SSC18-WKVIII-08

Small Satellites Contribute to the United Nations' Sustainable Development Goals

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ABSTRACT

The United Nations (UN) led the countries of the world to define and commit to the 2030 Agenda for Sustainable Development, which identifies 17 goals toward improving life on Earth. The Sustainable Development Goals (SDGs) provide the high-priority challenges for our generation in areas such as access to clean water, food security, poverty alleviation, health care, environmental sustainability and urban development. Space technology, including small satellites, can play a role in helping countries pursue the SDGs. Each goal includes a set of Targets countries are working to achieve by 2030. Each Target includes a set of indicators that define the quantitative measurement for the Targets. A key element of pursuing the SDGs is for nations to work with the UN to develop methods to measure progress toward the Targets on each indicator. Many of the indicators and targets relate to environmental factors, human infrastructure or investment in research and education. In each of these areas, small satellite missions can play a role as part of national strategies to both monitor progress toward the SDGs and to work toward achieving the Targets. This paper reviews examples showing how space technology, including satellite-based earth observation, communication and positioning services, is already being used to support the SDGs. The discussion illustrates how emerging business and operational models in each sector and exploring new ways to apply small satellites for earth observation, communication and positioning. The paper describes coordination activities by organizations such as the Group on Earth Observations, NASA and the UN that are designed to help national governments around the world increase the use of satellite-based technology in support of the SDGs. The paper also introduces a new academic Research Group at the Media Lab within the Massachusetts Institute of Technology. The mission of this research group is to increase the use of space technology in support of the SDGs. Small satellites provide an important opportunity to consider the needs defined by the Sustainable Development Goals and create customized space missions that respond to these needs.

INTRODUCTION

Space technology has the potential to bring tremendous societal benefit. One way to rigorously 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.[i] This agenda is formalized by a list of seventeen Sustainable Development Goals 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. Every member country of the United Nations has agreed that they are pursuing the Sustainable Development Goals as part of their national development strategy. There are six technologies derived from space exploration and research that already help support the global effort to achieve the Sustainable Development Goals. These space technologies include satellite earth observation, satellite communication, satellite navigation, microgravity research, technology transfer and inspiration via research and education. Technology from space supports the SDGs both by helping government agencies monitor and measure progress according to the SDG indicators. Space technology can also be harnessed to support achieving many of the SDGs. There are many examples of useful application of space and satellite technology for development. Barriers remain that limit the potential impact of space for development and make it difficult for some countries or communities to apply this technology. Several international organizations are working to reduce these barriers, such as the Group on Earth Observations and the United Nations Office of Outer Space Affairs. Meanwhile, changing business models and technology are creating new opportunities for inexperienced countries and organizations to harness space technology.

This paper examines the 2030 Agenda for Sustainable Development and notes which Sustainable Development Goals show high relevance to space. The paper also discusses the barriers that limit the application of satellite technology for the SDGs. The paper explains resources available to development organizations that seek to use satellite-based technology. The Space Enabled Research Group at MIT Media Lab is dedicated to reducing the barrier to applying space technology in support of the SDGs. We aim to advance justice in earth's complex systems using designs enabled by space. The paper discusses the research agenda of Space Enabled, which includes designing small satellites for development applications and proposing new engineering approaches to reduce the production of new space debris in earth orbit.

