

Online supplement

Capabilities of commercial satellite Earth observation systems and applications for nuclear verification and monitoring: overview of on-orbit and upcoming commercial Earth observation systems

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1 Introduction

This supplement provides additional information on operational Earth observation (EO) systems and constellations presented in the main paper. To be included, sensors in these systems needed to have a resolution better than 5-m in any band, and their data was publicly accessible. In addition, notable planned EO systems are included if their operators promised public access to imagery and they are well funded, or are already operating high-resolution observation satellites or demonstrators.

All satellites presented are in low Earth orbit (LEO), while a large majority are in sun-synchronous orbits where the angle of the orbital plane is at a constant angle with respect to the Sun. This means satellites will always pass over a location on the Earth's surface at approximately the same solar time of the day. Operators prefer this orbit as it provides a coverage of the entire planet in approximately equal conditions (for example shadows from ground objects are the same) which simplifies image comparison.

Not included in this overview are commercial systems offering radio frequency detection from space, such as those operated by the U.S. company HawkEye360. Their sensors

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can map ground emissions of a wide range of radio frequencies, including those of radar systems. The provider currently has three satellites in orbit, but is planning a 30-satellite constellation with launches starting in 2021.

A notable trend observed, initially introduced by Planet, is that operators are moving away from massive and costly satellites, instead launching proliferated constellations of cheaper and lighter systems built with commercial off-the-shelf technology (COTS) that is easy to maintain and replace. For example, Planet operates more than 300 PlanetScope satellites that are the size of a shoebox, use a camera not too dissimilar from a phone camera and cover the entire Earth's land surface each day with a ground resolution of about 3.7-m. Smaller satellites might have a shorter lifespan and are individually less capable at time of launch, but this approach allows for more frequent and cost-effective satellite replacements. In addition, a larger number of systems in orbit results in a greater persistency of coverage. To illustrate this trend, the U.S. Geological Survey (USGS) has used Union of Concerned Scientists (UCS) data to generate a plot showing launch mass as a function of time¹.

2 Overview of providers and systems

The system descriptions below are grouped by provider location and presented in alphabetical order. Data is current as of September 2021.

Argentina

Predominantly funded by the Chinese company Tencent and the Brazilian fund Pitanga, Satellogic operates the 22 satellite NuSat constellation (with a mass of only 41.5 kg and dimensions of 51×57×82cm), launched in 2016. Satellites are capable of imaging in the panchromatic and multispectral (1-m resolution) and hyperspectral (30-m resolution). Video with 1-m resolution is also offered. The mid-term plan is to have 90 satellites, with a long-term goal of 300 satellites for daily world remaps. Satellogic claims that 1-meter resolution is the sweet spot for monitoring economic activity and high-frequency change. Besides imagery, Satellogic offers analytical tools providing object identification, classification, semantic change detection and predictive models. Imagery is available for purchase on the official website².

Argentinian space agency CONAE (Comisión Nacional de Actividades Espaciales) operates the SAOCOM (Satélite Argentino de Observación COm Microondas) constellation of two SAR satellites (3050kg mass) launched in 2018 and 2020. The top resolution offered is 10-m. This constellation is primarily used for disaster management, agriculture support, mining and ocean monitoring. Imagery is available through the official website³. To complement its global coverage, the constellation operates jointly with the Italian COSMO-SkyMed constellation. Constellation expansion (with higher resolution) is expected with SAOCOM 2A and SAOCOM 2B whose launches are planned for 2023 and 2024, respectively.

Brazil

CBERS (China-Brazil Earth Resources Satellite) satellites are the product of collaboration between CAST (Chinese Academy of Space Technology) of China, and INPE (Instituto de Pesquisas Espaciais) of Brazil. CBERS-4 launched in 2014. It has four cameras with different swath widths able to image in the panchromatic, multispectral and at various infrared bands. Its top resolution is 5-m in the panchromatic and 10-m in the multispectral. Its partner satellite, CBERS-4A was launched in 2019 with a similar set of sensors. Its top resolution is 2-m in the panchromatic and 8-m in the multispectral. Each satellite has a mass of 1980 kg. CBERS data is used to control deforestation in the Amazon, monitor water resources, agriculture, and urban growth. The public can access imagery at their data portal. The plan is to launch follow-up optical satellites CBERS-5 and CBERS-6, and CBERS-7 (or CBSAR) as the first SAR satellite in the constellation⁴.

Canada

Funded by the Canadian Space Agency (CSA) and MDA (a Maxar Technologies company) and operated by Maxar, RADARSAT-2 (launched in 2007 with a mass of 2750 kg) is a SAR satellite capable of imaging with a top resolution of 1-m. Although primarily used to monitor the environment, manage natural resources and coastal surveillance, Maxar also distributes imagery commercially via their platform. CSA and MDA funded a successor mission to RADARSAT-2, the RCM (RADARSAT Constellation Mission) which launched in 2019. Unlike the large and expensive RADARSAT-2, RCM is a constellation of small satellites. It has three satellites, each with a mass of 1400 kg. RCM

sensors provide imagery with a top resolution of 1×3 -m. CSA offers free access to RCM image products to vetted users who adhere to their User License Agreement⁵.

China

According to a 2019 report, there are more than 78 commercial space companies operating in China, with the majority founded since 2014. Most of them focus on satellite manufacturing and launch services, but many offer imagery to the public [6]. Presented are a few providers offering imagery on their websites or through third party vendors.

