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Design Drivers for a Viable Commercial Remote Sensing Space Architecture

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ABSTRACT

Private sector investment into new commercial remote sensing constellations over the past five years has exceeded \$1B. The capabilities of these systems—many still in development or at pre-initial operational capability (IOC) thresholds—are intended to address a combination of new or underserved global markets. Additionally, the combination of ever-increasing technical collection requirements with static programmatic resources, has now driven historically traditional space system operators to embrace hybrid architectures that leverage commercially-sourced data into their service baselines. While enticing to many new entrants, many considerations must be practically addressed to field an enduring, commercially viable space architecture solution. Foremost it must deliver the expected type of data at sufficient quality that can be directly utilized by established users already sourcing other (typically exquisite) collections. Delivery of this capability must also necessarily be resilient, with business continuity secured through a mixture of customers that transcends venture-backed investments to a posture of sustained profitably. In 2017, Maxar (then operating as DigitalGlobe) decided to proceed with the self-financed development of a new \$600M Earth observation constellation comprised of six high-resolution satellites that are only 30% of the weight of the prior generation, but leverage technological advances for affordability and performance. Before doing so, however, a rigorous system engineering and business analysis study was undertaken to thoroughly understand customer key performance parameters (KPP) and design drivers to be addressed to ensure a delivered combination of product-market fit, flexibility/adaptability to evolving requirements, and overall capital efficiency. In this paper, we describe this effort to develop our design baseline and the corresponding operational commercial remote sensing constellation that will achieve its new IOC in 2021 to directly support both dedicated commercial and hybrid mission operator architectures.

INTRODUCTION

Maxar has been operating the industry's highest resolution commercial remote sensing systems since 1999, with the launch of Ikonos, and today operates four satellites: WorldViews 1, 2 and 3 along with GeoEye-1 (Figure 1). With over \$1 billion of revenue in our Earth Intelligence business, and with customers around the world—including national governments—who rely on our ability to continue to serve their needs, in 2017 we began planning our next generation satellite constellation, WorldView Legion.

We had four driving requirements. First, we had to assure continuity, which meant continuing to offer the highest resolution and most accurate commercial satellite imagery in the industry with collection and

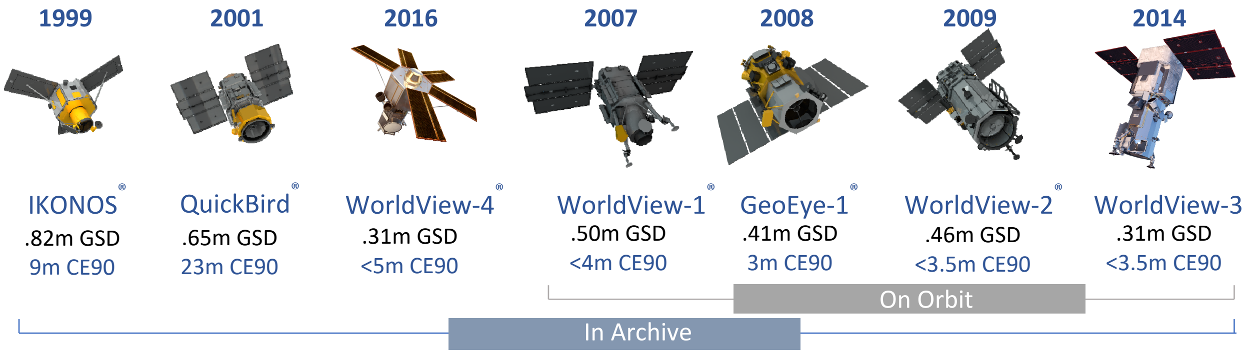


Figure 1. Maxar operates the industry's highest resolution commercial remote sensing satellite constellation, and has been doing so since 1999.

