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Small satellite solutions for land transport monitoring

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Abstract

Transportation is an area where significant development is expected in the coming decades. The biggest change is brought by connected and automated vehicles, but also by the smart digital infrastructure to support the development and to improve operation and efficiency. Vast areas and extensive infrastructures, e.g., road and rail networks, will require a more comprehensive up-to-date situational picture of the transport network and infrastructure as well as connectivity. One possibility is to extend the sensor and support network to space where small satellites can provide unprecedented observation frequency with a price much lower than that of traditional satellite solutions and complement existing terrestrial sensor networks, particularly in rural areas where the availability of data from infrastructure and vehicles is poor, occasional and costly. Various industry needs and desirable use cases for small satellites in land transport monitoring were identified in this paper and classified into three categories: operability and reliability of transport systems, proactive long-term transport system asset management, and digitalization of transport and mobility.

Keywords: Transport infrastructure, satellites, remote sensing

Introduction

Our mobility system serves multiple critical functions of our society. The movement of people and goods needs to be ensured not only under normal circumstances but also in harsher and more exceptional conditions, including rural and sparsely populated areas. Weather and infrastructure availability go hand in hand; different weather phenomena impact the transport environment and infrastructure in terms of safety, reliability, resilience and accessibility. Research findings show that the impacts of weather are significant (see e.g. Leviäkangas et al., 2013; Molarius et al., 2013); especially in the Northern Hemisphere, winter poses radical challenges to mobility and transport.

Shortfall in investments on maintenance and asset management generates increased risks of accidents, problems of congestion, increased disruptions and a reduced service to society. The value of the road network in the European Union is over 8000 billion euros, and the annual maintenance budget is close to 80 billion euros (European Union Road Federation, 2009). Also, the annual cost of extreme weather events (storms, floods, blizzards) on transportation in Europe is 13-18 billion Euros (Nokkala et al.

2012). Currently, large transport related infrastructures are mostly monitored from the ground, but shortly new disruptive technologies can change the field by finding both more cost-effective – presently annual maintenance and asset management cost in OECD countries are over 130 billion US dollars (ITF 2017) – and sustainable solutions for transport system management.

Spaceborne technologies are one of the most promising fields in enabling competitive solutions for intelligent transport systems (ITS). Already today, satellite-based Earth Observation (remote sensing) and positioning technologies provide several utilities for transportation needs and management. For instance, European Space Agency's Sentinel-1 -satellite provides data that can be used for monitoring risk areas (e.g., landslides) of the road and rail infrastructure (European Satellite Agency, 2014), not to mention commonly used GNSS-based positioning and navigation services. However, the revisit time (i.e., temporal coverage) of current Earth Observation (EO) satellites is not frequent enough for effective operational (i.e., near real-time) applications. This will change with emerging small satellite constellations which can provide frequent observations with relatively affordable price. Innovative exploitation of small satellite technology unlocks new application areas with a compelling value proposition of great benefit to countries like Finland that have a large land mass with a substantial road network and rural communities in remote areas.

The purpose of this paper is to identify potential uses cases for small satellite (mass <500kg) monitoring in the context of transport and mobility. To achieve this purpose, the following research questions must be answered: *1) how could small satellites be exploited for land transport*, and *2) what are the most desirable application areas of small satellites in transport system monitoring?*

The paper starts with an overview of small satellites including possibilities, market analysis and relevant remote sensing monitoring technologies. The paper continues with a method and empirical scope which is then followed by the empirical results and findings. Conclusions are presented in the last chapter.

Small satellite systems

In many global services, space segment already has an established role. Global navigation, communication and Earth observation are the most common application areas. A space platform provides, already at the moment, inherently global coverage for monitoring and communication. Unfortunately, space solutions, although global, usually come with high or very high price and only world superpowers and large organizations have had the possibility to launch and utilize space solutions. This has also hindered the development of commercial applications and services. The high price of space technology is largely defined by the high price per every kilogram transported to Earth orbit. Recent rapid developments in miniaturization of sensor technology and reducing power consumption have opened up a way to build much smaller systems (Table 1) – usually referred to as small satellites – therefore also drastically reducing the price of space assets. For instance, ability to launch multiple small satellites (up to 100) simultaneously at one launch has decreased the launching cost significantly. Currently launching costs of nano- and microsatellites are ca. 300 k€ per satellite, which is about 0,3% of the launching costs of a traditional satellite) (SpaceWorks 2016).