Chang Guang Satellite Technology ("Jilin") operates a large constellation of EO satellites offering high-resolution imagery and video. This includes 10 satellites (42 kg satellite mass) with a resolution of 1-m in the panchromatic and 4-m in multispectral, two satellites with a resolution of 0.75-m in the panchromatic and 3-m in multispectral, one satellite with 0.72-m in the panchromatic and 4-m in multispectral (420 kg satellite mass), two satellites with multispectral imagers and a resolution of 5-m in NWIR (also 100-m MWIR and 150-m LWIR), six satellites (around 200 kg satellite mass) providing 1-m resolution video, and one satellite with a wide-swath (135 km) and 4-m resolution in the multispectral. All satellites were launched between 2015 and 2020. The company's goal is to have 60 satellites in orbit in the short term, and 138 satellites by 2030 allowing for a revisit time of less than 10 minutes at any location. Imagery is available through their website⁷.

Gaofen constellation (launched 2013-2020) is being deployed as part of the state sponsored program China High-resolution Earth Observation System (CHEOS) which intends to construct a locally built advanced EO system with high spatial, spectral, and radiometric resolution. CHEOS is one of the key science and technology programs initiated under the Chinese government's Medium-to Long-term Development Plan for Science and Technology (2006—2020). The program contains an expanding series of both multispectral and SAR satellites with various degrees of civilian access and performances up to a top resolution of 0.5-m in the panchromatic. Imagery of at least eight satellites is available for purchase through third party vendors and through the international public platform of China's space agency CNSA, which also offers free global 16-m multispectral imagery⁸.

GaoJing/SuperView-1 constellation consists of four satellites (launched from 2018 to 2020) with 0.5-m resolution in the panchromatic and 2-m in the multispectral. All

satellites have a mass of 560 kg. The constellation is operated by Beijing Space View Tech Co Ltd. The company plans to deploy a total of 24 satellites including 16 optical, four high-resolution optical (better than 0.5-m), and four SAR satellites⁹. Imagery is available through multiple commercial third-party vendors.

Zhuhai Orbita Control Engineering Ltd. currently operates four high-resolution (0.9 to 1.98-m) video capable satellites with a mass of less than 100 kg. They also operate eight satellites with hyperspectral imagers that have 10-m resolution. All systems were launched between 2017 and 2019. The company plans to deploy a total of 34 satellites including high-resolution IR and SAR systems. Zhuhai also own four ground-stations with three more in construction. Imagery can be purchased on their website, and from commercial third-party vendors¹⁰.

Triplesat constellation was built by Airbus but is leased and operated by the Chinese company Twenty First Century Aerospace Technology Co. Ltd. Imagery is distributed by Airbus, and widely available through other third-party vendors, as well as the Disaster Monitoring Constellation site. The constellation consists of three satellites (each with 447 kg mass) launched in 2015 offering 0.8-m panchromatic imagery and 3.2-m visible and NWIR imagery. SSTL-S1 4 or Vision-1 which is identical in build to previous three satellite was added to the constellation in 2018¹¹.

Europe

Sentinel-1 and Sentinel-2 are operated by the European Space Agency which provides free access to data via the Copernicus Space infrastructure program¹². Sentinel-1 is composed of Sentinel-1A (launched in 2014 with a mass of 2280 kg) and Sentinel-1B (launched in 2016 with a mass of 2164 kg) SAR satellites, each with a top resolution of 5-m. Sentinel-2 is composed of Sentinel-2A (launched in 2015 with a mass of 1140 kg) and Sentinel-2B (launched in 2017 with a mass of 1200 kg) satellites offering 10-m resolution in four visible and near-infrared bands. Next generations of Sentinel-1 and Sentinel-2 are under development and satellites are to be launched starting 2022.

Italy

Constellation of Small Satellites for Mediterranean Basin Observation or COSMO-SkyMed (consisting of four satellites with a mass of 1700 kg and launched between 2007 and

2010) and COSMO-SkyMed Second Generation or CSSG (consisting of two satellites with a mass of 2230 kg and launched in 2019) are two constellations operated by the Italian Space Agency (Agenzia Spaziale Italiana or ASI) with funding received from the Italian Ministry of Defense (I-MoD). They provide SAR imagery with a top resolution of 1-m (COSMO-SkyMed) and 0.35×0.55 -m with simultaneous double polarization (COSMO-SkyMed SG). Constellations serve both civilian and military needs. Launch of an additional two satellites is planned to start in 2024. Commercial users can purchase data from the commercial provider, and ESA offers access for scientific research¹³.

PRISMA (PRecursorre IperSpettrale della Missione Applicativa) is a hyperspectral imaging mission of the Italian Space Agency ASI launched in 2019. With a swath width of 30 km it provides a top resolution of 5-m in the panchromatic, and 30-m in visible and near-infrared (VNIR) and short-wave infrared (SWIR) bands. Hyperspectral data is useful for forest analysis, agriculture, water management, environmental research and material exploration. Users can access the data through a web data portal¹⁴.

France

Spot Image is a subsidiary of Astrium, co-owned by France, Germany and Spain. It is the world's first commercial satellite imagery provider and the operator of the SPOT (Le Systeme Pour l'Observation de la Terre) constellation since 1986. As of September 2021 they have two satellites in orbit (both with a mass of 720 kg): SPOT-6 (launched in 2012) and SPOT-7 (launched in 2014). These satellites provide imagery with a resolution of 1.5-m in the panchromatic and 6-m in multispectral (swath width is 10-60 km depending on resolution). Spot Image is also the exclusive distributor of imagery from the Pléiades constellation composed of Pléiades-HR 1A and Pléiades-HR 1B (both launched in 2011 with a mass of 970 kg). Pléiades satellites were placed in the same orbit as SPOT-6 and SPOT-7, and are operated as a dual civil/military system by Spot Image and the French Ministry of Defense. Pléiades provides imagery with the resolution of 50-cm in the panchromatic and 2-m in multispectral with a swath width of 20 km¹⁵.