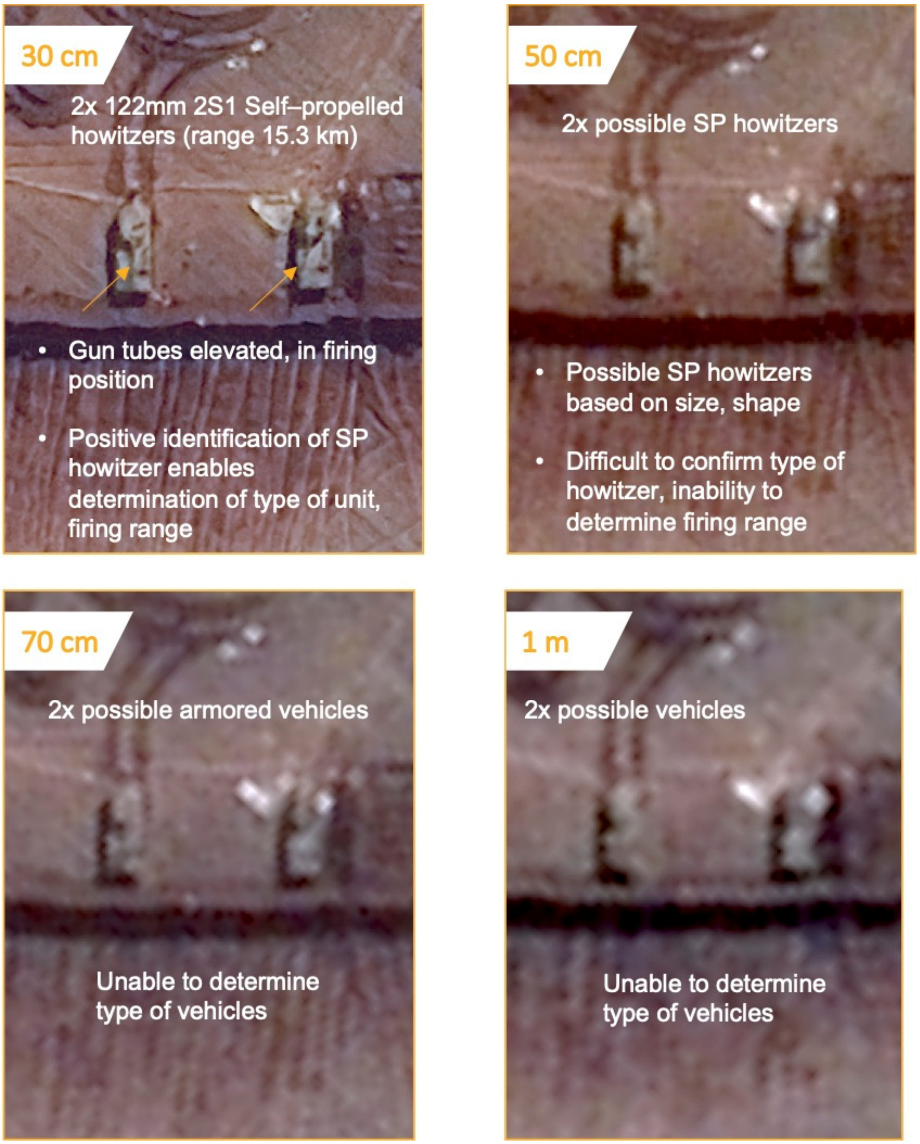


Figure 2. Only 30 cm resolution has sufficient detail to draw a meaningful conclusion about the type of military equipment in this image.

delivery characteristics matched to customer needs, and to begin launches in 2021. Second—as we will describe later—the land surface area of the planet is not uniformly interesting to paying customers. As a result, we wanted to maximize our imaging capacity over the parts of the world that would generate the most revenue, and to provide synoptic (contiguous) coverage of sufficiently large areas. Third, not everything happens at 10:30 AM, so we wanted to have the ability to image from dawn to dusk throughout the day. Fourth—and most importantly—since we're in business to be profitable, we had to do all of this for less than our previous constellation cost, i.e., we had to be even more capital efficient, as this creates the capacity to further invest in growing our business.

ASSURING CONTINUITY TO MATCH CUSTOMER NEEDS

Foundational to our business is providing timely data of the quality and other characteristics that our customers need. Key parameters are resolution, positional accuracy, capacity, and the ability to support simultaneous imaging while downlinking that imagery.

Resolution

A management principle is that if you can't measure it, you can't manage it. In the world of satellite imaging, if you can't recognize it, you can't react to it—or you may be reacting to the wrong thing. Figure 2 provides an example of where 30 cm ground sampled distance is required, and we are increasingly seeing customer use cases across a wide range of industries that similarly require this level of spatial resolution. Moreover, it's not enough just to have a small pixel size; the optical system has to provide sufficient resolution, there must be enough signal, and blur induced by all other optical or spacecraft disturbances must be kept in bounds.

This led us to require a system modulation transfer function (MTF) with a geometric mean of 9-10% at Nyquist. Image quality also drove a signal to noise ratio of >120 at a 15 degree sun elevation angle for a 15% reflective object in our panchromatic band; this was particularly important in light of our orbit choices as discussed subsequently. We had a parallel set of requirements for our 8 multispectral bands—which not only enable pan-sharpening but also a range of applications that utilize spectral analysis—including the ability to precisely align these bands with the Pan band, but to keep this discussion simple we are focusing just on the Pan band.

Positional Accuracy

For applications ranging from mapping to targeting, it's not enough to have high resolution, but it is also essential to know the precise location of each pixel in an image on the ground. Historically we have required that our systems be able to support a 5 meter CE90 for each individual image, with the ability to post-process to 1 meter CE90 when suitable elevation data is available. Figure 3 illustrates why this is important.

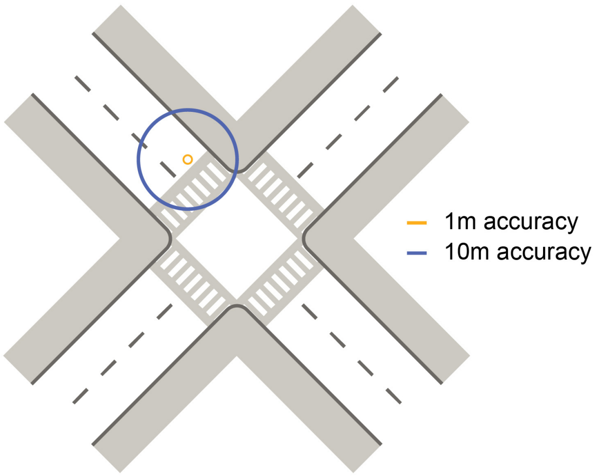


Figure 3: Good positional accuracy is essential for modern applications such as base layers for autonomous vehicles.

This drove the choice of attitude and position navigation instruments on the spacecraft, calibration stability requirements, timing requirements, and certain aspects of ground processing software. At this level of accuracy, it's simply not practical (or even possible) to skimp on the on-board navigation instruments and register against an accurate, global base layer—particularly as we are in the business of providing that accurate, global foundation base layer in the first place!

Collection Capacity

It's one thing to build a satellite capable of taking a single picture, but one can't build a business from that unless that one picture is unbelievably valuable—and to date, nobody has stepped up willing to pay the necessary price! To make money, a satellite constellation needs enough daily collection capacity to deliver a return on the investment required to build the constellation given the price customers are willing to pay for that capacity. It also has to be the right capacity in the right regions (and at the right resolution), which we will discuss in the next section. How much capacity? Fortunately, we have an excellent demand indicator—Maxar's current collection capacity, which customers are paying for today. This sets a floor for the required system capacity. There are also regions where there is even more demand for capacity, so our goal was to maximize capacity in those regions.

