Emerging Satellites

for Non-Proliferation and Disarmament Verification

Yongbyon 5MWe Reactor, North Korea, 2015.

Vienna Center for Disarmament and Non-Proliferation

in Partnership with Copernicus and European Space Imaging

Visit the project website:

http://www.satellites-nonproliferation.org/

Donau-City Strasse 6 Andromeda Tower, Floor 13th 1220

Vienna, Austria

This project examined the potential utility of emerging systems of commercial Earth observation (EO) satellites to support nuclear non-proliferation, disarmament and treaty verification efforts. Capabilities in focus include emerging constellations of small satellites capturing very high-resolution (VHR) imagery and high definition (HD) video, sub-50 centimeter resolution systems, and new regional systems. The report discusses these particular development trends in the commercial EO domain, followed by an examination of how such capabilities might apply to observing nuclear fuel cycle or weapon development facilities, using facilities in the DPRK as case studies. Treaty verification requirements are primarily examined in the contexts of the Comprehensive Nuclear Test Ban Treaty (CTBT), and the Nuclear Non-Proliferation Treaty (NPT) and the International Atomic Energy Agency (IAEA). Additionally new EO capabilities are looked at in the context of UN Security Council nuclear-related sanctions implementation, the Organisation for the Prohibition of Chemical Weapons (OPCW), and nuclear arms control and disarmament efforts.

This project is made available by the Counter-Proliferation Programme of the UK Foreign and Commonwealth Office. The project was initiated as part of the Copernicus Masters Competition as the winner of the European Space Imaging (EUSI) and Skybox Imaging High-Res Challenge. Imagery is supplied courtesy of EUSI.

Vienna Center for Disarmament & Non-Proliferation (VCDNP)

James Martin Center for Nonproliferation Studies (CNS)

Research Team

Tamara Patton

Jeffrey Lewis

Melissa Hanham

Catherine Dill

Lily Vaccaro

January 2016

EO Satellite Development Trends

The commercial satellite Earth observation (EO industry) is expanding rapidly both in terms of new companies and new capabilities. This can be attributed to factors such as the relaxing of certain government regulations, more affordable technology and components and increasing demand for imagery by a diverse and growing user base. Observable trends include startups launching large constellations of small EO satellites (20 to over 100 per constellation) with medium and high resolutions, an increasing number of satellites with resolutions below 50 centimeters and the emergence of additional active sensor systems like synthetic aperture radar. The following sections give an overview of recent developments and forward trajectories in these areas.

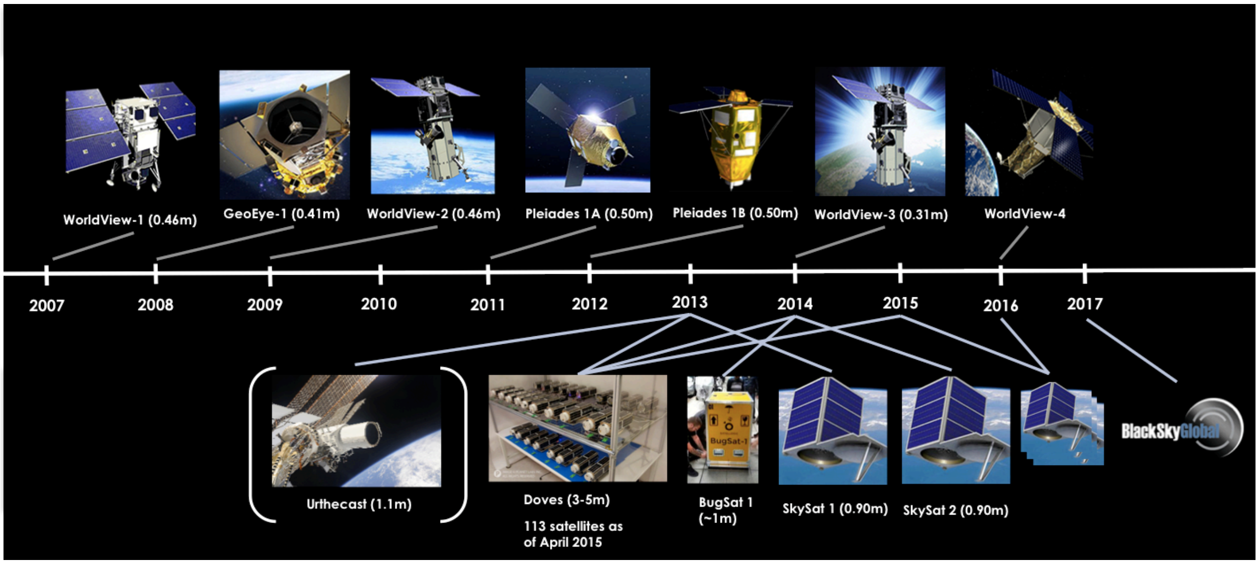
Trend 1: Small satellites | Emerging constellations of small satellites will bring several new EO capabilities to the public, including rapid revisit rates and video capture. The startup companies responsible for this development trend are taking a novel approach in using larger numbers of smaller, lower-budget satellites in order to be able to image the planet more frequently and more extensively at medium (three to five meters) and high resolutions (below two meters).

Smaller satellites using consumer electronic components are more affordable to construct and launch. Some of the tradeoffs include resolution (0.8-5 meters versus sub-0.5 meters for larger and more robust satellites) and some multispectral capabilities. The benefits of large constellations include greater global coverage, more frequent revisit rates, lower prices for imagery and taskings, and strategic redundancy lending toward more resilient overall systems.

A number of key small satellite companies have emerged in recent years. They include Skybox Imaging, Planet Labs, Satellogic, BlackSky Global and Urthecast:

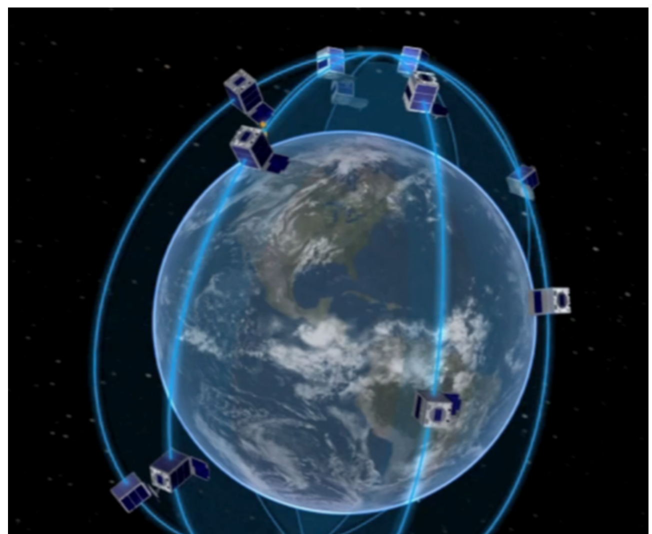
Skybox Imaging in Mountain View, California, USA aims to provide sub-meter resolution images and HD video with a developing constellation of small satellites. The company, purchased by Google in 2014, has launched two satellites as of 2015, SkySat-1 and SkySat-2, with plans to launch a significantly larger constellation with capabilities for making rapid revisits at high resolutions.[1] Google purchased Skybox Imaging in June 2014, stating "Skybox's satellites will help keep Google Maps accurate with up-to-date imagery. Over time, we also hope that Skybox's team and technology will be able to help improve Internet access and disaster relief — areas Google has long been interested in."[2]

The SkySats weigh about 100 kilograms and feature body-mounted solar panels. The optical imager covers a panchromatic band from 450 to 900 nanometers achieving a resolution of 80-90 centimeters at nadir. Four multispectral channels are covered by the satellite (Blue 450-515, Green 515-595, Red 605-695, and Near Infrared 740-900 nanometers), achieving a multispectral resolution of two meters at nadir. A ground swath of eight kilometers is covered at nadir, and the satellites support stereo imaging. SkySats acquire HD video in their panchromatic channel with durations of up to 90 seconds in which the satellites can fixate on a ground target by slewing to compensate for the movement in the orbit. Video is acquired at 30 frames per second with a resolution of 1.1 meters at nadir and a minimum field of view of 2.0 by 1.1 kilometers.