The first two satellites of the new four satellite Pléiades Neo constellation were launched in 2021 and the constellation will be completed in 2022. These systems will be phased within the same orbit and offer 30 cm-resolution¹⁶. The French Space Agency (CNES) and Airbus are also developing CO3D (Constellation Optique 3D), set to launch

in 2022 offering 50-cm resolution imagery with the goal of building a global high-resolution Digital Surface Model (DSM)¹⁷.

Germany

The German Aerospace Center (DLR) and EADS Astrium operate the radar EO satellites TerraSAR-X (launched in 2007) and TanDEM-X (launched in 2010)¹⁸. Both satellites have a mass of 1209 kg and provide imagery with a resolution of 0.24×1.1 -m. The satellites fly in close formation and are able to offer global digital elevation models with a vertical accuracy of 2-m relative and 10-m absolute. Based on the same design, PAZ SAR satellite operated by the Spanish Hisdesat was added to the same orbit in 2018. Satellites offer single, dual and quad polarization mode capability. This is helpful for image filtering, feature extraction, target detection and classification. Data is available through commercial third party vendors, the Airbus portal, and ESA's Earth Online platform¹⁹.

To improve information on global dynamic processes, and maintain data and service continuity beyond 2025, DLR and Airbus Defence and Space are planning follow-up missions including TSX-NG (TerraSAR-X Next Generation), Tandem-L and High Resolution Wide Swath (HRWS)²⁰.

Finland

ICEYE is a Finnish SAR commercial EO provider that currently operates 11 satellites (weight of 100 kg) offering imagery with a top resolution of 1-m after ground-plane adjustments. Satellites were launched between 2018 and 2021. In collaboration with ESA, ICEYE is planning to have a constellation of 18 satellites that will be able to provide near real-time SAR imagery. ICEYE claims its imagery is used for security, in the insurance industry, mining, maritime surveillance, civil government and other. Data is available for purchase on their website, or can be accessed on ESA's Earth Online platform if the user is approved²¹.

Spain

Deimos Imaging operates Deimos-1 (launched in 2009) and Deimos-2 (launched in 2014). Deimos-1 is part of the Disaster Monitoring Constellation and provides wide swath,

medium-resolution 22-m imagery. Deimos-2 (310 kg mass) offers 0.75-m azimuth resolution in the panchromatic and 4-m in multispectral. Imagery is available for purchase on their website and through commercial third-party vendors²².

PAZ or SEOSAR/PAZ (Satélite Español de Observación SAR) is a SAR satellite operated by Hisdesat and launched in 2018 to the same orbit as TerraSAR-X and TanDEM-X. It is intended for military and civilian use. Its top resolution is 0.24×1 -m (same as TerraSAR-X), and the satellite has a mass of 1341 kg. Imagery is available for purchase through ESA's and Airbus's data portals, and Hisdesat's website²³.

Israel

EROS-B (Earth Resources Observation Systems B) is operated by the Israeli company ImageSat International and was launched in 2006. It has a mass of 350 kg and provides imagery with a resolution of 70-cm in the panchromatic. The satellite is reaching its end of life, so the company has plans for a new EROS-NG constellation that should consist of three new optical 30-cm resolution satellites and two SAR capable satellites with unknown capabilities. They claim EROS-NG will offer direct access services and full control of the constellation to defense clients. EROS-B imagery is available through commercial third party vendors and their website. In addition to imagery, ImageSat offers data analytics services²⁴.

Japan

ASNARO (Advanced Satellite with New system ARchitecture for Observation) is an observation satellite launched in 2014 and funded by the Government of Japan. Its mission is to develop a high-performance mini-satellite bus system based on open architecture techniques and new manufacturing methodologies that can compete with other international advanced small satellite systems. It has a mass of 400 kg and can provide imagery with a resolution of 0.5-m in the panchromatic and 2-m in multispectral. A follow-up mission is ASNARO-2 (launched 2018) which is a SAR satellite with a mass of 507 kg capable of 1-m resolution imagery. Imagery is available for purchase through a data portal and third-party vendors. ASNARO-3 carrying a hyperspectral sensor is also planned, but with unknown launch date²⁵.

ALOS-2 (Advanced Land Observation Satellite) or Daichi-2 was launched in 2014 by JAXA (Japan Aerospace Exploration Agency). It is a SAR satellite with a mass of 2100 kg that offers a top resolution of 1×3 -m. Its data is used for cartography, regional observation, disaster monitoring, and environmental monitoring. Imagery can be purchased through an online data portal. In 2021, JAXA is planning ALOS-3 which should be an optical satellite with a resolution of 0.8-m and a wide swath of 70 km²⁶.

The Japanese startup Synspecive is planning a constellation of 30 SAR satellites with 1-m resolution. The company raised \$100 million from Japanese companies and funds in 2018²⁷. They launched the demonstrator StriX- α and plan to launch StriX- β in 2021.

Axelspace Corporation is building a constellation of 50 optical satellites (mass of 50 kg) with a projected resolution of 2.5-m in the panchromatic and 5-m in multispectral. In a Series B funding round, they raised \$22.8m in 2018. First launch of GRUS 1A was made in 2018, and additional four satellites were launched in March 2021²⁸.

