEO) microgravity research marketplace. The ISS has helped to build this marketplace over the course of the last two decades. This change is proposed as a way to allow government agencies to shift their focus and their funding toward the development of a cislunar space station and exploration of deeper space, including Mars [117]. By the end of this decade, therefore, the government owned and managed platform of the ISS may be replaced by privately-owned space stations as well as public-private partnerships offering a newly designed commercial economy of terrestrial and low-Earth orbit microgravity resources. One example of a proposed new space station with private ownership is the planned Orbital Reef station. A collaboration between Blue Origin and Sierra Space with further input from Boeing, Redwire Space, Genesis Engineering Solutions, and Arizona State University, Orbital Reef is expected to be fully operational before 2030, and will be available for mixed commercial, research, and recreational use [118]. Government agencies such as NASA propose that they will serve as customers to these privately operated space stations.

As Joseph and Wood suggest, the capacity of human spaceflight and microgravity research to support the SDGs in this new, commercialized marketplace of LEO resources will depend upon the economic and administrative openness of future platforms [119,120]. Economic openness refers to the costs associated with accessing a particular pathway for microgravity research; administrative openness refers to the restrictions that a pathway might impose on the basis of nationality, organization type, and/or project type [121,122]. The ISS's economic and administrative openness is shaped by its multi-use, multi-partner, quasi-commercial, and nationality-based operation, which emphasizes international cooperation and full utilization of its resources but imposes certain barriers to access based upon nationality [123]. Its successor platforms will fall along a spectrum between fully governmental and fully private pathways; Joseph and Wood suggest that hybrid public-private pathways may provide relatively higher economic and administrative openness than wholly public or private options [124]. Regardless, whether the ISS's successors will serve the needs of future governmental, commercial, and nontraditional users (e.g. emerging space nations, educational organizations targeting students and the lay-public, and early career researchers) hinges upon collective efforts to reduce costs, eliminate administrative barriers, and ultimately build an inclusive, accessible LEO marketplace.

2.5. Space technology transfer and spinoffs

The research and innovation that space activity has historically necessitated has often created knowledge, expertise, and technologies that benefit the general public on Earth through spinoffs and technology transfer. Spinoffs, as defined by NASA, are beneficial commercialized products that engage knowledge, processes, products, patents, or even personnel derived from/connected to NASA activity [125]. Space technology transfer refers more specifically to cases in which a system designed for the space sector is redesigned for an application on Earth. As humans make plans for long-term space flights and on habitation of planets such as Mars, the designs that enable human survival in low-resource environments can be adapted to support disaster recovery, emergency response, and many other needs on Earth.

A number of entities in both the commercial and nonprofit sectors have taken advantage of technology transfer opportunities to develop products in direct support of the SDGs. Mirico, for example, has repurposed technology developed for studying the Martian atmosphere to develop laboratory-grade medical devices and scientific instruments for terrestrial application. One such device can measure human breath exhalation to assist in the diagnosis of certain diseases [126]; another can support climate change research by measuring the presence of atmospheric pollutants in remote and hostile environments [127]. These examples show how space technology transfer may support SDG 3 ("Good Health and Well-Being") as well as SDG 13 ("Climate Action"). In another vein, the technology used to filter water on the ISS has also been applied in a system that is deployed for emergency water filtration needs around the world [128]. In this case, a key component of the NASA system was transferred to a non-profit that used it to design a ground-based system in direct support of SDG 6 ("Clean Water and Sanitation").

There are many such examples of transfer technologies and numerous space agencies have established initiatives and built institutional infrastructure to facilitate the development of spinoffs and expand technology transfer opportunities from and into the space sector. In the United States context, NASA has operated since its founding under a mandate to make the fruits of its research and innovation more widely available to the public, as reflected in Section 203a.3 of the National Aeronautics and Space Act (1958) [129]. The federal government has expanded this mandate in the ensuing decades using various legislative and executive tools. In particular, the Stevenson-Wydler Technology Innovation Act of 1980 (which required NASA to actively seek out and budget for technology transfer opportunities) and the Federal Technology Transfer Act of 1986 (which empowered government laboratories to pursue Cooperative Research and Development Agreements (CRADAs) and licensing negotiations with nongovernmental entities) helped establish institutionalized pathways for technology transfer [130]. Today, NASA's system for technology management identifies innovations from NASA teams and designs a process to manage or disclose the technology, thus fostering opportunities for spinoffs [131–133]. NASA's formal Technology Transfer Program manages a portfolio of patents available for commercial licensing [134], and its Innovative Partnerships Program (IPP) collaborations and technology transfer between NASA centres, university researchers, small businesses, and many other kinds of actors [135]. Similarly, the United States government's Small Business Innovative Research program provides businesses with fewer than 500 employees the opportunity to work with a government scientist at NASA or other science agencies to commercialize the results of government research [136]. This commercialization is one pathway for technology transfer.

NASA is not unique in this regard, as space agencies and national governments around the world have invested in technology transfer programs. JAXA, for example, facilitates a number of support initiatives like S-Matching [137] and J-SPARC [138] to encourage innovation, technology transfer, and entrepreneurship. ESA's Technology Transfer Programme (TTP)—which currently consists of 20 ESA Business Incubator Centres in 16 European countries– provides a platform for startups to develop Earth-based solutions from space technologies [139]. Between 2003 and 2016, ESA's TTP helped to support 400 new companies [140]. In a similar fashion, the German Aerospace Centre's "INNOspace Initiative" [141] and French Space Agency's (CNES) "ActInSpace" challenge [142] have used open competition to invite startups to spinoff space technology. It should be noted, too, that these agencies have made international collaboration toward technology transfer an integral aspect of their programs. In 2019, for example, ESA organized the annual meeting of the Space Agencies Technology Transfer Officers, a working group whose members come from NASA, ESA, CSA, the Centre National d'Études Spatiales (France), the Italian Space Agency (ASI), and the Israel Space Agency (ISA), among others [143]. The annual meeting of these agencies greatly expands opportunities for space technology transfer to support specific SDGs through product development and SDG 9 ("Industry, Innovation, and Infrastructure") overall. The Indian Space Research Organisation has evolved approaches to interact with both the domestic space commercial sector and the global market seeking services in areas such as launch and communications. ISRO formed Antrix to commercialize capabilities developed by the space agency [144]. Wood's research identifies examples in Malaysia, South Africa and Nigeria in which space organizations seek to apply their innovation and products in non-space sectors [145].

There are, however, steps that can be taken to maximize the potential of space spinoffs and technology transfer for global sustainable development. Firstly, many existing space technologies can be deployed more broadly to ensure the global reach of their benefits. In some cases, these technologies may be acquired directly by end users in the developing world; in situations where the technology in question is not financially or logistically accessible, regional governments and/or non-profit organizations may assist in "porting" innovations to the local context [146]. Secondly, more might be done to global stakeholders in the fields of development and the field of space technology to identify and act upon spinoff potential. This endeavor may involve engaging aspiring entrepreneurs in the developing world; fostering greater transnational and cross-sector research collaboration; encouraging volunteerism among the space workforce and scientific community; and facilitating dialogue among space technologists and those knowledgeable about community needs [147]. In short, realizing the potential of space spinoffs to solve global challenges depends largely on the global institutional and political infrastructure that is available to support it.

2.6. *Infrastructure and inspiration through basic scientific research*

Participation in basic scientific research regarding space—e.g. in areas such as astronomy, astrophysics, and ionospheric science– improves the infrastructural and innovation potential of a country. It is worth noting that the UN designated 2022 as the International Year of Basic Sciences for Sustainable Development, and that the International Astronomical Union (IAU) was one among many scientific organizations involved in convening the International Year and using space research to support the SDGs [148]. The declaration signals the importance of basic scientific research as a powerful driver of international development, dialogue, and collaboration towards the common good.

The positive infrastructural impacts of basic space research are embodied by the Square Kilometer Array project, which seeks to build world's largest radio telescope array using coordinated sites across the African and Australian continents [149]. South Africa leads a contingent of African nations including Botswana, Ghana, Kenya, Madagascar, Mauritius, Mozambique, Namibia, and Zambia that will host radio telescopes as part of the system [150,151]. In Ghana, the Space Science and Technology Institute has recently built infrastructure for their contribution to the Square Kilometer Array by converting a former satellite communication ground station into a radio telescope dish that can scan across the sky [152]. Each location that adds a radio telescope also invests in local engineering employment, communication and data management infrastructure, and improved regional education opportunities. Thus, the Square Kilometer Array supports SDG 9 ("Innovation and Infrastructure") by bringing new opportunities for innovation and infrastructure to regions that have previously not participated in astronomy, nor received economic or social benefits from astronomical research.

The International Year also thematizes the relationship between basic research and education [153]. Participation in scientific research and discovery often has an inspiring effect, particularly in relation to space. As countries invest in activities to engage learners in space-related education, they aim to improve the scientific literacy of the population and expand the national potential for future research and innovation. Entrepreneurial start-ups such as Black Girls Code [154] and OneUni [155] are examples of start-ups that address barriers to education such as lack of physical space at universities and financial constraints. These entrepreneurial initiatives introduce online open-source training and education programs through mobile apps helping to bridge the digital divide, supporting SDG 4 ("Quality Education") and SDG 5 ("Gender Equality"). Indeed, such programs enrich the scientific potential of future generations by fostering a more inclusive contexts for research and inspiration.