Simultaneous Imaging and Downlink

While much of the world accesses services via the Internet, this isn't always an option, particularly for defense customers. Maxar serves a number of allied governments around the world who need the ability to directly receive imagery from satellites along with the ability to uplink tasking requests to them. Additionally, we support mobile ground stations with similar functionality. This use case drives the need for our satellites to be able to image and downlink simultaneously (and independently), as illustrated in Figure 4.

Broadcasting omnidirectionally is both power inefficient and a spectrum hog, so this drove the requirement for a narrow beam, high data rate downlink that can be pointed independently from the instrument, and the associated mechanical stability required so that pointing this downlink does not induce jitter that blurs the images being taken at the same time. Given that spectrum bandwidth is finite, being able to simultaneously downlink while imaging allowed us to maximize the amount of imagery we could collect and transmit in a single pass. It was also superior to approaches that divided time between imaging and downlinking (such as body pointed antennas) because it allows us to maximize the time spent in revenue producing activity (imaging) by minimizing unneeded maneuvers.

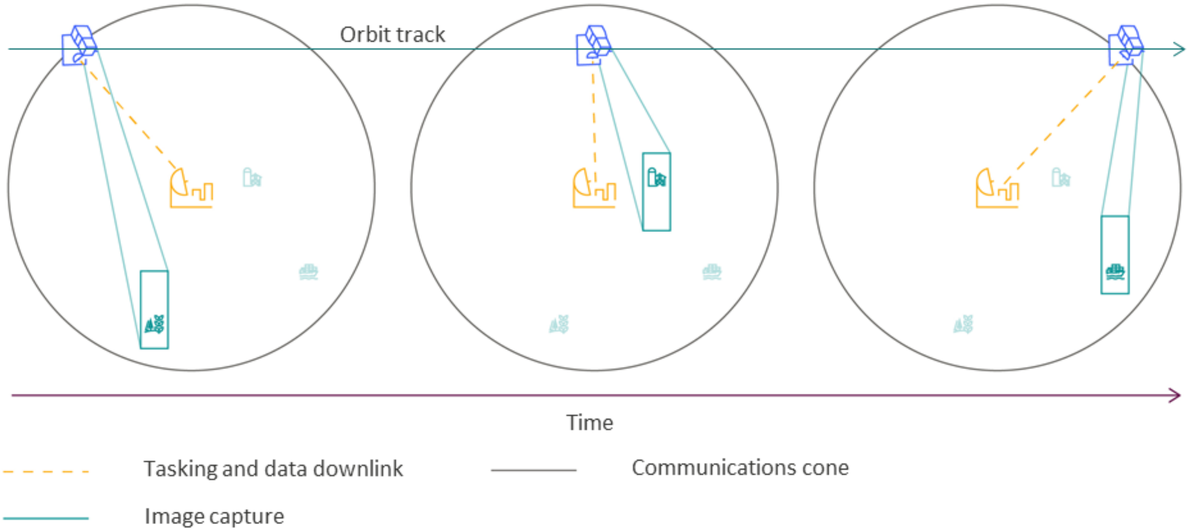


Figure 4. Supporting simultaneous imaging and downlink to a customer site requires a narrow beam down-link antenna that is independently steerable from the primary sensor. This enables the sensor to point at successive targets while maintaining contact with the ground station.

Maximizing Monetizable Imaging Capacity

The world is not uniformly interesting to paying customers, nor does it change with uniform frequency. Roughly 8% of the Earth's land is populated, and over 50% of the population lives in 0.6% of the land[1]. The highest rate of change occurs where humans live (as illustrated in Figure 5), which drives collection frequency requirements. Roughly 95% of the world's population lives in the band ±50° latitude[1]. And while global mapping requirements create a need for global coverage, less than 10% of the land surface of the planet drives nearly all customer demand as weighted by revenue. This nonuniformity of demand drove two key requirements: synopticity and a mix of sun-synchronous and mid-inclination orbits.

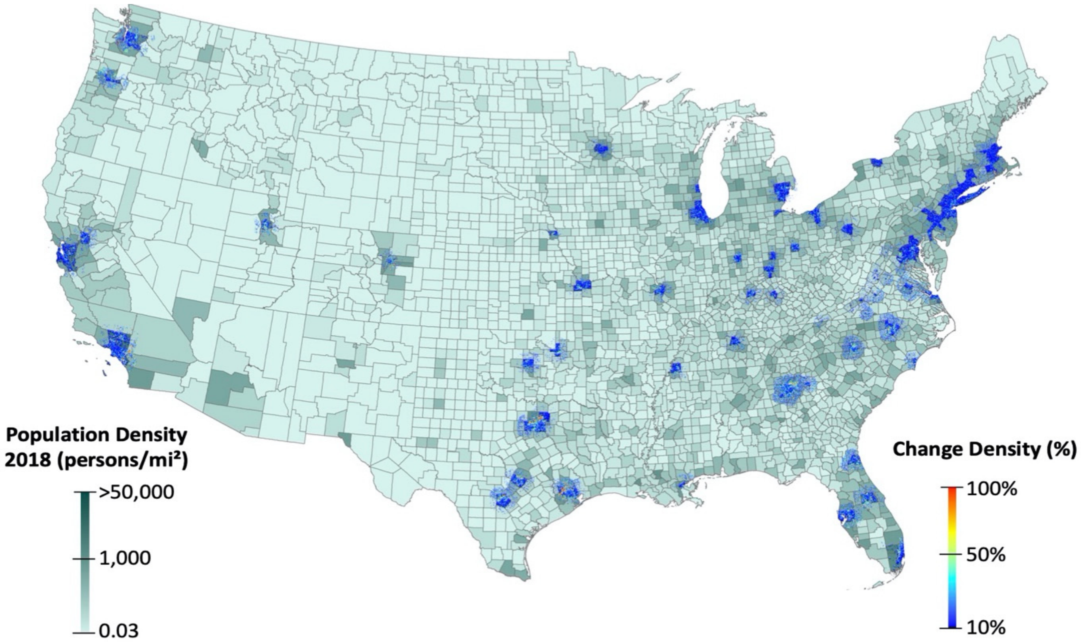


Figure 5. The most frequent change occurs where most people live, as illustrated by this sample of Maxar's Persistent Change Monitoring product, from a family of change products we have been providing to the US Government for over two decades.