Japan's Institute for Q-shu Pioneers of Space (iQPS) is planning a 1-m resolution 36 satellite (below 100 kg) SAR constellation by 2025 that should have a 10 minute revisit time of any point on Earth. The company launched its first prototype in 2019. It received a total of about \$20.6M in a Series A funding round in 2017²⁹.

Kazakhstan

KazEOSat is a Kazcosmos (Kazakhstan National Space Agency) funded Kazakhstani EO satellite program developed by EADS Astrium. KazEOSat-1 (launched in 2014 with a mass of 830 kg) provides 1-m resolution imagery in the panchromatic and 4-m resolution imagery in multispectral. KazEOSat-2 (launched 2014) is a wide-swath 77 km imager with a resolution of 6.5-m in the panchromatic. Imagery of both is available for purchase at the Airbus platform³⁰.

Nigeria

NIGERIASAT-2 satellite was developed with the funding of the Nigerian government and launched in 2011. The satellite has a mass of 300 kg and a resolution of 2.5-m in the panchromatic and 5-m in multispectral. The NX (NigeriaSat-X) satellite (22-m panchromatic resolution) is also in-orbit. It was launched in 2011 and built by Nigerian engineers

in SSTL's facilities in England. The goals of the NigeriaSat program are to provide continuity of Nigerian space presence, and support agricultural and geology applications. Imagery is available through the Disaster Monitoring Constellation consortium³¹.

Russia

Kanopus-V constellation is composed of five satellites launched between 2012 and 2018. It is a program of the Russian Space Agency, Roskosmos and ROSHYDROMET/Planeta. The satellites provide a top resolution of 2.1-m in the panchromatic and 10.5-m in the multispectral, with a satellite mass of 473 kg. Imagery is commercially available through a third-party vendor. Launches of two more satellites are planned for 2025. Kanopus-V-IK (formerly Kanopus-V 2) is another satellite (launched in 2017) within the same program that carries a multi-channel infrared radiometer (resolution of 200-m) along with panchromatic and multispectral cameras. The main task of the mission is to support the Russian hydro-meteorological and environment monitoring service³².

Resurs-P is a constellation of three satellites operated by Roskosmos capable of 1-m resolution panchromatic imagery. The satellites were launched between 2013 and 2016. Each has a mass of 6570 kg. In addition to the panchromatic imager, they also carry multispectral and hyperspectral cameras with a top resolution of 3-m and 30-m, respectively. The mission goal is to provide map updates and ensure economic activities of various Russian ministries. Two more launches are planned for 2022 and 2023¹. Imagery is offered commercially by a third-party vendor³³.

Singapore

TeLEOS-1 is a commercial satellite developed in Singapore offering 1-m resolution in the panchromatic. It was launched in 2015 with a mass of 400 kg. Imagery is used for homeland security, border control, but is commercially available³⁴. SAR satellite TeLEOS-2 is scheduled to launch in the 2021-2022 timeframe.

South Korea

KOMPSAT (Korea Multi-Purpose Satellite) program is developed by the Korean Aerospace Research Institute (KARI). It consists of a series of multipurpose satellites covering vari-

ous needs. This includes KOMPSAT-2 (1-m panchromatic resolution and 4-m multispectral with a mass of 800 kg) that was launched in 2006, KOMPSAT-3 (0.7-m panchromatic and 2.8-m multispectral resolution with a mass of 1990 kg) that was launched in 2012, KOMPSAT-3A (0.5 m panchromatic, 2.2-m multispectral and 5.5-m MWIR with a mass of 1100 kg) that was launched in 2015 and KOMPSAT-5 (1-m SAR at most narrow swath width and a mass of 1400 kg) that was launched in 2013. Imagery is available commercially, and used for land planning, agriculture, urban planning and defense³⁵. KOMPSAT-6, a successor SAR satellite with 0.5-m resolution, is planned to launch in 2022. KOMPSAT-7 is a follow-up satellite of KOMPSAT-3A and planned for launch in 2022.

KARI is also launching two 500 kg 50-cm resolution imaging satellites in 2021 and 2022. The goal of the program is to develop relevant technologies, and transfer them to the industry, which would then launch a additional three satellites³⁶.

Thailand

THEOS-1 or Thaichote (launched in 2008) is an EADS Astrium developed and Thai funded satellite with a mass of 750 kg. It can provide imagery with a resolution of 2-m in the panchromatic and 15-m in multispectral. The program is used to train Thai engineers, observe natural resources, support agriculture, monitor deforestation and other purposes. Imagery can be purchased on the website of Geo-Informatics and Space Technology Development Agency (GISTDA). The satellite is nearing end of life, so its successor, developed in collaboration with Airbus, is to be launched in 2021 or 2022, and will be able to deliver 0.5-m panchromatic ground resolution imagery³⁷.

Taiwan

Formosat-5 (mass of 475 kg) is operated by the National Space Organization (NSPO) of Taiwan. It was domestically developed and was launched in 2017. It offers panchromatic imagery with a resolution of 2-m, and multispectral with a resolution of 4-m³⁸. Imagery is available from third-party vendors. FORMOSAT-8 constellation with 6 high-resolution (1-m PAN) optical remote sensing satellites is planned for 2023-2028.

United Arab Emirates

Dubaisat-2 is a UAE funded project built in partnership with a satellite manufacturing company from South Korea. It was launched in 2013, has a mass of 300 kg, and resolution of 1-m in the panchromatic and 4-m in multispectral. KhalifaSat or DubaiSat-3 is locally designed and manufactured successor, launched in 2018 and providing a resolution of 0.75-m in the panchromatic and 2.98-m in multispectral. The program is intended to create training opportunities for the UAE's space program and provide imagery to local government entities and commercial users. Imagery is available from third-party vendors, and the Mohammed Bin Rashid Space Centre website³⁹.

