RECOMMENDATIONS FOR POSSIBLE FUTURE U.S. GLOBAL LAND DATA COLLECTION MISSIONS BEYOND LANDSAT 9

A Report of the National Geospatial Advisory Committee
Landsat Advisory Group
April 2018

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Executive Summary

In August of 2017, the U.S. Geological Survey (USGS) requested that the Landsat Advisory Group (LAG), a subcommittee of the National Geospatial Advisory Committee, provide recommendations in regards to possible future U.S. Global Land data collection missions beyond Landsat 9, which is currently planned for a launch in late 2020. The USGS asked that the recommendations be submitted in time to support a significant U.S. Government architecture review process anticipated to start in mid-2018, and that the recommendations consider:

1. Capabilities that are complementary to the expected capabilities of the commercial remote sensing industry, as well as the European Union's Copernicus Program, including discussion of utility and limitations for leveraging cubesat and smallsat technology,
2. Technical feasibility and application value of enhanced collection capabilities while maintaining continuity with historic and current Landsat system capabilities and applications, and
3. Opportunities for public-private partnerships (P3).

The following text summarizes the Landsat Advisory Group's findings and recommendations regarding these tasks. The findings and recommendations are numbered according to the relevant task (1-3 above).

Findings

- 1.a. None of the current smallsat or cubesat satellite systems deployed to date have the technical capabilities required by the thousands of researchers, government agencies, NGOs, and commercial companies who rely on Landsat continuity for research and operational decision making. While the smallsats and cubesats may exceed Landsat capabilities in spatial resolution and/or revisit time, none of these satellites currently have sensors with the needed spectral bands, calibration stability, or swath area required by tens of thousands of U.S. Landsat users.
- 1b. Commercial systems to date have targeted a higher spatial/temporal resolution market niche which is not served by government systems with free and open data policies such as Landsat, Sentinel-2, GOES, or MODIS.
- 1c. Unlike Sentinel and Landsat, none of the commercial providers offer imagery worldwide without use restrictions and at no cost, an important consideration for researchers and agencies relying on Landsat and Sentinel to support operational decisions.
- 1d. Landsat and the Copernicus Program's Sentinel-2 multispectral bands are very similar and can be used in combination with one another. However, only Landsat provides moderate resolution thermal imaging capabilities.
- 2a. Possibilities for enhanced capabilities for future Landsat Missions while maintaining continuity include maintaining current Landsat capabilities at lower cost by leveraging emerging technologies, adopting the Copernicus acquisition model for cost savings, increasing temporal and spatial resolutions, and improving Landsat spectral resolution.

3a. Public-private partnerships are successful only when there is a non-government required product with sufficient demand to generate significant commercial revenue for the private partner, and the public partner agrees to not make that product freely available.

Recommendations

2a. The U.S. Government should aggressively investigate rapidly emerging and increasingly proven technologies which could greatly reduce the cost of Landsat missions. Included in this investigation should be consideration of smaller satellites with Landsat 8/9 Operational Land Imager (OLI)-like performance along with free flyer thermal missions to maintain continuity in Landsat thermal measurements. As a test, it is recommended that the U.S. Government consider placing a thermal sensor on a dedicated free flyer companion satellite to one of the existing Sentinel-2 systems. Additionally, it is recommended that a study be undertaken to determine if additional Clouds, Aerosols, Vapors, Ice, and Snow (CAVIS) bands or input from a suitable auxiliary lower resolution satellite, could be used to reduce costs associated with sensors for radiometric calibration.

2b. Too many critical U.S. research and operational programs rely on U.S. leadership in moderate resolution earth observations for the U.S. to cede its leadership in moderate resolution earth observations to the European Union's Copernicus Program. Maintaining U.S. homeland, food, and environmental security are all dependent upon the Landsat program. However, the U.S. should continue to work closely with the European Union to better harmonize the Landsat and Sentinel data sets, obtain economies of scale where possible and share lessons learned. The Copernicus approach of building multiple satellite constellations at once and launching them over time should especially be investigated to reduce development and acquisition costs per satellite.

