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Capabilities of Commercial Satellite Earth Observation Systems and Applications for Nuclear Verification and Monitoring

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ABSTRACT

A growing number of commercial Earth observation satellite systems provide capabilities with significant application in nuclear verification, monitoring, and proliferation analysis. This article provides some relevant examples and a case study describing the importance of spatial, spectral, and temporal resolution on detectability of ground targets and monitoring of activity. The article also provides an overview of 300 operational (as of September 2021) optical and radar systems with a ground resolution of 5 m or better, whose imagery is available to the public. By merging all satellites into one super-constellation, a simulation was performed to describe its potential coverage. The analysis suggests that with current commercial capabilities it would be possible to image newly discovered alleged ICBM fields in China every few hours with a ground resolution sufficient to detect new construction and missile uploading.

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Introduction

Satellites have a long history of being used for treaty verification and arms control. They were first employed as part of National Technical Means within the SALT and ABM treaties signed in 1972. Satellite imagery is today used for verification within the New START treaty, and is a vital part of IAEA safeguards. For example, IAEA inspectors have not performed an on-site inspection in the DPRK since 2009. Instead, they rely on commercial imagery to monitor DPRK's nuclear program and to detect potential plutonium reprocessing activities and nuclear site construction and expansion.[1]

There are now more than 4,000 operational satellites in orbit, and it is estimated that this number could rise to 50,000 within the next 10 years.[2] This includes mega constellations of communication satellites planned by

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Supplemental data for this article can be accessed here.

Starlink and Amazon, but also many observation satellites. Advancements and miniaturization of satellite technology have led to significant improvements of Earth observation (EO) systems in terms of the spatial and spectral resolution they can offer. A growing number of commercial providers in combination with cheaper space launch services are resulting in a dramatic decline of prices of data and are enabling more persistent ground coverage. By integrating advanced big data analytics in the distribution chain, processing is automated, and more insights are made available from raw imagery. At the same time, distribution restrictions are being relaxed, resulting in wider availability and expanding commercial application. Even though the commercial EO sector was initially shaped by the needs of defense agencies, who remain their main client, they no longer hold a monopoly on all space-borne remote sensing systems or the data they produce. Private companies can sell imagery to both the government and the public.

States with and without their own dedicated satellite EO systems are leveraging commercial space-based assets to obtain more persistent ground coverage.[3] Commercial satellite imagery is being used for military reconnaissance and surveillance of borders and national territory, but also to monitor neighbors and verify compliance with treaties and agreements. The performance gap between commercial and dedicated national EO systems continues to narrow. The benefits of commercial systems are that they make possible sharing of unclassified data with partners and the public, and that having a larger number of systems at disposal provides a more comprehensive view of the surface.[4]

Commercial data is equally available to nongovernmental organizations (NGOs), journalists, experts, and enthusiasts who use it for open-source intelligence (OSINT) analysis and supervision of conventional and nuclear weapon activities.[5] Researchers can share insights and collaborate, building on each other's conclusions. Imagery can be supported by other open-source data, including news reports, geo-tagged social media posts, and official statements. With enough data and sufficient training, citizen groups can perform independent inspection of any site they are interested in and, in that way, verify government claims chipping away at state secrecy.[6]

Emerging capabilities of commercial EO systems can be exploited to detect presence of specific materials and equipment that are not compatible with their stated purposes. They might also be used to monitor activities associated with the development, acquisition, and maintenance of operational nuclear weapon capabilities with a much higher confidence.[7] If indicators observable from space that are relevant to the nuclear fuel cycle and weapon program can be identified, analysis can be expanded and automated over large areas or territories of entire states. The information acquired might allow observers to monitor various nuclear weapon related activities ranging from nuclear material acquisition to weaponization and ultimately testing. Having this ability is especially important to allow for verification at locations where it was not possible previously, due to political complications or genuine concerns of disclosure of sensitive information.[8]

However, wide availability of high-resolution satellite imagery does not mean that everything that happens on the ground is visible and easily observable. Viewing by remote satellite sensors is made difficult because of atmospheric conditions, but also because of deception, camouflage, and concealment that the observed party can implement to mask their activities. In addition, orbiting satellites are vulnerable to various forms of anti-satellite weapons (ASAT) which can range from temporary blinding of sensors to the destruction of the entire satellite system by kinetic or nonkinetic means. The usefulness of the data that finally gets delivered to the analyst is limited by technical constraints, but also because of the difficulties involved in verifying its authenticity.

This article evaluates the potential of commercial satellite imagery by examining coverage that could theoretically be achieved with combined operational constellations. A database of on-orbit EO satellite systems with an imaging ground resolution of better than 5 m in any band was compiled. The main selection condition was that the imagery was accessible by the public either without restriction or by purchase. Simulations were then performed to determine persistency of coverage for different relevant ground resolutions. In practice, it would be difficult to simultaneously acquire data from various operators distributed around the world due to constraints such as sensor availability and operational limitations, tasking priority and cost—as described later. Finally, some applications for nuclear verification and monitoring are described based on the derived performance of this super-constellation in terms of its ground resolution, revisit times, and available spectral information. Results show that most relevant ground objects and facilities can be successfully imaged on a global scale with an average frequency of only a few hours.

Operational EO systems and their properties

Overview of satellites

As of 2021, commercial, civil, military, or government satellite systems of various functions are operated from more than 100 countries. This includes 30 countries where some form of civilian or commercial EO providers are present.[9] Following the growth of the civilian space industry sector, commercial EO providers are deploying a host of new observation constellations and expanding their offerings. International competition and rising commercial and government demand are causing a continuing decline of prices; at the time of writing, 100 km^2 area can be imaged for less than a $1,000 while archived imagery ($<$ 90 days) for a 25 km^2 area can be purchased for as low as $200.[10]

To be able to estimate what type of coverage these EO systems can offer to the end user, a database of satellites with public access to imagery was compiled. Table 1 shows an overview of 300 (265 optical + 35 SAR) selected observation commercial or free-access satellites with a ground resolution of 5 m or better in any band, as of September 2021.[11] This is a ground resolution at which buildings and many military and civilian objects become recognizable from space.[12] As shown later in the text, lower resolution data is also useful for ground observation and regularly used for verification and monitoring.

More information on the systems considered in the analysis is given in the online supplement. In addition to satellites presented in this article, it also contains information on promising upcoming constellations with an imaging resolution of 1 m or better.

In addition to ground resolution, the introduction noted that the main condition to include an EO system in the overview was that their data is publicly accessible, including information as to how access could be gained—whether its through an online portal, third party vendor, or another method of contact. Still, such access might not be simply obtained, either because of a complex retrieval process or due to restricting customer terms, effectively making this imagery inaccessible to the public. If no method of access was found, these systems were not considered, even if the operator had promised some degree of civilian usage.[13] Access might still be possible, even if it's not obvious. In addition, states operating dual-use systems might be willing to provide imagery for purposes of nuclear arms control and nonproliferation monitoring.

