Rich Data, Cheap Satellites

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ABSTRACT

Earth Observation systems traditionally have followed the flagship mission approach. Surveillance missions carry large instruments, and focus on data quality and data volume to justify their investment. Earth science missions carry multiple instruments instead, and address a wide range of applications in order to justify their cost. Yet the "Big Data" value of these missions is often minimal, because the data sets cannot provide the temporal resolution ***and*** spatial resolution demanded by the majority of applications in trade, traffic, energy, disasters and even in providing useful information regarding slower phenomena like forestry and agriculture. Today it has become possible to do better than that, by utilising low cost small satellites in constellations with frequent global coverage. So far few small satellite Earth Observation constellations have been realised, but the parallel developments which have taken place in Cloud storage and Cloud computing have made it possible for EO data to be processed and distributed to worldwide users with diverse and different interests. When coupled with higher temporal resolution data from constellations this starts addressing specific opportunities. This paper focuses on the data richness that can be provided through small satellite constellations, and in particular focus on the OptiSAR and UrtheDaily constellations which aim to fuse optical, radar, video and global daily coverage of the Earth's landmass. This, coupled with novel distribution and processing methods, will change the paradigm in how end users interact with Earth Observation data sets and the information that can be extracted automatically.

ONE DIMENSIONAL DATA

The limits on Resolution, Capacity and Timeliness

The fast evolution of small satellite technology associated with the even faster evolution of data processing and storage solutions have revolutionized the way we access and use Earth Observation (EO) data. Applications of EO that were once the preserve of institutional government organizations are now in common use among commercial users and accessible to the general public. Despite this evolution, the data has remained mostly the same with visible and near infrared optical systems dominating.

The Ground Sampling Distance (GSD) has improved and the number of pixels that can be captured by the satellites has gone up dramatically, as illustrated in Figure 1. This fast growth in on-board storage is closely followed by more powerful on board processors, allowing for cost effective solutions for in-line compression of the imagery data.

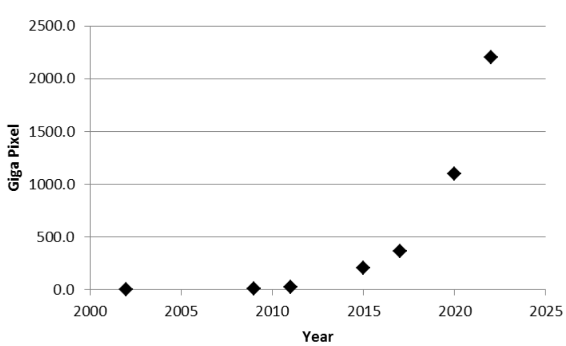

Figure 1: Example of evolution of pixel storage

When this is taken into account, the total capacity of many small satellites is now several orders of magnitude above what could be achieved 10 years ago, even with a "large satellite".

We have seen a growth of high resolution satellites in the last few years, with an increasing number of metric and sub-metric capable low cost missions being launched. The next generation of EO satellites is moving quickly to the 0.5m and better GSDs, even for low cost satellites, and we should expect to see several being available in the 2020 timeframe. But the technology has started to hit physical limits in the current generation of satellites.

Take for instance the graph of Figure 1: the exponential growth of on-board storage is quite clear but this does not necessarily translate into larger areas being captured because higher resolution requires an exponential growth in storage: for instance, a reduction of 1m to 0.5m in resolution means four times more storage required for the same captured area, and for 0.25m that is 16x more.

In Figure 2 the area captured is overlaid with storage – the squares represent high resolution missions, where the objective is to maximize the GSD (the X are medium GSD missions):

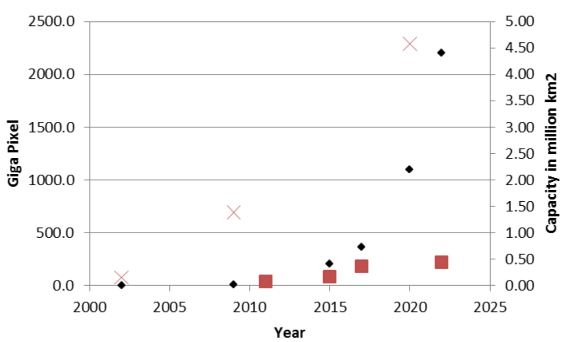

Figure 2: Storage and Area

And adding more storage does not actually improve things. Assuming we can solve the issues around the complexity of large sensors, data transfer and management within the satellite, the big bottleneck is more fundamental: downlink speed.