Planet Labs, based in San Francisco, California, USA and founded in 2010 by three former NASA scientists, has set the record for the largest fleet of satellites in history. To date this includes 101 satellites on 9 launch vehicles.[3] The constellation is composed of nano-satellites called Doves that operate in a sun-synchronous orbit and act as a line-scanner for the planet. The result is that new imagery is collected for the entire planet every 24 hours. Each Dove satellite has a resolution of 3-5 meters. The Flock 1 Doves have a launch mass of about 5 kilograms featuring body-mounted solar panels. Flock 1 satellites use a single-board computer to control all spacecraft and payload functions with a watchdog board able to reboot the flight computer in the event of errors or radiation related upsets. The main payload of each satellite is an optical telescope to acquire imagery, and the satellites use an X-Band system for the downlink of acquired images and systems telemetry at data rates of up to 120Mbit/s. The optical axis is down the central axis of the satellite to achieve a maximum focal length.[4]

Other companies in earlier stages of development include **Satellogic**, an Argentinian company seeking to offer "real-time coverage of


Artist's depiction of Skybox Imaging full constellation. © Skybox Imaging, Inc. All Rights Reserved.


Artist's depiction of Planet Labs full constellation. © Planet Labs. All Rights Reserved.

the living earth."[5] The company deployed two test satellites in 2013 - CubeBug1 and CubeBug2. BugSat-1 launched in June 2014 from Yasny, Russia, and will be followed shortly by a new set of prototypes, along with the first commercial services delivered from by Satellogic.[6] Another emerging company is **BlackSky Global** based out of Seattle, Washington, USA. The company plans to deploy six one meter imaging spacecraft in 2016 and a sixty-satellite constellation by 2019. The company reports that once completed it will be the largest fleet of high-resolution imaging satellites ever deployed.[7]

These new companies are also pursuing novel means of distributing the data to their users. With such large constellations capturing imagery frequently and acquiring large amounts of data, companies are turning to web and cloud based platforms. Skybox co-founder Dan Berkenstock says that customers will be able to buy images or an appliance to download information directly from the satellite. "They can log onto our satellite and ask it to take pictures," he said. For example, Japan Space Imaging signed a contract with Skybox allowing it to directly downlink imagery for agricultural and maritime monitoring as well as for disaster response.[8] Planet Labs says its global imagery will be updated and delivered via the web within hours of capture.[9] The Planet Platform Beta will enable public users to get access to the data, web-based tools and APIs. The company's current goal is to provide a "sandbox" for people to start developing and testing their apps on a stack of openly available imagery, and collecting data feedback on Planet's data, tools, and platform.[10]

***Cost considerations for small satellites* |** Emerging small satellite companies have not yet publically disclosed consumer prices for imagery, however, the expectation is that prices will generally be lower than providers using more traditional deployment models. For example, the cost of designing, building, launching and monitoring the US government's Landsat satellite is over $1 billion, according to the United States Geological Survey, which administers data from the satellite. In designing its satellites, Planet Labs discarded elements such as propulsion systems, because of the high cost and weight. Instead, the satellites use commercial light sensors, accelerometers and motors to orient their cameras. Laptop batteries were chosen over more expensive versions due to their economic price and small size.[11]

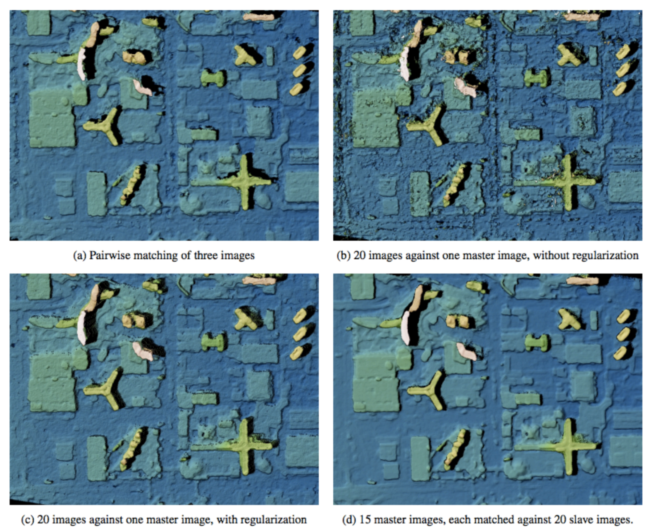
Skybox's SkySat fleet will also cost less to build and maintain given that the platform design is inspired by the CubeSat concept, or small (10 x 10 x 10 cm) satellite platforms built using a standard design based on cheap components. Skybox Imaging's platforms are somewhat bigger and heavier than the original CubeSat model, so they can accommodate enough hardware to capture images comparable in quality to existing commercial images, but efforts were made to maintain the simplicity and small size of the original concept.[12]

Another element of cost saving is the lower cost of launching small satellites. A Dnepr Rocket was launched from the Dombarovsky missile range at Yasny Launch Base, Russia on June 19, 2014 carrying a total of 37 satellites to orbit, setting a new record for most active satellites launched by a single launch vehicle. Eleven of Planet Labs' Dove satellites were aboard the rocket, as well as BugSat-1 from Satellogic. Dnepr is a Russian/Ukrainian Launch System based on the R-36M Intercontinental Ballistic Missile that is now operated by launch provider ISC Kosmotras for orbital launches.[13]

These cost-cutting factors seen in small satellite companies could offer important benefits for nuclear verification applications. Governments and international organizations with verification responsibilities deal with limited budgets with many tasking areas. As emerging systems continue to develop, the lower prices of small satellite data could allow practitioners to take greater advantage of the increasing availability of commercial Earth observation data.

Trend 2: HD Video | Improvements in lightweight and powerful video technology have enabled the deployment of cameras capturing HD video on small satellites. New systems include video cameras aboard Skybox Imaging's SkySat satellites (panchromatic, up to 1.1 meter resolution, 2 kilometer by 1.1 kilometer at nadir, and up to 90 second clips with 30 frames per second) and the Urthecast systems aboard the International Space Station (ISS). Urthecast has several systems deployed and planned. The main element is Iris, a full-color ultra HD video camera (CMOS detector) with up to one meter resolution and duration of 60 seconds with an incidence angle of less than 40 degrees. The camera's frame coverage is approximately 4.1 x 2.2 kilometers for Ultra-HD video (4096 × 2160 pixels) and 1.9 x 1.1 kilometers for HD video (1920 × 1080 pixels), with RGB spectral bands (Bayer filter), and up to 30 frames per second. Also aboard the Urthecast system is Theia, a conventional linear Charge-Coupled Device (CCD) pushbroom camera. It produces strips of medium-resolution, 4-channel multispectral imagery with a resolution of approximately five meters and a swath width of approximately 50 kilometers. Upcoming sensors include the HRC-DM dual-mode optical camera and the SAR-XL synthetic aperture radar sensor.[14] Both Skybox and Urthecast intend to allow users to directly access the satellite systems to search for and acquire available video in real or near-real time. Urthecast already presents a live stream from the ISS available here.