Properties of EO systems

The main properties of EO system capabilities are revisit time, spatial resolution, and the spectral information the satellite can acquire.[14]

EO providers typically offer data in the visible panchromatic bands (black and white) and/or multispectral covering additional intervals of the electromagnetic (EM) spectrum. For optical sensors, ground resolution is defined as the distance between adjacent pixel centers of the image the sensor acquires and is called ground sample distance (GSD). It is usually defined for when the sensor is looking straight down to the center of its ground swath and is also called nadir spatial resolution. In practice, the

Table 1. Overview of selected commercial and free-access EO satellites with ground resolution better than 5 m as of September 2021.

Name	Country	Number and type	Launch	Top sensor resolution	Mass	Comment
ASNARO	Japan	1 Optical 1 SAR	2014/2018	PAN (0.5 m), MS (2 m) SAR (1 m)	400 and 507 kg	Optical and SAR satellite. Hyperspectral satellite planned
ALOS	Japan	1 Optical	2014	SAR (1 × 3-m)	2,100 kg	New optical satellite PAN (0.8 m) planned for 2021
BlackSky	United States	7 Optical	2018–2020	MS (1 m)	50 kg	60 satellites planned
Capella Space	United States	5 SAR	2018/2020	SAR (0.5 m)	<40 kg	36 satellites planned
CBERS	Brazil	2 Optical	2014/2019	PAN (2.5 m and 5 m) MS (8 m and 10 m)	1,980 kg	3 more satellites planned
Cosmo SkyMed	Italy	6 SAR	2007–2019	SAR (1 m/0.55 m)	1,790 to 2,230 kg	2 generations in orbit; 2 new satellites planned for 2021
Deimos	Spain	1 Optical	2014	PAN (0.75 m) MS (2.8 m)	310 kg	Another lower resolution satellite
EROS-B	Israel	1 Optical	2006	PAN (0.7 m)	350 kg	EROS-NG constellation planned
Maxar	US	4 Optical	2007–2014	PAN (0.31 m to 0.5 m) MS (1.24 m to 1.85 m)	1,955 to 2,800 kg	New 29-cm Legion constellation planned
DubaiSat	UAE	2 Optical	2013–2018	PAN (0.75 m/1 m) MS (2.98 m/4 m)	300 kg	DubaiSat-2 or KhalifaSat
Gaofen (CHEOS)	China	7 Optical + 1 SAR	2013–2020	PAN (0.8 m to 2 m), MS (16 m), SAR (1 m)	805 to 2,950 kg	Dual-use constellation; limited public access
ICEYE-X	Finland	11 SAR	2018–2020	SAR (1 m)	<100 kg	18 satellites planned
Jilin	China	22 Optical	2015–2020	PAN (0.72 m to 1 m) MS (3 m to 4 m)	42–420 kg	Most provide some form of video
KANOPUS-V	Russia	6 Optical	2012–2018	PAN (2.1 m) MS (10.5 m)	473 kg	2 more satellites planned for 2025
KAZEOSAT	Kazakhstan	1 Optical	2014	PAN (1 m) MS (4 m)	830 kg	Another satellite with PAN (6.5 m) in orbit
KOMPSAT	SouthKorea	3 Optical + 1 SAR	2006–2015	PAN (0.5 m to 1 m) MS (2.2 m to 4 m) SAR (1 m)	800 to 1990 kg	KOMPSAT-6 SAR satellite planned for 2021
NigeriaSAT	Nigeria	1 Optical	2011	PAN (2.5 m) MS (5 m)	300 kg	Another satellite with PAN (22 m)
NuSat	Argentina	22 Optical	2016-2020	PAN/MS (1-m), HS (30-m), IR (90-m), video (1-m)	41.5 kg	Mid-term 90 satellites, long-term 300
PAZ	Spain	1 SAR	2018	SAR (1 m)	1,209 kg	Orbit with TerraSAR-X
Planet Labs PlanetScope (Doves)	United States	138* Optical	2013–2021	MS (3.7 m to 4.1 m)	5.8 kg	Multiple generations, regular launches
Planet Labs SkySat	US	21 Optical	2013–2020	PAN (0.57 m) MS (0.75 m)	110 kg	Multiple generations; New Pelican Constellation announced.

Pléiades	Europe	4 Optical	2011/2019	PAN (0.3 m/0.5 m) MS (2 m)	930 kg and 970 kg	2 more Pléiades Neo (30-cm) planned to launch 2021 and 2022. 50-cm constellation CO3D in development
PRISMA	Italy	1 Optical	2019	PAN (5 m), HS (30 m)	550 kg	Hyperspectral with 250 bands (400–2,500 nm)
Radarsat	Canada	4 SAR	2007/2019	SAR (1 m to 3 m)	2,750 kg and 1,400 kg	1 Radarsat-2 and 3 Radarsat Constellation Mission (RCM)
Resurs-P	Russia	3 Optical	2013–2016	PAN (1 m) MS (3 m)	6,570 kg	2 more launches for 2022 and 2023
Sentinel-1	Europe	2 SAR	2014/2016	SAR (5 m)	2,280 kg and 2,164 kg	Sentinel-1C and 1D in development; Sentinel-2 offers 10-m optical
SPOT	Europe/France	2 Optical	2012–2014	PAN (1.5-m) MS (6-m)	720 kg	Same orbit as Pleiades
Formosat	Taiwan	1 Optical	2017	PAN (2 m), MS (4 m)	475 kg	6 new satellites planned for 2023–2028
GaoJing (Superview)	China	4 Optical	2018–2020	PAN (0.5 m) MS (2 m)	560 kg	24 satellites planned
TeLEOS	Singapore	1 Optical	2015	PAN (1 m)	400 kg	SAR satellite planned for 2021
TerraSAR-X	Germany	2 SAR	2007/2010	SAR (1.1 m)	1,209 kg	TSX-NG, Tandem-L, and H RWS planned; orbit with PA.
THEOS	Thailand	1 Optical	2008	PAN (2 m), MS (15 m)	750 kg	Successor to be launched 2021
Triplesat	China	4 Optical	2015/2018	PAN (0.8 m) MS (3.2 m)	447 kg	3 + 1 constellation (SSTL-SL1 added)
Synspective	Japan	1 SAR	2020	SAR (3 m)	100 kg	1 more planned for 2021, 30 satellites constellation plan
Zhuhai	China	4 Optical	2017–2019	VIDEO (0.9 m to 1.98 m)	<100 kg	8 more satellites including HS with resolution >10 m
TOTAL (better than 5 m GSD) = 300 satellites (265 optical + 35 SAR)						

Optical systems are those with electro-optical sensors, while SAR are satellites with a synthetic aperture radar. Nadir resolution is provided for EO systems, and top imaging ground-adjusted resolution for SAR. A visible trend of reduction of launch mass with time can be observed. Providers are ordered alphabetically. For more details, see text and the online supplement.

*Planet does not disclose the exact number and IDs of operational Dove satellites, but claims more than 200 are in orbit. Provided number was obtained by the author by identifying unique satellite IDs from Planet's API metadata, over 5 days.

sensors rarely observe the target from nadir. A larger angle of imaging implies there is a longer distance from the sensor to the observed site and a larger area needs to be imaged with the same number of sensor pixels. This results in lower GSD.[15] However, in addition to a larger footprint, off-nadir imaging provides site information that might not be acquired if imaged directly from overhead. For example, it makes possible viewing of sides of buildings (windows, doors, etc.) and easier identification of vehicles and infrastructure.