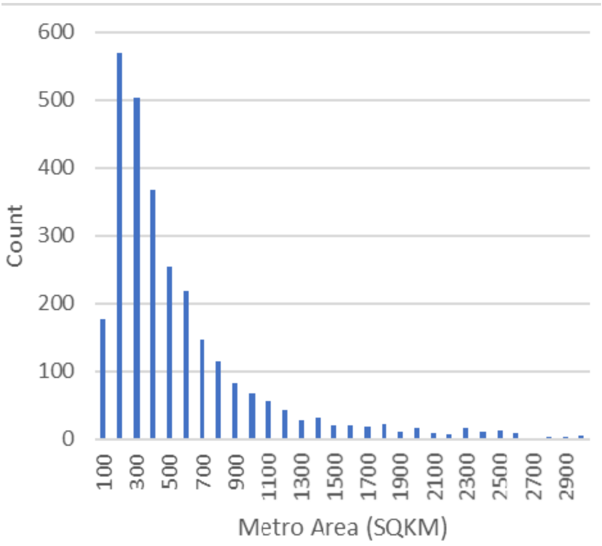


Figure 6. Most metropolitan areas are hundreds of square kilometers, driving requirements for synoptic coverage to enable consistency in change detection.

Synopticity

Demand is clustered. For example, Figure 6 shows the size distribution of urban areas. If one is mapping to identify change, it's important to capture the entire area at once, or at least within the time constant of the change that is being measured. This is particularly important when one is tracking activity, whether it is commercial or defense; if you can only see part of an area at a time, it's next to impossible to keep track of moving objects. Only with synoptic coverage is it possible to get an accurate snapshot of all activity in a given area, as illustrated in Figure 7. This led to a requirement for single satellite synoptic coverage of 6000 square kilometers at National Imagery Interpretability Rating Scale (NIIRS)[2] 5 or better.

Having such synopticity has already been very useful for Maxar, enabling us to capture the hardest hit areas of the Bahamas in a single pass after Hurricane Dorian, the entire country of Qatar in a single pass in preparation for an event, and numerous defense use cases as well.

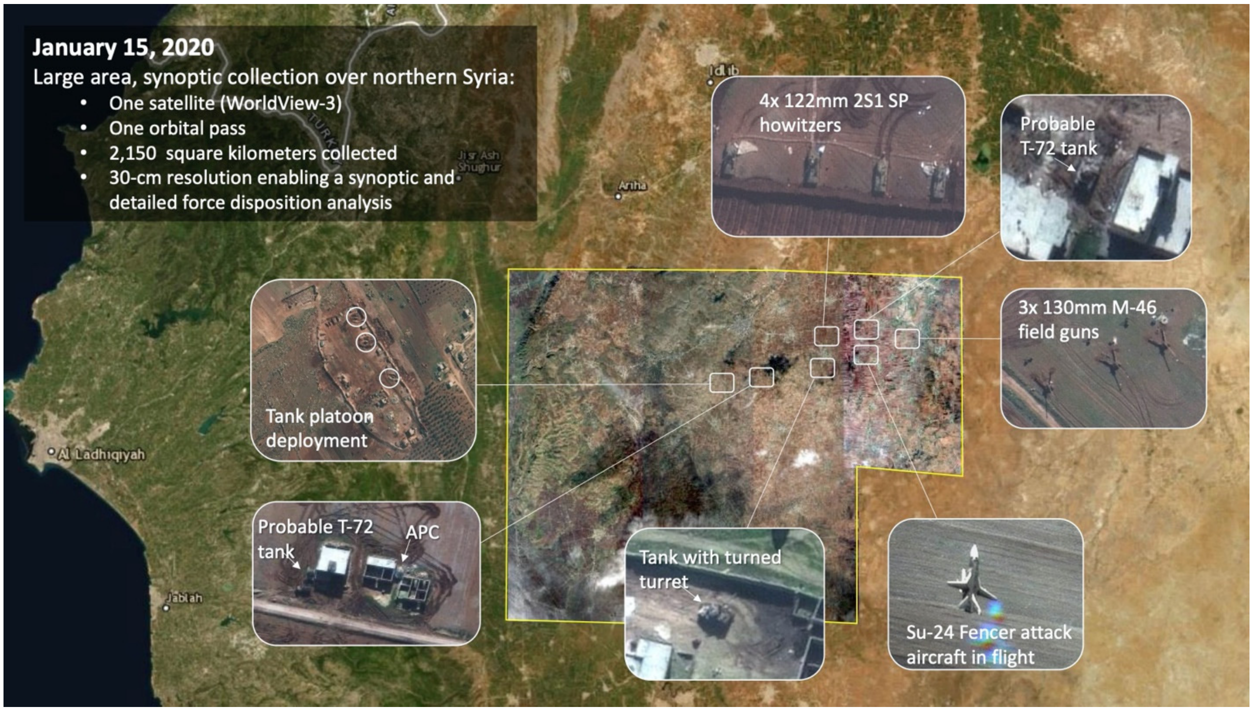


Figure 7. Synoptic coverage makes it possible to reliably inventory a set of mobile targets for force disposition analysis.