Institutional support for the basic sciences may help to both to amplify their impacts and focus those impacts on global sustainable development. To this end, the IAU operates an Office of Astronomy for Development (OAD). The OAD was formed as part of the IAU's Strategic Plan 2010–2020 (2009) [156], based on the recognition of astronomy's capacity to inspire, educate, and innovate across the realms of science, technology, and society. The OAD strategic plan identified the need for a full-time office to promote astronomic research and education across the developing world. Since 2011, the South Africa-based OAD has pursued its stated mission to "help further the use of astronomy, including its practitioners, skills and infrastructures, as a tool for development" [157]. As of 2018, the OAD awarded grants to 122 projects in 85 different countries and operated nine regional offices around the world [158].

The OAD's defines "development" using the 2030 Agenda for Sustainable Development, and the project proposals it has supported have directly furthered SDGs such as SDG 4 ("Quality Education"), SDG 5 ("Gender Equality"), and SDG 10 ("Reduced Inequalities") [159]. For example, the OAD has helped integrate basic astronomical training and equipment into the efforts of Global Himalayan Expedition to empower village women entrepreneurs in the Himalayan tourism industry [160]. In a different vein, OAD support is helping to preserve and revivify the oral astronomical knowledge of the Lamba people in Zambia [161]. By supporting projects such as these, the OAD highlights how the basic sciences may advance social and economic justice in addition to traditional epistemic goals. The IAU has prioritized the further expansion of the OAD's operating network of regional offices and projects in its Strategic Plan 2020–2030, such that it may serve more populations, foster greater interdisciplinary impact, and bolster its impacts on the SDGs [162].

3. Roles for governments, organizations, entrepreneurs, and universities in applying space technology towards sustainable development

The discussion thus far has given numerous examples showing how six areas of space technology support the monitoring and achievement of the SDGs. Much work remains, however, to reach the full potential of applying space for the SDGs. The capacity of each of the discussed technologies to support the SDGs is hampered by barriers in the areas of cost, accessibility, and design. Though science-informed analysis of interactions across SDG Targets can support more coherent and effective decision-making, local, national, and transnational entities are realizing that development requires a commitment to continuous iteration and improvement [163]. Countries must work alongside a variety of global actors to determine their development priorities and understand which approaches are suited to the complex challenges they face. The following section explores the roles that four different kinds of institutions—national governments, non- or inter-governmental organizations, entrepreneurs, and universities—might play in shaping the application of space technology for sustainable development, and notes obstacles that these institutions face in doing so.

3.1. Governments

National and supra-national governments must play an outsized role in maximizing the use of space technology for sustainable development. Governments shape the policy agenda and manage the capital necessary for social and economic development; they also often set the tone on scientific and space research, policy, and technology within each country by disbursing funds to academic institutions and running national laboratories. Further, partnerships between governments at regional, continental, and global levels often lead to the implementation of concrete projects applying space for the SDGS. Governments will lead the charge to use space technologies to further the SDGs; however, a combination of historical, technological, and political challenges limit their current capacity to do so.

Countries sometimes lack the fully-developed infrastructure for encouragement of science, technology, engineering, and mathematics education and technical activities based on needs assessments. They may also lack the technological or financial capacity to pursue space-enabled development at scale. Many of these obstacles reflect the legacies of colonialism, which helped imperial nations adopt some technologies earlier—and using the resources of—colonized nations in Latin America, Africa, Asia, and Oceania. Countries that have experienced colonialism are, however, among those most committed to increasing their domestic space capability and activity and using space technologies to advance sustainable development. Capacity building and development needs are highlighted among the seven thematic priorities of the United Nations Office of Outer Space Affairs (UNOOSA) UNISPACE+50; it is a fundamental pillar of global space governance [164]. Previous work by Wood and Weigel summarized major milestones as nations in these regions initiated their satellite programs [165]. Typically, the LEO satellites bought or built by the nations have been used for Earth observation or for scientific missions, while geostationary satellites are used for communication. Elsewhere, these authors have also explored the general motivations developing nations have in pursuing space activity by linking satellite programs to stakeholder needs and objectives [166,167].

While much progress has been made, there remain key obstacles to applying certain space technologies discussed above. In the case of satellite Earth observation, for example, the volume and complexity of available data may sometimes make it difficult for developing nations to use this technology. As noted above, it is significant that government agencies such as NASA and ESA provide large amounts of satellite Earth observation data freely on their websites [168,169], but there is such a large amount of data available that those who are new to data applications often struggle to decide what data they need and where to find it. Traditionally, government-owned Earth observation satellites have been designed as customized, one-time projects that produce unique data sets. Standardization and verification of data must be open access. Poor reporting, differences between country standards and methods, and variations in metadata could potentially hamper the use of space data for decision making processes.

Satellite navigation is also crucial for national governments, who utilize the technology for transportation infrastructure, aviation, shipping, coastline monitoring, seismology, and other public services. A variety of global navigation systems—including the United States' G.P.S., China's BeiDou/COMPASS, Europe's Galileo, and Russia's GLONASS—provide open satellite navigation services free of charge. Other countries may use these global services to enhance their own development initiatives, with the proper governmental support. For example, Operation Phakisa—which means "hurry up" in Sesotho—is an initiative of the South African government focused on prioritizing results and fasttracking progress on development programs related to the National Development Plan 2030; this initiative incorporates and maximizes its effectiveness through supportive technologies such as satellite positioning and Earth observation [170].

Research by Wood and colleagues has revealed that some countries choose to pursue international cooperation as a means to build capability in their national space programs and development strategies. One form of this pursuit can be characterized as Complex International Science, Technology & Innovation Partnerships (CISTIPs) [171]. CISTIPs are instruments for national technological development through cross-border learning, typically initiated by a learning country that wants to achieve growth in a particular area of science or technology but lacks the requisite expertise in the domestic population. These countries seek out a foreign expert partner, and the two partners engage in a long-term relationship during which individuals from both partners work jointly on collaborative research, engineering, or education activities. Typically, the expert partner provides education, mentoring, or training services to representatives of the learning partner. Through this sustained interaction, each partner is impacted by the social and cultural context of the other. Many CISTIPs occur in public service sectors and are led by government organizations, and thus are one of the most robust tools governments have for addressing obstacles in deploying space technology for sustainable development.

Outside of CISTIPs, national governments may also pursue multinational collaborations for research and development in which the involved parties work on equal footing. In recent years, we have seen an increase in international ground-based and space-based projects: the Aerosol Robotic Network (AERONET) project, for example, has federated a number of ground-based remote sensing systems across the world to further the study of aerosols [172]. Many collaborative projects are also led by emerging space nations and developing countries, as in the aforementioned Square Kilometer Array project and in research collaborations such as the West African Science Service Centre on Climate Change and Adapted Land Use [173]. The potential of these projects to foster political goodwill and progress towards the SDGs gestures to the overall capacity of space technology and activity to effect transformation across the world, provided national governments can integrate them into their development strategies.

Governments also play a role to foster an ecosystem that allows commercial entities and private sector organizations to develop applications of space for the SDGs. Several authors have studied how the government policies of Russia, Europe, South Korea, Japan, India and the United States have fostered commercial space innovation [174–178].

3.2. *Organizations*

For the purposes of this paper, "organizations" are multilateral and non- or inter-government entities that work on development in collaboration with national governments and the private sector. Space-related infrastructure, data, and integrated services will play an important role in the advancement of the SDGs if they become an integral part of countries' 'toolkit' for development, but these tools are often only available in theory; organizations often attempt to actualize these possibilities. As a critical interface between public, private, and academic entities, organizations can facilitate access to and instruction in space technology as well as encourage international collaboration on technology transfer and development. In order for the developmental potential of space technology to be fully realized, organizations will need to build their technical capability and invite their diverse partners to do the same. The United Nations Office of Outer Space Affairs plays a key role to spread awareness about the applications of space for the Sustainable Development Goals and to facilitate initiatives across all six space technologies to reduce barriers to their application [179].

Using the example of satellite Earth observation, organizations have recognized the need to improve and coordinate observation systems across all societal benefit areas. Strong advocacy of open data-sharing policies and practices as well as increased use of Earth observation data are the foundation of moving forward in these vital areas. Several international organizations work diligently to ensure that satellite Earth observation data is applied in support of the SDGs. Entities such as UNOOSA, the United Nations Development Programme (UNDP) and the Group on Earth Observations (GEO) are currently integrating opportunities to further global partnerships. These collaborative efforts are aimed at closing the technological and infrastructural gaps that prevent some actors from fully utilizing space assets for sustainable development. As discussed above, the GEO is a multilateral group whose members are national governments and non-governmental groups. GEO works through member governments to demonstrate the essential need for earth observation data and information to support sustainable development within communities, national governments, and other global development initiatives. The African Global Earth Observation System of Systems (AfriGEOSS) initiative of GEO focuses on engaging with relevant user communities and empowering them to assume a leading role in the implementation of data [180]. AfriGEOSS works to build human, institutional, and technological capabilities by strengthening links between current GEO activities with existing capabilities and initiatives in Africa. In doing so, they help to provide the necessary framework for countries and organizations to leverage on-going bilateral and multilateral earth observation-based initiatives across Africa [181].

Organizations are particularly adept at fostering opportunity and inclusivity through educational programs. Under its Human Space Technology Initiative (HSTI), the UNOOSA Programme on Space Applications initiated the "Zero-Gravity Instrument Project" (ZGIP) in 2012 [182]. This project aimed to distribute a number of microgravity-simulating instruments to selected schools and institutions worldwide. The 'Clinostats' instruments allowed students to observe natural phenomena of samples under simulated microgravity conditions on the ground and create datasets of plant species with their gravity response, contributing to design of future space experiments and to the advancement of microgravity research. In a related vein, the Drop Tower Experiment Series (DROPTES)—a collaboration between the UNOOSA, Center of Applied Space Technology and Microgravity (ZARM) and the German Aerospace Center (DLR)—is a fellowship program in the field of microgravity research [183]. The Drop Tower Experiment Series allows a selected research team the opportunity to conduct its own microgravity experiments over the course of four drops or catapult launches, which are capable of simulating microgravity conditions for 5 or 10 s respectively. Simlarly, DreamUp—a public-benefit corporation and spin-off company of NanoRacks, LLC—entered into a Space Act Agreement in 2018 to facilitate the sending of student research payloads to the ISS and offer educational research opportunities on Blue Origin's New Shepard space vehicle [184]. DreamUp has launched over 375 student payloads via its launch partner NanoRacks LLC, and continues to design contests enabling students to submit a payload design for microgravity experiments.