The highest commercial optical resolution is currently provided by the two Pléiades Neo satellites from Airbus. They offer 30-cm ground resolution in the panchromatic band and are to be soon joined by an additional two satellites with the same sensor. A U.S. company Maxar operates the WorldView-3 satellite, which has a native ground resolution of 31 cm in the panchromatic band, which the company claims can be enhanced algorithmically to 15 cm. Maxar is also preparing to launch its new constellation called Legion, which will be composed of six satellites offering 29-cm ground resolution. This resolution will likely remain the standard for top systems, as it currently satisfies most commercial and military needs. Providers are competing by expanding their spectral acquisition capabilities, offering more frequent revisits by enlarging their constellations, improving distribution chains, reducing data processing times, and offering data analytics services. The U.S. company Planet focuses on providing more persistent coverage of the ground. They operate the PlanetScope constellation with about 138 operational Dove satellites (up to 3.7-m resolution) and the SkySat constellation with 21 satellites (57–86-cm resolution). Some companies also offer video acquisition that is useful in constructing 3-D models of observed objects and characterization of equipment and ground activity. The SkySat constellation can provide clips of up to 120 seconds duration with sub-meter ground resolution. Other systems with video capabilities are Zhuhai-1 OVS with 90-cm resolution and Nusat, BlackSky, and Chang Guang (Jilin) constellations with 1-m resolution.

Multispectral capable sensors can see beyond the capabilities of the human eye, provide more information on the material of the observed ground targets, and improve visibility for different weather and observation conditions.[16] Hyperspectral imaging samples the full spectrum into even finer bands, which allows for better classification of material. The highest resolution commercially available hyperspectral systems are Zhuhai OHS-2, with 10-m ground resolution, and PRISMA, Resurs-P, and NuSat with 30-m resolution. Some satellites are also capable of infrared (IR) optical imaging. This permits detection of thermal signatures and offers limited night viewing, some visibility in case of dense smoke or cloud coverage, and observation of changes in ground vegetation. However, IR imaging is more complex, may require special cooling and such satellites are less numerous. Deployed and publicly accessible long wave infrared (LWIR) sensors currently have at least two magnitudes lower ground resolution than what is typically commercially offered in the panchromatic and multispectral range. At the moment, free access Landsat satellites (60–100-m resolution) offer publicly accessible LWIR imagery with the highest ground resolution. Kompsat 3 A satellite provides midwave infrared (MWIR) imagery with 5.5-m resolution. MWIR has less thermal sensitivity but is still useful for nighttime observation of thermal outputs.

Use of systems with electro-optical sensors is limited at night and depends on atmospheric conditions above the observation site. On average, clouds cover more than 55% of the Earth's land surface at any moment in time, and some locations are permanently obscured.[17] It is not easy to successfully image a location on demand. Observation can be complemented with data from synthetic-aperture radar (SAR) EO systems that enable observation under all weather and all illumination conditions. The radar antenna produces bursts of microwave pulses that are transmitted from space, bounced off ground targets and then detected on return. As the satellite orbits, the system records the variation of intensity and a change of frequency in the backscattered signal and, in that way, forms an image. Radar imagery facilitates detection of metallic objects and it also makes possible the creation of digital elevation models (DEM) containing information on dimensions of observed infrastructure and ground targets.[18]

In the case of SAR, resolution refers to how well different ground scatterers can be distinguished once radar pulses are received by the antenna. SAR has to observe from the side and cannot look straight down as objects will have the same distance to the receiver and cannot be distinguished. Its resolution will differ in the flight direction (azimuth) and the direction perpendicular to the flight direction (range). Range resolution will depend on the imaging mode, bandwidth of the pulses, and the terrain. Movement of the satellite over the horizon acts to *synthetically* increase the aperture size of the antenna and, in that way, improve the azimuth resolution. By adjusting the direction of the beam, observation duration can be extended and a finer resolution achieved.[19]

Because of the nature of radar imaging, Earth's curvature, and effects of terrain, a SAR image in its native form will be distorted. It must be transformed into ground range geometry to express true horizontal distances between objects and to be more readable to the human eye. The end result requires a significant amount of processing and is not as intuitive to understand as optical imagery. Analysis is more challenging and analysts need additional training to be able to derive any useful insight. Resolution is defined in the slant range or along the line between the antenna and the ground target. To obtain a value equivalent to those of optical sensors, slant range resolution is projected to the ground plane. This is taken here as the resolution of SAR systems and used in simulations presented later in the article.

U.S. company Capella Space is currently deploying SAR satellites with a ground resolution of 50 cm and plans to have a constellation of 36 satellites able to image the Earth's surface with sub-hourly revisit times. Other notable high-resolution systems include the Italian Cosmo-SkyMed (55 cm to 1 m) composed of 6 satellites, Finnish ICEYE (1m) with 11 satellites in orbit and planned 18, and the German-Spanish TerraSAR-X/PAZ (1.1 -m) constellation with 3 satellites in orbit and new generations planned.

All these systems produce enormous amounts of data. For example, Planet claims it downloads more than 15 Tb of new imagery each day. To deliver the product to users as fast as possible, operators are maintaining data pipelines where processing and analytics are performed by employing automated algorithms including machine learning (ML). Algorithms are used to correct raw data (for example, adjusting for atmospheric conditions, optimizing sensor parameters, or correcting for effects of terrain) and perform automated detection of objects and identification of patterns. To obtain a cohesive and more persistent view of the ground, such algorithms are also applied to merge data from different systems, angles of observations, and spectral bands. Some operators offer this service in-house, while others collaborate with IT companies that specialize in different types of monitoring. Open-source algorithms are also available online.

Simulation of coverage of the selected EO systems

Software configuration

A software package SaVoir v9.2 was used to simulate the coverage capabilities of electro-optical and SAR systems that are presented in Table 1. SaVoir is a multi-satellite swath planner developed for ESA to support operations of the International Charter for Space and Major Disasters.[20] The software contains information on EO system orbits and their sensor capabilities and can simulate satellite passes during some period. Additional plugin "Charts" was used to produce an interactive color map of observation revisit times over selected territories.

Satellite revisit time is typically defined as the time interval between two subsequent satellite revisits of the same ground point. However, observation satellites are equipped with three-axis attitude control systems and steerable sensors to be able to select ground targets. The goal of the simulations was to produce an interval between repeated successful observations of some site. For a given ground resolution and location, this will depend on the