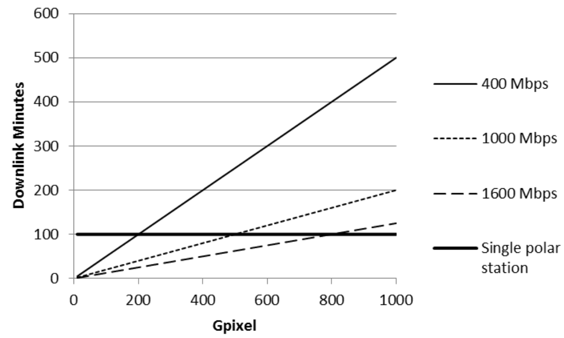

Figure 3: Time to download different amounts of imaging data (assuming no compression)

At current maximum downlink speeds, using X-band, we are effectively limited to downlinking a few thousand Gpixel per day, assuming access to a large network of ground stations. This is expensive both in terms of the ground segment, but also in terms of power on-board, requiring more energy generation and storage, which at this point are some of the biggest costs in building a satellite. Moving up in band, to Ka band for instance, is an option, but requires significantly more expensive ground segments. Compression can help, but reaches a limit on what can be achieved before data quality degrades beyond an acceptable limit.

Single satellites also have the obvious limitation of target access opportunities, creating issues with timeliness of data. Assuming a maximum off point angle of 30º, a constellation of at least three satellites is required to access any point on the globe every day. Small constellations offer an improvement, but spaceborne imaging data still struggles to offer users a reliable, systemic solution for high temporal resolution imaging – taking cloud cover into account most systems will only be able to deliver a repeat service every "few" weeks. Coordinating satellites as "virtual" constellations provides better solutions, but they have to contend with non-phased satellites, different sensors, etc.

The one-dimensionality of optical visible and NIR data

Most commercial EO systems being built can be considered "one dimensional" in the sense they deliver one type of data: optical, multispectral still imagery. The main improvements over the last few years have been GSD, capacity and a reduction in price of the satellites. There are other systems with different sensors (SAR, AIS, IR, etc.) flying but they tend to operate in isolation, without a clear synergetic use of the different types of sensor to improve the information provided to the user. Again these are used in a "one dimensional" approach: data is often acquired without a common purpose and then haphazardly brought together – sometimes it works well, others it doesn't.

One of the first truly multidimensional EO systems is the Copernicus programme of the European Union (EU), implemented by the European Space Agency (ESA). The system offers optical, SAR, oceanographic, and atmospheric data through an integrated range of sensors, designed from the beginning to work together. The challenge to the user community is the limited ability to requests specific sets of data and the limited temporal resolution of the data – possibly linked to the cost of individual satellites, that does force only pairs of sensors to be built.

INCREASING THE TEMPORAL RESOLUTION

The Constellation solution

Constellations offer solutions to overcoming physics problems, and offer flexibility to engineering problems. They can be used to maximize data acquisition by building a constellation of powerful satellites, or instead they allow a complex satellite to be broken into simpler systems that are less costly to build and launch.

When used to maximize data acquisition, constellations can overcome some of the limitations identified for single satellites: multiple orbital planes allow increased target access and hence an increased temporal resolution. And the distributed nature of a constellation allows a better balance between the data capture capacity and the downlink capacity.

The whole land mass, every day

By carefully choosing the parameters of a constellation it is possible to design a system that captures the entire landmass of the Earth's surface every day. The design tradeoffs should take into account re-visit, the design of the spacecraft and the physical realities. But more important than any of these are two "downstream" considerations: what do users need, and does the business case close?

Constellations like the DMC showed that it is possible to build a commercial case for a medium resolution EO system. RapidEye demonstrated that there are applications and a customer base for 5m class data in the agricultural market. As RapidEye approaches its end of life, a replacement is needed, particularly since its operation created a need for data to support precision agriculture.

URTHEDAILY

In order to provide a service for the user community in the agriculture sector, SSTL and UrtheCast have designed a new constellation currently being planned to be operational in 2020. This has been designed from the ground up to provide scientific grade imaging data, suitable for geoanalytics applications.

UrtheDaily Constellation

The UrtheDaily constellation is composed of 8 satellites in a 600 km sun synchronous orbit with a local time of descending node of 10:30. The multispectral cameras, on the satellites provide a ground sample distance of 5 m over a swath of 360 km. The satellite design, orbit selection, and distributed ground stations allow imaging of the entire land mass every single day providing a daily global map. In addition, the cloud based processing, archiving, and data delivery will enable an entirely new class of precision agriculture, water management, change detection, and geoanalytic products and services.