Table 1 – Small spacecraft classification (SpaceWorks 2016)

Type of satellite	Mass
Femtosatellite	10-100g
Picosatellite	<1kg
Nanosatellite	1-10kg
Microsatellite	10-100kg
Small satellite	*<500kg*

This development has had far-reaching implications. Smaller investment requirements open up the market for a wide range of actors, such as small countries that have previously had no space program, companies who need space segment services and even start-up companies who enter the market with completely new ideas and innovative business models. This has generated unprecedented commercial activity in the Earth Observation and digital communication markets (Radhakrishnan 2016, NASA 2015).

One of the main benefits of affordable space systems is that they can be produced and launched in large quantities (Radhakrishnan 2016). A large number of satellites means a large constellation and helps to resolve the coverage problem. For example, most of the traditional Earth Observation m monitoring sensors orbit the Earth in the polar orbit are only on a few satellites. This configuration provides a revisit time of around one to two weeks. It is evident that such satellite revisit times only allow the mapping of slow processes, ruling out applications such as traffic and local conditions that require near real-time information.

The rapid development has stumbled on some serious obstacles which hinder progress. Despite the challenges, small satellite market shows strong growth trend and venture capital has made significant investments to the sector. For example Planet Labs Inc. has launched a significant number of small optical EO satellites and can already provide optical images around the world with unprecedented refresh frequency, and now they have ability to image all the Earth´s landmass every day by using they constellation of 149 small satellites. Each of the latest Flock 3p satellite has a a 200 mbps downlink speed and is capable of collecting over 2 million km² per day. Planet Labs has also bought Google's subsidiary Terra Bella and its SkySat satellite constellation with a multi-year agreement to purchase SkySat imaging data (Planet Labs Inc. 2017).

Also Oneweb (2016) is building the largest Low Earth Orbit (LEO) communication network, and many companies, such as Iridium, are upgrading their satellite constellations with next generation satellites. The biggest game changers will be the availability of affordable telecommunication and imaging services around the globe. Table 2 lists the key promises and obstacles regarding small satellites.

Table 2 – Key promises and obstacles of small satellites

Key promises	Obstacles
Rapidly decreasing cost of a single satellite enables large satellite constellations	Space debris is a growing risk and launching a large number of satellites is controversial
Large number of satellites enables global coverage with a short revisit time	Frequency coordination according to current practices is too slow
Decreasing expenses allow entry of new providers to the field	Small satellite reliability (e.g., miniaturized technology) is not yet on par with requirements
New constellations enable newapplication areas and open new markets	Small size of the satellite limits the performance (size of payload, energy, monitoring capability) of the single satellite
Decreased maintenance and asset management costs	
New business opportunities in technology	

Current satellites' possibilities and remote sensing technologies

In order to prepare current traffic asset management systems for the future, the already existing space segment services should be more tightly integrated into the system. Many of the space segment services are already available for a very attractive price. For example most global navigation satellite system (GNSS) services are available for free, The European Union's Copernicus program provides both optical (Sentinel 2 series satellites) and radar (Sentinel 1 series satellites) images from space for free and first commercial services, such as Planet and Astro Digital are already selling their products. Also worth mentioning are TerresarX satellite, Landsat satellites, TanDEM-X satellite constellation, Cosmo Skymed SAR satellites, growing Radarsat 2 satellite family, Iridium satellites, Orbcomm satellites and all GNSS satellite networks.

Various technologies are currently exploited for remote sensing purposes. *Optical remote sensing* is based on detecting solar radiation reflected or scattered from the earth, forming images resembling photographs taken by a camera high up in space. The wavelength can vary from the visible and near infrared to the short-wave infrared. Also surface temperatures can be measured by using infrared sensors (CRISP 2001). *Microwave radar sensing* measures the microwave energy scattered by the ground or sea back to the sensors. These satellites have "flashlight" emitting microwaves to illuminate their targets, and therefore images can be taken day and night. Microwaves have an additional advantage as they can penetrate clouds and images can be acquired even when clouds are covering the Earth's surface (CRISP 2001). *Light detection and ranging (LiDAR)*, also known as laser detection and ranging (LaDAR) is an active remote sensing technique which uses electromagnetic energy in the optical range to detect an object (target), determine the distance between the target and the instrument (range) (Diaz et al., 2012). *Synthetic aperture radar (SAR)* is a radar that is used to create high-resolution images of objects, such as landscapes, either two or three dimensional. SAR uses the motion of the radar antenna over a targeted region to provide finer spatial resolution than is possible with conventional beam-scanning radars. SAR offers terrain structural information for example about mineral exploration to geologists, oil spill on water sea state and ice hazard maps to navigators, and reconnaissance and even targeting information to military operations. (Sandia National Laboratories, 2016)