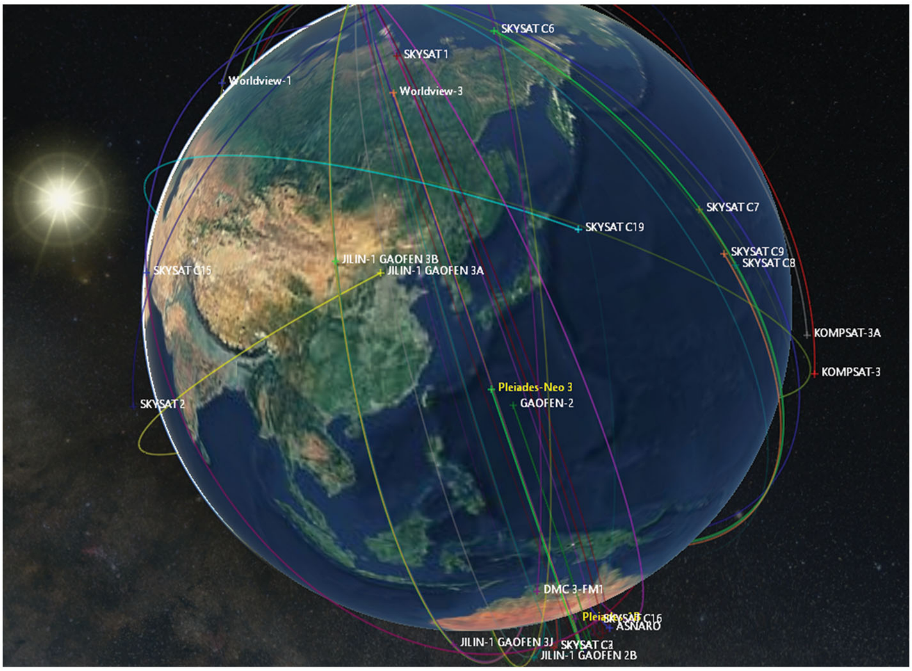


Figure 1. Example of a SaVoir setup. Satellites are selected from the software database, which also contains information on their orbits, imaging sensors characteristics, and system swaths. After choosing the interval of observation and applying sensor limitations, the user can perform a simulation on revisit times for a specific area on the surface.

satellite orbit, atmospheric conditions that influence visibility from space in case of optical sensors, the area a satellite sensor can observe on each pass (its swath width), and the angle at which it can observe. Figure 1 illustrates the initial satellite setup showing several different satellite systems and their orbits on a 3-D map.

Simulations were performed separately for electro-optical and SAR systems and over different ground resolution values. While SAR systems are active sensors that can image the ground during night and with cloud cover, electro-optical EO systems require adequate illumination and clear visibility. This is taken into account.

If too many pixels are obscured, the product is not useful to the customer and the observation pass is rejected. SaVoir performs a statistical evaluation of cloud coverage by implementing information from NASA’s Moderate Resolution Imaging Spectroradiometer (MODIS), which flies onboard the Terra satellite and has provided global data for the last 20 years. If the sun is too low on the horizon, optical sensors imaging in the visible spectrum might not be able to acquire any useful data. Illumination could also be obstructed by terrain and infrastructure. Based on Maxar and Planet Labs product information, the solar zenith angle (SZA) is required to be smaller than 80° for all optical systems (0° implies the sun is directly overhead). Otherwise, the satellite pass was also rejected.

Even though the optical and SAR coverage were simulated separately, the data could be fused to provide more persistent coverage and more information than the sum of its parts. In addition, IR systems offering limited visibility in cloudy conditions and during night were not considered in the simulation. There are not many of these systems operational and their ground resolutions are typically much lower than for optical and SAR systems.

The goal of this analysis is to show what would be possible by an accessible decentralized observation system (already in operation) if all the operators would agree to provide the imagery of some site. Most satellites have multiple modes of imaging influencing the width of their swath and ground resolution. In the simulation, sensor targeting was optimized to cover as much area as possible for a given resolution range. In reality, satellites would be tasked to observe a certain site and would not be able to image the entire area. It was also assumed that observation time is always available, which may not be true. During standard operation, sensors of EO systems will regularly be turned off during large parts of their orbits to save energy. It is likely that the end user would experience difficulty in regularly obtaining imagery from all the providers.

Results

Average frequency of successful ground observation for territories of selected states for a given period is provided. Simulations were performed separately for electro-optical (for the panchromatic band) and SAR EO systems during 14 days and for selected sensor ground-resolution values. For each resolution, sensor-imaging mode with the widest ground swath possible was chosen. To account for seasonal illumination and weather variations and their effects on visibility, simulations for optical systems were performed twice during an average winter (January) and an average summer month (June).

Figure 2 provides an example of the graphical output from SaVoir (+ Charts plugin), showing average revisit times for North America, Europe, and most of Asia for a ground resolution of 5 m or better. Because most EO systems are in polar orbits and converge at the pole, optical satellite revisit times should decrease with larger latitude. However, imaging conditions have a significant effect on passive optical EO systems. During January, these will offer poor coverage in northern latitudes, and none above about 65° because of the polar night. This is important when imaging Russia and northern parts of the United States (Alaska). Better optical

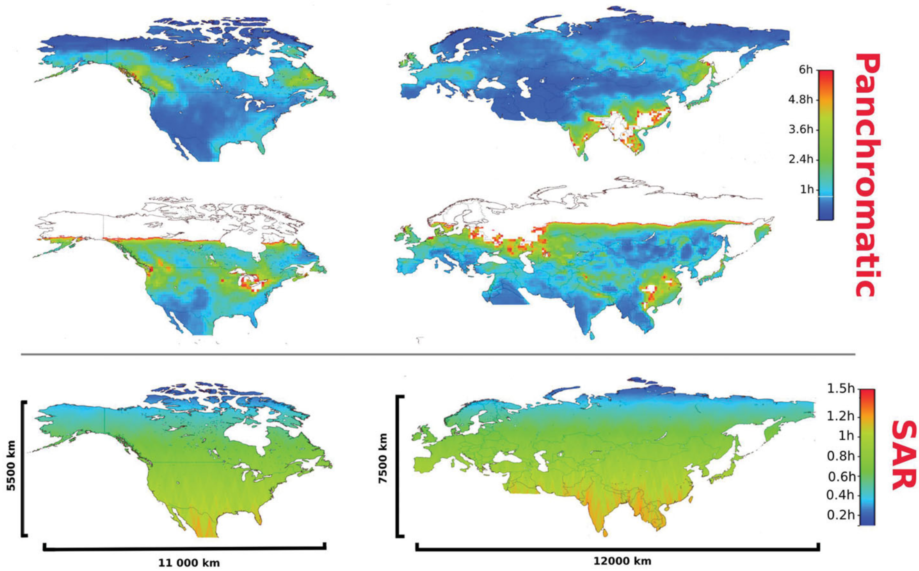


Figure 2. Example of the SaVoir output showing average observation frequency in North America, Europe, and Asia for a ground resolution of 5 m or better using optical and SAR commercial EO systems. Coverage of commercial optical EO systems was simulated twice–during an average June (top row) and January (middle row) month. Combined SAR satellites (bottom row) were simulated only once as atmospheric conditions should not influence visibility. Note that the scales are different for optical and SAR systems. In case of optical coverage, regions that are clipped out have frequent cloud cover or low illumination. SAR systems are able to fill those coverage gaps and can image the entire northern hemisphere with a frequency of less than 90 minutes.

coverage is available in the northern hemisphere during June. On the other hand, persistent cloud coverage due to the rainy season in South and Southeast Asia will result in larger gaps of optical visibility in June compared to January. These areas can instead be imaged with SAR systems. Even though optical systems are more numerous and on average offer better resolution, combined SAR systems have wider area coverage and can image for all atmospheric conditions and during night.