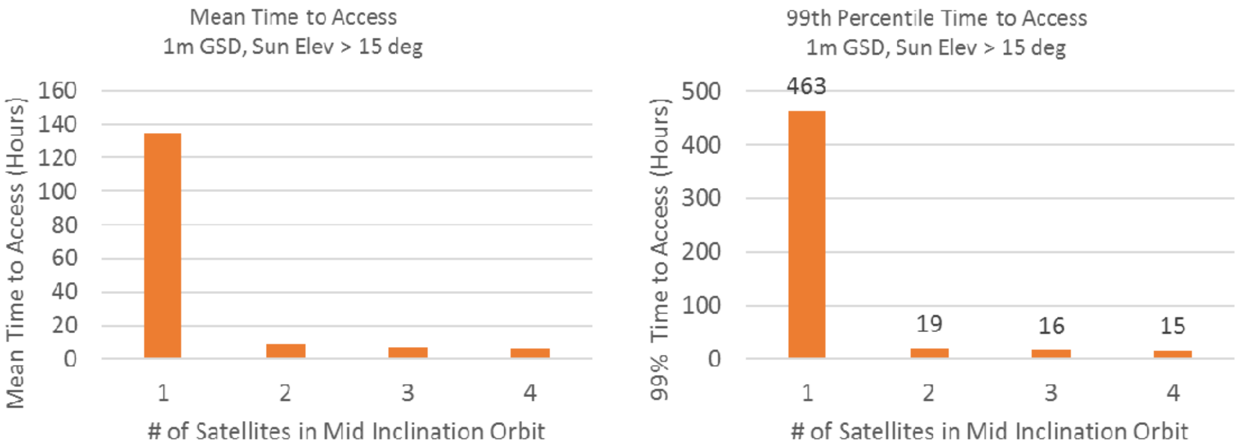


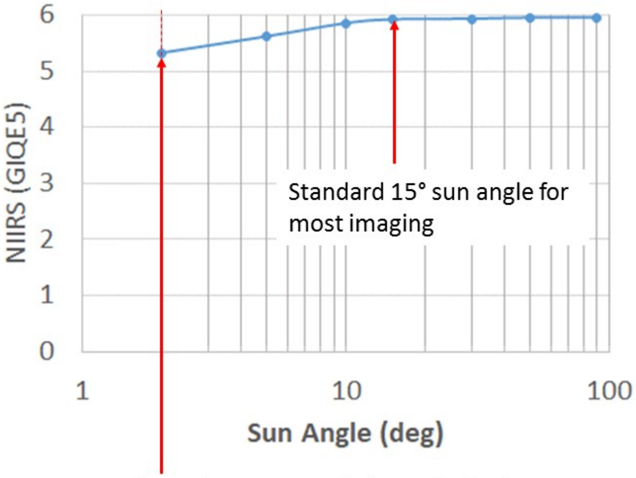
Figure 8. At least two satellites are required in mid inclination orbits to avoid long "blackout" (eclipse) periods of low sun angle imaging. More than two satellites provide resiliency, as well as more diversity in sun elevation angles.

Mid-Inclination Orbits

Satellites in sun synchronous orbits spend much of their time outside of the ±50 degree latitude band where most people live, and correspondingly those areas that are most in demand to be imaged. Mid inclination orbits spend much more of their time over the interesting parts of the planet, but because the local time of imaging varies (unlike a sun synchronous orbit), a single satellite will experience "blackouts" (eclipses) over a given geography, i.e., there will be multi day periods when it is only in view of that geography during local nighttime. This fact drives a minimum number of satellites as well as driving the required signal-to-noise ratio to assure good image quality across a range of sun elevation angles throughout the day.

Figure 8 illustrates the first point. With a single mid inclination satellite, there are multiday long blackouts. With two satellites that are 180 degrees out of phase, when one is in blackout, the other is able to image. This in fact was what Maxar (then DigitalGlobe) had planned with its original QuickBird system of two spacecraft, but when the first QuickBird was lost in 2000 due to a launch failure, the remaining QuickBird was placed into a sun synchronous orbit. Building in resiliency against loss of a satellite drives a desire for three or more satellites, which also provides more opportunity for imaging at a range of sun elevation angles, as well as requiring less re-phasing of the orbit RAANs in the event of a satellite loss. Maxar selected four mid inclination satellites for Legion, in addition to two sun synchronous Legions to provide coverage of the higher latitudes.

It was also important to ensure that image quality does not degrade at lower sun elevation angles, which contributed to our requirement for signal to noise ratio. By doing so, we were able to achieve high image quality (measured by NIIRS[2]) throughout the day, as shown in Figure 9, even for extremely low sun elevation angles.



For comparison, the sun was 2° above the horizon at Anchorage, Alaska (62.1°N) at 7:05 AM on 22 Sep 2017

Figure 9. The WorldView Legion sensor maintains high signal-to-noise ratio over a wide range of sun elevation angles, resulting in high image quality throughout the day for the mid inclination Legions.

Figure 10. With sun elevation above 15°, at 36°N latitude, on a representative day, the Legion constellation can image a point 6 times at ≤50cm (blue), 10 times at ≤1m (green), or 14 times at <≤1.3m (gold). There are ≥16 visits/day at 1.3m with sun elevation above 0 ("dawn to dusk").

PROVIDING INTRA-DAY REVISIT

The standard, historical orbit for earth observation satellites is a sun-synchronous orbit with a morning descending node; if you have only a single satellite, this clearly makes sense. The excellent reasoning for this goes back to the original Landsat program. A morning descending node optimizes for diurnal cloud cover to maximize cloud free viewing globally. A 1030 sun synchronous orbit further is late enough in the morning to provide good illumination for most northern latitudes during winter.

However, while a sun synchronous orbit only sees the ground beneath it at a single local time per day, activity happens throughout the day. Having multiple spacecraft in mid inclination orbits, which we settled on for reasons of optimizing capacity, has the added benefit of providing imaging opportunities throughout the day. The six satellite Legion constellation provides up to 14 revisits per day above 15° sun angle between 0.3–1.3 meter GSD at 36°N latitude throughout the day (Figure 10), with even more revisits at lower sun elevation angles which still provide good image quality as noted above.