Concept of Operations

For UrtheDaily, the prime concept of operations is simple: fully automatic tasking, collection, downlink, backhaul, processing, cataloguing, and distribution of the Earth's land surface every single day. The daily monitoring and change detection capability provided by UrtheDaily can be used to tip and cue the world's most advanced fully integrated Optical and SAR collection system, the OptiSAR™ Constellation, with unprecedented spectral diversity, revisit rates, resolution, 24/7 all-weather imaging, and advanced operating modes.

The Satellites

The primary structure for the UrtheDaily satellite is based on the SSTL250 platform, a part of the SSTL300 family, and is of a cuboid shape with external dimensions of 1060 x 850 x 750 mm in the stowed configuration. The re-use of an existing bus design ensures a minimal cost through the re-use of hardware and software solutions.

Two body fixed solar panels and two deployed panels, at an angle of 30° and 60° with respect to the body, are used to generate and orbit average power of 230W. Five sides of the spacecraft are made of structural honeycomb panels while the separation panel is made of milled-aluminium.

Internally, the platform is split into two sections: avionics bay and payload bay. The avionics bay is housed in the bottom half of the platform while the payloads is mounted on the payload panel. Most platform avionics items are positioned on the separation panel which is based on a milled-aluminium construction providing a good thermal sink for the high power units. In addition, this configuration aids the AIT/EVT campaign as the spacecraft can be built and tested in a flat-sat configuration using the flight equipment and separation panel. This decouples the need to have the entire structural and solar panels ready for assembly at the same time and a more staggered approach to delivery can be realised.

Figure 4: UrthDaily satellite

The propulsion system is also housed on the separation panel with its thruster pointed through the separation ring. This approach allows the propulsion system to be designed, built and tested independently of the platform. As a result, this sub-system can be treated as a standalone unit which can be integrated with the rest of the platform at a later stage during AIT allowing parallel activities to be carried out on the platform

Similarly, the camera system is mounted onto a separate payload panel which can be integrated and tested as a payload chain prior to integration onto the satellite. This payload mounting approach allows for the camera system to be tested independent of the platform, mounted and aligned separately, and then integrated to the platform.

Launch	2019
Constellation Design	8 satellites equally spaced by 45° in a single plane
Orbit	600 km Sun Synchronous Orbit with LTAN of 10:30
Payload Data Downlink Rate	Two X-band transmitters per satellite 500 Mbps per X-band transmitter
Mass Memory	Two 1.5 TeraByte Payload Data Handling Units
Propulsion Type	Xenon
Delta-V	56 m/s
Orbit Average Power Generation	230 W
Mass (wet)	372 kg
Lifetime	10 years

Payload Summary	
Spectral bands	6
Ground Sample Distance (native)	5 m (@600km altitude)
Swath	360 km (@600 km altitude)

INCREASING THE DIMENSIONS OF DATA: RICH DATA

The UrtheDaily constellation offers a high temporal resolution, with, cloud permitting, a daily image of the Earth's landmass. This ability to monitor fields, forests, urban areas on a daily basis increases the data value and its usefulness to the user community. The extra spectral bands being included further enrich the data set and support additional applications of the data.

To radically change the way we use EO data we need to have different types of data coming together to increase the richness of the data set. Adding a "multi-dimension" to the data opens whole new ranges of applications and uses.

A simple example is the fusion of SAR and AIS soon to be deployed in several missions (NovaSAR, PAZ, Radarsat Constellation). The co-temporal capture of these two sets of data will allow the real time detection of non-cooperative AIS targets and allow coast guards an opportunity to intercept them. Figure 5**Error! Reference source not found.** demonstrates how SAR can be used with AIS, in this case using a prototype of the NovaSAR instrument flying on an aircraft and using coastal AIS receivers. Even in the well regulated environment of a southern England coastal town it was visible that several vessels were not broadcasting an AIS signal.

Figure 5: SAR+AIS from an aicraft flying the NovaSAR proototototype (Credit: Airbus DS)

The ability to use more than one set of data attracts different users and expands the application set for a mission. NovaSAR is a good example: although originally planned as a maritime, disaster monitoring and deforestation prevention tool, the inclusion of an

AIS receiver has made it a predominantly maritime surveillance system.