Simulations of coverage were performed for a set of different ground resolutions of better than 5, 3, 1.4, 0.9, 0.5, and 0.3 m. These values were selected based on criteria explained later in the text. Tables 2 and 3 show ranges of observation frequencies as a function of sensor resolution with optical and SAR coverage for selected states either possessing nuclear weapons or actively developing nuclear programs.

For example, results show that excluding a cloudy region in the southeast, most territory of China can be imaged with 5 m or better in the panchromatic with an average of 20-h frequency for a sample observation interval in June and under 6 h in January. Relatively small spots in the south with no optical visibility were not considered in the Table. With

Table 2. OPTICAL–results of the SaVoir simulation show average observation frequency for 265 commercial electro-optical EO systems over selected states and for a range of ground-resolution values, during a period of 14 days.

	OPTICAL coverage											
	5 m		3 m		1.4 m		0.9 m		0.5 m		0.3 m	
	Jun	Jan	Jun	Jan	Jun	Jan	Jun	Jan	Jun	Jan	Jun	Jan
United States (not Alaska)	0.5–1.5 h	1–4 h	0.5–2 h	1–5 h	1–2.5 h	1–9 h	1–5 h	2–14 h	3.5–10 h	5–35 h	20–40 h	15–80 h
Alaska	0.5 to 2 h	4 h–∞	0.5–2 h	3.5 h–∞	0.5–3.5 h	6 h–∞	1.5–3 h	6 h–∞	1.5–10 h	9h–∞	7.5–50 h	15h–∞
Russia	0.5 to 3.5 h	1 h–∞	0.5–4 h	1 h–∞	1–3.5 h	2 h–∞	1.5–5 h	2 h–∞	2–15 h	5 h–∞	10–50 h	20 h–∞
China	0.5 to 20 h	1–6 h	1–20 h	1–7 h	1–20 h	1–11 h	1.5–20 h	2–15 h	4.5–60 h	5–40 h	20–130 h	20–80 h
U.K.	1.5 to 2.5 h	1.5–4 h	1.5–2.5 h	2–4 h	1.5–3.5 h	2.5–6 h	2.5–6 h	4–9 h	6–14 h	8–20 h	35–60 h	30–50 h
France	1 to 1.5 h	1.5–2.5 h	1–1.5 h	1.5–2.5 h	1.5–2 h	2–3 h	2–3.5 h	3–5 h	5–9 h	9–15 h	25–40 h	25–35 h
India	1 to 8 h	0.5–3 h	1–9 h	1–3 h	1–12 h	1–3.5 h	1.5–18 h	2–6 h	5–45 h	5–15 h	20–115 h	15–40 h
Pakistan	0.5 to 1 h	1–2.5 h	0.5–1 h	1–4 h	1–1.5 h	1–3.5 h	1.5–3 h	2–6 h	3.5–7.5 h	5–15 h	15–30 h	15–50 h
Israel	0.5 h	1.5–2 h	0.5 h	1.5–2 h	1 h	1.5–2.5 h	1–1.5 h	3–4 h	3–4 h	6–12 h	15–18 h	20–35 h
Iran	0.5 h	1–1.5 h	0.5 h	1–1.5 h	1 h	1–3 h	1–1.5 h	2–3 h	3–4 h	5–11 h	25–45 h	20–30 h
DPRK	1–1.5 h	1–2 h	1–1.5 h	1–1.5 h	1.5–2 h	1.5–2 h	2–3 h	2.5–3 h	6–12 h	6–12 h	35–55 h	20–30 h

Simulation was repeated during an average January (JAN) and June (JUN) month to account for variations of atmospheric conditions. Persistent cloud coverage in relatively small regions impedes observation and can cause a significant deviation in average observation time compared to the rest of the territory. This includes, for example, spots in southeast China, southwest India, northeast Pakistan, northeast United States, and southeast Russia. In case of no optical visibility due to permanent cloud coverage, such spots were excluded from the results as their area is very small compared to the total territory. Effect of polar night on visibility is observed above 60° in Russia and United States (Alaska) in January.

Table 3. SAR–results of the SaVoir simulation show average observation frequency for 35 selected SAR EO systems for selected states and ground resolution ranges during a period of 14 days.

	SAR coverage				
	5 m	3 m	1.4 m	0.9 m	0.48 m
United States (not Alaska)	1 h	1 h	1–2 h	2.5–4 h	3–4.5 h
Alaska	0.5 h	0.5 h	1 h	2–3 h	2–3.5 h
Russia	0.5–1 h	0.5–1 h	0.5–1.5 h	1.5–3.5 h	1.5–3.5 h
China	1–1.5 h	1.5 h	1–2 h	2-3 h	3–6 h
U.K.	0.5–1 h	1 h	1–1.5 h	3–3.5 h	3–3.5 h
France	1 h	1 h	1–1.5 h	2.5–3.5 h	2.5–3.5 h
India	1–1.5 h	1–1.5 h	1.5–2 h	4–5 h	4–5 h
Pakistan	1 h	1 h	1.5–2 h	3.5–5 h	4–5 h
Israel	1 h	1 h	1–1.5 h	3.5–4 h	4 h
Iran	1 h	1 h	1.5 h	3.5–4 h	3.5–4.5 h
DPRK	1 h	1 h	1–1.5 h	2.5–3 h	3 h

It is assumed SAR systems can see during night and through clouds.

SAR, imagery of the entirety of China is available every 1.5 h with the same ground resolution.

Currently, data distribution times of EO providers lag rate of sensor acquisition frequency. Unless a user arranges for a direct downlink to their ground station, delivery of "fresh" processed imagery is delayed at least several hours and only if a priority service is used (carrying higher price). For most operators, regular service implies data delivery takes days or weeks. Distribution time will depend on the level of processing, relative ground station location, and delay until the system is flying overhead the target site. Nevertheless, once available, imagery can be analyzed in a time series and provide valuable insight. With the growth in the number of available EO systems and ground stations, increased commercial demand for actionable up-to-date imagery, development of automated data processing pipelines, and low-latency distribution channels, delivery times will continue to decrease.

Discussion: applications of satellite imagery in nuclear verification and monitoring

This section describes the relevance of sensor ground resolution, spectral acquisition capabilities, and revisit time for monitoring of sites, detection of objects and items, and tracking of ground activity. It also presents some applications in nuclear verification, monitoring, and nonproliferation analysis while considering results from the previously presented simulations.

Physical limitations on what a sensor can see from a distance of a few hundred kilometers can work as an advantage. The inspecting party is able to confirm the presence or absence of exposed objects of adequate size, but not much else. Counting may be feasible but detailed, and more intrusive, inspection revealing classified information is difficult. Cheating can be discovered if its part of a larger pattern of behavior, while individual instances are not easy to detect. With better sensor performance, faster distribution of data and more persistent coverage provided by swarms of artificial intelligence (AI) operated satellites, the utility of satellite imagery as a verification and disarmament tool will increase.

How sensor ground resolution and spectral information affects detectability of sites and objects

Construction of nuclear facilities takes a long period of time and produces observables that can be seen from space. This includes the presence of excavations, stockpiling of equipment and materials, and gradual addition of new buildings and roads. Recently, using Planet's 3.7-m and Sentinel-2 10-m resolution optical imagery, construction of what appears to be about 300 new missile silos was discovered at three locations in China.[21] Lower resolution optical wide area imagery enabled a successful manual search over Chinese territory and was subsequently used to cue higher resolution EO systems, which were able to validate the findings and provide more detail. Discovery of such unreported locations is aided by identification of buildings and features present at other known weapon, enrichment, and reprocessing sites. For example, what supported the finding of alleged missile silos in China was observation of inflatable environmental shelters that were previously used (with the same dimensions) at another Chinese missile silo site.