DOING THIS ALL AFFORDABLY

With these top-level trades behind us, we then set out to perform a series of optimizations around the spacecraft, considering aperture, agility, field of view, sensor type, collection rate, downlink data rate, etc. These weren't performed in a vacuum, but rather were informed by cost data from our supplier base, since we were optimizing for the maximum revenue relative to system cost. For example, a larger aperture is generally better because it allows one to fly at a higher altitude to achieve a given resolution, which provides a wider field-of-regard and reduces angular agility requirements on the spacecraft—but it comes at a cost, which means that there is an optimum point in the price-performance curve, and this optimum point changes over time with changes in optics manufacturing technology. This allowed us to select an aperture for Legion that is slightly below 1 meter, compared with the prior WorldView satellites' 1.1 meter apertures.

The specifications for the Legion spacecraft design to support the mission were carefully developed. Foremost the system needed to support the tasking and collection requirements of the commercial remote sensing business. This is principally achieved through highly accurate, stable (low jitter), agile stellar-inertial attitude knowledge and control with >10 different pointing modes to accommodate various use cases. To deliver the return on investment (i.e., to avoid a too-rapid replenishment cycle), the spacecraft was developed for longevity and reliability using class B mission assurance standards[3]. Inherent to this baseline, Legion utilizes a fully redundant design, with rad-hard/tolerant level 1/2 electronic parts and high technology readiness level (TRL), flight proven, heritage subsystem hardware and software elements and test equipment, as well as proven processes for producing the specific elements unique for the mission (e.g., solar panel, structure). The integrated system uses the established Maxar best commercial manufacturing capabilities and supply chain management to ensure quality and consistency. The overall development program employed traditional system engineering practices, including robust testing, verification and validation processes, along with manufacturing to cleanliness standards appropriate for optical payloads and integrated EMI/EMC mitigations.

We implemented Legion's requisite system performance holistically, beginning with state-of-industry fully redundant avionics and heritage software that can be reconfigured on-orbit for both the spacecraft and instrument. Legion's configurable TTC and mission data architecture includes a gimbaled wideband mission data antenna and hemi/omni narrow-band communications with NSA Type-1/2 encryption. Robustly margined payload thermal control includes precision heater control, configurable conductive and radiative payload interfaces. Likewise, since the satellite is intended to be operated as part of a constellation, it includes propulsion for orbit establishment, maintenance, collision avoidance, and end of life (EOL) disposal. To maintain flexibility for both dedicated and secondary launch options, Legion is compatible with multiple prevailing vehicles (e.g., Falcon-9, Vega).

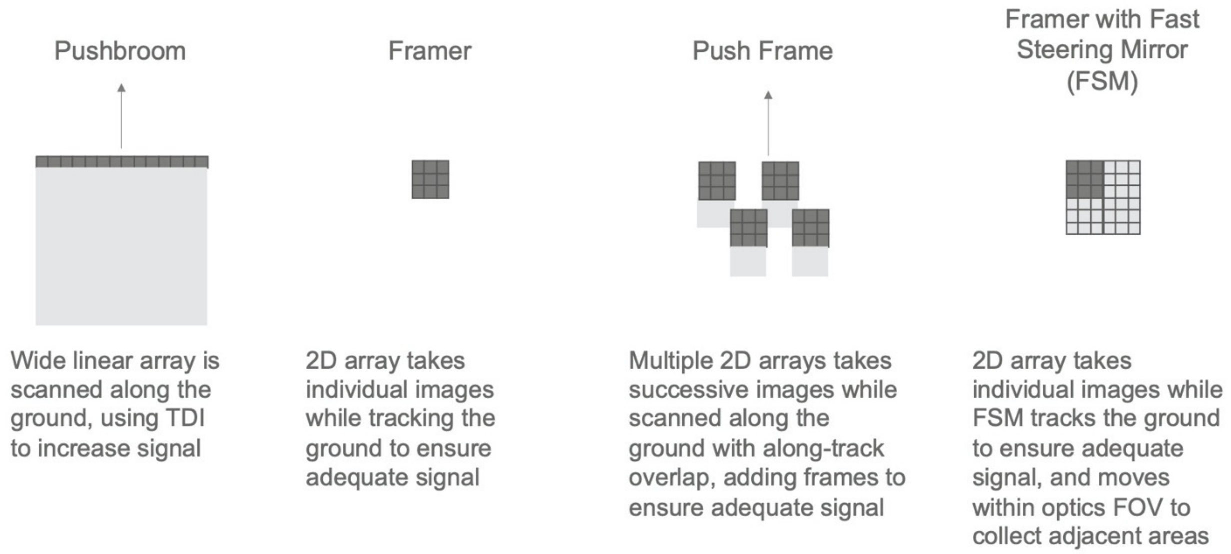


Figure 11. Maxar had to choose between using a pushbroom scanner, which uses a wide linear array, and one of several approaches that utilize large format 2-D staring arrays.

One trade was particularly instructive. Historically, Maxar satellites have used pushbroom scanners as these enable efficient area collection. However, the emergence of low-cost, large format area arrays has led some spacecraft designers to use them instead, in one of several modes as illustrated in Figure 11.

Table 1 illustrates the qualitative tradeoffs between these approaches. Maxar had used a version of push framer for its earliest (albeit unsuccessful) satellite, EarlyBird, back in 1997, as shown in Figure 12; we chose it for its low cost as EarlyBird was intended as an entry level capability. The pushbroom scanner has a much higher area collection rate, as shown in Figure 13, and this was the rationale for our having used it in all subsequent satellites.