One possible application for HD video products from emerging commercial satellites is the generation of a Digital Surface Model (DSM) for 3D analysis of buildings and terrain. With traditional satellite imaging systems, typically only a stereo pair or triplet is available. With HD video, users receive 30 frames per second, meaning that a 60 to 90 second video clip lends 1800 to 2700 individual images. A recent study by the German Aerospace Center (DLR) tested DSM generation using Skybox Imaging video.[15] The group processed raw video data of Las Vegas and the Mirny mine sequences into DSMs, each consisting of 1800 images. They subsampled the sequence to 60 images, as adjacent frames have a very small baseline and cannot be used for matching. They note that in the future, the high redundancy could be used for additional noise reduction and super-resolution matching.



(a) Pairwise matching of three images
(b) 20 images against one master image, without regularization
(c) 20 images against one master image, with regularization
(d) 15 master images, each matched against 20 slave images.

Image Credit: D'Angelo, Kuschk, and Reinartz, DLR, Study on "Evaluation Of Skybox Video And Still Image Products," http://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XL-1/95/2014/isprsarchives-XL-1-95-2014.pdf

DLR's results showed that multiple methods can be used to generate a DSM from Skybox raw video data. These methods included: 1. Pairwise matching of three images and averaging of the resulting DSMs (a method similar to triplets acquired by other satellite sensors, such as Pleiades or WorldView-2). 2. Matching of one master image against the 20 closest images. Here the data term was computed as average of the AD-Census score of the master with respect to every slave image. To evaluate whether the higher redundancy allows the derivation of DSMs without a complex regularisation algorithm, only a simple winner takes it all approach was used. 3. Method 2, but with total variation regularization. 4. Applying method 3 to 20 master images and averaging the resulting DSMs.

The group recommended that regularization should still be used, even when multiple images are available, and data redundancy alone is not enough for good reconstruction, particularly in shadow areas. However, they concluded that compared to triplets, multi image matching increases the height accuracy, and they recommend that further research needs to be done to effectively utilize the highly redundant information, and exploit the video frame rate for image de-noising and super-resolution matching. [16]

Constructing DSMs from satellite HD video could be useful for treaty verification both at urban sites and more remote sites with varied terrain such as the Punggye-ri nuclear weapon test site in North Korea. The added dimension of height and greater precision could aid in constructing more detailed 3D models to support inspection activities and planning, and they might also assist in characterizing any unknown buildings or equipment appearing at site.

Trend 3: Higher Spatial Resolutions | The industry's established players such as Airbus and Digital Globe typically have just a few satellites in orbit at once, which means they can only photograph specific areas on a regular basis, not the whole world.[17] However, these companies still present significant advantages in terms of higher resolutions and accuracy than smaller start-ups, and can also update their images sub-daily. In 2014, the US Department of Commerce relaxed the resolution of imagery that could be sold to the public from 0.5 meters to 0.25 meters.[18]

WorldView 3, Punggye-ri Nuclear Weapon Test Site, North Korea, 9 April 2015.

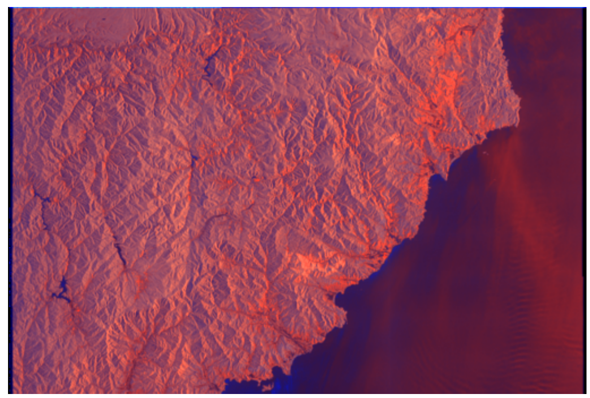
This was driven by concerns that US companies would lose their ability to compete with foreign companies operating without the resolution restriction.[19] Thus far, DigitalGlobe is the first to sell sub-0.5 meter imagery commercially with its WorldView-3 satellite offering up to 0.31 meter resolution. The company states that compared to traditional ground and aerial surveying, 0.30 meter satellite data and information is more cost-effective, saving resources and time.

DigitalGlobe, along with other international companies, are working to deploy new satellites over the coming years that meet this new limit, offering an array of opportunities for more precise imagery analysis for international organizations and governments. Sub-50 centimeter imagery can usefully complement the lower-cost, lower-resolution imagery from small satellite systems by enabling practitioners to perform more detailed analysis when needed.

Trend 4: Synthetic aperture radar |

Synthetic aperture radar (SAR) systems offer the benefit of all-weather capability due to their nature as an active sensor. To create a SAR image, pulses of radio waves are transmitted to "illuminate" a target, and the echo of each pulse is received and recorded. Given the pervasive risk of cloud cover when making time sensitive image captures, SAR can offer an additional capability and reassurance in collecting imagery. In addition, SAR data offers unique information such as the ability to collect elevation data through certain deployment and analysis methods.

A recently launched SAR satellite is Sentinel-1A, which was deployed as the first of a series of several satellites by the European Union's Copernicus programme in 2014. The satellite carries a C-SAR sensor, which offers medium and high resolution imaging in all weather conditions. Sentinel-1B is scheduled for 2016, and together Sentinel-1A and 1B will have an operational lifespan of 7 years (with consumables for 12). [20] During 2015, Sentinel-1A made regular passes over the Punggye-ri nuclear weapon test site, capturing imagery in Interferometric Wide Swath Mode at medium resolution. This includes a 250 kilometer swath, and a 5 x 20 meter spatial resolution. Higher resolution imagery is only available through the Strip Map (SM) collection mode (80 km swath, 5 x 5 m spatial resolution), Stripmap mode is used in exceptional cases only, to support emergency management actions.[21]



Sentinel 1A image of region surrounding Punggyeri (Interferometric Wide Swath Mode), June 11, 2015.

Copernicus is the long-term European Union Earth observation and monitoring programme under the former name of GMES (Global Monitoring for Environment and Security) and established by a regulation that entered into force in 2014. It is a user-driven programme under civil control, which will encompass the launch of six families of dedicated, EU-owned earth observation satellites and instruments - the Sentinels - and the ramp-up of the 6 Copernicus Services in the fields of atmosphere-, marine- and land-monitoring, climate change, emergency management and security. Copernicus data and services are available on a full, open and free-of charge basis to users, including EU institutions, Member States' authorities, the private sector for the development of commercial downstream applications and services, international partners, the global scientific community, and interested citizens.[22]

Another upcoming addition to the commercial SAR domain will be Urthecast's planned launch of a 16-satellite constellation, which will be a combination of optical and SAR imaging satellites. One of the innovative aspects of Urthecast's proposed constellation is the intention to pair an optical satellite with a radar platform for an all-weather capability. Four of these pairs would be launched in two planes - one going over the poles, the other plane concentrating its observations on mid-latitudes. The radar sensor would lead, with the optical camera following about a minute behind. Like other new small satellite companies, Urthecast's goal is to make large amounts of Earth observation imagery from multiple sensors, and place the data in a cloud-based platform available to consumers.[23]

The all-weather, day-or-night reliability of SAR systems can be particularly useful for treaty verification applications that require a time-sensitive capture, e.g. in the aftermath of a suspected nuclear test or in preparation for an on-site inspection. In addition, the elevation data could offer verification practitioners useful details regarding the height or volume of ground features or buildings.