The International Space Station is currently the primary platform for long term microgravity research. For organizations from non-ISS partner countries, access to the ISS must be facilitated by a partner agency and the organization must work within the legal and logistical conditions set by the partner agency. For example, the U.S. Congress designates the U. S. research facility the ISS National Lab and assigns the Center for the Advancement of Science in Space to manage access. By design, the main users of the ISS National Lab capability are U.S.-based. As part of the HSTI, UNOOSA partners with space agencies and private firms to facilitate agreements to broker access for non-spacefaring nations to conduct ISS research. JAXA and the United Nations offer the KiboCUBE program, allowing institutions from emerging space nations the opportunity to deploy 1-Unit CubeSats from the Japanese Kibo module of the ISS [185]. Similarly, UNOOSA and the China Manned Space Agency provide countries with opportunities to fly experiments onboard China's

Space Station. In 2016, UNOOSA signed a Memorandum of Understanding with Sierra Nevada Corporation (SNC) to fly experiments onboard SNC's DreamChaser® spacecraft [186,187]. These initiatives testify to the capacity of organizations to bring new and non-traditional users into the world of space technology.

3.3. Entrepreneurs

One of the most notable distinctions between the present space landscape and the early era of space exploration is the relative prominence of the private-sector in space ventures today. While early space activity was essentially monopolized by national governments (and those of the United States and Soviet Union in particular), in recent decades we have seen governments and companies alike build a veritable industry and a robust marketplace for aerospace activity. The rise of the tech-entrepreneur in particular has created new opportunities for global businesses and novel solutions to pressing social and economic challenges. Armed with expertise in local contextual factors and an understanding of end-user needs, innovators harness digital technology to drive a social-tech movement aimed at improving economic and environmental conditions in their respective cities, countries, and regions. Many of these entrepreneurs are focusing their transformative private-sector initiatives in space or use space technologies to create change on Earth. In this way, entrepreneurs and private capital will also play a large role in purposing space technologies for sustainable social and economic development.

The UN Development Program has identified the importance of private sector partnerships to the pursuit of the SDGs [188], and start-ups in particular may play a role in deepening productive ties between space technologies and sustainable development. Space-enabled technologies often feature in/contribute to the success and innovation potential of start-ups due to the high degree of innovation intrinsic to the space industry and the potential for technology transfer (as discussed above). The SMART Tire Company, for example, has repurposed the pneumatic tire technology used in NASA rovers to produce a more durable, never-flat bicycle wheel that will reduce waste [189]. The growing importance of the tech-entrepreneur in the sustainable development sphere has been accompanied—and to a certain extent enabled—by an explosion of institutional support for start-ups. NASA continues to support startups through its Startup License, which provides new companies seeking to commercialize NASA technology with nonexclusive, affordable licenses for three years as they develop their products [190]. Internationally, other funding instruments have been created to support spin-offs and private-sector technology transfer; these national and international instruments— such as the Poland Prize [191] and ESA's Copernicus opportunities [192]– frequently maintain a special focus on start-ups. Similarly, hackathons and start-up prizes incentivize further intellectual, creative, and financial investment in private-sector support of the SDGs.

Entrepreneurs also have relatively more freedom and flexibility than governments and non-governmental organizations when it comes to working quickly in diverse contexts and emerging markets. While many African governments are building up their space capacity through CISTIPs and other mechanisms, several African startups are already operating on the global stage by taking advantage of international investment capital. The South African firm Aerobotics [193] and the Zimbabwean firm YouFarm [194] are examples of start-ups leveraging satellite imagery and machine learning to increase crop yield and improve disease resistance, in direct support of SDGs 2 ("No Hunger") and 3 ("Good Health and Well-Being"). Recognizing the potential for innovation and profit that these African start-ups possess, international companies have also scaled up their investment in the African continent. For example, Airbus's #Africa4Future initiative fosters collaboration between Airbus and African start-ups by offering mentorship, networking, and coaching. In early 2019, 10 African tech start-ups were selected to take part in the latest Airbus Bizlab #Africa4Future accelerator program [195].

Africa's economic significance as the world's second largest mobile market and its peoples' increasing access to education has helped entrepreneurship grow rapidly at the national and regional levels. This growth promises to bring about greater adoption and utilization of space technologies for sustainable development across the continent. There is no shortage of capital seeking to take advantage of opportunities across the developing world; there is only the question of whether investors and funding instruments can back the right projects to create the best results, both in Africa and around the world more generally.

3.4. Universities

Universities directly address the SDGs through research, innovation, and teaching. The knowledge creation of the academic enterprise oftentimes precedes, makes possible, or builds upon practical solutions propose and/or implemented by governments, non-governmental organizations, and entrepreneurs. Furthermore, universities are responsible for educating successive generations of global leaders by providing their students with the foundational knowledge and critical thinking acumen necessary for solving the unprecedented challenges we now face as a species. Ultimately, universities convene and unlock the potential of theoretical and practical expertise across every facet of society, and are thus uniquely placed to lead the cross-sectoral pursuit of the SDGs.

A number of university- and academic-led projects have successfully applied space technologies and science in support of the SDGs. Researchers at MIT, for example, recently worked toward designing a Drought Decision Support System for Angola [196]. By integrating Earth observation and positioning data, this system allows the Angolan government to soil moisture and socioeconomic vulnerability throughout vulnerable provinces and thus better mitigate the harmful effects of periodic flood and drought cycles. Researchers have similarly used satellite Earth observation to study deforestation caused by artisanal gold mining in Ghana [197] and to manage invasive plants in Lake Nokoue, Benin [198]. Such projects exemplify how university-led endeavors may use space technologies to solve challenges around the world.

The capacity—and perhaps responsibility—of universities to educate and inspire should also not be overlooked. As teaching institutions, universities are able to bring advanced knowledge and learning opportunities to local communities as well as a global audience, in direct support of SDGs 4 ("Quality Education"), 5 ("Gender Equality"), and 10 ("Reduced Inequalities"), among others. The Zero Robotics Educational Outreach Program—led by the Space Enabled Research Group at the MIT Media Lab—engages middle- and high-school students in tournaments that teach them to write code and program robots to be deployed on board the ISS [199]. Through programs like Zero Robotics, universities are able to bring their technical expertise to the broader public and inspire the next generation of space technology and development leaders. As another example, the Kyushu Institute of Technology collaborates with the UNOOSA to offer the Postgraduate Fellowship in Nanosatellite Technology. This experience, with funding from the government of Japan, allows students from emerging space nations to earn Masters or Doctoral Degrees in satellite engineering and participate in building a CubeSat [200].Other impactful educational programs that contribute to capabilities to apply space to the SDGs include the International Space University and the UN-affiliated Regional Centres for Space Science and Technology Education among others [201].

Universities also have certain strengths in fostering collaboration between different types of entities. They can, for example, engage in collaborative knowledge generation alongside other stakeholders to document case studies and evaluations illustrating the impacts of space research, space activity, and space-enabled technology for pursuit of the SDGs. They can further consult on methods to define and assess user needs and provide a neutral platform for cross-sectoral dialogue. Additionally, universities have the capacity to generate, translate, and disseminate knowledge relevant to achieving the SDGs. This can be done by hosting capability-building programs, international research collaboration, and personnel exchange. They can work with policymakers and other stakeholders to identify and evaluate capacity-building outcomes, and can act as mechanisms for space systems capacity coordination and initiate access to space assets.

In this way, universities provide an ideal environment through teaching, research, and outreach to shape the future of space technology and sustainable development. By integrating the SDGs and their overarching considerations into course curricula, collaborative ventures, and public programs, universities can provide a number of audiences with the knowledge and skills needed to address the SDGs, emphasizing interdisciplinary learning and promoting multidisciplinary, systems approaches to solving the increasingly complex challenges facing societies today.

4. Conclusions

This paper has provided several concrete examples of how technology from space supports a range of SDGs. Six space technologies have been identified that already support sustainable development: namely, satellite Earth observation, satellite positioning and navigation, satellite communication, human space flight and microgravity research, space technology transfer, as well as the infrastructure and inspiration from basic scientific research. Each of these technologies has made and may continue to make unique contributions to the monitoring and achievement of the SDGs.

Despite increased access to space data and new investments in space, however, more work needs to be done to reduce administrative, technological, and economic barriers to applying space for development. Applying space technology for development is sometimes difficult because the technology was not originally intended to be used for applications such as the SDGs. Several strategies for overcoming these obstacles are being proposed and tested across the globe, largely by the four different types of entities—national governments, non-governmental organizations, entrepreneurs, and universities—that operate across the space and development sectors. These institutions have unique roles to play in creating the public policy, cross-sectoral collaborations, business practices, technological innovations, and cultural conditions for the beneficial use of space for sustainable development. This paper has provided a brief overview of what these roles might be and highlighted obstacles these institutions face in assuming these roles.