Confirmation of discovery of relevant sites can additionally be verified by observation of nearby recent addition of roads, detection of distinctive ground activity and objects, such as guard towers, double fences, and presence of specific vehicles and military forces. The smaller the targets on ground are, the higher the ground resolution needed to identify and describe them. As a simple rule, 2.5 pixels (in the optical) are needed to resolve an object. However, there are other factors to consider such as shape and length (for example, even thin roads can be detected), presence of shadows, and atmospheric conditions.[22] The National Imagery Interpretability Rating Scale (NIIRS) and a note from the U.S. Bureau of Intelligence and Research (INR) provide more detailed information indicating site and item interpretability by satellite imagery.[23] Adapted from their analysis and derived sources, Table 4 shows what ground resolution in the optical and radar is necessary to detect, identify, and describe selected objects relevant for arms control, nonproliferation, and disarmament monitoring. For example, analysts need about 4.5-m optical ground resolution to detect roads, buildings, large ships, and surfaced submarines; 2.5 m to 4.5 m to detect radars, missile sites, nuclear weapon components, and identify ships and submarines; 1.2 m to 2.5 m to detect vehicles and open missile silo doors, and 0.4 m to 0.75 m to identify rockets and artillery. Even though interpretation is more difficult, SAR-produced imagery is also useful and can complement what is observed in the optical. Using radar, about 4.5-m resolution is needed to detect roads, buildings, large aircraft, and ships; 2.5 m to 4.5 m to detect medium sized aircraft and vehicles; 1.2 m to 2.5 m to distinguish vehicles; and 0.75 m to 1.2 m to detect missile support equipment.

The values of ground resolutions used for the SaVoir simulation in the preceding section and presented in Tables 2 and 3 were selected based on lower bounds of ranges in Table 4 with an added margin of about 20%. For example, 1.4-m ground resolution is considered sufficient to detect sites and items contained in the 1.2–2.5 m range of the NIIRS/INR table. This information can be used in conjunction to determine visibility of ground objects. To detect a vehicle, optical imagery with a ground resolution of 1.2 to 2.5 m is needed. Based on the SaVoir simulation, optical imagery of this quality covering the entire territory of DPRK is available every 1.5–2 h. For the United States (excluding Alaska), the equivalent time spread is 1–2.5 h in June and 1–9 h in January. This range is wider for the United States because of its larger territory; it extends farther to the south and has cloudy areas (for example northeast regions close to the Great Lakes). In addition, if Alaska is included, poor illumination due to polar night makes this range

Table 4. Ground resolution needed for detection, identification, and description of various objects.

Resolution	OPTICAL (panchromatic)	RADAR
4.5 m	Detection of roads, hangars, ports, airfields, bridges, large buildings, ships, and surfaced submarines.	Detection of large aircraft, large ships, port and military facilities, roads and rail, and fences.
2.5 m to 4.5 m	Detection of radars, missile sites, aircraft, trains, and nuclear weapon components. Identification of ships, submarines, and radar areas at SAM sites.	Detection of medium-sized aircraft and vehicles at known missile sites.
1.2 m to 2.5 m	Detection of vehicles, open missile silo door and presence of radar antennas. Identification of nuclear weapon components and field artillery.	Detection of bridges and ability to distinguish vehicles in a row.
0.75 m to 1.2 m	Identification of radar and radio sites. Ability to distinguish large aircraft, a TEL, and support vehicle at a known site.	Detection of missile support equipment. Ability to distinguish SSNs, count railcars and helicopters.
0.4 m to 0.75 m	Identification of launcher covers, vehicles, rockets, and artillery. Ability to distinguish missile airframes.	Identification of a railcar launcher setup like SS-24.
0.2 m to 0.4 m	Identification of launch tubes on a battleship, precise identification of nuclear weapon components and vehicles.	Identification of small aircraft and tanks.

Adapted from National Imagery Interpretability Rating Scale (NIIRS) and U.S. Bureau of Intelligence and Research (INR) research.[23]

even wider. With SAR, the entire territory of the United States can be imaged under 2 h for the same ground resolution.

Data in different spectral bands can be superimposed to provide more spatial and spectral information and improve detectability. EO providers employ a technique called *pansharpening* to merge pixels between standard optical imagery and lower resolution multispectral and IR data. The end result has higher resolution than its lowest denominator, but contains most of the combined spectral information. Similarly, optical and SAR imagery can be analyzed in tandem and provide more insight for a given resolution than if the data is analyzed separately.[24] In this article, revisit times were simulated and presented separately because the resolution values are not equivalent. Optical imagery might be better at observation of details, texture, and movement, while SAR imagery can produce object dimensions, reveal contours, and provide visibility during night or when the target is obscured by adverse weather conditions or material. Moving objects will appear defocused when imaged with SAR, but other imaging modalities that use radar could be implemented.[25] Similar distinctions apply for other observation bands.

How observation frequency affects monitoring of ground activity

Satellite orbits are known, and if the pass-over is infrequent enough, the observed party can implement countermeasures—hide objects, pause and restart activity. To make observation more difficult, the activity can be placed underground and various deception and decoy techniques employed. However, with a high frequency of multi-band observation over a period of years, this becomes much more demanding. This section illustrates what frequency of observation is needed to detect and monitor various activities relevant for arms control, nuclear proliferation, and disarmament.

Monthly and weekly revisits

Rapid revisit times are not essential for detecting addition of new structures. Construction of enrichment, fuel fabrication and reprocessing plants, and military facilities takes years and can easily be detected with imagery taken at a low frequency. For example, Russian military buildup and expansion of facilities in the Arctic can be tracked with monthly and even yearly observations.[26] Likewise, commissioning and decommissioning of reactors and reprocessing plants can also be detected and monitored on a longer time scale. Low-resolution commercial imagery taken at monthly rates was employed in nuclear nonproliferation analysis for the detection of construction of a heavy water nuclear reactor inside the Khushab complex in Pakistan in 2006. Subsequently, the same type of imagery was used to produce a 3-D model of the facility and estimate its plutonium production capacity based on its dimensions.[27]

Observation at a weekly rate enables better monitoring of reactor and enrichment facility operation and increases the probability of detection of attempts of covert material production or diversion. Having such capabilities is especially important when monitoring sites in inaccessible environments. Tracking the size of a waste pile at a yellowcake plant in Iran site suggests its production activity and can serve to indicate possible technical issues.[28] Optical and IR monitoring of thermal outputs, such as vapor plume emissions from cooling towers or steam discharges into surrounding water, can also help establish the status of the facility and even estimate its nuclear material output. In addition, hyperspectral imaging systems might allow remote probing of output and analyzing its chemical composition.[29] All this data combined could provide regular information on internal plant operation.[30] What can be imaged by satellites is always limited and cannot be considered as conclusive, but a deviation from normal activity can be a strong indication that more attention is needed.