KEY ISSUE: The need for data provenance and standards

In a treaty verification context, the ability to ensure the authenticity and validity of satellite imagery is of utmost importance. Major components of this confidence include ensuring the imagery was collected at the time and place indicated, and that it was not altered during various stages of processing from the raw data captured by the sensor to the useable imagery product handled by an analyst. Two key elements of this process include chain of custody and the use of international data standards.

Several issues arise in establishing and maintaining a chain of custody of satellite EO data. The first is a digital signature, which could be a system such as the Public Key Infrastructure (PKI) encryption system. The image would contain a time stamp and this unique digital signature. It is important to sign raw data as close to the point of collection as possible. Ideally the company would "sign" the data at the point of capture at the satellite sensor, or as soon as possible at a receiving ground station, though this is less desirable as there is more room for uncertainty. A second chain of custody issue involves being able to track the various stages of processing that an image undergoes in being transformed from raw collection data to various display formats utilized by analysts. This process would benefit from satellite companies being able to share calibration files and documentation on the processing algorithms applied to the data. While this tracing process may not need to happen in every instance of imagery use by an international organization, the ability to re-trace all of the processing steps applied to the original raw data capture should be readily available if needed.

International standards are a beneficial element of the satellite EO data provenance process. In general, this includes the ISO 19 series. Benefits of using the ISO 19 series include ease of checking and backtracking steps for verification and validation procedures, making data easier to debug, and helping prevent a company from having to reveal proprietary information or methods. For example, ISO 19130 presents imagery sensor models for geo-positioning, where the model is applied to sensor data to convert it to a mapped imagery product. When backtracking or retracing, an international organization or government could simply reference 19130 model rather than having to deal with custom company procedures. A company may not use the extensive body of ISO 19 standardization exactly, but may use a combination of elements from the larger series. As long as the company makes these details public, and the process can be retraced, then a chain of custody can still be verified if needed. Another more nuanced issue in the retracing process is making sure sensitivity in dynamic range is documented and algorithms applied to the data are appropriate to the actual sensitivity of the sensor, as some algorithms don't have utility below a specific dynamic range. Put simply, if an analyst filters noise, they will get noise.

One issue that arises in the case of newer startup EO companies is the use of the JSON metadata schema versus the more traditional XML. ISO standards are currently only available for XML. However, some emerging companies prefer JSON because the characteristics that make XML suitable for data interchange may be stronger in JSON. JSON also has the ability to represent most general computer science data structures (records, lists and trees) directly, whereas XML must use transformations. JSON's similarity to conventional programming language structures also eliminates the need for restructuring, and the language is thought to be more flexible in some cases.[24] Nevertheless, although ISO standards and XML may be more convenient for verification needs given the greater availability of precision models, even if a company uses another metadata format such as JSON, the retracing process will still be possible as long as the standard is public and defined.

In brief, in order to maintain the ability to trust in data collected by commercial satellites, both current and emerging companies could aim to sign the data at the sensor source and have a mechanism to document and reproduce the processing stream (data, algorithms and parameters) used in processing the product. Making details of their chosen data standardization method public and well defined would also benefit the process. In a verification context, while retracing the chain of custody may not be necessary in every use case, it is important that the ability to do so if needed is available.

Emerging EO Systems & Possible Nuclear Verification Support Applications

Small satellite systems and other emerging EO capabilities have significant potential for supporting verification under international treaties relevant to nuclear non-proliferation, arms control and disarmament. The following sections draw from the project website (http://www.satellites-nonproliferation.org/), where imagery from Skybox Imaging and DigitalGlobe has been made available for input by experts from NGOs, academia, governments and international organizations.

Comprehensive Nuclear Test Ban Treaty (CTBT)

Small satellites could possibly support Comprehensive Test Ban Treaty (CTBT) verification through providing high-temporal VHR satellite data that is accessible to all member states, as well as agile and relatively affordable remote sensing support to other OSI technologies and procedures. The trend of increasing resolutions for large commercial satellites can be usefully complemented by the rapid emergence of agile small satellite systems with more frequent and affordable imagery. Larger numbers of satellites allow for greater global coverage, a dense historical archive, more frequent revisit rates and affordable tasking.

Possible benefits for CTBT verification include:

1. Ability to fill the **imagery data gap** existing **before and soon after** an explosive event with high temporal commercial satellite imagery archives accessible to all parties
2. Their more **agile and affordable** nature allows for greater feasibility for taskings in direct correlation with airborne MSIR and other advanced satellite systems (e.g. VHR, 8 band systems, or SAR systems)
3. More accurate **change detection analysis** or **object based classification** resulting from using the same sensor type across all images
4. As small satellite technology continues to develop, a **dedicated CTBTO constellation of satellites** could be within economic and technical reach, allowing even greater accessibility of data to member states
5. Potentially important **deterrent for nuclear proliferation** or cheating on arms control commitments due the new existence of detailed daily imagery records

From project website | Punggye-ri Nuclear Weapon Test Site Case Study

To examine aspects of the applicability of emerging satellite systems to CTBT verification needs, North Korea's Punggye-ri nuclear weapon test site was observed over the course of 2015 using Skybox imagery and DigitalGlobe imagery.

Background | Three explosive underground nuclear tests have been detected at Punggye-ri, each occurring in October 2006, May 2009 and February 2013. The site remains active, with construction and maintenance activities evident throughout 2015, including the construction of a possible new testing tunnel. Punggye-ri is seen as an important puzzle piece for understanding the nature and intent of Pyongyang's weapon development plans. Testing activities have the potential to evolve from being politically-aimed one-off events toward being conducted routinely as part of a more rigorous technical development process aimed at creating a deployable nuclear arsenal.[1]

Site Layout | The site currently consists of three active portal entrances, known as the North portal (formerly the West portal), the South portal, and a new tunnel developed in 2015, now known as the (new) West Portal. All three tunnels lead to testing chambers within the mountains. An additional East portal, believed to be the entrance area of the 2006 nuclear test, no longer appears active. The site is supported by a central support area located between the two portals, consisting of administrative and control buildings, garages and storage areas, and a sawmill.

Satellite imagery observation | In the aftermath of the DPRK's threats of a fourth test early last year, there was a significant level of activity at the site in 2014. At the North portal, a new solid roof structure was erected in May 2014 at the site of a similar structure that was demolished in 2013. Part of the adjacent

Punggye-ri Nuclear Weapon Test Site, North Korea, 11 July 2015.

building closest to the suspected tunnel entrance was also removed as of May 2014. [2] Excavation activities continued, evidenced by the changing large spoil pile and soil scarring at the North portal. Excavation activities appear to have ceased in late 2014. At the South portal, during April and May 2014, numerous vehicles (possibly large white trucks and smaller black vehicles), containers and equipment were identified.[3]

Construction activities have continued through 2015:

(New) West portal

Satellite imagery from as early as March 2015 shows signs of construction of an additional testing tunnel directed westward from the complex. Cloud cover during the summer months prevented observation via optical imagery during this time, inhibiting identification of the tunnel until later in 2015. Developing SAR systems should help mitigate this challenge in the future. Optical imagery from November 2015 shows continued growth of the spoil pile.