Governments set the global political climate and are partnering with both public and private institutions to influence and shape public policy, particularly with regards to the sustainable development. The SDGs themselves reflect how partnerships between governments can establish durable, articulate, and robust international frameworks for promoting better use of analysis-ready data, capitalize on emerging business opportunities, and drive the construction of infrastructure. While factors including political, economic, strategic, and technical considerations determine if a nation finds it valuable to maintain a long-term satellite program, governments are increasingly recognizing the developmental value of space technologies. Alongside governments, many international organizations are using an array of initiatives to increase capacity-building programs and design system approaches that combine space-based information with insights from socioeconomic data for societal benefit. Several of these non- or inter-governmental organizations work diligently to provide opportunities for partner countries to build their space capabilities. Strong advocacy of open data-sharing policies and practices, as well as opportunities to offer microgravity and launch platforms allow nations to increase domestic capability and activity related to space.

As technology innovation increases, new opportunities have opened for entrepreneurs to develop novel solutions to pressing social and economic challenges in their respective cities, countries, and regions. Space technology provides capabilities that are relevant to many entrepreneurial firms and, as such, multiple funding instruments have been created to support the growth of start-up ventures and maximize the social benefits of innovative businesses. Finally, universities, too, have a role in supporting the SDGs, one that stems from their ability to engage in collaborative knowledge generation alongside other stakeholders without ignoring the nuances of local social and political contexts.

Achieving the SDGs is vital to enabled future of environmental, economic, social, and cultural well-being on Earth. Our investments in space predate the SDGs; even so, the fruits of human labor in and on space have the potential help address the challenge of realizing sustainable development models and practices. This paper has attempted to highlight how space technologies are already working to secure sustainable human futures, but while it is clear in 2023—at the halfway point of Agenda 2030—that significant progress has been made, there is work left to be done. Designers of space technology must work to learn to design systems that are customized to the opportunities for supporting the Sustainable Development Goals.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The work was funded via the Media Lab Consortium of Member Organizations and a grant from the National Science Foundation, United States (2047513).

References

[1] United Nations, Transforming our World: The 2030 Agenda for Sustainable Development (2015). https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf. (Accessed 4 February 2019).
[2] United Nations, Sustainable Development Goals (2015). https://sustainabledevelopment.un.org/?menu=1300. (Accessed 2 January 2019).
[3] United Nations, Sendai Framework for Disaster Risk Reduction (2015). https://www.unisdr.org/we/inform/publications/43291. (Accessed 2 January 2019).
[4] United Nations, The Paris Agreement, 2015, in: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement. (Accessed 2 January 2019).
[5] United Nations, The Sustainable Development Agenda (2015). https://www.un.org/sustainabledevelopment/development-agenda/. (Accessed 2 January 2019).
[6] United Nations, Millennium Development Goals (2000). http://www.un.org/millenniumgoals/. (Accessed 2 January 2019).
[7] United Nations, Millennium Development Goals Report (2015). http://www.un.org/millenniumgoals/pdf/MDG_Gap_2015_Executive_Summary_web.pdf. (Accessed 2 January 2019).
[8] United Nations, Major Groups and other Stakeholders (2015). https://sustainabledevelopment.un.org/majorgroups/about. (Accessed 2 January 2019).
[9] D. Wood, A. Weigel, Building technological capability within satellite programs in developing countries, Acta Astronaut. 69 (11–12) (2011) 1110–1122, https://doi.org/10.1016/j.actaastro.2011.06.008.
[10] D. Wood, A. Weigel, Charting the evolution of satellite programs in developing countries: the space technology Ladder, Space Pol. 28 (1) (2012) 15–24, https://doi.org/10.1016/j.spacepol.2011.11.001.
[11] D. Wood, A. Weigel, "Technological learning through international collaboration: Lessons from the field," Acta Astronaut. 83, 260-272. https://doi.org/10.1016/j.actaastro.2012.09.014.
[12] D. Wood, A. Weigel, Architectures of small satellite programs in developing countries, Acta Astronaut. 97 (2014) 109–121, https://doi.org/10.1016/j.actaastro.2013.12.015.
[13] A.J. Tatem, S.J. Goetz, S. Hay, Fifty Years of earth-observation satellites, Am. Sci. 96 (5) (2008) 390. https://www.americanscientist.org/article/fifty-years-of-earth-observation-satellites. (Accessed 2 May 2023).
[14] United States Geological Survey, "Landsat Data," https://pubs.usgs.gov/fs/1997/0084/report.pdf (Accessed 2 May 2023).
[15] Melanie van Driel, Frank Biermann, Rakhyun E. Kim, Marjanneke J. Vijge, International organisations as 'custodians' of the sustainable development goals? Fragmentation and coordination in sustainability governance, Global Policy 13 (5) (2022) 669–682.
[16] M. Paganini, I. Petiteville, S. Ward, G. Dyke, M. Steventon, J. Harry, F. Kerblat, Satellite earth observation in support of the sustainable development goals. http://eohandbook.com/sdg/files/CEOS_EOHB_2018_SDG.pdf, 2018. (Accessed 11 February 2019).
[17] A. Ravichandran, The State of Commercial Earth Observation, TerraWatch Space Insights, 2022. https://newsletter.terrawatchspace.com/p/the-state-of-commercial-earth-observation. (Accessed 16 June 2023), 28 Aug.

[18] A. Anyamba, J.R. Eastman, Interannual variability of NDVI over Africa and its relation to El Niño/southern Oscillation, Int. J. Rem. Sens. 17 (13) (1996) 2533–2548, https://doi.org/10.1080/01431169608949091.

[19] A. Anyamba, C.J. Tucker, R. Mahoney, From El Niño to La Niña: vegetation response patterns over east and southern Africa during the 1997-2000 period, J. Clim. 15 (21) (2002) 3096–3103. https://www.jstor.org/stable/26249478.

[20] NASA/Goddard Space Flight Center Scientific Visualization Studio, Global Sea Surface Currents and Temperature, 2012. https://svs.gsfc.nasa.gov/3912. (Accessed 4 February 2019).

[21] S.V. Kumar, C.D. Peters-Lidard, Y. Tian, P.R. Houser, J. Geiger, S. Olden, L. Lighty, J.L. Eastman, B. Doty, P. Dirmeyer, J. Adams, Land information system: an interoperable framework for high resolution land surface modeling, Environ. Model. Software 21 (10) (2006) 1402–1415, https://doi.org/10.1016/j.envsoft.2005.07.004.

[22] FEWSNET, Famine Early Warning Systems Network, 2019. http://fews.net/. (Accessed 2 January 2019).

[23] NASA Harvest, "Our Mission," https://nasaharvest.org/about (Accessed 28 May 2023).

[24] I. Becker-Reshef, B. Barker, A. Whitcraft, P. Oliva, K. Mobley, C. Justice, R. Sahajpal, Crop type maps for operational global agricultural monitoring, Sci. Data 10 (2023), https://doi.org/10.1038/s41597-023-02047-9.

[25] C. Nakalembe, H. Kerner, Considerations for AI-EO for agriculture in sub-Saharan Africa, Environ. Res. Lett. 18 (4) (2023), https://doi.org/10.1088/1748-9326/acc476.

[26] C. Abys, S. Skakun, I. Becker-Reshef, The rise and volatility of Russian winter wheat production, Environmental Research Communications 4 (10) (2022), https://doi.org/10.1088/2515-7620/ac97d2.

[27] Gabriel MS. Vianna, Dirk Zeller, Daniel Pauly, Fisheries and policy implications for human nutrition, Current Environmental Health Reports 7 (2020) 161–169.

[28] Ágúst Einarsson, Ásta Dís Óladóttir, Fisheries and Aquaculture: the Food Security of the Future, Academic Press, 2020.

[29] Claude E. Boyd, Aaron A. McNevin, Robert P. Davis, The contribution of fisheries and aquaculture to the global protein supply, Food Secur. 14 (3) (2022) 805–827.

[30] Rodney T. Muringai, Paramu Mafongoya, Romano T. Lottering, Raymond Mugandani, Denver Naidoo, Unlocking the potential of fish to improve food and nutrition security in Sub-Saharan Africa, Sustainability 14 (1) (2021) 318.

[31] Antaya March, Pierre Failler, Small-scale fisheries development in Africa: lessons learned and best practices for enhancing food security and livelihoods, Mar. Pol. 136 (2022) 104925.

[32] John Connell, Kristen Lowitt (Eds.), Food Security in Small Island States, Springer, Singapore, 2020.

[33] United Nations, "Sustainable Development Goal #14 Targets and Indicators," https://sdgs.un.org/goals/goal14#targets_and_indicators, Accessed January 15, 2024.

[34] P.V. Nair, V.K. Pillai, V.K. Balachandran, Potential applications of satellite remote sensing technique in oceanography and fisheries, in: CMFRI Bulletin: National Symposium on Research and Development in Marine Fisheries Sessions I & II 1987, vol. 44, CMFRI, Kochi, 1987, pp. 177–181, no. Part-.

[35] Jitender Saroha, IRS satellites: history, characteristics and applications, International Journal of Research and Analytical Reviews 5 (4) (2018) 815–820.

[36] S. Karuppasamy, T.P. Ashitha, R. Padmanaban, M. Shamsudeen, J.M.N. Silva, A Remote Sensing Approach to Monitor Potential Fishing Zone Associated with Sea Surface Temperature and Chlorophyll Concentration, 2020.

[37] Yeny Nadira Kamaruzzaman, Muzzneena Ahmad Mustapha, An overview assessment of the effectiveness of satellite images and remote sensing in predicting potential fishing grounds and its applicability for Rastrelliger kanagurta in the Malaysian EEZ off the South China Sea, Reviews in Fisheries Science & Aquaculture (2023) 1–22.

[38] Swarnali Majumder, Sourav Maity, T.M. Balakrishnan Nair, Rose P. Bright, M. Nagaraja Kumar, Naga Shwetha, Nimit Kumar, Potential fishing Zone characterization in the Indian ocean by machine learning approach, in: Soft Computing for Problem Solving: Proceedings of SocProS 2020, Springer, Singapore, 2021, pp. 43–54, vol. 2.