For example, frequent shutting down of reactors can suggest production of plutonium.[31] Detection of various ground activities and monitoring of snow cover and vapor allowed 38 North analysts to determine that the 5 MWe reactor was in operation at North Korea's Yongbyon Nuclear Scientific Research Center in 2018, as well as observe progress in construction of the Experimental Light Water Reactor (ELWR) at the same location. In March 2021, CSIS researchers were able to detect activity at Yongbyon's radiochemistry laboratory and conclude that the 5-MWe reactor and ELWR are not operational. In August 2021, radiochemistry laboratory activity seems to have ceased, and ELWR construction and 5-MWe reactor operation restarted, as observed by 38 North analysts. According to a recent IAEA report, duration of observed activities at the 5-MWe reactor and the radiochemistry laboratory match the time needed to reprocess irradiated fuel from the reactor and produce plutonium.[32]

Commercial satellite imagery taken at the weekly rate can be employed to detect upcoming missile launch tests. Locations chosen are usually arid regions without much ground activity and with atmospheric conditions ideal for optical observation from space.[33] Observables include increased traffic at a known site, arrival of specialized equipment and vehicles, detection of presence of fuel containers or of a platform used to assemble and inspect the rocket.[34] In addition, IR imaging allows detection of signatures such as vehicle tracks or burns from missile launches. If located in areas more difficult to observe due to cloud coverage or low illumination, SAR imaging is also effective as shown by the recent observation of the preparation for a test of the Russian nuclear-powered cruise missile Burevestnik in the often cloud covered nuclear test site Novaya Zemlya.[35] While optical imagery was able to detect increased ship traffic, cloud cover did not allow imaging of the actual site. With SAR imagery provided by Capella Space, researchers were able to see containers and increased vehicle traffic at the location in the days leading to the actual launch.[36]

To simplify and speed up analysis, inspectors can apply AI/ML algorithms on multidimensional datasets and task them to automatically look for objects, features, or patterns of interest at a specific site or over broad geographical areas and automatically alert in case of detection, or if deviations from normal behavior are observed. For example, upticks in road and building construction or increasing vehicle traffic might imply something is happening in the monitored area.[37] Once tipped, the operator can proceed to task other EO systems to obtain imagery with greater resolution or cadence, deploy UAVs, or demand a ground inspection. To contextualize the results and add complementary insight, the output can be integrated with geo tagged data extracted from social media (Twitter, Facebook, Instagram, etc.), news outlets, shipping and aviation data, official statements, and other data sources.

Daily, hourly and near-real time revisits

More frequent observations add more stringent limits on what types of activities the observed party can conduct without being detected. They also add confidence in the analysis involving tracking of ground activity (including automated change detection) and mapping out of trends.

For example, daily imagery was recently used to count the number of trucks stuck in traffic at each side of the Sino-Korean Friendship Bridge, which allowed tracking of trade activity between North Korea and China.[38] This type of analysis was made possible because of algorithms enabling rapid data processing and target recognition. Commercial data analytics services employing satellite imagery range from counting cars on parking lots to evaluating the level of manufacturing activity in some region.[39] Similarly, commercial imagery taken at a daily rate with sub-meter resolution enables automated detection of an increase in activity at airports or ports and identification of aircraft and ships.[40] Same capabilities can also be applied to warn analysts of increased military activity at monitored sites, count the number of deployed military vehicles over a wide area, or verify for presence or absence of nuclear-capable delivery systems such as bombers at airfields or surfaced SSBNs in ports.

By monitoring what enters or leaves nuclear facilities, valuable information can be derived. Personal vehicle traffic correlates with site staffing demand, indicating site activity, while truck traffic can reflect variations in demand for material and suggest facility production rates.[41] Research using aerial imagery and neural networks illustrates how this might look like when near-real time and real-time satellite coverage is established in the near future.[42] Commercial services will enable tracking movement of trucks over broad areas as they travel between enrichment plants, reactors, weapon assembly, dismantlement, or storage sites. This will make possible accurate monitoring of fluctuations and trends and tracing out life cycles of national nuclear civilian and weapon programs.[43]

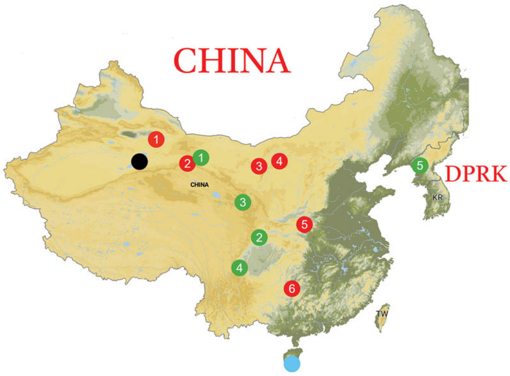
Commercial satellite imagery could be employed as a tool to verify absence of silo-based ballistic missiles or detect warhead uploading. Based on NIIRS information, optical imagery with resolution between 1.2 m and 2.5 m is sufficient to detect an open missile silo door, while 2.5 m to 4.5 m is needed to observe support vehicles and equipment surrounding it. It takes around 12 hours to upload a warhead on the SS-18, and the process should not be too dissimilar for other ICBMs.[44] As simulations from the previous section show, both optical and SAR imagery with 1.4-m ground resolution is accessible commercially at the required rate and better on a global scale.

Case study: territory of China and the DPRK

Considering which activities can be observed at different intervals for different types of sites and considering information on detectability from Table 2, SaVoir simulations were performed over territories of China and DPRK. This simulation included a subset of EO systems from Table 1 that are operated by companies not located in China that would likely not resist imaging of sensitive sites within the country. Analogous analysis could be made for the United States and Russia.

Figure 3 shows selected sites and the average availability of imagery in the optical and SAR. Locations selected include the Chinese DF-5 ICBM bases as provided by a recent FAS report, the newly discovered missile silo fields, Chinese nuclear test base at Lop Nur, Chinese Yulin submarine base, and Chinese and DPRK's major nuclear facilities.[45] Ground resolutions were chosen based on the type of the site. 5-m optical and SAR imagery allows detection of new roads, buildings, and ports at missile locations and nuclear facilities. The 5-m optical also makes possible detection of surfaced submarines in a naval base. The 3-m optical permits identification of ships and submarines, while 3-m SAR allows detection of vehicles at known sites (making it possible to track activity). The 1.4-m optical is enough to detect open missile silo doors and vehicles and identify nuclear weapon components, while 0.9-m SAR enables distinguishing SSNs.