North portal

From March 2015 imagery, independent analysts identified log piles near the North and West portal entrances, which could possibly be used as support frames for the tunnels.[4] These log piles are visible in Skybox imagery from 20 March, 14 April, and 22 May. In a Skybox image from 22 July, the log piles are no longer present. If no further logging activity is observed at the North and West portals in coming months, this could possibly indicate that the tunnels are nearing stages of completion.

Excavation activities at the North portal do not seem to have resumed in 2015, with no sign of changes to the large spoil pile. Some experts have noted that a cease in excavation could also indicate the tunnel is nearing completion.[5]

South portal

Vehicle tracks through February and March 2015 indicate some, albeit low, levels of activity at the South portal during these months. A log pile is also visible near the South portal, as early as March 2015 (it could have been present in winter months but obscured by snow cover). The log pile is still visible in Skybox imagery from July 11. In imagery from 29 September, the pile is no longer present, suggesting that work on reinforcing the tunnel may be winding down.

Central support area

Construction on a new building in the central support area began in April 2015. The building is located near the sawmill at the North end of the central support area. From March to April 2015, imagery shows increased activity at the two saw mills at the North and South ends of the central support area. On May 22, several vehicles and piles of cut lumber are visible near the sawmills. Independent analysts speculated that this cut lumber could be used for construction activity at the central support area, as well as for producing logs for use in the tunnels.

New EO Capabilities | Rapid Revisits and HD Video | In the case of nuclear testing, imagery and video from small satellites could provide support across the areas of test site detection, test preparation analysis and post-test analysis. With imagery and video ranging from 0.8 to 1.1 meters, features such as spoil piles, logging trails, vehicle activity and construction activity at significant levels can be readily observed. Challenges with 0.8 to 1.1 meters resolutions emerge with identifying certain smaller pieces of equipment, vehicle types, identifying objects located in a shadow and detecting camouflage efforts such as tarps or netting.


New spoil pile and tunnel entrance. Punggye-ri Nuclear Weapon Test Site, North Korea, 29 September 2015.

The benefits of small satellite constellations could be effectively leveraged in cooperation with higher resolution commercial satellites at 0.3 to 0.5 meter levels. As the small satellite constellations discussed in this project continue to develop, increasingly large historical archives will become available as a resource in the event of a detected explosive event by the CTBT's International Monitoring System (IMS). The roughly one meter resolution imagery from these constellations will be capable of recording increased activity indicative of test preparations, and higher resolution imagery (0.3 to 0.5 meters) could then be used at strategic points in time to identify and characterize possible nuclear testing signatures and equipment.

New EO capabilities: Summary |

Multi-sensor synergy applications:

- 0.8 meter imagery is capable of detecting changes at a nuclear test site involving spoil piles, logging trails, vehicle activity and construction activity at significant levels. 0.3 meter imagery can be cued at higher activity points to further characterize the nature of activities and equipment leading up to a nuclear test or in its aftermath.

Possible benefits of high revisit rates:

- Establishing more detailed chronologies of activities leading up to a suspected nuclear test and providing a greater basis of assessment
- Characterizing increased vehicle activity that could indicate significant new construction or preparations for a nuclear test
- Capturing the placement of cables or other key equipment involved in conducting and measuring a nuclear test

Possible benefits of HD video:

- During high activity periods, HD video could help in better understanding activities based on movement patterns, since resolution constraints of both imagery and video can sometimes inhibit object identification (e.g. vehicles versus large containers or equipment)

Possible constraints of emerging EO capabilities:

- Resolution (0.8 to 1.1 meters) may pose challenges for discerning vehicle types and nuclear test supporting equipment
- Detecting a change in activity levels at a test site still requires frequent imagery collection, which will only be possible and economic with a more expansive deployment of small satellite systems

---

***[1]** Jeffrey Lewis, "The Tunnels at Punggye-ri: An Alternative View," 38 North, 20 March 2014,http://38north.org/2014/03/jlewis032014/ **[2]** Jack Liu and Nick Hansen, "Update on Punggye-ri: Stepped Up Activity at West Portal, Drawdown at the South Portal," 38North, 2 May 2014,http://38north.org/2014/05/punggye050214/figure2-punggye-050214/ **[3]** David Albright, Serena Kelleher-Vergantini, and Priscilla Kim, "On-going Activity at North Korea's Punggye-ri Test Site," Institute for Science and International Security, 9 May 2014, http://isis-online.org/isis-reports/detail/on-going-activity-at-north-koreas-punggye-ri-test-site/10#images **[4]** Jack Liu, "North Korea's Punggye-ri Nuclear Test Site: Spring Construction and Maintenance Activities Continue," 38 North, 5 June 2015, http://38north.org/2015/06/punggye060415/ **[5]** Jack Liu and Nick Hansen, "North Korea's Nuclear and Rocket Test Sites: Limited Activity, No Tests Likely in the Near Future, " 38 North, 10 March 2015,http://38north.org/2015/03/sohaepunggye031015/*

NPT and the IAEA

The IAEA already makes use of satellite imagery to support its verification work and stands to benefit from the increasing diversity and decreasing costs of commercial imagery and video products. The agile nature of emerging small satellite systems and their ability to rapidly image sites of interest at lower costs presents unique potential for both identifying and analyzing non-proliferation relevant developments. This includes the ability to access a dense historical archive of "before and after" imagery of a facility or occurrence.

Example areas of utility include the detection and identification of undeclared nuclear facilities. In historical cases such as Iran's Natanz centrifuge facility or Syria's Al Kibar nuclear reactor, access to a historical imagery archive detailing construction might have enabled more efficient and conclusive identification of the sites once identified. While the IAEA does not have the ability to purchase imagery to conduct wide area searches, the readiness and lower costs of imagery from small satellites might have enabled other governments to detect the illicit sites sooner. For identified sites of concern, such as the Parchin complex in Iran, the rapid revisit rates and HD video capabilities of small satellite constellations could yield additional insight in making determinations about the nuclear or non-nuclear nature of a site.

From project website | Yongbyon Enrichment Facility Case Study

To examine aspects of the applicability of emerging satellite systems to IAEA verification needs, North Korea's Yongbyon enrichment facility was observed over the course of 2015 using Skybox imagery and DigitalGlobe imagery.

Background | North Korea has been steadily developing its gas centrifuge uranium enrichment infrastructure in recent years. While the stated purpose of the facility is enriching uranium for nuclear energy, concerns remain that the product could be used in the country's nuclear weapon program. In 2009, the government announced publicly that it was building an enrichment facility, and a metal fuel rod fabrication building in Yongbyon was shut down for conversion into the new site.[1] In 2010, Dr. Siegfried Hecker and two other American experts toured the inside of the building with North Korean escorts, who reported that the facility contained 2,000 centrifuges in six cascades with 8000 kg SWU/year. Hecker reported that the centrifuges are likely P-2 designs.[2] From 2013, the hall housing the centrifuges and other infrastructure has been further expanded, as detailed in the following sections.