OPTISAR™

Based on its experience with using high resolution and medium resolution video imagers on the ISS, UrtheCast developed a portfolio of processing and analytics solutions for the EO user community. It was immediately recognized that there are limited available data sets, and most tend to be limited to optical medium and high resolution satellites and limited availability of SAR data. Existing services are non-coordinated making it almost impossible to capture co-temporal data and in most cases data is expensive and difficult to access. UrtheCast decided to create its own constellation, providing not only a high quality set of optical and SAR data, but one that also captured co-temporal data and can in this way add substantial value to the data. Given the complexity of the desired products, the only realistic way to deliver a system of this nature is to split the sensors by different satellites. Again constellations offer a solution by distributing capacity across the constellation.

The OptiSAR™ Mission Description

The OptiSAR™ Constellation comprises 8 tandem pairs of SAR and Optical Satellites divided into two orbit planes. The 4 tandem pairs will be equi-spaced around an orbit plane, where each tandem pair consists of a leading SAR satellite, which uses UrtheCast's SAR-XL technology for its payload, and a trailing Optical satellite that is following approximately 2 minutes behind the SAR satellite.

Figure 6 shows the OptiSAR™ tandem satellite pair configuration.

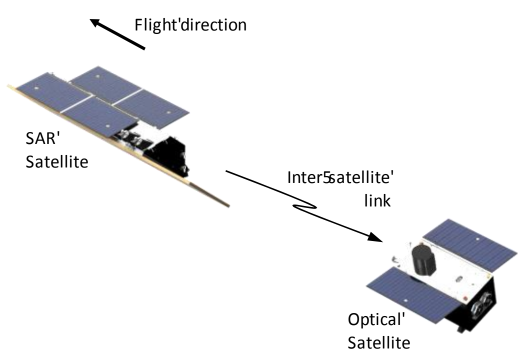

Figure 6: UrtheCast OptiSAR™ Constellation Tandem Satellite Pair

The first orbit plane is a Sun-Synchronous Orbit (SSO) with a 10:30 a.m. equator crossing time that is a commonly used orbit for Earth Observation missions, and the second plane is a Mid-Inclination Orbit (MIO) with a ~45 deg inclination. The MIO is used to provide ultra-high revisit in mid latitude regions of the earth where the bulk of the world's population reside. Both orbit planes have a satellite altitude of 450 km. The orbit plane configuration and the satellite phasing within each orbit plane is given in Figure 7.

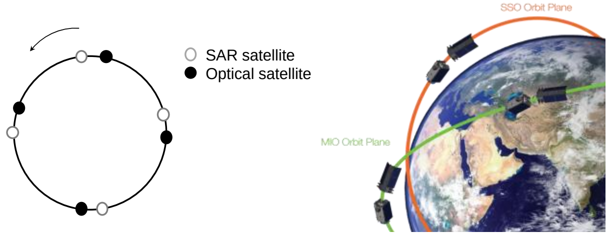

Figure 7: Arrangement of SAR–Optical Pairs in Each Orbital Plane

The OptiSAR™ constellation represents a capability shift in space-based remote sensing. The optical satellite uses a high-resolution (0.5m GSD) dual-mode (multi-spectral pushbroom and RGB colour video) optical camera, while the SAR satellite uses UrtheCast's SAR-XL technology that provides a dual-band (X-band and L-band) SAR instrument configured with 6 fully independent apertures. The SAR-XL payload provides 1-metre class X-band (VV polarization) imagery and 5-meter class fully polarimetric L-band imagery.

OptiSAR™ optical satellites

The optical satellite shown in Figure 8: The OptiSAR™ Optical satellitesFigure 8 is a highly agile, high resolution Earth Observation platform originally based on the SSTL300 system, but given the need to service a large complex imager it is a 700kg class satellite. Although a "large" satellite, its core architecture is the same as the SSTL300 and largely uses similar avionics.

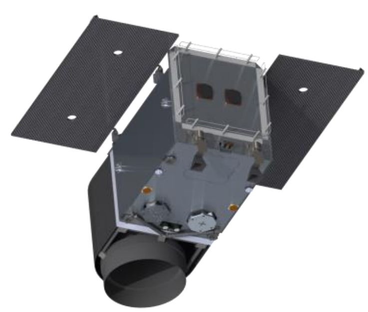

Figure 8: The OptiSAR™ Optical satellites

It will fly a High Resolution Camera designed and built by SSTL with a seven band push broom still camera, plus a colour video, as described in Table 1.

The HRC-DM includes a focus mechanism that allows focus after launch to compensate for barrel moisture outgassing and seasonal focus to maintain MTF performance. This has been successfully used in previous SSTL satellites and focus mechanisms are now routinely used in high resolution missions.