[39] Xun Zhang, Sei-Ichi Saitoh, Toru Hirawake, Predicting potential fishing zones of Japanese common squid (Todarodes pacificus) using remotely sensed images in coastal waters of south-western Hokkaido, Japan, in: Remote Sensing of Night-Time Light, Routledge, 2021, pp. 275–292.

[40] Yeny Nadira Kamaruzzaman, Muzzneena Ahmad Mustapha, An overview assessment of the effectiveness of satellite images and remote sensing in predicting potential fishing grounds and its applicability for Rastrelliger kanagurta in the Malaysian EEZ off the South China Sea, Reviews in Fisheries Science & Aquaculture (2023) 1–22.

[41] James M. Kapetsky, José Aguilar-Manjarrez, Geographic Information Systems, Remote Sensing and Mapping for the Development and Management of Marine Aquaculture, Food & Agriculture Org., 2007. No. 458.

[42] Qianguo Xing, Deyu An, Xiangyang Zheng, Zhenning Wei, Xinhua Wang, Li Lin, Liqiao Tian, Jun Chen, Monitoring seaweed aquaculture in the Yellow Sea with multiple sensors for managing the disaster of macroalgal blooms, Rem. Sens. Environ. 231 (2019) 111279.

[43] Sei-Ichi Saitoh, Robinson Mugo, I. Nyoman Radiarta, Shinsuke Asaga, Fumihiro Takahashi, Toru Hirawake, Yoichi Ishikawa, Toshiyuki Awaji, Teiji In, Shigeki Shima, Some operational uses of satellite remote sensing and marine GIS for sustainable fisheries and aquaculture, ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 68 (4) (2011) 687–695.

[44] Nicolas Longépé, Guillaume Hajduch, Romy Ardianto, Romain De Joux, Béatrice Nhunfat, Marza I. Marzuki, Ronan Fablet, et al., Completing fishing monitoring with spaceborne vessel detection system (VDS) and automatic identification system (AIS) to assess illegal fishing in Indonesia, Mar. Pollut. Bull. 131 (2018) 33–39.

[45] Andrey A. Kurekin, R. Loveday Benjamin, Oliver Clements, Graham D. Quartly, Peter I. Miller, Wiafe George, Kwame Adu Agyekum, Operational monitoring of illegal fishing in Ghana through exploitation of satellite earth observation and AIS data, Rem. Sens. 11 (3) (2019) 293.

[46] Group on Earth Observations, About Us: GEO Community (2022). https://www.earthobservations.org/geo_community.php. (Accessed 27 October 2022).

[47] Group on Earth Observations, Work Programme (2019). https://www.earthobservations.org/geoss_wp.php. (Accessed 2 January 2019).

[48] Group on Earth Observations , "Earth Observations for the Sustainable Development Goals," http://eo4sdg.org/(Accessed 2 January. 2019).

[49] Group on Earth Observations, "GEOGLAM Crop Monitor." https://cropmonitor.org/, 2019 (Accessed 13 February. 2019).

[50] I. Becker-Reshef, C. Justice, M. Sullivan, E. Vermote, C. Tucker, A. Anyamba, J. Small, E. Pak, E. Masuoka, J. Schmaltz, M. Hansen, Monitoring global croplands with coarse resolution earth observations, Rem. Sens. 2 (6) (2010) 1589–1609, https://doi.org/10.3390/rs2061589.

[51] A.K. Whitcraft, I. Becker-Reshef, C.O. Justice, A framework for defining spatially explicit earth observation requirements for a global agricultural monitoring initiative (GEOGLAM), Rem. Sens. 7 (2) (2015) 1461–1481, https://doi.org/10.3390/rs70201461.

[52] Group on Earth Observation, GEO Global Agricultural Monitoring (GEOGLAM), 2019. https://www.earthobservations.org/activity.php?id=129. (Accessed 11 February 2019).

[53] X.P. Song, M.C. Hansen, S.V. Stehman, P.V. Potapov, A. Tyukavina, E.F. Vermote, J.R. Townshend, Global land change from 1982 to 2016, Nature 560 (7720) (2018) 639, https://doi.org/10.1038/s41586-018-0411-9.

[54] C. Giri, E. Ochieng, L.L. Tieszen, Z. Zhu, A. Singh, T. Loveland, J. Masek, N. Duke, Status and distribution of mangrove forests of the world using earth observation satellite data, Global Ecol. Biogeogr. 20 (1) (2011) 154–159, https://doi.org/10.1111/j.1466-8238.2010.00584.x.

[55] S.E. Hamilton, G.A. Castellanos-Galindo, M. Millones-Mayer, M. Chen, Remote sensing of mangrove forests: current techniques and existing databases, in: C. Makowski, C. Finkl (Eds.), Threats to Mangrove Forests, Springer, Cham, 2018, pp. 497–520.

[56] N. Thomas, P. Bunting, R. Lucas, A. Hardy, A. Rosenqvist, T. Fatoyinbo, Mapping mangrove extent and change: a globally applicable approach, Rem. Sens. 10 (9) (2018) 1466, https://doi.org/10.3390/rs10091466.

[57] Global Forest Watch, Homepage, 2019. https://www.globalforestwatch.org/. (Accessed 14 February 2019).

[58] B.N. Duncan, A.I. Prados, L.N. Lamsal, Y. Liu, D.G. Streets, P. Gupta, E. Hilsenrath, R.A. Kahn, J.E. Nielsen, A.J. Beyersdorf, S.P. Burton, Satellite data of atmospheric pollution for US air quality applications: examples of applications, summary of data end-user resources, answers to FAQs, and common mistakes to avoid, Atmos. Environ. 94 (2014) 647–662, https://doi.org/10.1016/j.atmosenv.2014.05.061.

[59] N.A. Krotkov, C.A. McLinden, C. Li, L.N. Lamsal, E.A. Celarier, S.V. Marchenko, W.H. Swartz, E.J. Bucsela, J. Joiner, B.N. Duncan, K.F. Boersma, Aura OMI observations of regional SO2 and NO2 pollution changes from 2005 to 2015, Atmos. Chem. Phys. 16 (7) (2016) 4605–4629, https://doi.org/10.5194/acp-16-4605-2016.

[60] NASA Health and Air Quality Applied Sciences Team, About, 2023. https://haqast.org/nasa-applied-science-team/. (Accessed 3 May 2023).

[61] D. Odo, I. Yang, S. Dey, M. Hammer, A. van Donkelaar, R. Martin, G. Dong, B. Yang, P. Hystad, L. Knibbs, A cross-sectoral analysis of long-term exposure to ambient air pollution and cognitive development in children aged 3-4 years living in 12 low- and middle-income countries, Environ. Pollut. 318 (2023), https://doi.org/10.1016/j.envpol.2022.120916.

[62] NASA Health and Air Quality Applied Sciences Team, Rapid Response Teams, 2023. https://haqast.org/rapid-response-teams/. (Accessed 3 May 2023).

[63] M. Borowitz, Open Space: the Global Effort for Open Access to Environmental Satellite Data, MIT Press, Cambridge, 2018.

[64] NASA, "Data Processing Levels," earthdata.nasa.gov/engage/open-data-services-and-software/data-information-policy/data-levels (Accessed 29 May 2023).

[65] Manil Maskey, Alfreda Hall, Kevin Murphy, Compton Tucker, Will McCarty, Aaron Kaulfus, Commercial smallsat data acquisition: program update, in: 2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS, IEEE, 2021, pp. 600–603.

[66] Umbra, Umbra releases over $1 Milloin of Free SAR Data (2023). https://umbra.space/blog/umbra-releases-over-1-million-of-free-sar-data. (Accessed 15 January 2024). July 27.

[67] International Telecommunication Union, Global Connectivity Report 2022, 2022. https://www.itu.int/hub/publication/d-ind-global-01-2022/. (Accessed 4 May 2023).

[68] C. Henry, Disaster relief 2.0: lessons learned after Typhoon Haiyan, Via Satell. (2014) published 24 Feb, https://www.satellitetoday.com/uncategorized/2014/02/24/disaster-relief-2-0-lessons-learned-after-typhoon-haiyan/. (Accessed 4 May 2023).

[69] A.C. Clarke, Extra-terrestrial relays: can rocket stations give world-wide radio coverage? Wireless World (October 1945) 305–308. http://clarkeinstitute.org/wp-content/uploads/2010/04/ClarkeWirelessWorldArticle.pdf.