Method and empirical scope

The emerging development of information and communication technologies (ICT) has introduced many changes in various sectors (Ezell, 2010). Transportation is an area where significant development is expected in the coming decades for example by various ICT empowered Intelligent Transportation Systems (ITS). ITS is the collective term for the use of electronics, communications, and information processing technology to improve all aspects of transportation (The Intelligent Transportation Society of America, 2011). ITS covers all modes of transport for both passengers and goods and brings significant improvement in transport system performance, including reduced congestion, increased safety, and traveler convenience.

The potential impacts of ITS have been studied and discussed widely. For example, Ferreira (2010) estimated that emerging ITS applications can reduce congestion by 5-15%; 5-15% fewer fatalities and 5-10% fewer injuries; and possibly save 10-20% CO_2 emissions. Grant-Muller and Usher's (2014) later estimations indicate that the environmental impacts of ITS vary from 10-15% reduced congestion to 5-20% fewer emissions. According to Öörni (2012), deployment of vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) safety applications will probably have a reducing effect on crash rates; 2-25% fewer fatalities and 1-20% fewer injuries.

Connectivity and digitalization provide various possibilities for improving asset management, traffic safety and travel comfort. The biggest benefits will be the intelligent traffic enabled by the connectivity and sharing of up-to-date information (e.g., congestion, road conditions, warnings). Congestions cause major problems in urban areas globally, creating pollution, damaging the environment and inconveniencing people traveling. At the same time, information and knowledge of transport systems' operability in rural areas is an equally important issue as information about congestions in cities. If traffic and transport infrastructure assets are to be successfully managed, it is not just a matter of connectivity but also producing and having access to comprehensive data cost-efficiently.

In this paper, we use a project called Namis-car (Nano- and microsatellites for competitive transport) as a qualitative and an illustrative case study to analyze the potential and plausible application areas for small satellite based remote sensing in the transport sector. The project was conducted in 2016 by the Transport team of VTT Technological Research Centre of Finland Ltd. and the Department of Radio Science and Engineering of Aalto University. The project was one of the first Finnish public initiatives assessing the feasibility and applicability of small satellite technology and services for future traffic monitoring and transport infrastructure management.

Even though applying small satellites in transport is a new approach and area for both research and industry, and therefore would warrant extensive study with a broad scope, this project was kept compact by limiting the scope to two main focuses: land transport and remote sensing (i.e., earth observing). Hence, maritime and air transport as well as satellite-based communication technologies were excluded at this point. Finland has both world-class expertise in winter road maintenance and current mega trends in transport and mobility (e.g., connected and automated driving) Additionally, the government will invest annually 360 M€ in transport systems long-term maintenance and asset management, and will invest 35 M€ in transport digitalization (e.g., new technologies and methods) in 2016-2018. Due to these things, the applicability of small satellite technology and services to land transport was decided to be studied in three interrelated categories: *operability and reliability of transport systems in all conditions* (i.e., up-to-date traffic management); *long-term proactive transport systems asset management*; and *digitalization of transport and mobility* (e.g., requirements for connected and automated vehicles).

To reveal the potential application and research areas of small satellite based remote sensing in the transport sector, the authors arranged a workshop to map the possibilities and use cases arising from a disruptive change in space technology and transportation technology. Also, we wanted to promote new ideas and provide opportunities to empower Finnish society and industry with new business prospects on a global scale. The workshop brought together over 40 industry and research players as well as governmental entities (e.g., road authorities) who mainly act in the field of land transportation and space technology. Also, authors conducted eight expert interviews during the project. All the results presented in this paper are based on the workshop and the interviews. The following section summarizes the findings (use cases for small satellite remote sensing) of the workshop in three categories above.