2c. Regarding the capabilities of Landsat 10, it is recommended that:

- The Landsat 10 ground sample distance be set to 10 meters or larger, so as to increase compatibility with Sentinel sensors, ensure wider swath widths, increase coverage, and reduce overlap with commercial providers.
- The U.S. Government should investigate the benefits and costs of increasing Landsat spectral resolution.
- From the standpoint of continuity with previous Landsat missions for change monitoring applications, wide swath scanning sensors are probably preferable in that they offer greater synopticity (simultaneous collection of large areas).

3a. The U.S. Government should conduct a market study to determine if sufficient demand exists to support exploration of the creation of a public-private partnership where the contractor provides two or more tiers of data - one meeting U.S. Government Landsat technical requirements for open and free distribution, and others that provide "superior" data which is sold to users, thereby creating a sufficient revenue stream to offset at least some of the costs of building and operating the system. If this model is pursued, the Government must ensure that there is an equitable balance of risk between the Government and its private sector partner.

Introduction

For most of its long 45 year history[1] the Landsat data has been unique in providing free or low cost moderate resolution (10m-100m) multispectral imagery with regular 16 day global coverage. USGS's decision in 2008 to make Landsat data freely available to the public has set global expectations for the availability of free high-quality imagery, and sparked a wave of commercial activity based on this opportunity. Providing an estimated $1.79 billion dollars/year of value to U.S. governmental, commercial, academic, and non-governmental organizations (Miller et al, 2012), Landsat has continually been "the gold standard of remote sensing from space" (Castle, 2012). Commercial U.S. satellite image analysis companies Orbital Insight, Descartes Labs, SpaceKnow, GDA Corporation, Esri, and U.S. commercial satellite companies DigitalGlobe (now part of Maxar Technologies), Planet, AstroDigital, BlackSky and others all provide Landsat imagery through their platforms and offer various levels of value-added products based on the Landsat public imagery. The success of the Landsat program has also inspired similar non-U.S. satellite systems, primarily the European Space Agency (ESA) Copernicus Program Sentinel-2 satellite constellation, and a new generation of commercial satellite constellations like the RapidEye small-sat, SkyBox small-sat and Dove cube-sat constellations (all developed or acquired by Planet), that provide higher spatial resolution and better temporal coverage than Landsat, though with reduced spatial coverage per image and reduced spectral capability. Any future Landsat capabilities must be considered within this dynamic and complex market.

In August of 2017, the USGS requested that the Landsat Advisory Group (LAG), a subcommittee of the National Geospatial Advisory Committee, provide recommendations in regards to possible future U.S. global land data collection missions beyond Landsat 9, which is currently planned for a launch in late 2020. The USGS asked that the recommendations be submitted in time to support a significant U.S. Government architecture review process anticipated to start in mid-2018, and that the recommendations consider:

- Capabilities that are complementary to the expected capabilities of the commercial remote sensing industry, as well as the European Union's Copernicus Program[2], including discussion of utility and limitations for leveraging cubesat and smallsat technology,
- Technical feasibility and application value of enhanced collection capabilities while maintaining continuity with historic and current Landsat system capabilities and applications, and
- Opportunities for public-private partnerships (P3).

This report first reviews current Landsat capabilities within the context of existing government and commercially operated satellites. It next discusses potential future Landsat capabilities given expected advances in technology and a need to maintain data continuity with past and current Landsat mission data. The third section of the report summarizes different models for public-private partnerships that could potentially be used in future Landsat missions.

[1] From 1985 to 1992 the U.S. government experimented with commercializing Landsat data. During this period, Landsat imagery was expensive ($4400/scene) and use was license restricted.
[2] Please see http://ec.europa.eu/growth/sectors/space/copernicus/ for in depth information regarding the Copernicus Program.