The HRC-DM delivers pushbroom strips of up to 8.5 minutes (equivalent to ~3600km strip length on ground) as well as supporting area & stereo modes and video modes. Additionally the satellite also flies a meteorological camera, known as the MetCam that supports atmospheric correction in the ground post-processing of the imagery captured by the HRC-DM.

Each satellite has on-board data storage for 3 TBytes of non-volatile flash memory and it supports JPEG-LS or JPEG-2000 compression with variable compression ratios up to 5:1. Each satellites has two X-band data transmitter, using together to deliver 2 x 800 Mbps using cross-polarised antennas.

Parameter	Value
Aperture	0.56 m
Swath width	12.28 km (pushbroom) 1.9 x 2.5 km (video)
Ground sampling distance (Native)	0.5 m PAN, 1.0 m MS 0.5 m Video
Spectral Bands - Pushbroom	Panchromatic Blue, Green, Red, NIR, Red-Edge, Yellow
Spectral Bands - Video	RGB
Video frame rate	30 fps

Table 1: OptiSAR™ HRC-DM imager specifications

OptiSAR™ SAR satellites

The OptiSAR SAR satellite is a dual frequency X and L band SAR, built around the SAR-XL payload that is the world's most technologically advanced SAR. There is no SAR operating or under development that embodies all of the capabilities and technologies of the UrtheCast SAR-XL in a single instrument. Additionally, the satellites carry an S-band inter-satellite link to the optical spacecraft (Tx only) providing processed data to enable autonomous scheduling on board the optical S/C for cloud optimisation/avoidance and maritime surveillance.

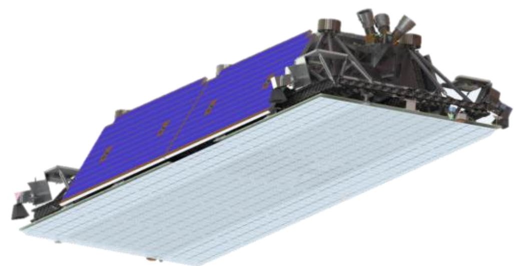

Figure 9: The OptiSAR™ SAR satellites

The design of the satellite started with a standard SSTL300 as the basis bus, but given the size of the instrument and the power requirements has evolved to a large platform, of around 1.8t of mass. The core avionics and architecture are directly derived from the SSTL300 series and are common to the Optical satellites, allowing for communality of operational concepts. This together with the re-use of the avionics design allows for a significant reduction of the cost of the satellite. The production of a series of these satellites at the same time as the optical satellites further reduces the cost.

The SAR-XL technology is the world's first dual-frequency, quad polarization, multi-aperture, fully-active phased-array and all digitally-beamformed (in both azimuth and elevation) space-based Synthetic Aperture Radar (SAR). The SAR-XL instrument is architected and designed to be highly flexible in terms of operational beam modes and also modular in nature so the antenna can be sized to achieve the performance required. Each aperture is essentially a complete SAR instrument unto itself, so that the SAR antenna can be made up of a selected number of individual apertures. The flexibility provided by the instrument can serve a wide variety of applications that includes commercial geoanalytics applications such as crop monitoring, forest structure modelling and biomass estimation, soil moisture retrieval, as well as very high resolution surveillance and wide-swath maritime domain surveillance for ship detection, ice monitoring and ocean winds.

The SAR-XL instrument has a dual-frequency (L & X band) shared aperture phased-array antenna, driven by multiple digital receiver-exciters. Each antenna aperture segment is 1.8 m (in elevation) x 1.0 m (in azimuth). The OptiSAR™ constellation SAR Satellite uses an antenna with 6 dual-frequency apertures, although the SAR-XL design is scalable and can accommodate any number of apertures in principle. For example, a configuration with 16 apertures is possible with the current hardware.. These apertures are combined digitally to form the transmit beam, and to form multiple simultaneous receive beams, in both azimuth and elevation.

This architecture, as well as other features of the multiple digital receiver exciters, results in a Multi-Aperture Multi-Frequency Digitally Beamformed SAR with full Multi-Input-Multi-Output (MIMO) capabilities. To further extend the dimensionality of the trade space that this MIMO SAR architecture enables, SAR-XL takes the MIMO architecture further, providing digital simultaneous beamforming of multiple azimuth and elevation beams, at both X-Band and L-Band, from the same aperture. It is these capabilities that allow a relatively small antenna to meet the requirement of wide swath surveillance modes without excessive range ambiguities.