[70] D. Whalen, Communications Satellites: Making the Global Village Possible, National Aeronautics and Space Administration, 2010. https://history.nasa.gov/satcomhistory.html. (Accessed 4 May 2023).
[71] International Telecommunications Satellite Organization, "About Us," https://itso.int/about-us/more/(Accessed 4 May 2023).
[72] International Telecommunications Satellite Organization, "About Us," https://itso.int/about-us/more/(Accessed 4 May 2023).
[73] International Mobile Satellite Organization, List of parties to the convention on the international mobile satellite organization (member states) and status of acceptance of the 2008 amendments to the convention. https://imso.org/wp-content/uploads/2022/09/List-of-Parties.pdf. (Accessed 4 May 2023).
[74] M. Jarrold, Open and closed skies: satellite access in Africa, in: S. Danofsky (Ed.), Open Access for Africa: Challenges, Recommendations and Examples, United Nations Information and Communication Technologies Task Force, 2005, pp. 140–154. New York.
[75] D. Wood, The Use of Satellite-Based Technology to Meet Needs in Developing Countries, Massachusetts Institute of Technology, 2008. https://dspace.mit.edu/handle/1721.1/46371.
[76] M. Conradi, C. Keogh, Expanding into Africa: regulatory challenges for satellite broadband providers, DLA Piper (2021) published 27 Apr, https://www.lexology.com/library/detail.aspx?g=908037e3-558c-490a-b31b-6e2962ff9b15. (Accessed 18 October 2022).
[77] A. Amsden, Escape from Empire: the Developing World's Journey through Heaven and Hell, MIT Press, Cambridge, 2007.
[78] W. Adelanwa, M. Iderawumi, A. Adetola, J. Faleti, A. Asunloye, V. Asefon, P. Adekolu, African Space Industry Annual Report, 2022 Edition, 2022. *Space in Africa*, published.
[79] J. Faleti, Angola launches its second satellite, angosat-2, today, Space in Africa (2022) published 12 Oct, https://africanews.space/angola-launches-its-second-satellite-angosat-2-today/. (Accessed 5 May 2023).
[80] Thaicom, "About Us," https://www.thaicom.net/about-us/(Accessed 5 May 2023).
[81] NileSat, "About Us," https://www.nilesat.com.eg/en#aboutus (Accessed 5 May 2023).
[82] MEASAT, "About Us," http://www.measat.com/company-profile/(Accessed 5 May 2023).
[83] C. Christensen, S. Beard, Iridium: failures and successes, Acta Astronaut. 48 (5–12) (2001) 817–825, https://doi.org/10.1016/S0094-5765(01)00036-4.
[84] M. Graydon, L. Parks, 'Connecting the unconnected': a critical assessment of US satellite internet services, Media Cult. Soc. 42 (2) (2019) 270–276, https://doi.org/10.1177/0163443719861835.
[85] J. Garrity, A. Husar, Digital Connectivity and Low Earth Orbit Satellite Constellations: Opportunities for Asia and the Pacific, Asian Development Bank, 2021. https://www.adb.org/publications/digital-connectivity-low-earth-orbit-satellite-opportunities. (Accessed 12 September 2022).
[86] M. Graydon, L. Parks, 'Connecting the unconnected': a critical assessment of US satellite internet services, Media Cult. Soc. 42 (2) (2019) 270–276, https://doi.org/10.1177/0163443719861835.
[87] C. Daehnick, I. Klinghofer, B. Maritz, B. Wiseman, Large LEO Satellite Constellations: Will it Be Different This Time? McKinsey and Company, 2020. https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/large-leo-satellite-constellations-will-it-be-different-this-time. (Accessed 12 September 2022).
[88] T.S. Kelso, Analysis of the Iridium 33-cosmos 2251 collision, Adv. Astronaut. Sci. 135 (2) (2009) 1099–1112. https://www.researchgate.net/publication/242543407_Analysis_of_the_Iridium_33Cosmos_2251_Collision. (Accessed 29 May 2023).
[89] C. Daehnick, I. Klinghofer, B. Maritz, B. Wiseman, Large LEO Satellite Constellations: Will it Be Different This Time? McKinsey and Company, 2020. https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/large-leo-satellite-constellations-will-it-be-different-this-time. (Accessed 12 September 2022).
[90] M. Graydon, L. Parks, 'Connecting the unconnected': a critical assessment of US satellite internet services, Media Cult. Soc. 42 (2) (2019) 270–276, https://doi.org/10.1177/0163443719861835.
[91] J. Garrity, A. Husar, Digital Connectivity and Low Earth Orbit Satellite Constellations: Opportunities for Asia and the Pacific, Asian Development Bank, 2021. https://www.adb.org/publications/digital-connectivity-low-earth-orbit-satellite-opportunities. (Accessed 12 September 2022).
[92] C. Alexandrow, "The Story of GPS," DARPA, https://www.darpa.mil/attachments/(2O10)%20Global%20Nav%20-%20About%20Us%20-%20History%20-%20Resources%20-%2050th%20-%20GPS%20(Approved).pdf (Accessed 20 May 2023).
[93] C. Alexandrow, "The Story of GPS," DARPA, https://www.darpa.mil/attachments/(2O10)%20Global%20Nav%20-%20About%20Us%20-%20History%20-%20Resources%20-%2050th%20-%20GPS%20(Approved).pdf (Accessed 20 May 2023).
[94] Aerospace Corporation, "A Brief History of GPS," https://aerospace.org/article/brief-history-gps (Accessed 6 May 2023).
[95] United States Government, The Global Positioning System (2019). https://www.gps.gov/systems/gps/. (Accessed 2 January 2019).
[96] EUSPA, "Galileo is the European global satellite-based navigation system," https://www.euspa.europa.eu/european-space/galileo/What-Galileo (Accessed 6 May 2023).
[97] Roscosmos, "About GLONASS," https://glonass-iac.ru/en/about_glonass/(Accessed 6 May 2023).
[98] Aerospace Technology, "Bei-Dou 3 Navigation Satellite System," https://www.aerospace-technology.com/projects/beidou-3-navigation-satellite-system/(Accessed 6 May 2023).
[99] Government of Japan, Overview of the Quasi-Zenith Satellite System (2022). https://qzss.go.jp/en/overview/services/sv01_what.html. (Accessed 4 December 2022).
[100] M. Vengattil, A. Kalra, Explainer: NavIC, India's home-grown alternative to the GPS navigation system, Reuters (2022). https://www.reuters.com/technology/navic-indias-home-grown-alternative-gps-navigation-system-2022-09-26/. (Accessed 4 December 2022).
[101] United Nations, International Committee on GNSS, 2023. http://www.unoosa.org/oosa/en/ourwork/icg/icg.html. (Accessed 2 January 2019).
[102] United Nations Office for Outer Space Affairs, International Committee on Global Navigation Satellite Systems (ICG): Members, 2019. http://www.unoosa.org/oosa/en/ourwork/icg/members.html. (Accessed 11 February 2019).
[103] C. Giannopapa, Securing Galileo's and GMES's place in European policy, Space Pol. 28 (4) (2012) 270–282, https://doi.org/10.1016/j.spacepol.2012.09.008.
[104] Sea Turtle Conservancy, Sea Turtle Tracking (2019). https://conserveturtles.org/sea-turtle-tracking/. (Accessed 2 January 2019).
[105] Y. Kazansky, D. Wood, J. Sutherlun, The current and potential role of satellite remote sensing in the campaign against malaria, Acta Astronaut. 121 (2016) 292–305, https://doi.org/10.1016/j.actaastro.2015.09.021.
[106] G. Newby, A. Bennett, E. Larson, C. Cotter, R. Shretta, A.A. Phillips, R. G. Feachem, The path to eradication: a progress report on the malaria-eliminating countries, Lancet 387 (10029) (2016) 1775–1784, https://doi.org/10.1016/S0140-6736(16)00230-0.
[107] SADC Elimination 8 Initiative, "Annual Report 2021," http://malariaelimination8.org/sites/default/files/publications/e8_annual_report_2021_eng-compressed.pdf (Accessed 6 May 2023).
[108] NASA Glenn Research Center, "2.2 Second Drop Tower," https://www1.grc.nasa.gov/facilities/drop/#:~:text=The%202.2%20Second%20Drop%20Tower,Quick%20Facts (Accessed 8 May 2023).
[109] J. Kiss, C. Wolverton, S. Wyatt, K. Hassenstein, J. van Loon, Comparison of microgravity analogs to spaceflight in studies of plant growth and development, Plant Sci. 10 (2019) 1577, https://doi.org/10.3389/fpls.2019.01577.
[110] P.D. Jost, Simulating human space physiology with bed rest, Hippokratia 12 (1) (2008) 37–40. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2577398/.
[111] A. Hargens, L. Vico, Long-duration bed rest as an analogue to microgravity, J. Appl. Physiol. 120 (8) (2016) 891–903, https://doi.org/10.1152/japplphysiol.00935.2015.
[112] National Aeronautics and Space Administration, "Analog Missions: Parabolic Flight," https://www.nasa.gov/analogs/parabolic-flight (Accessed 8 May 2023).
[113] Center for the Advancement of Science in Space, About the ISS National Lab, 2022. https://www.issnationallab.org/about/about-the-iss-national-lab. (Accessed 30 October 2022).
[114] Center for the Advancement of Science in Space, About the ISS National Lab, 2022. https://www.issnationallab.org/about/about-the-iss-national-lab. (Accessed 30 October 2022).
[115] Center for the Advancement of Science in Space, Successful Space-X Demo-2 Mission Leaves its Mark on Space Station Science (2020). https://www.issnationallab.org/iss360/spacex-demo-2-mission-national-lab-science-on-station. (Accessed 30 October 2022).
[116] Center for the Advancement of Science in Space, 3D Printer for Human Tissue Now Available for Research Onboard the ISS National Laborator, 2019. https://www.issnationallab.org/iss360/3d-printer-for-human-tissue-now-available-for-research-onboard-the-iss-national-laboratory. (Accessed 30 October 2022).
[117] NASA, FAQ: the international space station 2022 transition plan. https://www.nasa.gov/feature/faq-the-international-space-station-2022-transition-plan, 2022. (Accessed 1 November 2022).
[118] Blue Origin, Blue Origin and Sierra Space Developing Commercial Space Station, 2021. https://www.blueorigin.com/news/orbital-reef-commercial-space-station/. (Accessed 2 November 2022).
[119] C. Joseph, D. Wood, Understanding socio-technical issues affecting the current microgravity research marketplace, in: 2019 IEEE Aerospace Conference, 2019, pp. 1–10. https://ieeexplore.ieee.org/document/8742202.
[120] C. Joseph, D. Wood, Analysis of the microgravity research ecosystem and market drivers of accessibility, New Space 9 (2) (2021) 123–138, https://doi.org/10.1089/space.2020.0044.
[121] C. Joseph, D. Wood, Understanding socio-technical issues affecting the current microgravity research marketplace, in: 2019 IEEE Aerospace Conference, 2019, pp. 1–10. https://ieeexplore.ieee.org/document/8742202.
[122] C. Joseph, D. Wood, Analysis of the microgravity research ecosystem and market drivers of accessibility, New Space 9 (2) (2021) 123–138, https://doi.org/10.1089/space.2020.0044.
[123] C. Joseph, D. Wood, Analysis of the microgravity research ecosystem and market drivers of accessibility, New Space 9 (2) (2021) 123–138, https://doi.org/10.1089/space.2020.0044.
[124] C. Joseph, D. Wood, Understanding socio-technical issues affecting the current microgravity research marketplace, in: 2019 IEEE Aerospace Conference, 2019, pp. 1–10. https://ieeexplore.ieee.org/document/8742202.
[125] D. Wood, Transfer of space technology for spinoff application in developing countries: past examples and future potential, 62nd International Astronautical Congress (2011) 1–14. https://iafastro.directory/iac/archive/browse/IAC-11/E5/2/10704/.