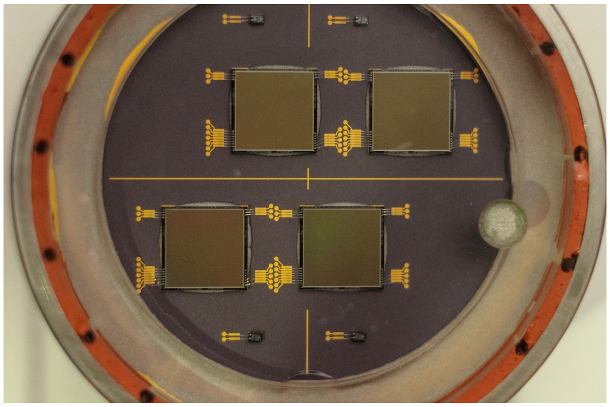


Figure 12. Maxar utilized a push framer in 1997 for its EarlyBird satellite, given that the low cost of this approach was appropriate for an (albeit unsuccessful) entry-level capability.

Table 1. A qualitative comparison of the pros/cons of various focal plane approaches is insufficient to determine which is more cost effective.

	Pushbroom	Framer	Push Frame	Framer with fast steering mirror
Required spacecraft stability	High	Low	Low	Low
Cost (sensor + spacecraft)	High	Very low	Low	Moderate
Area collection rate	Very high	Very low	Low	Moderate

However, to understand the current cost effectiveness of these approaches, it's easiest to compare two reasonably contemporaneous point designs: WorldView Legion and the Planet Skysat, since the costs for these have been described publicly[4,5]. Legion is a pushbroom scanner and the Skysat is a push framer.

Table 2 illustrates that despite the lower per-satellite cost of the push framer, the pushbroom approach is substantially more cost-effective at area collection.

Simply selecting pushbroom was not enough; we were challenged to make Legion even more cost effective than the prior generation of Maxar spacecraft. Table 3 shows what we were able to achieve. By doing a block build of six spacecraft, we achieved economies of scale and were able to amortize the non-recurring costs across the entire build. Use of more highly integrated electronics that are available today (vs in 2009) not only reduced size, weight and power but reduced the complexity of the interconnects between hardware units, simplifying assembly, integration and test. Optics manufacturing innovations have continued to drive down the cost of high quality telescopes; this also fed into our altitude and aperture optimizations.

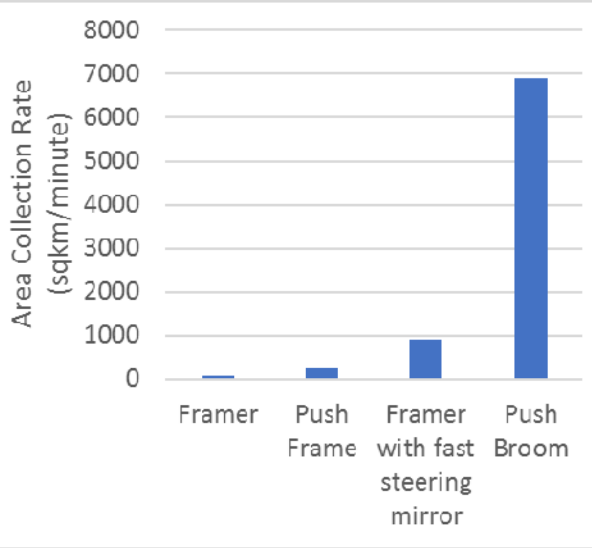


Figure 13. Pushbroom sensors have the highest area collection rate (all normalized to 50 cm GSD with comparable optics and satellite altitude).

Table 2. When normalized to 50cm area collection, the Legion pushbroom scanning approach is 7.5X more cost effective than the SkySat multi-chip framer approach.

	Legion (Pushbroom)	SkySat (Push Framer)
# satellites to collect 10^6 sqkm/day @ 50 cm GSD	1	75
Satellite lifetime (years)	> 10	<< 5
Amortized unit cost*	$100 million	$5 million[5]
Annualized cost** to collect 10^6 sqkm/day	< $10 million	> $75 million

* Amortized unit cost is total cost for the initial block, including non-recurring engineering (NRE), divided by number of satellites in the block.

**Annualized cost is amortized unit cost times number of satellites to collect 1 million sqkm/day, divided by number of years of satellite lifetime.

Table 3. WorldView Legion is significantly more affordable than the prior generation (WorldView-4) while offering superior product quality and capacity.

	WorldView-4	WorldView-Legion
Construction began	2009	2017
Per spacecraft mass (kg)	2500	750
Number of satellites per system	1	6
Total system cost*	$850 million	$600 million
Nadir resolution	31 cm	29 cm
Daily system capacity	1x	3x

*Total system cost includes NRE (all spacecraft, launch, ground system upgrades and insurance).

Competition in the launch market allowed us to procure two launches for what previously was the price of one. Further cost efficiencies were a result of well-tuned commercial practices such as a high engineering-to-oversight ratio that Maxar has used previously to build over 300 satellites for missions spanning communications to earth observation, deployed across LEO, MEO and GEO, for a broad array of commercial and Government customers. As has been previously discussed[6,7], Maxar is the world leader in production engineering of quality, affordable space systems; Maxar currently has over 90 geosynchronous communications satellites on orbit today operating with an availability of 99.9996%.