THE 2030 AGENDA FOR SUSTAINABLE DEVELOPMENT

The global community is galvanized around three mandates that outline the changes we seek to make by 2030. These mandates come from the 2030 Agenda for Sustainable Development, the Sendai Framework for Disaster Risk Reduction[ii] and the Paris Agreement on Climate Change[iii]. This paper focuses on the 2030 Agenda for Sustainable Development, while noting that all three international agreements play an integrated role in defining objectives for the future. The 2030 Agenda for Sustainable Development continues a precedent set by the Millennium Development Goals[iv], which set ambitious targets for developing countries between 2000 and 2015. While some derided the Millennium Development Goals for being too lofty or unrealistic, it is now possible to show that setting idealistic goals has had an impact. The first Millennium Development Goal was to reduce global poverty by half between 2000 and 2015; this goal was met.[v] Although not all of the Millennium Development Goals were met, there is still evidence that setting these ambitious targets for global progress encourages people from all sectors to collaborate toward development. There is a key difference between the Sustainable Development Goals and the Millennium Development Goals. While the Millennium Development Goals set targets for countries labeled as 'developing' from the global south, the Sustainable Development Goals are set for all countries. This acknowledges that there is no artificial distinction between "less developed" and "more developed" countries. All countries have areas in which they need to improve to reach the Sustainable Development Goal targets. The United Nations led a global dialog prior to 2015 to determine the definition of the Sustainable Development Goals, their targets and the quantitative indicators measure progress. This dialog included representatives from many segments of society, including governments, farmers, youth, indigenous peoples, and other populations[vi]. The 17 Sustainable Development Goals 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. The first of the goals starts where the Millennium Development Goals made a major achievement. The first goal is to end extreme poverty, which is defined as people who live with less than $1.25 per day[vii]. The Sustainable Development Goals cover every aspect of human life; thus, any person can consider how their work and passions could contribute to some aspect of the goals. The definition of the Sustainable Development Goals includes identifying 169 measurable Targets toward which nations are working. Each of these Targets is evaluated using one or more Indicators that are quantitatively defined[viii]. The national statistics agencies in each country take the lead to define and measure their country's progress toward attaining the Sustainable Development Goals. Technology from space can play a role to support measurement of national progress toward achieving the 169 Targets behind the Sustainable Development Goals. Space technology can also be part of the systems that provide information or services that allow decision makers to achieve the Sustainable Development Goals. This paper shows examples of a full range of space technologies that support the SDGs; the discussion continues by exploring the specific roles for small satellites.

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 and achievement of the Sustainable Development Goals. These technologies include satellite earth observation, satellite communication, satellite positioning, microgravity research, technology transfer and the inspiration drawn from research and education. This section discusses each area of space technology briefly and shows current examples of how these technologies are used in support of the Sustainable Development Goals.

Satellite Earth Observation

Satellite earth observation refers to the wide set of systems that use space-based platforms to measure phenomena in near-earth space, the atmosphere, the ocean, the polar regions and on land. These satellites carry sensors that operate across the electromagnetic spectrum to take passive or active measurements using microwave, infrared, ultraviolet and visible energy. Earth observation satellites are operated by national governments, multinational agencies such as the European Space Agency, private companies, universities and research institutes. According to the Committee on Earth Observation Satellites, which represents national and supranational satellite operators, about 60 governments or multi-government entities operate earth observation satellites for scientific or public service measurements[ix]. In recent decades the number of privately owned and operated earth observation satellites has greatly increased. In the United States, for example, the market was dominated for years by a few large firms that eventually merged[x]. More recently, start up firms are pursuing a business model of building and operating small satellites with imagers that capture light in the visible spectrum (especially red, green, blue and near-infrared). The longest running set of satellites for earth observation is the Landsat series of satellites, which are built by the National Aeronautics and Space Administration of the United States and operated by the U.S. Geological Survey[xi]. The Landsat series includes a set of similar satellites that provide a continuous dataset with images of every location on land starting in 1972 with a revisit rate of about once every 8 to 16 days. The Landsat program puts a strong emphasis on calibrating between spacecraft to ensure that data from the different satellites can be compared to create multi-decadal time series[xii]. Because of the long history of Landsat data and the consistent, comparable dataset that it provides, Landsat has become a de facto standard among satellite earth observation systems. Other nationally owned and privately-owned satellites often aim to collect data that can be used in coordination with Landsat images. The European Union leads the Copernicus program for earth observation systems, which includes the Sentinel series of satellites[xiii]. Several of the Sentinel satellites provide data that is comparable and highly complementary to Landsat[xiv]. With these combined data sets, it is now possible to have increased revisit time to view the same location. Landsat has medium resolution data of 30 meters of Ground Sampling Distance; this means that objects in the image must be 30 meters or greater to be clearly resolved as specific details[xv]. Some of the recent commercial companies, such as Planet, that operate small satellites for earth observation, seek to improve both in terms of resolution and revisit frequency. Planet has specific mission to take an image everywhere on earth every day. Planet operates an ever-changing fleet of small, 3 unit CubeSats that carry imagers that take measurements in wavelengths similar to the Landsat system but they do not follow all the same calibration practices[xvi].