Layout | The main feature at the site is a rectangular hall (approximately 120 meters long) with a blue-roofed section, which is where gas centrifuge enrichment takes place.[3] Additional activities reportedly taking place within the greater perimeter at the site include uranium trioxide to uranium dioxide conversion, uranium dioxide to uranium tetrafluoride to uranium metal conversion, and hydrogen fluoride production, with electricity needs for the entire site possibly supported by a steam plant in the south east corner of the site.[4]

Satellite imagery observation |

Enrichment hall **|** Beginning in March 2013, satellite imagery showed that the enrichment facility was expanding (corroborated by statements made by the North Korean government), possibly to provide more space for additional centrifuges.[5] The extension was positioned directly adjacent to the portion of the facility known to house the centrifuge

Yongbyon Uranium Enrichment Facility, North Korea, 12 October 2015.

cascades. An image from June 2013 shows the foundation structure of the building, which appears to include two smaller sections on each side of a long hall. The roof was then added to the structure, shown in place by an image from October 2013. See the August 2013 report from ISIS for imagery and analysis of the extension process.

As part of the extension construction, an additional three-fan mechanical draft cooling tower was added near the building in 2013. Given that the operation of centrifuge cascades requires industrial cooling infrastructure in part to solidify UF6 after it is enriched in a gaseous form, this new cooling tower addition supports the notion that the new hall may be used to support additional cascades. As of January 2015, both Skybox and DigitalGlobe imagery show that the new three-fan unit has been removed, and the original three-fan unit that existed prior to the facility extension has been expanded to a six-fan unit. No steam is visible throughout the 2015 imagery collections from both Skybox and DigitalGlobe.

Throughout 2015, a steady stream of vehicles and containers are visible near the west end of the enrichment building, visible in both Skybox and DigitalGlobe imagery. For example, vehicles are visible at this location in an 80cm Skybox image from 21 May 2015. A few days later, a 30cm WorldView image captured on 24 May seems to clarify the activity, showing a large truck and smaller white containers. It is not clear whether these containers contain UF6 cylinders.

New construction area **|** Beginning around March 2015, the construction of a new building began in the south east area of the complex, near what is thought to be a steam plant supporting the electrical needs of the complex. Skybox imagery from March 2015 shows soil preparation activities taking place, and subsequent imagery from April shows the foundation being laid. By May, the floor plan of the building was solidified, showing five square cells in the southern half of the building. 38 North reported from DigitalGlobe imagery in May 2015 that the DPRK may be constructing hot cells at the site for remote handling of radioactive nuclear material for either civilian or military purposes. From imagery collected on July 2 the group further speculated that these cells may instead be used to assemble or store conventional high explosive components, possibly for nuclear weapon purposes.[6] By July, Skybox imagery showed the roof was added to the building.

New EO capabilities: Summary |

Multi-sensor synergy applications:

- 0.8 meter Skybox imagery can detect vehicle presence at key points in the site. 0.3 meter imagery could be cued to capture activities supporting enrichment identification such as UF6 cylinder offloading or pickup, though this relies on being able to view uncontained cylinders.
- The 0.8 meter resolution of Skybox imagery is enough to detect the early stages of new construction (e.g. soil preparation for laying a new foundation). It is also sufficient to monitor construction progress, including the delineation of floor plans and cooling systems. 0.3 meter imagery could be cued to examine key elements of a structure as they become visible (e.g. construction of cells in new building at Yongbyon)

Possible benefits of high revisit rates:

- Possibly identify patterns for delivery and pickup of UF6 cylinders and supporting vehicles to understand enrichment pace

- Clarifying reasons for new construction (e.g. enrichment facility extension or new building construction in southeast of complex)

Possible benefits of HD video:

- Better understanding the directional flow of activities at the site for identifying building functions
- When combined with high revisit imagery, video capture could possibly be timed to capture UF6 cylinder delivery and pickup

Possible constraints of emerging EO capabilities:

- A resolution of 0.8 meters may not be enough for discerning vehicle types or distinguishing the presence of UF6 cylinders, depending on containers for delivery or pickup
- Analyzing patterns related to UF6 enrichment would require daily or sub-daily captures for success. This will only be possible and economic with a more expansive deployment small satellite systems

---

__[1]__ Siegfried S. Hecker, "Return Trip to North Korea's Yongbyon Nuclear Complex," Center for International Security and Cooperation, Stanford University, November 20, 2010, 4; Siegfried Hecker, "What I found in Yongbyon and Why it Matters," APS Physics, The Back Page. __[2]__ Siegfried S. Hecker, "Return Trip to North Korea's Yongbyon Nuclear Complex," 5. __[3]__ Ibid. __[4]__ IHS Jane's Satellite Imagery Analysis, Site Analysis: Yongbyon Nuclear Scientific Research Centre, 25 April 2014 __[5]__ David Albright and Serena Kelleher-Vergantini, "Increased Activity at the Yongbyon Nuclear Site," ISIS Reports, December 5, 2013, http://isis-online.org/isis-reports/detail/increased-activity-at-the-yongbyon-nuclear-site/10. __[6]__ 38 North, "Update on North Korea's Yongbyon Nuclear Facility," 17 June 2015,http://38north.org/2015/06/yongbyon061715/ ; 38 North, "North Korea's Yongbyon Nuclear Facility: Sporadic Operations at the 5 MWe Reactor but Construction Elsewhere Moves Forward," 24 July 2015;http://38north.org/2015/07/yongbyon072415/

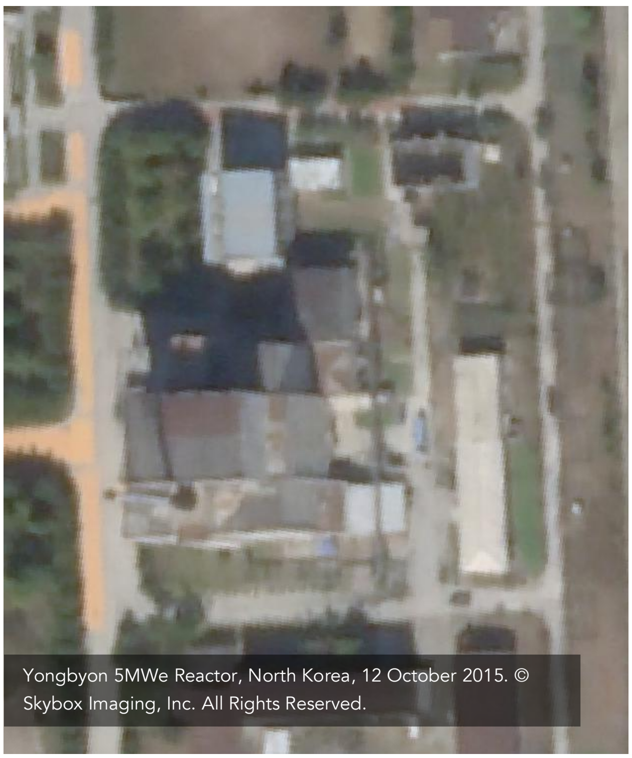
From project website | Yongbyon 5MWe Reactor and LWR case study

To examine aspects of the applicability of emerging satellite systems to IAEA verification needs, North Korea's Yongbyon 5MWe reactor and Light Water Reactor (LWR) complex was observed over the course of 2015 using Skybox imagery and DigitalGlobe imagery.