Results show that all locations can be imaged in the optical within 24 hours irrelevant of the ground resolution. Newly discovered possible



NON-CHINESE EO SYSTEMS

OPTICAL	*SAR*
BlackSky (US)	Capella Space (US)
Deimos (EU)	Cosmo SkyMed (EU)
Maxar (US)	ICEYE (EU)
KOMPSAT (ROK)	RADARSAT+RCM (CAN)
Nusat (ARG)	Sentinel-1 (EU)
Planet (US)	TerraSAR-X + PAZ (EU)
Pleiades (EU)	ALOS-2 (JAP)
SPOT (EU)	ASNARO (JAP)
ASNARO (JAP)	STRIX-A (JAP)
EROS-B (ISR)	
PRISMA (EU)	

LOCATIONS & FREQUENCY

	SILOS	5-m optical*	5-m SAR	3-m SAR	1.4m optical*
1	Hami Missile Field	1h to 3h		1h	1.5h to 4h
2	Yumen Missile Field	2h to 3h		1h	2.5h to 4h
3	Jilantai Training Area	1.5h to 3h		1h	2h to 4h
4	Ordos Missile Field	1.5h to 3h		1h	2h to 4h
5	Lushi Base (DF-5B) and Luanchuan Base (DF-5A/B)	4h to 6h		1h	5h to 9h
6	Huitong Base (DF-5A)	8h to 23h		1h	21h to 31h

	NUCLEAR FACILITIES	5-m optical*	5-m SAR	3-m SAR	1.4m optical*
1	Jiuquan Plutonium Plant	2h to 3h		1h	2.5h to 4h
2	Guangyuan Plutonium Plant	7h		1h	4h to 10h
3	Langzhou Gaseous Diffusion Plant	2.5h to 5h		1h	3.5h to 7h
4	Heping Gaseous Diffusion Plant	6.5h to 8h		1h	9.5h to 11.5h
5	Yongbyon (DPRK)	2h to 3h		1h	3.5h to 4.5h

	OTHER	5-m optical*	3-m optical*	3-m SAR	0.9-m SAR
●	Lop Nor Nuclear Test Base	1.5h to 3h	1.5h to 4h	1h	2.5h
●	Yulin Naval Base	3h to 3.5h	4h	1h	3h

*Results are given for a period of 14 days during an average January/June month.

Figure 3. Frequency of observation for different relevant locations in China and DPRK. Locations are known missile silo sites, nuclear facilities, a nuclear test base, and a submarine base. Ground resolutions were selected based on the type of the target as explained in the text. Simulations were performed for EO systems operated by companies located in countries that would probably not oppose imaging of sensitive areas in China and the DPRK.

ICBM missile silo fields are located in northern dry regions of China, allowing frequent imaging by optical systems. Locations in the southeast of China are more difficult to image in the optical because of cloud coverage. SAR systems can be used in conjunction to reduce gaps and enable imaging of all the locations with a frequency of less than a few hours. In case China would attempt to implement the “shell game” deployment strategy for its ICBMs, it might find it difficult to avoid uploading/downloading of individual missiles being detected.

Conclusion

Performances of commercial satellite EO systems have recently significantly improved in terms of sensor ground resolution and the amount of spectral information they can acquire. A dramatic rise in the number of EO systems in combination with powerful algorithms capable of managing huge amounts of data is leading to more persistent coverage of the surface and better understanding of all human interaction. Satellite-sourced information is used for a variety of civilian and military purposes and is critical for addressing global challenges such as climate change, water availability, and disaster management, and local needs including agriculture, traffic, and urban planning. Due to mounting international competition and relaxation of legal restrictions, prices are declining and access to imagery is extended beyond the reach of only governments. Discussions are no longer confined to closed circles—and NGOs and individuals are able to form an international crowdsourced system of verification of governmental behavior.

Companies located in various countries around the world operate more than 300 EO systems providing panchromatic, multispectral, hyperspectral, IR, or SAR imagery to the public. Simulations presented show that with merged data, it is possible to image most places on the surface with a ground resolution under a meter at an average observation frequency of under 15 h in the panchromatic and under 5 h with SAR. Available sensor ground resolutions are sufficient to detect, identify and monitor most objects (aircraft, vehicles, missile sites, nuclear facilities, weapon components, rockets and artillery) relevant for arms control and nuclear proliferation analysis. Commercial systems are also able to image locations at sufficient cadence to detect attempts of missile silo uploading or downloading. Results serve to illustrate the potential of commercial operational EO systems. Due to several constraints it would be difficult to collect all the data from a variety of dispersed EO providers.

Before imagery is delivered to the customer, it needs to be acquired by an electronic sensor, downlinked to a ground station, processed by algorithms (that might lack explainability), distributed and finally interpreted. In every step of this process, an error can be introduced deliberately or accidentally, producing a significantly different end result. Most commercial EO providers have close ties to the governments of countries they are based in, as a large part of their budget is typically fueled by defense contracts. This reliance implies a conflict of interest if the sensors were to image something that might be considered embarrassing or harmful to the government. EO providers are staking their reputation on the authenticity of their product, but they still maintain the ability to doctor the data downlinked from the acquisition system. The company may also censor imagery or simply refuse to deliver it.

Authentication is complex and often impossible. To a degree, imagery obtained from commercial providers can be corroborated by other open sources and verified by software that can check the data structure for modifications.[46] The most secure approach to validate imagery is to acquire data from multiple providers. For example, if a user suspects imagery from a U.S. commercial provider is not authentic, they can use imagery from a Chinese or Russian company to verify, or vice versa. The decentralized nature of the commercial EO market facilitates validation of authenticity and ensures widening access. For example, if a U.S.-based provider refuses to image a territory the U.S. government deems sensitive, a Chinese provider might see no issue.

In general, confidence provided by satellite imagery and its utility scale with the amount of aggregated data and temporal, spectral, and spatial resolution of the EO system sensors. However, what sensors see from orbit is rarely conclusive information. Delays, gaps in coverage, obstruction attempts, processing errors, and technical limitations introduce new dangers of miscalculation and can upset relationships between nuclear weapons states. Blind spots and ambiguity may always remain no matter the capabilities of existing or future remote sensing systems. Satellites will never be able to track everything as sophisticated deception and denial measures are able to conceal smaller scale activity, especially at nondeclared locations or in inaccessible environments. Observed states might also decide to place illicit activity underground or employ various forms of ASAT with the intention to temporarily or permanently disable or impede operation of the passing EO systems.[47]

How useful commercial satellite imagery can become as a verification and monitoring mechanism will depend on the capabilities of EO systems, public availability of imagery, but also on skills and motivations of civilian inspectors. Proliferation of EO systems will result in a proliferation of bad analysis. Easy accessibility to data makes it possible for unverified and wrongly analyzed (and potentially fake) imagery to circulate over social media and produce a significant amount of public pressure on decision makers before there is enough time to corroborate the veracity of data or the interpretation. When making any kind of decision, imagery should never be more than one piece of the puzzle. Misrepresentation and misinformation can cause serious consequences, increase international tensions, and endanger lives.[48] Equal access to data ensures that countries, agencies, NGOs, and individuals can cross check their sources, methods, and ultimately their claims.

Within the decade, major EO providers are promising significant extensions to their existing constellations or entirely new constellations individually offering sub-hourly global revisit times with sub-meter ground resolution. Following these trends, the overall growth of the civil space industry and advancements of supporting technologies, soon we might reach the establishment of accessible real-time monitoring capabilities on a global scale. The role of decentralized commercial satellite imagery in treaty verification, crisis management, and decision making will further increase. In sync with growing demand and more data produced, advanced AI/ML are being developed that can perform object identification, analyze variations, and extract valuable insights on the fly and without human intervention. Detection of clandestine activities could be automated and direct or indirect signs of proliferation and weaponization visible to all introducing a new age of transparency on the state of nuclear facilities and weapons.

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