Workshop and interviews results: application and research areas of small satellites in transport

Transport systems' operability and reliability in all conditions

Land transport infrastructures must be kept in usable condition. For example, in winter, snow must be removed and ice melted or treated, and road users, travelers and transport operators must be made aware of the condition and availability of their route and modal options. In other words, a transport system must have an ability to hold the desired course in an increasingly turbulent world where the unexpected is taking place. To ensure the operability and reliability of transport infrastructure, collecting up-to-date (i.e., near real-time) and accurate road weather and condition data are essential since weather is the most important factor that influences traffic and road safety. However, observing large areas and extensive infrastructures by traditional means and sensors (road weather stations, patrolling etc.) is incredibly challenging and expensive. Small satellites could be a supplementary and cost-effective solution providing current traffic situation through unprecedented observation frequency and coverage. Table 3 presents the desired use cases and research areas of small satellites to ensure the land transport systems operability, as identified in the workshop and interviews.

Table 3 – Industry needs to ensure operability in all conditions

Desirable use cases	
Snow and frozen ground maps	Frost heave and bearing capacity
Sudden extreme weather events (floods, snow/sand storms/blizzards, downpour…)	On-road/-rail condition detection (snow, slush, packed snow)
Traffic census (congestions, incidents)	Thermal mapping (friction, surface temperature)
Detection of on-road/-rail obstacles	Sky and atmospheric condition observations for weather forecast

Proactive long-term transport systems' asset management

Damages caused by extreme weather and climate change have gained much attention recently. Both aspects require actions especially considering the life-cycle of any transport infrastructure and system asset. The more durable and resilient a system is built and maintained, the fewer resources are needed to keep it in good condition. Combined with traffic management and operable transport systems, asset management forms the resilience of a transport system. According to Ayyub (2013), resilience is the ability to prepare for and adapt to changing conditions and to withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from disturbances of deliberate attack types, accidents, or naturally occurring threats or incidents. Efficient use of satellite data may improve the resilience of critical infrastructures; see figure 2 illustrating land subsidence along the Val Nalps in Switzerland. Results on the left are obtained from ERS-1/2 satellite data from 1992 to 2000 and on the right from Envisat data from 2004-2010.

Even though up-to-date traffic management and long-term asset management are partially overlapping as well as supporting themes,certain aspects for both of those can be separated. Transport system asset management, in general, is mostly based on long-term monitoring and evaluation rather than rapid response and decision-making. Hence, asset management is not as time-dependent as traffic management. Table 4 summarizes desired use cases for transport asset management.

Table 4 – Industry needs for effective asset management

Desirable use cases	
Surface damages (e.g., frost damages, rutting, cracking)	Road and rail infrastructure monitoring (bridges, tunnels, culverts, subways, embankments)

Landslide warnings (movement of ground)	Wildfires (not in Finland)
Floods	Earthquakes (not in Finland)
Vegetation height measuring (e.g., trees next to rails cause risks of falling)	

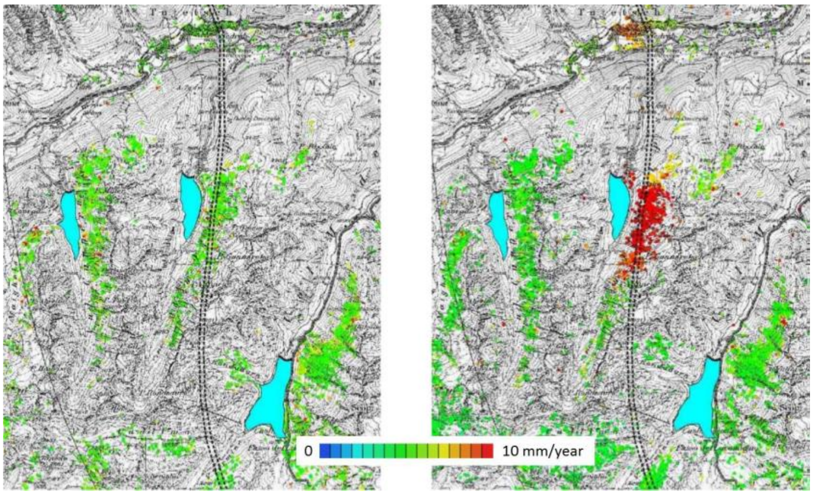

Figure 2 – Satellite data reveals small geological movement (©MATIST)

Digitalization of transport and mobility

One of the biggest changes in future transportation is realized through digitalization through for example automated vehicles as well as shared and demand responsive transport services (that may also be automated) that require a comprehensive situational picture and connectivity for optimization. Human drivers can adapt their driving based on the prevailing road weather and conditions. In order to do the same, automated vehicles must have an ability to obtain and process data and then interpret it to ensure they are driving safely. For this, communication and positioning methods are crucial for connected and automated vehicles to small satellites can be used to provide related services. Automated vehicles will have to rely not only on their own sensors but also those of other vehicles as well as remote sensing data. An increasing amount of information has to reach its destination with very low latency. These requirements for the future communication system are so high that both terrestrial and satellite components are needed. Small satellites could be used in the near future to provide decent data connection speeds in sparsely populated areas where the building of dense mobile cellular networks is too costly. Table 5 summarize the finding of workshop related to the digitalization of transport and mobility.