Background | This section focuses on two nuclear reactors at the Yongbyon complex: the 5MWe reactor and an experimental 25-30MWe light water reactor (LWR). The 5MWe reactor is graphite-moderated and gas cooled with a thermal power range of 20-25MW. Modeled after the U.K.'s Calder Hall reactor, the reactor was operational by 1986.[1] Given the design's suitability for weapon grade plutonium production, a military-purpose for the facility has long been suspected. The reactor has undergone numerous periods of operation and shutdown in line with stated North Korean weapon development objectives and international pressure to halt these efforts. In 2007, as a result of the Six Party Talks, the reactor was once again shut down and the large natural draft cooling tower was dismantled a year later. The site of the water-cooling tower would later occupy the LWR, a reactor described by North Korea as a prototype reactor for future civilian electricity production ambitions.[2]

Site Layout | To the north sits the 5MWe reactor and slightly south is the LWR. Currently both reactors are cooled by water from the river to the east of the complex. Notable supporting structures include turbine generator buildings adjacent to each reactor, a possible spent fuel rod building, and pump houses supporting the river intake cooling systems.

Satellite imagery observation | In April 2013, North Korea announced it will restart the Yongbyon 5MWe Reactor for plutonium production as part of a nationwide restart of all its nuclear facilities.[3] Commercial satellite imagery of the site from late March 2013 showed signs of work on connecting the reactor's secondary cooling system to the pump house likely associated with the LWR.[4] By September 2013, satellite imagery indicated



Yongbyon 5MWe Reactor, North Korea, 12 October 2015. © Skybox Imaging, Inc. All Rights Reserved.

that North Korea restarted the 5 MWe reactor, evidenced by snowmelt and hot water discharge at the sight of a recently constructed drainage pipe leading from the reactor to the river [5]. Construction of the LWR likely began in 2010, and by November 2011, the majority of the external construction was complete.[6] By May 2013, experts believed it would be operational by mid-June, provided fuel was available.[7]

In imagery throughout 2015, commercial satellite imagery shows ongoing activity at the site. A DigitalGlobe WorldView 3 image from January 2015 shows snowmelt on the river indicative of hot water discharge from the cooling system. These same discharge points remain visible in Skybox imagery from February and March 2015, possibly indicating continued operation during this period. Nevertheless, without thermal imagery, it remains difficult to assess the operation of the reactors through observation of the cooling system throughout 2015. At the 5MWe reactor, activity involving vehicle traffic is visible throughout 2015 in all imagery sources near the east entrance to the main reactor building. Vehicle presence is visible in Skybox imagery, and WorldView 3 images further clarify the presence of large trucks, containers and construction equipment. 38North reported in August 2015 that imagery indicated a high level of vehicle activity not previously observed in front of the 5 MWe reactor hall. In an August 22 image, the group observed vehicle tracks that extend into the ground level of the building beneath an overhanging four-story annex on the east end of the reactor hall out to a road, including the presence of a large truck.[8]

New construction is visible from as early as January 2015 near the LWR on what appears to be an electrical substation. From as early as April 2015, Skybox imagery showed the introduction of a large unit to the substation site, identified by 38North as a possible transformer.[9] While the nature of the construction could not immediately be determined from Skybox imagery, the construction activity involving laying the foundation is clearly visible. WorldView 3 imagery was then able to clarify the electrical nature of the new addition.

New EO capabilities: Summary | *Multi-sensor synergy applications:*

- 0.8 meter Skybox imagery useful for detecting new construction activity (e.g. electrical substation at ELWR)

- 0.3 meter DigitalGlobe imagery useful for identifying nature of construction (e.g. possible transformer unit at ELWR)

Possible benefits of high revisit rates:

- Detect periods of high level activity related to reactor maintenance or possible fuel unloading, at which point analysts could cue the collection of 0.3 meter imagery or HD video

Possible benefits of HD video:

- When combined with high revisit imagery, video capture could possibly be timed to capture fuel unloading
- Depending on depth of cooling water discharge, water disturbances may be more easily visible in video than in imagery

Possible constraints of emerging EO capabilities:

- Resolution (0.8 to 1.1 meters) may pose challenges for discerning vehicle types and supporting equipment
- Detecting changes related to reactor maintenance or fuel unloading would require daily or sub-daily captures for success. This will only be possible and economic with a more expansive deployment small satellite systems

---

[1] *International Atomic Energy Agency, "IAEA and DPRK: Fact Sheet on DPRK Nuclear Safeguards," www.iaea.org.* ***[2]*** *Siegfried S. Hecker, "Return Trip to North Korea's Yongbyon Nuclear Complex," 20 November 2010, http://iis-db.stanford.edu/pubs/23035/HeckerYongbyon.pdf* ***[3]*** *"DPRK to Adjust Uses of Existing Nuclear Facilities," KCNA, 2 April 2013, www.kcna.co.jp.* ***[4]*** *Nick Hansen and Jeffrey Lewis, "Satellite Images Show New Construction at North Korea's Plutonium Production Reactor; Rapid Restart?" 38 North, 3 April 2013, www.38north.org.* ***[5]*** *Nick Hansen and Jeffrey Lewis, "North Korea Restarting Its 5 MW Reactor," 38 North, 11 September 2013, www.38north.org; Nick Hansen, "More Evidence That North Korea Has Restarted Its 5 MWe Reactor," 38 North, 2 October 2013, www.38north.org.* ***[6]*** *Niko Milonopoulos, Siegfried S. Hecker, Robert Carlin, "North Korea from 30,000 feet," Bulletin of the Atomic Scientists, opinion, January 6, 2012, http://thebulletin.org/north-korea-30000-feet.* ***[7]*** *Jeffrey Lewis and Nick Hansen, "Start-up of North Korean Experimental Light Water Reactor Could Begin by Mid-2013 if Fuel is Available," 38 North, May 1, 2013, http://38north.org/2013/05/yongbyon050113/.* ***[8]*** *"North Korea's Yongbyon Nuclear Facility: Sporadic Operations at the 5 MWe Reactor but Construction Elsewhere Moves Forward," 38North, 8 September 2015, http://38north.org/2015/07/yongbyon072415/* ***[9]*** *Ibid.*

Other verification support applications

UNSC Sanctions Implementation | Emerging Earth observation systems may also offer benefits for sanctions implementation and monitoring objectives by the UN Security Council. In order to make determinations about whether sanctions are having the desired effect or to detect signs of evasion, the UNSC's Panels of Experts for various regimes may have the option to observe relevant sites via commercial satellite imagery. For example, the DPRK Panel of Experts regularly references satellite imagery in its reporting to observe the presence or absence of progress in the DPRK's efforts to enlarge and enhance its nuclear weapon arsenal.

In this context, small satellites could be especially useful for time sensitive captures, such as imagery surrounding an event such as a missile launch or a military parade. The greater flexibility and affordability of time-specific taskings offered by small satellite providers could enable the Panel to gather necessary information to make its determinations.

Organisation for the Prohibition of Chemical Weapons | Emerging EO systems could benefit the verification efforts of the Organisation for the Prohibition of Chemical Weapons (OPCW) in several ways. As most recently observed in the case of Syria, the OPCW bears the responsibility of ensuring the decommissioning of chemical weapon facilities in the country. The greater affordability of time-specific taskings could offer useful support to OPCW on-site inspection efforts in the contexts of planning, implementation and follow-up. For example, guidelines for the closure or inactivation of chemical weapon production facilities include the interruption of rail, road and other access routes for heavy transport to the facility except those required for agreed activities, as well as the prohibition of the occupation of specialized buildings and standard buildings of the facility except for agreed activities. More affordable imagery from emerging small satellite providers could support inspection efforts in verifying these measures, and in some cases could allow inspectors to be less intrusive or conserve resources. In addition, as the wide area coverage capabilities of small satellite constellations develop, governments and international organisations might use these additional resources to help ensure the completeness of chemical weapon declarations. While chemical weapon production facilities can be difficult to detect via satellite imagery alone, a more diverse and affordable commercial EO data resource base could support the investigation of other indicators and information sources.