It is helpful to distinguish between satellite earth observation data that is processed as imagery of the earth in the visible part of the spectrum and systems that produce measurements that estimate variables regarding the state of the land, ocean, atmosphere or polar regions. Some information derived from imagery can be converted into variable values, such as when a visible image is used to calculate the Normalized Differential Vegetation Index based on the relationship between the red and near-infrared signals[xvii]. More generally, sensors on satellites take measurements of variables such as the humidity, temperature and pressure of the atmosphere; the temperature and salinity of the ocean; the density of ice within a glacier; and locations of heat sources that could indicate fires on land. Satellites based observation of these types of variables is helpful because it is global and consistent. There is a challenge, however, because satellites in Low Earth Orbit circle the globe and have gaps in their data record. For a given time and place, there is a sparse set of data from direct observation. One approach to address this concern is to combine estimates of environmental variables from earth observation measurements with estimates enabled by physics-based models. Earth scientists often specialize in specific aspects of the global earth system, such as the hydrosphere for water, biosphere for vegetation, cryosphere for ice, and the atmosphere. Within each of these disciplines, scientists have developed physics-based models that are used to simulate and forecast the behavior of the atmosphere, vegetation, ocean and glaciers. These models are defined as simulations that take initial conditions and propagate forward in time to estimate the value of variables of interest at each location and each time step within a finite element model. The process of data assimilation means that scientists use Kalman Filters to combine measurements of the variables with the estimates derived from models. The Kalman Filter considers both the measurement and the model-based estimate and provides the value that is the highest quality estimate of the actual value. Global models that assimilate data from satellite, airborne and in-situ observations provide powerful tools to inform weather forecasting and climate understanding. One example is the work of the Global Modeling and Assimilation Office at NASA's Goddard Space Flight Center.[xviii]

Satellite earth observation systems provide consistent and accessible information about the state of the natural environment. Much of the government-owned environmental satellite data is provided freely to users around the world. For example, NASA operates approximately 20 earth observation satellites and provides this data online via a series of Distributed Active Archive Centers (DAACs)[xix]. The European Union collaborates with the European Space Agency to operate the Copernicus Program which provides environmental data from a series of satellites for free to users. Other government agencies in countries such as Japan, India, Brazil, China and South Korea operate earth observation satellites and provide at least some of the data for free[xx]. The emerging for-profit companies mainly operate satellites with cameras that produce imagery in the visible part of the spectrum. Some companies are exploring other types of satellite data, such a Radio-Occultation using signals from Global Navigation Satellite Systems. The output of these systems provides input into global weather forecasting models. The commercial satellite earth observation companies generally charge a fee for users to access either their original data or to access value-added services based on their data. The market for commercial satellite earth observation is still evolving, and new business models are being proposed and examined. It remains to be seen what the long-term business approach will be, although there is still a tendency toward consolidation in which a few satellite manufacturing and operating companies buy and competing companies when these competitors are not able to sustain themselves commercially.

Information derived from Satellite Earth Observation systems has high relevance to both the monitoring and achievement of the Sustainable Development Goals. This is true for information derived from direct images of the earth, from measurements of environmental variables and from the outputs of earth science models that have assimilated observations from space-based platforms. To give a few examples, SDG #2 aims for Zero Hunger, to ensure that everyone has access to safe, nutritious food. Part of this work involves evaluating the food security and crop health of regions around the world to identify locations that are at risk of a famine or a drought. In order to evaluate risk of famine or drought, scientists consider the following factors. What is the state of the ocean with regard to temperature and climate variations that are often called El Nino or La Nina. These patterns of ocean temperature influence the rainfall patterns in nearby continents. Satellite based earth observation systems measure the ocean temperature; these measurements are assimilated into global physics models that create a complete picture with no gaps in time or space of the estimated ocean temperature and infer the movement of currents based on conservation of energy. Global models like this are an input into atmospheric models that forecast rainfall. These atmospheric models are improved using historical rainfall measurements from satellites and from ground-based weather stations. By understanding ocean temperature which influences rainfall, scientists can estimate whether food growing regions have adequate soil moisture to support crops. For a given crops, 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. Satellites can estimate photosynthesis by measurement evapotranspiration and the level of chlorophyll in plans using satellite measurements. Thus, a full chain in investigation starts with ocean temperature which influences rainfall, which influences soil moisture, which supports vigorous crops which leads to food security. There are already multiple international groups that have created operational routines to consult satellite-based measurements and estimate locations in the world that may face food insecurity based on satellite and ground-based measurements. The US Agency for International Development operates the Famine Earthly Warning Systems Network (FEWS.net) along with NASA and the US Geological Survey to identify countries in Africa that may be at risk for famine or drought[xxi]. The Group on Earth Observations 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[xxii].