United Kingdom

Vivid-i is a constellation planned by a U.K. company Earth-i. The goal is to launch 15 satellites able to capture imagery with 0.6-m resolution and full color video with 1-m resolution. Deployment is planned to start in 2022. In 2018 the British Royal Air Force (RAF) launched a 100 kg demonstrator called VividX2 or Carbonite-2 which delivers 1-m resolution images and HD video clips⁴⁰.

United States

Maxar Technologies

Maxar Technologies is a space technology company offering various space related services. Their current observation constellation is composed of WorldView-1 (launched 2007), WorldView-2 (launched 2009), WorldView-3 (launched 2014) and GeoEye-1 (launched 2008)⁴¹.

WorldView-1 (mass of 2500 kg) provides coverage with 0.5-m resolution in the panchromatic and 2-m in multispectral (swath width of 17.6 km). GeoEye-1 (mass of 1955 kg) offers imagery with 46-cm resolution in the panchromatic band and 1.84-m in multispectral (swath width of 15.3 km). WorldView-2 (mass of 2800 kg) offers 46-cm resolution in the panchromatic band (swath width of 16.5 km) and 1.85-m in 8-band multispectral imagery. WorldView-3 (mass of 2800 kg) provides 31-cm panchromatic imagery resolution (swath width of 13.1 km), 1.24-m multispectral imagery resolution and 3.7-m SWIR. Maxar recently introduced a product they claim is equivalent to 15-cm resolution imagery,

but obtained by applying algorithmic processing to native 30-cm resolution WorldView-3 data. Maxar also operates RADARSAT-2 which is a Canadian SAR satellite offering 1-m resolution.

Maxar promises a median time of under one hour from collection to customer delivery, and offers a 100+ petabyte image archive with data going back to the early 2000s. They supply free imagery to large media organizations in return for attribution, and provide in-house analytical support⁴². A "Direct Access Program" allows customers to integrate their own ground stations with Maxar's satellites and take full control of the sensor during dedicated observation windows. In this scenario, the customer downloads the encrypted raw imagery directly to their ground site via secure FTP, and performs their own processing.

Starting in 2021, Maxar plans to deploy a new 6-satellite constellation called Legion that will fly on sun-synchronous and mid-inclination orbits, collect 5 000 000 square kilometers per day with up to 15 revisits in 29-cm resolution in the panchromatic⁴³. Satellites constituting the Legion constellation are much smaller (750 kg) and less expensive than the previous Maxar constellation. Maxar also has a contract with the Saudi Arabia's King Abdul Aziz City for Science and Technology Space Research Institute to develop the WorldView Scout constellation with an imaging resolution of 80-cm¹.

The company has signed contracts with various U.S. defense agencies, including the U.S. Department of Homeland Security (DHS), the U.S. Air Force, U.S. Special Operations Command, National Geospatial-Intelligence Agency, and the National Reconnaissance Office⁴⁴.

Planet

Planet is focused on providing EO services. It was founded in 2010, and is operating a large PlanetScope constellation of small satellites built with COTS components and replenished with regular launches. In addition, they currently operate the higher-resolution SkySat constellations. In total, Planet has built over 500 satellites⁴⁵.

PlanetScope constellation is composed of three generations of Dove satellites (Dove Classic, Dove-R and SuperDove), with the first satellite launched in 2013. Satellites are CubeSat 3U form factor (10-cm × 10-cm × 30-cm). The constellation can image 200 million square kilometers per day (multispectral) with the highest resolution of 3.7-m in

RGB and NIR bands and a swath width of 77 km. Planet does not disclose which Doves are operational, but claims there are more than 200 in orbit. By using Planet’s API to obtain PlanetScope’s data during 5 days in October 2021, the author identified 138 unique satellite IDs that acquired imagery during that period.

SkySat constellation is also operated by Planet. It was acquired from Google in 2017, and its satellites launched between 2013 and 2020. The constellation is composed of 21 (110 kg mass with 60×60×95cm dimensions) satellites in mixed sun-synchronous and mid-inclination orbits. Satellites offer multispectral, panchromatic, and video imagery (30-120 seconds). Panchromatic imagery has a spatial resolution between 0.57-m and 0.86-m (depending on the generation) at nadir in the 400-900 nm panchromatic band, and between 0.75-m and 1-m resolution in the multispectral with a swath width of 8 km. Planet claims SkySat constellation offers a maximum of 12 daily revisits with an average of 7 at select areas⁴⁶.

Planet Labs promises delivery time of a few hours via an API or a web-based dashboard. Their historical archive for PlanetScope ranges from 2016 and for SkySat from 2014. The company also offers an archive of imagery produced by the retired Rapid-Eye constellation with 5-m resolution from January 2009 to March 2020. Planet Labs reportedly has agreements to provide free imagery access to media outlets such as The New York Times, The Washington Post, The British Broadcasting Corporation, and The Financial Times, and claims it does not provide exclusive access to anyone⁴². Planet also has multiple contracts with various U.S. defense agencies⁴⁷. Planet has recently announced a new “very high resolution” constellation called Pelican, with first satellites to be launched in 2022. Planet is also introducing a new product fusing optical data with SAR to provide additional insights to customers⁴⁸.