Current Capabilities

Remote sensing system capabilities are typically categorized by technical characteristics such as area coverage, spatial accuracy, and spatial, spectral, and temporal resolutions, as well as organizational characteristics such as pricing and licensing. This section of the report compares current Landsat capabilities to those of the space based commercial remote sensing industry, as well as the European Union's Copernicus Program Sentinel-2 satellites. It includes a discussion of utility and limitations for leveraging cubesat and smallsat technology to meet Landsat user requirements. Please see http://learngis.maps.arcgis.com/apps/MapSeries/index.html?appid=f01fba8fa601497092a183d1a31788f7&entry=5 for a comparison of these systems to one another. Approximate costs to build and launch these systems range from $855 million for a Landsat type satellite, $500-800 million for Worldview satellites, $250-300 million for a Sentinel 2 satellite, several million dollars each for RapidEye and Skybox smallsats, and less than a million dollars for a Planet Dove cubesat.

Area Coverage

There are two system-level approaches to collecting large areas. One can employ wide swath scanning sensors on a relatively small number of spacecraft to achieve synoptic coverage, as is done in Landsat and Sentinel-2. While these needn't be nearly as costly as Landsat 8 (given the declining cost of sensors and electronics), they do tend to be more expensive on a per-satellite basis than the alternative, which is to employ a larger number of staring arrays across a constellation, similar to Planet's constellation. It is not a foregone conclusion which approach is more cost effective and both should be considered. However, from the standpoint of continuity with previous Landsat missions for change monitoring applications, wide swath scanning sensors are probably preferable in that they offer greater synopticity (simultaneous collection of large areas).

Spatial Resolution

Spatial resolution is the smallest spatial unit on the ground that the sensor is capable of imaging which is usually expressed as the length on the ground of one side of a pixel termed the system's ground sample distance (GSD). For the same sized sensor, high resolution is inversely proportional to the area coverage, so high resolutions typically result in smaller coverage. Since the launch of Landsat 4 in 1982, the spatial resolution of Landsat's non-thermal multispectral sensors has been maintained at 30 meters. Sentinel-2's multispectral spatial resolutions are 10 meters for Red, Green, Blue, and Infrared bands and 20 or 60 meters for the other spectral bands. Conversely, commercial high resolution systems have much higher spatial resolutions, with the highest provided by Digital Globe's Worldview 3 and 4 satellites at 31 centimeters.

Temporal Resolution

Temporal resolution is expressed in two ways:

1. The time it takes to collect everywhere, which is the frequency of global refresh, (or how often the entire planet is re-collected), or
2. How often a given site anywhere can be revisited, which is the frequency of revisit.

Refresh and revisit are dependent upon orbit, swath width, satellite pointability and constellation. Both should be represented because each is relevant to different use cases. Because Landsat systems have limited pointability, their refresh and revisit are the same – 16 days for each satellite which translates to 8 days for the combined constellation of Landsats 7 and 8. Adding the Sentinel-2 non-pointable systems results in a refresh and revisit of every 3 days to 5 days. Alternatively, Planet's Dove constellation refresh is daily while DigitalGlobe's constellation is every few weeks. On the revisit metric, Planet's non-pointable constellation is still daily, while DigitalGlobe's constellation can achieve ~5 revisits/day because the satellites are pointable.

Figure 1 compares Landsat and Sentinel's spatial and revisit temporal resolutions with that of example commercial systems, Sentinel-2, other lower spatial resolution government systems such as NOAA's GOES weather satellites, and NASA's MODIS. The chart illustrates that commercial systems to date have targeted a higher spatial/temporal resolution market niche which is not served by government systems with free and open data policies such as Landsat, Sentinel-2, GOES, or MODIS.