Conclusions and Recommendations

The study has identified opportunities, obstacles and future considerations for the application and implementation of emerging types of commercial EO satellite data for various treaty verification domains.

1. **Data provenance**: As numerous startup companies enter an industry long dominated by a few large companies, they are occasionally adopting non-traditional approaches to imagery and metadata formatting and distribution, including distribution of imagery via web platforms and the cloud, and the use of JSON formats rather than XML and ISO standards. To ensure data provenance and reliability of imagery for verification purposes, extra measures such as digital signatures, as well as the ability to retrace all processing steps that an image undergoes from the satellite to those used by analyst would be useful. Emerging satellite companies could be prepared to share calibration files and documentation on the processing algorithms applied to the data to support international organizations in using their data.

2. **Treaty verification support:** Emerging commercial satellite EO capabilities have the potential to support existing verification mechanisms under nuclear agreements, while also offering new capabilities that might strengthen verification regimes in the future. In the case of the CTBT, small satellites offering agile and more affordable imagery might usefully support existing IMS technologies and on-site inspection mechanisms, including airborne MSIR

capabilities. Beyond this, historical archives of global small satellite data could assist in identifying whether or not an explosive event is nuclear in nature by providing high-temporal imagery of a site before the event was detected by the IMS. In the case of the IAEA, rapid revisit imagery and HD video could give member states a minimally intrusive means to decipher the nature of a site suspected of being an undeclared nuclear facility. Higher temporal resolutions give a greater chance of capturing activity that could indicate potential non-compliance, such as the presence of certain equipment, UF6 cylinder deliver, or fuel unloading. For both the CTBTO and IAEA, imagery from small satellites could serve as a useful complement to advancing higher resolution systems, which due to high costs, must be purchased more sparingly and for specific uses. HD video, in addition to motion capture, could support the generation of more accurate 3D models for site characterization or inspection planning.

3. **Continued engagement:** Small satellite companies such as Skybox Imaging, Planet Labs, Urthecast, Satellogic and BlackSky Global are in the early stages of development, and may yet be joined by new actors in this expanding sector. This is a valuable time to engage such companies on needs in the field of verification, both in terms of desired capabilities and the restrictions of the operational environment. Many of these companies are actively seeking feedback from current and potential future users of their data, and are now in a best position to adapt to expressed needs.

---

[1] "European Space Imaging partners with Skybox Imaging to offer new Challenge for the Copernicus Masters", 3 April 2014, http://www.euspaceimaging.com/category-news/item/european-space-imaging-partners-with-skybox-imaging-to-offer-new-challenge-for-the-copernicus-masters
[2] "Google and Skybox Imaging Sign Acquisition Agreement," 10 June 2014, http://investor.google.com/releases/2014/0609.html.
[3] Planet Labs Press, https://www.planet.com/press/, Accessed 24 October 2015.
[4] "Dnepr Rocket successfully Launches Cluster of 37 Satellites," 19 June 2014, http://www.spaceflight101.net/dnepr-launch-updates---2014-cluster-launch.html, Accessed 24 October 2015.
[5] Satellogic – Home, http://www.satellogic.com/#!home/c1sf0, Accessed December 10, 2015.
[6] Satellogic – Our Technology, http://www.satellogic.com/#!technology/c1w2a, Accessed 24 October 2015.
[7] BlackSky Global, http://www.blacksky.com/, Accessed 24 October 2015.
[8] "Microsatellites: What Big Eyes They Have," New York Times, 10 August 2013, http://www.nytimes.com/2013/08/11/business/microsatellites-what-big-eyes-they-have.html
[9] Planet Labs Press, https://www.planet.com/press/, Accessed 24 October 2015.
[10] "Planet Platform Beta & Open California: Our Data, Your Creativity," Planet Labs Pulse, https://www.planet.com/pulse/planet-platform-beta-open-california-our-data-your-creativity/, Accessed 15 October 2015.
[11] "Startups aim to conquer space market," New York Times, 17 March 2014, http://www.nytimes.com/2014/03/17/technology/start-ups-aim-to-conquer-space-market.html
[12] "Inside a Startup's Plan to Turn a Swarm of DIY Satellites Into an All-Seeing Eye," Wired, June 18, 2013, http://www.wired.com/2013/06/startup-skybox/
[13] "Dnepr Rocket successfully Launches Cluster of 37 Satellites," 19 June 2014, http://www.spaceflight101.net/dnepr-launch-updates---2014-cluster-launch.html, Accessed 24 October 2015.
[14] Urthecast, https://www.urthecast.com/enterprise/cameras, Accessed 24 October 2015.
[15] Pablo d'Angelo, Georg Kuschk, Peter Reinartz, "Evaluation of Skybox Video and Still Imaging Products," German Aerospace Center (DLR), Remote Sensing Technology Institute D-82234 Wessling, Germany; Publish in The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-1, 2014, ISPRS Technical Commission I Symposium, 17 – 20 November 2014, Denver, Colorado, USA, http://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XL-1/95/2014/isprsarchives-XL-1-95-2014.pdf
[16] Pablo d'Angelo, Georg Kuschk, Peter Reinartz, "Evaluation of Skybox Video and Still Imaging Products," German Aerospace Center (DLR), Remote Sensing

Technology Institute D-82234 Wessling, Germany; Publish in The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-1, 2014, ISPRS Technical Commission I Symposium, 17 – 20 November 2014, Denver, Colorado, USA, http://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XL-1/95/2014/isprsarchives-XL-1-95-2014.pdf

[17] Tim Bradshaw, "Planet Labs aims for new frontier of image data," Financial Times, 14 March 2014. http://www.ft.com/intl/cms/s/0/1eb31e04-ab17-11e3-83a2-00144feab7de.html#axzz36IwqXeVu

[18] "U.S. Department of Commerce Relaxes Resolution Restrictions DigitalGlobe Extends Lead in Image Quality," Market Watch, 11 June 2014, http://www.marketwatch.com/story/us-department-of-commerce-relaxes-resolution-restrictions-digitalglobe-extends-lead-in-image-quality-2014-06-11 Accessed 24 October 2015.

[19] "U.S. agencies back DigitalGlobe bid to sell sharper images," Reuters, 21 April 2014, http://www.reuters.com/article/2014/04/21/us-digitalglobe-satellite-idUSBREA3E1L820140421, Accessed 24 October 2015.

[20] European Space Imaging, "Sentinel 1A," https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/sentinel-1, Accessed 29 November 2015

[21] European Space Agency, Sentinel Online, Stripmap mode, Accessed November 30, 2015, https://sentinel.esa.int/web/sentinel/user-guides/sentinel-1-sar/acquisition-modes/stripmap

[22] European Space Imaging, "Copernicus, Observing the Earth," http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Overview4, Accessed 29 November 2015

[23] Urthecast Blog "UrtheCast Announces World's First Commercial SAR and Optical 16-satellite Constellation," https://blog.urthecast.com/updates/urthecast-announces-worlds-first-commercial-sar-and-optical-16-satellite-constellation/, Accessed 29 November 2015

[24] "JSON: The Fat-Free Alternative to XML," Presented at XML 2006 in Boston, December 6 by Douglas Crockford, http://www.json.org/fatfree.html, Accessed 24 October 2015.