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. Several United Nations Agencies provide support to help national governments apply satellite earth observation inputs as part of the monitoring and management of the Sustainable Development Goals[xxiii]. Space agencies such as NASA, the European Space Agency, the Japanese Aerospace Exploration Agency and the Indian Space Research Organization participate in research and application projects to apply satellite earth observation for development.

While much progress has been made to apply satellite earth observation measurements and model output to the Sustainable Development Goals, barriers remain that create a challenge for novices to use this technology. It is significant that organizations such as NASA and ESA provide large amounts of satellite earth observation data freely on their websites. Meanwhile, 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. A new approach is being explored by commercial satellite operators who are learning to build many similar small satellites and operate them as a coordinated constellation. There has been an ongoing international debate about the ethics and policies related to the cost of data. 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 data analysis levels[xxiv]. 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 satellites 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. Thus, a government or academic user doing research for the public good should receive free data while a commercial user should pay. All of these examples of data sharing and costing policies are used within the global marketplace of satellite earth observation data. There is no universal consensus on what payment structure is equitable or appropriate. Prof Mariel Borowitz explores these issues deeply in her book *Open Space*[xxv]. 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 produce a software-based tool combining several times of data and algorithms to produce a report or recommendation. Commercial companies are emerging that harness a combination of satellite, airborne, social media, cell-phone activity and socio-economic data to inform decision making or make predictions.

Several international organizations work diligently to ensure that satellite earth observation data is applied in support of the Sustainable Development Goals. One of the primary organizations in this work is the Group on Earth Observation, a multilateral group whose members are national governments. The Group on Earth Observations pursues a work program in areas including agriculture, biodiversity, forest management and mercury monitoring. The Group on Earth Observations works diligently to increase free access to satellite based and other sources of environmental monitoring data[xxvi].

Satellite Communication

Satellite communication systems provide access to bandwidth that enables connectivity to broadcast radio and television signals, to establish internet connections or to carry out phone or video-based calls. This supports Sustainable Development Goal #9, Industry, Innovation and Infrastructure. Satellite based communication is highly valuable to connect rural or remote communities to communication infrastructure. The government of India develops communication satellites and operates them to benefit both commercial and social goals. They provide telemedicine services to help people in rural areas that do not have easy access to medical specialists meet virtually with doctors. Satellite communication is highly valuable during the recovery period after natural disasters destroy local communication infrastructure. The company called GATR provides an inflatable antenna that be easily transported in a carry-on suitcase while deflated. It sits on the ground and connects with communication satellites to provide a local network for areas impacted by disasters. The GATR system was used during the recovery of Typhoon Haiyan in the Philippines[xxvii].

The majority of communication satellites are operated in geostationary orbit at 36,000 kilometers altitude above the equator. At this orbit the rotation period of the satellites matches the orbit of the earth, thus a satellite is always pointed at the same region of the earth. The International Telecommunications Union manages the process to allocate frequency licenses and orbital slots to operators in the geostationary orbit due to the scare resource[xxviii]. The majority of communication satellites operated in geostationary orbit are owned by national governments or large, established commercial companies. Many of the communication satellite systems provide commercial services for broadcast or point to point communication that is priced too high to serve low-income communities that are not well-served by mobile phone connections or ground-based internet.

For the last few decades, the Iridium company stood out as a unique satellite constellation operated in Low Earth Orbit[xxix]. Iridium is often considered a technical success and financial failure because the company developed their global satellite communication concept just at the dawn of the personal mobile phone era. While the technology came online many people were able to access lower cost communication service via mobile phones and satellite-based phones became less appealing due to their high cost and heavy weight. The Iridium company continued to operate and was redefined to serve those in extreme communication environments such as the military, people working in remote locations, people on ships and people who travel extensively. The Iridium satellites are not in the family of "small satellites;" they use more traditional manufacturing methods and their mass is larger than most small satellites. Currently, multiple companies are proposing to operate small satellite constellations in Low Earth Orbit or Medium Earth Orbit to provide global communication services[xxx]. The constellation sizes that are proposed range from dozens to thousands[xxxi]. The emerging companies claim that they will serve markets that are not yet served by mobile phone services in rural areas. More time and experience is needed to determine whether the service costs and quality provided by the small satellite communication constellations will meet the needs of remote communities in the countries of the global south. The scale of the proposed satellite communication constellations offers concerns regarding the creation of new space debris. Each company must determine what approach they will take for manufacturing, launching, decommissioning and de-orbiting satellites to maintain their desired service quality with their constellations. At the international level there are ongoing policy dialogs about potential approaches to future space traffic management, situational awareness and debris mitigation guidelines. These topics are under regular discussion within international space policy fora such as the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS)[xxxii]. The technology proposals being generated by new space companies in the communications sector are currently outpacing the process to develop national and international policies to set up a framework to ensure that space debris is managed when these new, large communication constellations begin operations.