Other U.S. commercial companies

BlackSky is a U.S. based commercial provider of optical EO imagery with currently eight satellites (launched between 2018 and 2021) in orbit. These satellites have a mass of about 50 kg and offer imagery and video with a resolution of 0.9 to 1-m in the multispectral. The short-term plan of the company is to have a total of 24 satellites in orbit in the next few years. The long-term plan is to have a 60-satellite constellation with a resolution of 1-m and revisit time of 10-15 min for any location, all interconnected by a ground

network of gateway stations⁴⁹. Recently, NRO has awarded a contract to BlackSky Global (and Maxar Technologies and Planet) to "take full advantage of the U.S. commercial remote sensing market to build an even more responsive, robust, and affordable GEOINT architecture"⁵⁰. Blacksky imagery is available for sale on their website.

Capella Space is a U.S. based commercial EO provider claiming to be the "first American SAR operator"⁵¹. The first satellite of the new Whitney sub-constellation was launched in August 2020 to an altitude of 525 kilometers on a mid-inclination orbit. It joined their prototype satellite which was launched back in 2018. Currently the company operate five satellites. Imagery can be purchased on their website. In the next 3-4 years, Capella Space has plans for 36 satellites (< 40 kg mass) with a 3.5-meter aperture, deployed with a mesh-based reflector antenna able to provide all-weather and illumination resolution of 0.5-m. Capella claims the constellation will deliver hourly SAR global coverage. Capella also plans to offer real-time customer tasking using inter-satellite links provided by a network of geostationary communications satellites owned by Inmarsat. Like Maxar, to serve the defense industry, they will offer a direct access program enabling the transfer of satellite control to the customer and direct downlink of data to the ground-station of their choice⁵². Capella Space already has contracts with the U.S. Navy to deliver satellite imagery, U.S. Air Force to adapt its commercial synthetic aperture radar (SAR) for military applications, with the National Geospatial-Intelligence Agency to provide "intelligence professionals key insight and strategic advantage," and with National Reconnaissance Office to "explore opportunities to integrate commercial SAR in support of the NRO's national security mission"⁵³.

Umbra Lab is another U.S. company planning to build a constellation of SAR satellites. These should have a mass of 50 kg and be capable of imaging with 25-cm resolution. The completed constellation would have 12 satellites and provide hourly revisits. Umbra boasts a high compaction ratio of their antenna which should significantly improve their observation performance⁵⁴.

EOS SAR is planning a constellation of six optical and six SAR satellites with resolution down to 25-cm and satellite mass of around 200 kg. The constellation should enable 2-3 hours revisit times for a given area. The company is funded by Noosphere Ventures which also owns EOS DATA Analytics and a small-launcher company Firefly Aerospace⁵⁵.

Hera Systems is a U.S.-based company developing an eight optical satellite 1HOPSat (1st generation High Optical Performance Satellite) constellation. The satellites are being built within the 12U CubeSat form factor and would provide 50-cm resolution imagery and video. The long-term plan is to have a total of 48 satellites providing near-hourly updates. The company launched a demonstrator mission 1HOPSat-TD in 2019⁵⁶.

Notes and references

- [1] Chandra, Shankar N. Ramaseri, Jon B. Christopherson, and Kimberly A. Casey, "2020 Joint Agency Commercial Imagery Evaluation: Remote Sensing Satellite," <https://on.doi.gov/3yBKgIn>. For launch mass through time plot, see page 4.
- [2] "Satellogic-NuSat EO (Earth Observation) Microsatellite Constellation," ESA EO Portal, accessed August 2021, <https://bit.ly/3b1nwHA>. Imagery can be purchased at <https://satellogic.com>.
- [3] "Mission summary SAOCOM-2A," Committee on Earth Observation Satellites (CEOS), accessed February 2021, <https://bit.ly/3aXNb3L>. Imagery from multiple products is marketed and sold on the SAOCOM website at <https://saocom.veng.com.ar/en>.
- [4] "CBERS-3 and 4 (China-Brazil Earth Resources Satellite) 2nd Generation Satellite Series", ESA EO Portal, accessed June 2021, <https://bit.ly/3piZz3A>. For detailed information on CBERS-4A see "CBERS-4A (China-Brazil Earth Resources Satellite-4A)," ESA EO Portal, accessed June 2021, <https://bit.ly/3rNUsdi>. The data portal of the constellation can be accessed at <https://bit.ly/3rC99zH>.
- [5] "RADARSAT-2: High Resolution, Operationally-focused SAR Data for near-real Time Applications," MDA, accessed August 2021, <https://bit.ly/36qE8a1>. More details on the RCM can be found at "RCM (RADARSAT Constellation Mission)," ESA EO Portal, accessed June 2021, <https://bit.ly/3aiUIeB>. Information regarding accessibility is on the Canadian Space Agency (CSA) website at <https://bit.ly/3wgH4kQ>.
- [6] Irina Liu et al., "Evaluation of China's Commercial Space Sector," The Institute for Defense Analyses, 2019, <https://bit.ly/3f770y6>.