[126] J. Edwards, Rainbow seed fund backs new STFC spin out MIRICO, PRWeb (2016). , published 12 May, https://www.prweb.com/releases/rainbowseedfund/mirico/prweb13394668.htm. (Accessed 28 May 2023).
[127] R. Gibbs, New method of greenhouse gas emission mapping to be developed with mirico's orion, PRWeb (2022). https://www.prnewswire.com/news-releases/new-method-of-greenhouse-gas-emission-mapping-to-be-developed-with-mirico s-orion-301545285.html. (Accessed 28 May 2023).
[128] NASA Spinoff Database, Fast-flow nanofiber filters purify water at home and in the field NASA center. http://spinoff.nasa.gov/Spinoff2017/pdf/ps_5.pdf, 2017. (Accessed 13 February 2019).
[129] U.S. Congress, National Aeronautics and Space Act of 1958 (Unamended), NASA, 1958. https://history.nasa.gov/spaceact.html. (Accessed 8 May 2023).
[130] D. Comstock, D. Lockney, NASA's legacy of technology transfer and prospects for future benefits, in: AIAA SPACE 2007 Conference and Exhibition, 2007. https://www.nasa.gov/pdf/330841main_aiaa_2007_6283_31.pdf. (Accessed 9 May 2023).
[131] D. Lockney, T.L. Taylor, Bringing NASA technology down to earth, in: 2018 IEEE Aerospace Conference, 2018. https://ieeexplore-ieee-org.ezproxy.cul.columbia.edu/document/8396834.
[132] T.L. Taylor, A.M. Harkey, NASA technology transfer program: FY2017 accomplishments and FY2018 program plan, NASA Technical Reports Server, http s://ntrs.nasa.gov/citations/20180001756, 2018. (Accessed 13 February 2019).
[133] N. Cheeks, The social benefits of space spin-offs: an introduction, International Astronautical Congress 56 (2005). https://ntrs.nasa.gov/citations/20050244969.
[134] NASA Technology Transfer Program, "Patent Portfolio," National Aeronautics and Space Administration, https://technology.nasa.gov/patents (Accessed 9 May 2023).
[135] National Aeronautics and Space Administration, "Innovative Partnerships Program," National Aeronautics and Space Administration, nasa.gov/centers /ryden/news/X-Press/aerovations/dynamic_ipp.html (Accessed 9 May 2023).
[136] National Aeronautics and Space Administration, Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) program (2019). https://sbir.nasa.gov/. (Accessed 13 February 2019).
[137] J. Foust, New Fund to Boost Japanese Space Startups, Space News, 21 Mar 2018. https://spacenews.com/new-fund-to-boost-japanese-space-startups/. (Accessed 9 May 2023).
[138] D. Messier, JAXA Collaborating with Private Businesses on Innovative Projects, Parabolic Arc, 2019 published 27 Oct. https://parabolicarc.com/2019/10/27/jaxa-collaborating-with-private-businesses-on-innovative-projects/. (Accessed 9 May 2023).
[139] European Space Agency, "Technology Transfer Programme," https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Technology_Business_Opportunities/Technology_Transfer_Programme (Accessed 9 May 2023).
[140] European Space Agency, Space spin-off fosters 400 new companies. https://www.esa.int/Applications/Technology_Transfer/Space_spin-off_fosters_400_new_companies, 2016. (Accessed 13 February 2019).
[141] Spaceoneers, INNOSpace – Space Tech Transfer and Innovation in the German Aerospace Industry (2017). https://spaceoneers.io/2017/07/28/innospace/. (Accessed 13 February 2019).
[142] Centre National d'Études Spatiales, "ActInSpace," https://entreprises.cnes.fr/fr/actinspace (Accessed 9 May 2023).
[143] European Space Agency, Seven space agencies presented space spin-off potentials. https://www.esa.int/Applications/Technology_Transfer/Seven_space_agencies_presented_space_spin-off_potentials, 2019. (Accessed 3 November 2022).
[144] KR Sridhara Murthi, Mukund Kadursrinivas Rao, India's space industry ecosystem: challenges of innovations and incentives, New Space 3 (3) (2015) 165–171.
[145] D. Wood, Transfer of space technology for spinoff application in developing countries: past examples and future potential, 62nd International Astronautical Congress (2011) 1–14. https://iafastro.directory/iac/archive/browse/IAC-11/E5/2/10704/.
[146] D. Wood, Transfer of space technology for spinoff application in developing countries: past examples and future potential, 62nd International Astronautical Congress (2011) 1–14. https://iafastro.directory/iac/archive/browse/IAC-11/E5/2/10704/.
[147] D. Wood, Transfer of space technology for spinoff application in developing countries: past examples and future potential, 62nd International Astronautical Congress (2011) 1–14. https://iafastro.directory/iac/archive/browse/IAC-11/E5/2/10704/.
[148] International Astronomical Union Office of Astronomy for Development, Annual Report 21/22 (2022). https://indd.adobe.com/view/33fc99c5-344e-4238-81e7-9687955acfac. (Accessed 14 November 2022).
[149] K. Cooper, SKA Observatory (SKAO): A Guide to the Soon-To-Be Largest Radio Telescopes in the World, SPACE.com, 2023. https://www.space.com/square-kilometre-array-observatory-skao. (Accessed 10 May 2023).
[150] South African Radio Astronomy Observatory, "The project," https://www.sarao.ac.za/about/the-project/, 2022 (accessed 10 January. 2023).
[151] South African Radio Astronomy, "Location," https://www.sarao.ac.za/about/location/, 2023 (accessed 10 January. 2023).
[152] P. Emmanuel, N. Klutse, D. Adomako, P. Ashilevi, E. Aggrey, Ghana in the Square kilometer array, Advances in Research 2 (12) (2014) 1040–1045, https://doi.org/10.9734/AIR/2014/12228.
[153] International Year of Basic Sciences for Sustainable Development, About IYBSSD 2022 (2022). https://www.iybssd2022.org/en/about-us/. (Accessed 15 November 2022).
[154] Black Girls Code, Homepage, 2019. http://www.blackgirlscode.com/. (Accessed 3 January 2019).
[155] Impact Space, OneUni, 2019. https://impactspace.com/company/oneuni. (Accessed 3 January 2019).
[156] International Astronomical Union, Strategic Plan 2010-2020 (2009). https://iau.org/static/education/strategicplan_2010-2020.pdf. (Accessed 13 May 2023).
[157] IAU Office of Astronomy for Development, "About the IAU OAD," https://www.astro4dev.org/aboutiauoad/(Accessed 13 May 2023).
[158] International Astronomical Union, Strategic Plan 2020-2030 (2019). https://www.iau.org/static/administration/about/strategic_plan/strategicplan-2020-2030.pdf. (Accessed 13 May 2023).
[159] IAU Office of Astronomy for Development, OAD Coffee Table Book (2018). https://cloudcape.saao.ac.za/index.php/s/S6OZsnqTRbjfUmN. (Accessed 13 May 2023).
[160] IAU Office of Astronomy for Development, OAD Projects: Astronomy for Himalayan Livelihood Creation, 2018. https://www.astro4dev.org/astronomy-for-himalayan-livelihood-creation/. (Accessed 13 May 2023).
[161] IAU Office of Astronomy for Development, OAD Projects: Lamba Indigenous Astronomy, 2018. https://www.astro4dev.org/lamba-indigenous-astronomy/. (Accessed 13 May 2023).
[162] International Astronomical Union, Strategic plan 2020-2030. https://www.iau.org/static/administration/about/strategic_plan/strategicplan-2020-2030.pdf, 2019. (Accessed 13 May 2023).
[163] D. Griggs, A. Stevance, D. McCollum, A guide to SDG interactions: from science to implementation, International Science Council (2017). https://council.science/publications/a-guide-to-sdg-interactions-from-science-to-implementation/. (Accessed 2 January 2019).
[164] UN office of outer space Affairs, UNISPACE+50 (2018). https://www.unoosa.org/oosa/en/ourwork/unispaceplus50/index.html. (Accessed 15 May 2023).
[165] A.J. Tatem, S.J. Goetz, S. Hay, Fifty years of earth-observation satellites, Am. Sci. 96 (5) (2008) 390. https://www.americanscientist.org/article/fifty-years-of-earth-observation-satellites. (Accessed 2 May 2023).
[166] D. Wood, A. Weigel, "Technological learning through international collaboration: Lessons from the field," Acta Astronaut. 83, 260-272. https://doi.org/10.1016/j.actaastro.2012.09.014.
[167] D. Wood, A. Weigel, "Technological learning through international collaboration: Lessons from the field," Acta Astronaut. 83, 260-272. https://doi.org/10.1016/j.actaastro.2012.09.014.
[168] National Aeronautics and Space Administration, "Down Earth," https://www.earthdata.nasa.gov/(Accessed 15 May 2023).
[169] European Space Agency, "ESA Earth Online: Data," https://earth.esa.int/eogateway/catalog (Accessed 15 May 2023).
[170] Republic of South Africa, Operation Phakisa, 2023. https://www.operationphakisa.gov.za/Pages/Home.aspx. (Accessed 10 January 2023).
[171] S. Pfotenhauer, D. Wood, D. Roos, D. Newman, Architecting complex international science, technology and innovation partnerships (CISTIPs): a study of four global MIT collaborations, Technol. Forecast. Soc. Change 104 (2016) 38–56, https://doi.org/10.1016/j.techfore.2015.12.006.
[172] Aerosol robotic network, Aeronet (2019). https://aeronet.gsfc.nasa.gov/. (Accessed 3 January 2019).
[173] WASCAL, West African Science Service Center on Climate Change and Adapted Land Use (2019). https://www.wascal.org/. (Accessed 3 January 2019).
[174] Alessandra Vernile, The Rise of Private Actors in the Space Sector, Springer, Cham, 2018.
[175] Douglas KR. Robinson, Mariana Mazzucato, The evolution of mission-oriented policies: exploring changing market creating policies in the US and European space sector, Res. Pol. 48 (4) (2019) 936–948.
[176] James Clay Moltz, The Russian space program, Asia Policy 15 (2) (2020) 19–26.
[177] Junho Lee, Ikjun Kim, Hyomin Kim, Juyoung Kang, SWOT-AHP analysis of the Korean satellite and space industry: strategy recommendations for development, Technol. Forecast. Soc. Change 164 (2021) 120515.
[178] Matthew Weinzierl, Space, the final economic frontier, J. Econ. Perspect. 32 (2) (2018) 173–192.
[179] André Baumgart, Eirini Ioanna Vlachopoulou, Jorge Del Rio Vera, Simonetta Di Pippo, Space for the sustainable development goals: mapping the contributions of space-based projects and technologies to the achievement of the 2030 agenda for sustainable development, Sustainable Earth 4 (1) (2021) 6.
[180] Group on Earth Observations, "AfriGEO," https://earthobservations.org/afrigeo.php, (Accessed June 8, 2023).
[181] G.I. Agbaje, O.N. John, Cooperation in earth observation missions in Africa: a role for afrigeoss, Geojournal 83 (6) (2018) 1361–1372, https://doi.org/10.1007/s10708-017-9840-5.
[182] United Nations Office of Outer Space Affairs, "Zero-Gravity Instrument Project (ZGIP),"http://www.unoosa.org/oosa/en/ourwork/psa/hsti/capacity-building/zgip.html, (Accessed 19 February. 2019.
[183] United Nations Office of Outer Space Affairs, "Fellowship Programme for "Drop Tower Experiment Series" (DropTES)",http://www.unoosa.org/oosa/en/ourwork/psa/hsti/capacity-building/droptes.html, (Accessed 19 February. 2019).
[184] DreamUp, Homepage (2019). https://www.dreamup.org/. (Accessed 19 February 2019).
[185] United Nations Office of Outer Space Affairs, "United Nations/Japan Cooperation Programme on CubeSat Deployment from the International Space Station (ISS) Japanese Experiment Module 'KiboCUBE'," https://www.unoosa.org/oosa/en/ourwork/access2space4all/KiboCUBE/KiboCUBE_Index.html (Accessed 28 May 2023).