Satellite Positioning, Navigation and Timing

Global Navigation Satellite Systems are operated by several national or multi-lateral space agencies to provide services in the areas of positioning, navigation and timing[xxxiii]. The United States operates the Global Positioning System; the European Union operates the Galileo system and a supporting augmentation system called EGNOS. Russia operates a global system called GLONASS and China is building up a global system called BEIDOU or Compass. Meanwhile, Japan and India operate regional systems. All of these GNSS operators coordinate via the International Committee on GNSS hosted by the United Nations Office of Outer Space Affairs. All the GNSS systems have a basic operational design in common. The satellites send out signals that provide a highly accurate estimate of their location and the time that the signal was sent. This allows users with radio receivers to receive signals from three to four satellites and calculate their location[xxxiv]. Some GNSS applications rely primarily on timing, in areas such as coordinating financial transactions. Global Navigation Satellite Systems support the Sustainable Development Goals by enabling better operations in areas such as tracking of endangered wildlife and combatting vector borne disease. Scientists track 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[xxxv]. Meanwhile, in the area of disease monitoring, there are several applications for GNSS services. Diseases such as malaria, chikungunya, dengue and zika are spread by mosquitos that expose people to a parasite that caries the disease. In many cases, it is possible to predict which regions are in danger of exposure to mosquito behavior and potential transmission between people. First, satellite-based earth observation data can be used to estimate which areas have favorable weather, soil and moisture conditions to support mosquito activity. Second, satellite images can point out where human settlements are located and how easy it is to access them via transportation networks. Third, information about the location of recent medical cases can be mapped to show if specific diseases have been treated. One way to reduce the spread of vector borne disease is to spray homes and mosquito breeding areas to reduce vector activity. Often is it helpful to use satellite images to map out a route for people to visit specific households to apply the spray. It is also important that each location that has received spray be mapped using satellite-based positioning data in order to confirm that an adequate barrier has been applied to reduce vector activity. Organizations in southern Africa are applying all of these techniques to reduce malaria transmission in support of Sustainable Development Goal #3, Good Health and Well-Being[xxxvi].

Currently the government operators of Global Navigation Satellite Systems provide the service freely. The United States government made a key policy decision to make a highquality service for general use by removing selective availability, which limited the quality of signals used by the public[xxxvii]. Many commercially available GNSS receiver systems are capable of receiving the signals from the constellations of multiple countries. Smart phones operated around the world include GNSS receivers and software to geolocate images and other data collection. This infrastructure makes it easy for many users to apply GNSS services in support of the Sustainable Development Goals by novices and experts.

The GNSS satellites operated by the United States, Russia, Europe, China, Japan and India are not small satellites. There are several examples, however, of small satellite missions that support the Sustainable Development Goals by using GNSS signals as part of their scientific measurement process. The NASA mission called CYGNSS (Cyclone Global Navigation Satellite System) uses eight micro-satellites to receive reflected signals from GPS as they scatter from the earth's surface are influenced by wind speed[xxxviii]. The objective of the mission is to measure wind speed over the ocean in tropical latitudes, thus improving understanding of storms and contributing to SDG#13, Climate Action. In addition, several small satellite missions have demonstrated that GPS Radio Occultation measurements contribute to the quality of weather forecasting models, a referenced earlier. In the United States, the National Oceanographic and Atmospheric Administration (NOAA) includes the National Weather Service. NOAA operates the US weather satellite constellation. The US and Taiwan collaborated on the mission called COSMIC which uses microsatellites weighing about 70 kilograms to receive GNSS signals that have passed through the atmosphere. The goal is to understand how distortions in the signals provide estimates of temperature, pressure and humidity, which are key parameters within weather forecasting models[xxxix].

The United Nations Office of Outer Space Affairs and the European Global Navigation Satellite System pursued a study showing the relationship between the

Sustainable Development Goals and GNSS services. The work showed that many of the SDG indicators can be supported by applications of satellite-based positioning and navigation[xl].