Table 5 – Industry needs for digitalization of transport and mobility

Desirable features and needs	
Detection of on-road obstacles and incidents	Positioning
Traffic census and decentralization/balancing	Communication, especially in rural areas
High-definition up-to-date maps	

Conclusions

Currently the large traffic related infrastructures are mostly monitored from the ground, but spaceborne technologies can soon provide competitive and complementary solutions. The typical limitations for terrestrial sensors (e.g., ground sensors, fixed observation points, distributed observations) are spatial and geometrical resolution as well as location specificness, whereas satellite observations are currently limited in temporal resolution. Satellite observations can also be limited in the spatial dimension (e.g., resolution of images is not good enough). In addition, optical solutions (such as hyperspectral cameras) are dependent on weather and cannot see through clouds. However, (small) satellite-based observation networks are also automatically assets that provide services globally.

Satellite technology will probably not replace the existing terrestrial systems but complement them. Terrestrial systems can be used for verifying satellite data (i.e., ground truth). A fusion of Earth Observation and terrestrial sensor data can deliver a comprehensive understanding of transport conditions (e.g., network usage, traffic flows, road surface moisture) or environmental impacts (e.g., greenhouse gas monitoring, ground frost damages, weather forecasts and predictions) and also helps to prepare for sudden natural events (earthquakes, landslides, floods and extreme weather) in risk prone areas.

Despite the poor temporal resolution of traditional satellites, satellite-based earth observation technologies can help to assess and monitor high-risk areas by providing more information on geological hazards along road and rail networks using integrated data. In our work we have identified several existing technologies which could be further exploited to bring additional value to traffic and infrastructure asset management:

- SAR interferometry techniques in road and railroad infrastructure health monitoring in northern areas
- Road weather forecast improvement based on satellite images
- Road maintenance related asset management in remote areas based on satellite images

When digitalization revolutionizes infrastructure and transport, small satellites can have a positive contribute by bringing high data accuracy and coverage in space and time. Affordable small satellites enable unprecedented monitoring capability from space. We would especially emphasize the rapid development of active microwave radars, as they can bring truly weather and time independent imaging and therefore can provide information in northern areas, where cloudiness and long nights are a problem, operatively.

If and when nearly real-time data and observations from small satellite constellations are available, the operability of lower road and rail network is likely to be among the most important land transport aspects where small satellites can contribute by improving situational picture and proactive asset management. Same goes with the new ways of communication (e.g., integrated satellite and terrestrial 5G) (Corici, 2016) which may provide possibilities to have fast and reliable network connections for connected and automated vehicles in rural and sparsely populated areas which after all contain an extensive amount of transport infrastructure. Low-volume roads (less than 1000 vehicles per day) account for about 80% to 85% of the global road network (Transportation Reseach Board 2012). Figure 3 provides an upfront illustration of land transport monitoring supported by satellites and machine vision