The SAR-XL dual-frequency shared aperture antenna uses highly efficient radiators integrated directly into the structural elements in such a manner that every piece of metal forms multiple functions of electromagnetic radiation, power distribution, structural strength, and thermal management. The antenna itself is also the support structure for the electronics units

SAR-XL Beams and Modes Specifications

The UrtheCast OptiSAR™ constellation will fly a 6 aperture configuration SAR-XL resulting in an antenna 6m in length (azimuth) by 1.8m (elevation). This configuration of the SAR-XL instrument has been modeled and analyzed in detail, and the models were confirmed by ground tests of the prototype antenna. The baseline beam modes are illustrated in Figure 4 with a brief description provided below.

SpotLight Mode products will have a nominal scene size of 10km (cross-track) by 5km (along-track) with an X-band ground resolution as fine as 1.0m by 1.1m (Range x Azimuth), typical ambiguity ratios of -25dB and typical NESZ of between -20dB and -24dB.

Multi-Aperture StripMap Mode products will have a nominal swath width of 7.5km with an X-band ground resolution as fine as 1.0m by 1.0m (Range x Azimuth), typical ambiguity ratios of -19dB and typical NESZ of between -19dB and -23dB. The multi-aperture stripmap mode products have approximately the same resolution as spotlight mode products, but they are capable of yielding long strips providing much greater coverage.

Dual-Band StripMap Mode products will have a nominal swath width of 10km. The X-band ground resolution will be 1.0m by 3.5m (Range x Azimuth), with typical range ambiguity ratios of -20dB to -25dB, typical azimuth ambiguity ratios of -19dB to -22 dB, and typical NESZ of between -23dB and -26dB. For single, dual and compact polarizations, the L-band ground resolution will be 7.5m x 7.5m, with typical ambiguity ratios of -22dB and typical NESZ of between -23dB to -26dB. For L-band quad polarization, the swath width will be 7.5 km and the ground resolution will be 16m x 7.5m (Range x Azimuth), with a typical range ambiguity ratio of -26dB, typical azimuth amibiguity ratio of -21dB, and a typical NESZ of between -28dB and -30dB.

ScanSAR Mode products will have a nominal swath width of 140km, with an L-band ground-range resolution of 30m by 30m (Range x Azimuth), typical range ambiguity ratio betweeen -21dB to -24dB, typical azimuth ambiguity ratio between -19dB to -22dB, and typical NESZ of between -23dB to -26dB. In addition there are ScanSAR modes optimized for Ship Detection that have 225 km swath widths and have very good ship detection performance in high sea states (e.g., sea state 5).

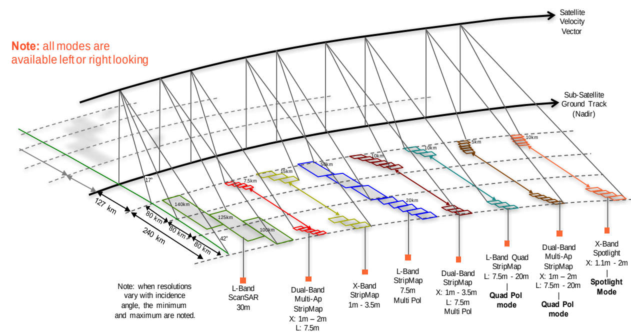

Figure 10: SAR-XL Beam Modes

OptiSAR™ CONOPS

A key feature of the OptiSAR™ constellation is the cross-cueing capability between the SAR and optical satellites which enables the system to have a wide swath surveillance mode with the SAR satellite and, using onboard processing, detect and classify objects of interest (e.g., ships), and then automatically task the optical satellite to take a high-resolution image or video of the selected objects within 2minutes.

CONCLUSION

The ability to build constellations of satellites dramatically improves their usefulness, be it by significantly increasing the temporal resolution of the system, or by allowing the deployment of complex systems that would not be possible with single satellites. In the case of OptiSAR™, the ultimate goal is to combine these two facets: combine formation flying optical-SAR pairs, with a sufficient total number of satellites to provide good temporal resolution.

Building large constellations of this type requires low cost technical solutions, capable of handling the large and complex payloads that are required to achieve the performance. Re-using existing designs and keeping the system design simple, whilst keeping focus on cost effective choices, allows the business case for these constellations to close.

A constellation like OptiSAR™ will deliver a paradigm shift in the use of EO data: "multi-dimensional", rich EO data will become available to the user community, allowing a new set of analytics to be derived of satellite borne data. And at an affordable price!

References

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