- [7] Information on various Jilin satellites is provided by Gunther's Space Page. For example, see "Jilin-1 Gaofen-03A, -03B, 03C, 03D (Jilin-1 High Resolution-03A, 03B, 03C, 03D)," <https://bit.ly/39sjGxK>, accessed August 2021. Imagery can be purchased on the company's website at <https://www.cgsatellite.com/>. The website also contains information on satellites, and future launch plans.
- [8] CNSA-GEO international website, accessed June 2021, <http://www.cnsageo.com>.
- [9] "GaoJing / SuperView Earth Observation Constellation", ESA EO Portal, accessed June 2021, <https://bit.ly/3da0CjH>.
- [10] Zhuhai Orbita website, <https://www.obtdata.com/en>.
- [11] "Airbus further strengthens its Earth observation imagery portfolio with the addition of TripleSat satellite data", Airbus, accessed August 2021, <https://bit.ly/3tXYBxh>. For more information on the constellation see "DMC 3 (TripletSat) / SSTL-S1 1, 2, 3, 4," Gunther's Space Page, accessed August 2021, <https://bit.ly/3dyCDcS>.
- [12] ESA Copernicus Portal, <https://www.copernicus.eu/en/access-data>.
- [13] "COSMO-SkyMed Second Generation (CSG) Constellation," ESA EO Portal, accessed June 2021, <https://bit.ly/3sQAwaM>, and "COSMO-SkyMed (Constellation of 4 SAR Satellites)," <https://bit.ly/2NpRTiw>. eGeos offers additional information on the constellations and data sales, <https://bit.ly/2UvZoZ3>.
- [14] "PRISMA: the first images from the ASI hyperspectral satellite are now available," Telespazio, accessed August 2021, <https://bit.ly/3qe620o>. Data portal of PRISMA can be accessed at <https://bit.ly/3hD60N2>.
- [15] "SPOT-6 and SPOT-7 Commercial Imaging Constellation," ESA EO Portal, accessed August 2021, <https://bit.ly/3qiq9er>. "Pleiades-HR (High-Resolution Optical Imaging Constellation of CNES)," ESA EO Portal, accessed August 2021, <https://bit.ly/3ahChXz>.
- [16] "Pléiades Neo set for launch in early 2021," Airbus, 2020, <https://bit.ly/39zhWfm>.
- [17] "Airbus to develop CO3D Earth Observation programme for CNES," Airbus 2019, <https://bit.ly/3d7ZHk2>.

- [18] "TDX (TanDEM-X: TerraSAR-X add-on for Digital Elevation Measurement)," ESA EO Portal, accessed June 2021, <https://bit.ly/2ZdLYQr>.
- [19] Airbus Defense and Space website, <https://www.intelligence-airbusds.com/>.
- [20] "TSX-NG (TerraSAR-X Next Generation)," ESA EO Portal, accessed June 2021, <https://bit.ly/3rRL1Za>. For HRWS see Sofya Spiridonova and Ralph Kahle "HRWS – An Ambitious 4+ Satellite Formation Flying Mission," <https://bit.ly/3jF6vXy>.
- [21] ICEYE website offers information on the constellations and how to purchase images, <https://www.iceye.com/sar-data/>.
- [22] "Deimos-2 Minisatellite Mission," ESA EO Portal, accessed June 2021, <https://bit.ly/3aeelEt>. Deimos Imaging website offers imagery for purchase: <https://bit.ly/3xphYR6>.
- [23] "PAZ SAR satellite mission", ESA EO Portal, accessed June 2021, <https://bit.ly/3rGvQTE>.
- [24] "EROS-B (Earth Remote Observation Satellite-B)," ESA EO Portal, accessed June 2021, <https://bit.ly/36PNu2k>. For information on EROS NG see company website: <https://bit.ly/36ocRo8>.
- [25] "ASNARO (Advanced Satellite with New system ARchitecture for Observation)", ESA EO Portal, accessed June 2021, <https://bit.ly/3d7r0e0> and "ASNARO-2 (Advanced Satellite with New system ARchitecture for Observation-2," ESA EO Portal, accessed June 2021, <https://bit.ly/3rRe7cr>. Imagery is available at the JEOSS company website: <https://jeoss.co.jp/>.
- [26] "ALOS-2 (Advanced Land Observing Satellite-2 SAR mission) / Daichi-2," ESA EO Portal, accessed June 2021, <https://bit.ly/37a9UbL>. ALOS-2 data portal: <http://en.alos-pasco.com/>.
- [27] Caleb Henry, "Japanese SAR startup Synspective reaches 100 million USD in funding," *SpaceNews*, 2019, <https://bit.ly/2PvWMbp>.

- [28] Information on first demonstrator flight is given by Deyana Go, "Axelspace's first sat for Earth Observation constellation successfully orbited," Space Tech Asia, 2018, <https://bit.ly/2Z8xAbZ>. For information on their funding see Caleb Henry, "Axelspace raises 22.8 million USD for remote-sensing constellation," SpaceNews, 2018, <https://bit.ly/39IQz3x>. More details on Axelspace constellation and service are available on Axelspace's website: <https://bit.ly/31GTVPu>.
- [29] For information on the constellation see Debra Werner "Japan's iQPS to update technology for future radar satellites," SpaceNews, 2020, <https://bit.ly/3AFq5La>. Also see "IZANAMI" to launch on Spaceflight's SXRS-3 rideshare mission no earlier than December 2020" on company website: <https://i-qps.net/news/316>. Funding information provided by Crunchbase: <https://bit.ly/3rLmuFK>.
- [30] Information on KazEOSat satellites is available on "KazEOSat-1 Technical and Product ordering Description Sheet," Airbus, <https://bit.ly/3acGsUh> and "KazEOSat-2 Technical Sheet," Airbus, <https://bit.ly/3rNY8fa>.
- [31] Information on NigeriaSat-2 available on "N2 (NigeriaSat-2)," ESA EO Portal, accessed June 2021, <https://bit.ly/3pf5ExN>. Imagery available through DMC International Imaging: <http://www.dmcii.com>.
- [32] "Kanopus-V 1, 2," Gunther's Space Page, accessed June 2021, <https://bit.ly/3cG7btL> and "Kanopus-V-IK 1," Gunther's Space Page, accessed June 2021, <https://bit.ly/31H89zS>. Innoter sells Canopus imagery: <https://bit.ly/3rHvv2F>.
- [33] "Resurs-P (Resurs-Prospective) Remote Sensing Mission Constellation," ESA EO Portal, accessed June 2021, <https://bit.ly/2NmVORW>. Innoter sells Resurs-P 1,2,3 imagery: <https://bit.ly/39BjUff>.
- [34] "TeLEOS-1 commercial imaging satellite of Singapore," ESA EO Portal, accessed June 2021, <https://bit.ly/2QZJWma>. Imagery sold by SIIS: <https://bit.ly/3meDpiR>.
- [35] KOMPSAT satellites imagery available at SIIS website: <https://bit.ly/3f05BrZ>.
- [36] "CAS500 (Compact Advanced Satellite 500," KARI website, accessed June 2021, <https://bit.ly/3yvuG0B>.