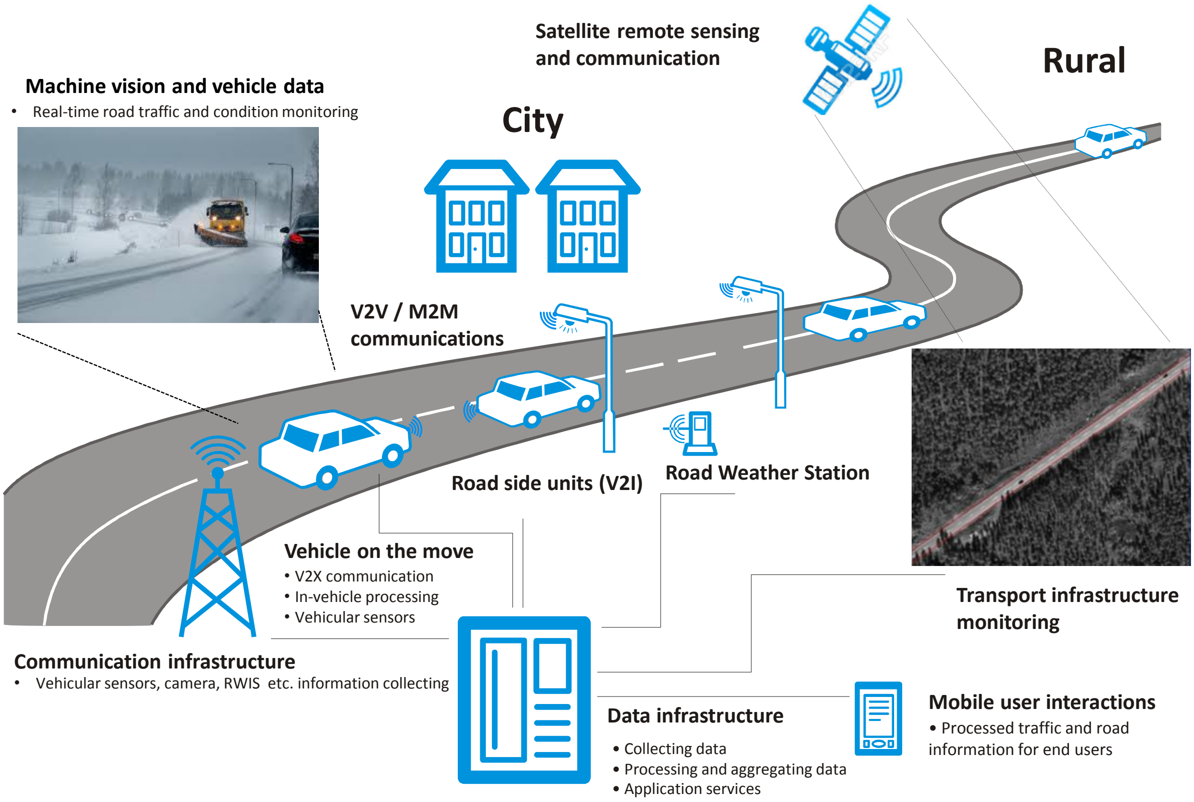

Figure 3 – Future land transport monitoring and management (modified from ©Huusko & Piri 2017)

In addition to land transport, it has been recognized that the maritime sector is expected to be a favorable application area for satellite-based remote sensing and communications. Potential use cases include ice navigation, ship detection and tracking (AIS-system), traffic patterns, collision avoidance, fleet monitoring, regulation enforcement, environmental protection (e.g., oil spills) and weather monitoring. Current communication infrastructure cannot support all the data transfer needs of an autonomous ship that is operating far from the shoreline. Sometimes the ship itself cannot make operational decisions based on sensor data. Then, there is a need to have a real-time connection to the remote shore control centre possibly with high quality video transfer so that good and safe decisions can be made by a human operator. Small satellites flying on the Low Earth Orbit promise to provide required capacity to enable this

Even though some technological areas such as satellite data is starting to be relatively mature, especially small satellite technologies and concepts are not yet developed enough for commercial use and hence they still require research to enable large-scale market penetration. Some emerging research areas for small satellites are presented in table 6.

Table 6 – Emerging research areas

Research topics	Subtopics
Data fusion and analytics	Integration of multisource data (satellites and terrestrial) Analytics of remote sensing data and added value information
Standardization and legislation	Communication formats and interfaces Satellite structure and modularity International legislation and coordination
Remote sensing technologies and data resolution	Radio, radar and optical imaging capability and application areas
Communication technologies	Miniaturized radio technologies Integration of satellite and terrestrial systems Inter-satellite communications
Technological validation and socio-economic assessment	Pilots and proof-of-concepts, Technological and economic validation and assessments

Another challenge is finding appropriate and plausible actors (firms, authorities, research institutes etc.) to form business ecosystems that can develop, demonstrate and exploit the possibilities of emerging technologies. Attracting and convincing especially private companies mostly requires a clear demonstration of business opportunities which can often be a challeng for emerging technologies and services. Hence to create new business opportunities for companies, societies' proactive support for and investments in emerging themes, technologies and research is required in order to reveal the breakthrough applications and expertise areas before others do it. Since emerging technologies can create room for new kinds of competencies and services, ecosystems must be kept open for new actors too.

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