[186] S. Di Pippo, The contribution of space for a more sustainable Earth: leveraging space to achieve the sustainable development goals, Global Sustainability 2 (2019) 1–3, https://doi.org/10.1017/sus.2018.17.
[187] D.G. Yárnoz, A. Kojima, S. Di Pippo, Access to Space: capacity-building for development through experiment and payload opportunities, Acta Astronaut. 154 (2019) 227–232, https://doi.org/10.1016/j.actaastro.2018.03.034.
[188] United Nations Development Programme, "UNDP and the Private Sector," https://www.undp.org/partners/private-sector (Accessed 16 May 2023).
[189] The SMART Tire Company, "Shape Memory Alloy Radial Technology," https://www.smarttirecompany.com/about.
[190] J. Nurton, Tech transfer at NASA: bringing NASA technology down to Earth, WIPO Magazine (2022). https://www.wipo.int/wipo_magazine/en/2022/02/article_0005.html. (Accessed 16 May 2023).
[191] Space3ac, "Poland Prize," https://polandprize.space3.ac/(Accessed 27 May 2023).
[192] EU Copernicus, "Opportunities," https://www.copernicus.eu/en/opportunities (Accessed 27 May 2023).
[193] Aerobotics, "About Us," https://www.aerobotics.com/about-us (Accessed 27 May 2023).
[194] T. Jackson, Zimbabwe's 'YouFarm' helps farmers raise funding, Disrupt Africa (2018). https://disrupt-africa.com/2018/07/04/zimbabwes-youfarm-helps-farmers-raise-funding/. (Accessed 27 May 2023).
[195] Space in Africa, Airbus Announces Top 10 African Aerospace Startups Selected for #Africa4Future Accelerator Program, 2019. https://africanews.space/airbus-announces-top-10-african-aerospace-startups-selected-for-africa4future-accelerator-program/. (Accessed 21 February 2019).
[196] Katlyn Turner, Dara Entekhabi, Yusuke Kuwayama, Catherine Lu, Zolana Joao, Danielle R. Wood, " Systems architecture as a tool for developing decision support systems: Angolan drought,", in: Proceedings of the International Astronautical Congress, Baku, 2023. https://iafastro.directory/iac/paper/id/80287/summary/.
[197] A. Barenblitt, A. Payton, D. Lagomasino, L. Fatoyinbo, K. Asare, K. Aidoo, H. Pigott, C.K. Som, L. Smeets, O. Seidu, D. Wood, The large footprint of small-scale artisanal gold mining in Ghana, Sci. Total Environ. 781 (2021), https://doi.org/10.1016/j.scitotenv.2021.146644.
[198] Ufuoma Ovienmhada, Fohla Mouftaou, Danielle Wood, Inclusive design of earth observation decision support systems for environmental governance: a case study of Lake Nokoué, Frontiers in Climate 3 (2021) 717418.
[199] Danielle Wood, Yiyun Zhang, Dorrington Scott, The Zero Robotics program invites youth to program robots on the international space station. https://iafastro.directory/iac/paper/id/79547/summary/, 2023. (Accessed 15 January 2024). October 3.
[200] M. Cho, M. Teramoto, T. Yamauchi, G. Maeda, S. Kim, H. Masui, Program management for sustainable university CubeSat programs based on the experience of five generations of CubeSat projects, BIRDS program, in: 36th Annual Small Satellite Conference, 2022. Logan, Utah, 2022.
[201] Ganiyu I. Agbaje, United nations regional Centre for space science and technology education in Africa: achievements, opportunities, challenges, and the future, Environment and Ecology Research 5 (5) (2017) 386–394.

Professor Danielle Wood serves as an Assistant Professor in the Program in Media Arts & Sciences and holds a joint appointment in the Department of Aeronautics & Astronautics at the Massachusetts Institute of Technology. Professor Wood serves at MIT as the Faculty Lead for African and African Diaspora Studies. Within the Media Lab, Prof. Wood leads the Space Enabled Research Group which seeks to advance justice in Earth's complex systems using designs enabled by space. The research of Space Enabled designs systems that use tools from space to promote sustainability on Earth and designs approaches to support sustainability in Space. Prof. Wood studied at the Massachusetts Institute of Technology, where she earned a PhD in engineering systems, SM in aeronautics and astronautics, SM in technology policy, and SB in aerospace engineering.

Dr. Minoo Rathnasabapathy is a Research Engineer at the MIT Media Lab, and Project Fellow, Future of Space at the World Economic Forum. Her work is centred at the intersection of space technology, policy, and action-driven partnerships to tackle pressing socio-economic and environmental challenges. Dr. Rathnasabapathy's focus and research interests include space sustainability and governance, climate, and broader cross-industry collaborations. Prior to joining MIT, Dr. Rathnasabapathy served as the Executive Director of the Space Generation Advisory Council (SGAC), a global non-governmental organisation which acts in support of the United Nations. Dr. Rathnasabapathy earned her PhD in Aerospace Engineering from RMIT University, researching the impact dynamics of novel materials used in aerospace structures. Minoo serves as a member of the World Economic Forum Global Future Council on Space, and advisory board member to Via Satellite. From 2018 to 2021, she served as Vice President of the International Astronautical Federation.

Dr. Javier Stober previously served as a Research Engineer in the Space Enabled Research Group. In that role, he led the development and operations of the satellite laboratory and fostered collaborations with partnering organizations. Javier earned Ph.D. and M.S. degrees in Aeronautics and Astronautics from Stanford University, researching novel propellants in the area of experimental hybrid rocket propulsion, as well as B.S. degrees in Mechanical and Aerospace Engineering from the University of Florida. He has worked at various organizations across the engineering landscape, public and private, small and large, foreign and domestic, including NASA, Honeywell Aerospace, Boeing, and Space Propulsion Group.

Pranav Menon is a Research Associate in the Space Enabled Group at the MIT Media Lab. He is also a doctoral student in English and Comparative Literature at Columbia University with research interests in postcolonial literatures, the environmental humanities, and global economic history. He holds M.A. and M.Phil. degrees in English and Comparative Literature from Columbia University and a B.A. in English from Tufts University.