Human Space Flight and Microgravity Research

The knowledge gained via human space flight about the human body, plants, animals and materials can support SDGs such as #3 (Good Health and Well Being). Currently the main platform available for routine human space flight and microgravity research is the International Space Station. The US laboratory portion of the International Space Station has been established as a National Laboratory with access coordinated by the Center for Advancement of Science in Space[xli]. CASIS facilitates research in the areas of physical sciences, life sciences, technology development and remote sensing. Scientists from NASA and other ISS partner nations study the impacts of microgravity on the human body. The lack of gravity mimics accelerated aging; thus, the techniques used to keep astronauts healthy are also applied to support healthy aging among people on earth. The International Space Station also has a link to microsatellites because it is a platform for launching small satellites via services from companies such as Nanoracks[xlii] and the Japanese Kibo Experiment Module. Several emerging space nations have been able to launch their first satellites via the Japanese Kibo Small Satellite Orbital Deployer[xliii]. In May 2018, the first Kenyan satellite was launched via the Japanese Kibo module[xliv]. By supporting emerging space nations, the International Space Station supports SDG#9 (Industry, Innovation and Infrastructure).

Space Technology Transfer

Space technology transfer refers to cases in which a system designed for space operations is redesigned for an application on earth. Several examples come from human space flight, such as the technology used to filter water on the International Space Station which has also been applied in a system that is deployed for emergency water filtration needs around the world. In this case, a key component of the NASA system was transferred to a non-profit that used it design a ground-based system which supports SDG#6. As humans make plans to live in long term space flights and on planets such as Mars, the designs that enable human survival in low-resource environments can be adapted to support conditions on earth such as disaster recovery, displaced people and emergency response.

Inspiration through Research and Education

Space brings inspiration as people of all ages participate in or learn about basic scientific research and education programs about the universe. As countries invest in activities to engage learners in space related education, they support SDG#4 (Quality Education). One current example of new investments in space research that expand development opportunities is the Square Kilometer Array project which will establish the world's largest radio telescope array in both the African continent and in Australia. In Africa, the country of South Africa is taking the lead, but other countries in eastern, southern and western Africa will also host radio telescopes as part of the system[xlv]. Specifically, the additional countries include Botswana, Ghana, Kenya, Madagascar, Mauritius, Mozambique, Namibia and Zambia[xlvi]. In Ghana the Space Science and Technology Institute has recently completed 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[xlvii]. The Square Kilometer Array supports SDG#9 by bringing new opportunities for innovation and infrastructure to regions that have previously not participated in astronomy. Each location that adds a radio telescope also invests in local engineering employment, communication and data management infrastructure and improved regional education opportunities.

RESEARCH AGENDA FOR THE SPACE ENABLED RESEARCH GROUP, MIT MEDIA LAB

Small satellites and other technologies from the space sector are already a part of many initiatives and programs to pursue the Sustainable Development Goals. There is still work to do that will reduce the barriers for development leaders in government, academia and the private sector apply space technology in their work.

In response to the trends and opportunities discussed above, Professor Danielle Wood has established the Space Enabled Research Group within the MIT Media Lab with the goal to make it easier for organizations around the world to apply space for development. The mission of the Space Enabled Research Group is to advance justice in earth's complex systems using designs enabled by space. Within Space Enabled, the team draws from the full range of space technologies that contribute to the Sustainable Development Goals, including satellite earth observation, satellite communication, satellite positioning, microgravity research, technology transfer and inspiration through research. The Space Enabled team is composed of researchers, graduate students and undergraduate students. These scholars represent six discipline areas, including design, art, social science, complex systems modeling, satellite engineering and data science. Space Enabled pursues both fundamental academic research projects as well as applied projects to prototype approaches to apply space for in support of an SDG. On the fundamental research side, Space Enabled is pursuing new research directions in the following areas.

First, Space Enabled seeks to improve the use of model-based systems engineering to design small satellites while considering how end users will apply the services provided by the satellites in support of sustainable development. Second, Space Enabled seeks to re-imagine the lifecycle of small satellites to minimize the creation of new space debris. This means using mechanical design approaches to ensure that the satellite can be efficiently deorbited when the useful life is finished. It also means fundamental research in the area of green propellants for small satellites that are affordable and benign for human handling. Space Enabled imagines a future in which small satellites can be manufactured on-orbit in response to the latest user requirements. After the satellites are operated their components will be reused or recycled to enable future missions. The work of Space Enabled combines social and technical competencies because the challenges of the Sustainable Development Goals are multifaceted. Ultimately, the research vision of Space Enabled seeks to understand how to effectively combine the social and technical knowledge within the team to design system approaches to achieve the important objectives of our generation.

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