GETTING DATA TO THE USER—TIMELINESS OF SERVICE

To satisfy time dominant use cases, in addition to having higher revisit it is also important to be able to get that data to the ground—and into the hands of end users—quickly. We looked at several approaches:

- Leverage our existing global network of data downlink stations;
- Direct downlink to users; and
- Relay via satellite

There has been substantial progress in the latter area, such as the ESA/Airbus Space Data Highway[8], and we believe that this may eventually become a very useful tool in certain situations. Ultimately, however, for reasons both of cost and technological maturity, we chose to leverage the first method, in addition to continuing our support for direct downlink as noted previously. We are augmenting our existing global ground network to provide better coverage of the mid inclination orbits. This will maintain our current real-time coverage over 40– 45% of the landmass, with over 90% real-time coverage in the areas of highest demand. This ground network supports rapid delivery to the Maxar cloud environment, and feeds our online platforms such as SecureWatch and Global EGD which serve over 350,000 end users with a median delivery time of under 1 hour for high priority imagery, and as fast as 11 minutes. We have also demonstrated <1 minute from the time of imaging to availability within an AWS S3 bucket by leveraging Amazon Ground Station.[9]

MEETING A 2021 LAUNCH DATE

The typical spacecraft build cycle at Maxar is 24-36 months. Key to this is starting from the perspective of the desired schedule and then working backwards to a supply chain that supports this schedule. This involves a rigorous process of eliminating components that have a very long lead time as well as proactive inventory management, which is possible because of the number of satellites that we build. Also, by placing experienced engineers in positions of authority, we are able to make complex technical decisions rapidly. This is done without sacrificing quality; our mission assurance processes have consistently enabled us to achieve high on-orbit availability

The Legion spacecraft was placed on contract with Space Systems/Loral (SSL, now part of Maxar) in July 2017, and the instrument on contract with Raytheon in January 2018. The instrument critical design review (CDR) was held in late 2018 and the spacecraft CDR in mid 2019. We began spacecraft integration in November 2019, and are on track for our first launch in early 2021. Figure 13 shows a few examples of Legion hardware in various stages of construction.

CONCLUSION

Maxar is now into its 20th year of providing high-resolution, high-quality, high-quantity, space-based imagery to national and commercial customers around the world. It ushered in the “Age of Transparency” and forever changed the way we see, understand and monitor changes to our world. WorldView Legion is the latest addition to that 20 year history. Our conviction of the value that satellite imagery brings to the world is enabled by the choices we have made to create a profitable and self-sustaining business.

Acknowledgments

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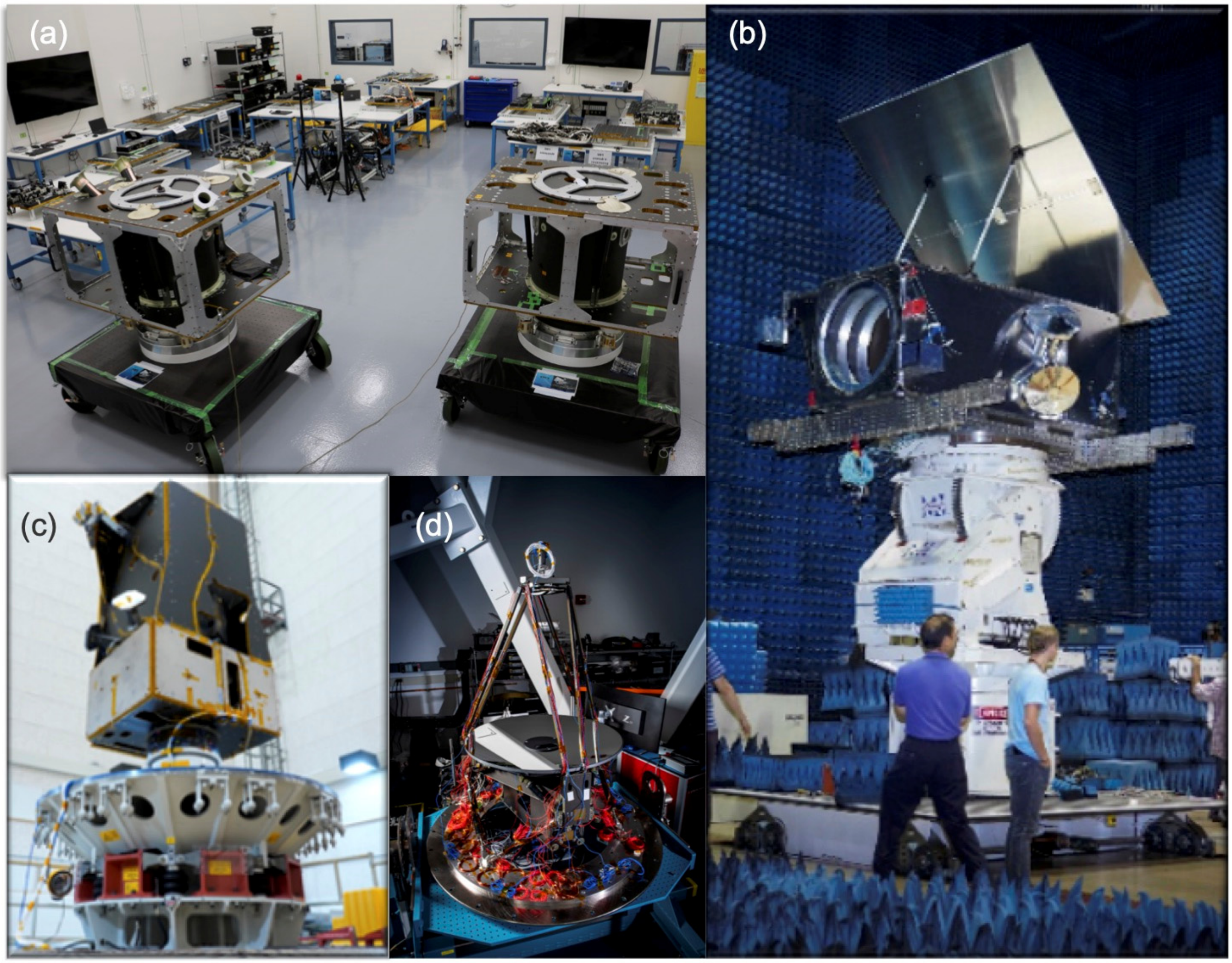

Figure 14. Legion hardware under construction. (a) Legions buses 1, 2 and 3 being integrated; (b) antenna pattern testing; (c) structure testing; and (d) Legion telescope.

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