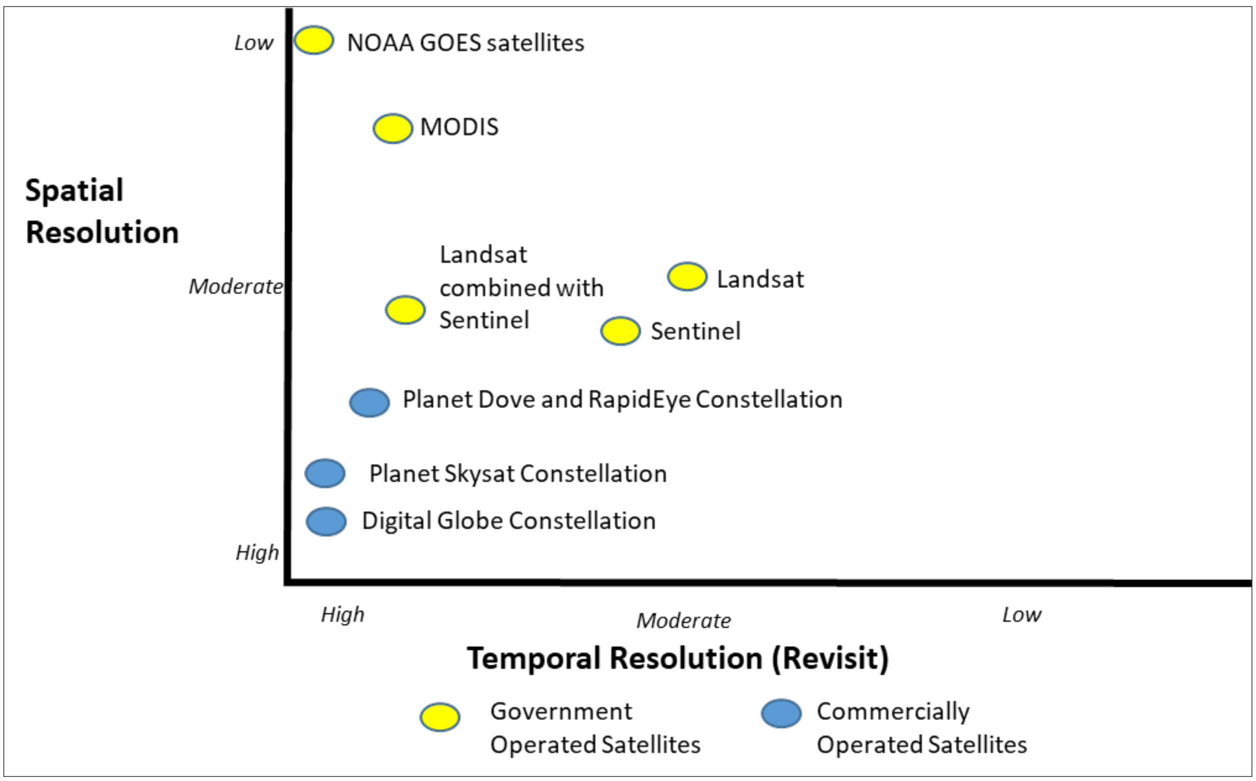

Figure 1. Comparison of spatial and revisit temporal resolution of several Earth observing satellites. (Source: Landsat Advisory Group)

Spectral Resolution

Spectral resolution is driven by the focal plane of a sensor, and sensor calibration. Sensor focal planes can vary considerably in complexity. Figures 2 and 3 compare the location and width of bands of Landsats 7, 8, and 9 to those of the recently launched European Sentinel-2 and most of the existing and proposed smallsats and cubesats. Landsat is distinguished from the commercial smallsats and cubesats by its inclusion of shortwave infrared (SWIR)[3] and thermal infrared spectral

[3] Though DigitalGlobe does include eight 3.7 meter resolution SWIR bands on its WorldView-3 satellite.

bands which are critical for applications such as vegetation identification, crop and water use monitoring, and forest management. Most of the new small and cube satellites capture imagery in only 1-4 spectral bands verses Landsat's 11 bands and Sentinel-2's 12 bands. Specifically, the smallsats and cubesats on orbit today are incapable of sensing energy in the middle infrared and thermal bands. Alternatively, the Sentinel-2 constellation's spectral bands were purposely designed to be similar to Landsat bands so that data from the systems can be synergistically combined. Sentinel-2 provides additional spectral coverage compared to Landsat, e.g., in the "red edge" between visible and near infrared (previously only available via the RapidEye constellation, now a part of Planet's constellation). However, Sentinel-2 does not provide a capability for thermal infrared imaging.