- [37] "THEOS (Thailand Earth Observation System)," ESA EO Portal, accessed June 2021, <https://bit.ly/3aWtFop>. Data portal provided by the Geo-Informatics and Space Technology Development Agency (GISTDA), <https://bit.ly/3dwM3VU>.
- [38] "FormoSat-5," ESA EO Portal, accessed June 2021, <https://bit.ly/39biPed>.
- [39] SIIS offers Dubaisat-2 and Khalifasat imagery and information: <https://bit.ly/20kd8mW>. Imagery can also be accessed on the website of the Mohammed Bin Rashid Space Centre: <https://bit.ly/3cItXRd>.
- [40] "Carbonite 2," Gunther's Space Page, accessed June 2021, <https://bit.ly/39zIi0k>. Vivid-i constellation website: <https://earthii.space/constellations/>. This imagery is currently used by the British Ministry of Defence, Andrew Chuter, "Carbonite-2 satellite enters orbit to test British intel-gathering capability," *Defense News*, 2018, <https://bit.ly/3pf1vdk>.
- [41] Maxar website: <https://www.maxar.com/constellation/>. Accessed February 2021.
- [42] Mark Corcoran, "*Satellite Journalism – The Big Picture Newsgathering applications of emerging satellite technology*," Reuters Institute Fellowship Paper, University of Oxford (2018).
- [43] See for example Maxar's website on Legion: <https://bit.ly/2SRpAN4>. Also Maxar's videos on Legion: <https://bit.ly/3qgVMWA>.
- [44] "Maxar awarded \$95 Million in US government contracts," *Satellite Today*, 2019, <https://bit.ly/3rKiwH6>.
- [45] Email correspondence with Planet's Director of Communications.
- [46] SkySat: "SkySat," ESA, accessed August 2021, <https://bit.ly/36jo3m5>. PlanetScope: "Flocks," Gunther's Space Page, <https://bit.ly/2Pro1m0>.
- [47] See Jen Marcus, "Planet Awarded New Contract With National Geospatial-Intelligence Agency," Planet, 2018, <https://bit.ly/3un4zHr>. Also, Jen Marcus, "National Reconnaissance Office Signs Contract With Planet Federal," Planet, 2019, <https://bit.ly/3sFUyed>.
- [48] Debra Werner, "Planet unveils Pelican Earth-imaging constellation," *SpaceNews*, October 2021, <https://bit.ly/3EQHfqP>.

- [49] Riccardo Nasini, "BlackSky constellation: very high resolution optical data for multi-daily revisit," 24th MARS Conference, 2018, <https://bit.ly/3wleTRV>. Also useful is "New BlackSky Satellites Deliver First Images Within 58 Hours of Launch," *Business Wire*, 2020, <https://bwnews.pr/3tMfcE9>.
- [50] For example, NRO awarded contracts to Maxar, Planet and Blacksky: "NRO Awards Commercial Imagery Study Contracts," National Reconnaissance Office, 2019, <https://bit.ly/3mSVHWy>.
- [51] Ishveena Singh, "Capella Space unveils first commercial SAR images from Sequoia satellite," *Geoawesomeness*, 2020, <https://bit.ly/2N05LjN>.
- [52] See Capella Space website: <https://www.capellaspace.com/>. Also Stephen Clark, "Rocket Lab returns to service with successful launch for Capella," *Space Flight Now*, 2020, <https://bit.ly/2ZajV4f>. See also Rao S. Ramayanam, "Capella Space's X-Band Synthetic Aperture Radar Satellite Constellation with Hourly Monitoring Capability for National Security," conference presentation, 2019, <https://bit.ly/3qh9Dv5>.
- [53] See Debra Werner, "National Geospatial-Intelligence Agency Signs CRADA with Capella Space," *Space News*, 2021, <https://bit.ly/2Uwza8M> and Debra Werner, "Capella wins Air Force small business contract," *Space News*, 2019, <https://bit.ly/3r4RodP>. Also "NRO awards two commercial integration study contracts," NRO article, 2019, <https://bit.ly/3qAuVVb>.
- [54] SARjournal, "Umbra's antenna gives them a lot to gain in the SAR Wars," 2020, <https://bit.ly/3aeqfyc>.
- [55] "EOS to create its own radar microsatellite constellation EOS SAR," *CISION PR Newswire*, 2019, <https://prn.to/2ZaMpLk>.
- [56] See company website <https://www.herasys.com> and "Hera Systems Reveals Satellite Constellation Launch Plans for 2016, Secures Initial Investment Funding," *Business Wire*, 2015, <https://bwnews.pr/3rM1Bx9>.