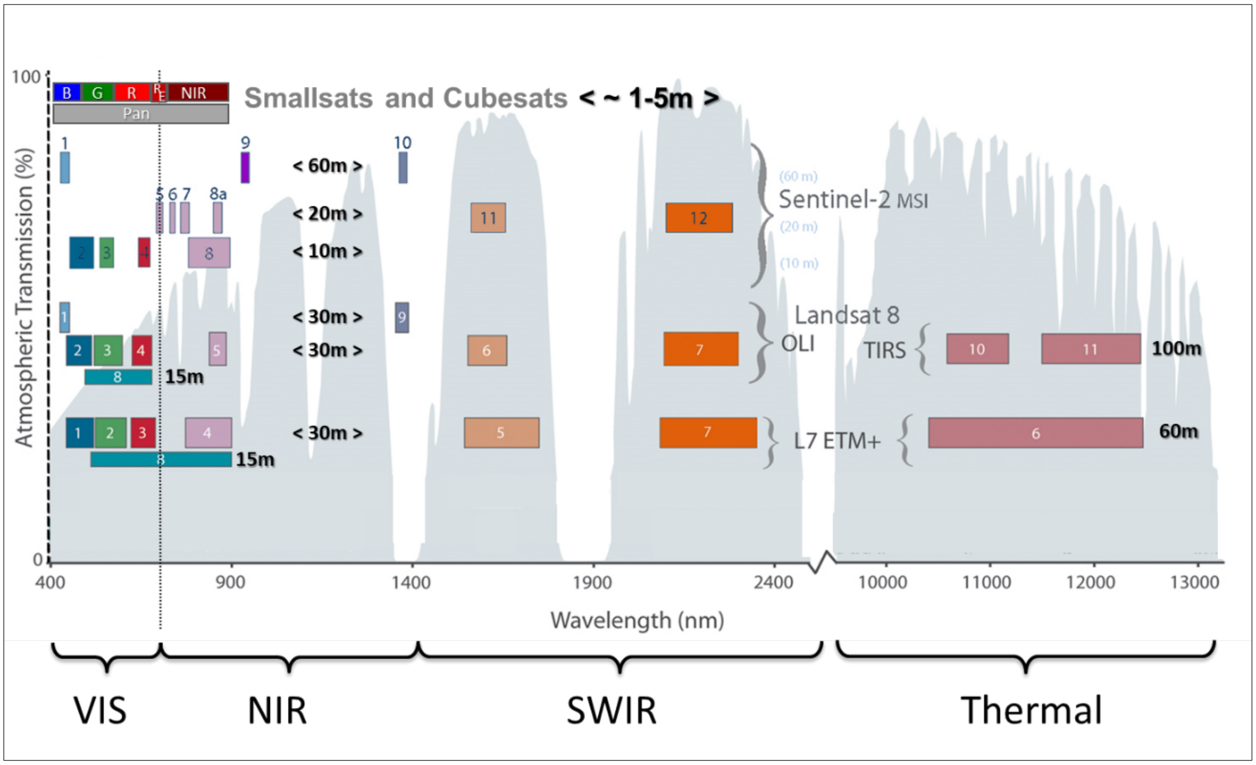

Figure 2. Comparison of the spectral and spatial resolutions of Landsat 7 and 8 imagery versus those of the Sentinel-2 constellation, and existing and proposed, cubesats and smallsats. (Source: USGS)

The signal to noise ratio (SNR) of the imagery is also important to ensure suitable accuracy in spectral measurements, especially in areas that are dark, such as shadow sides of mountains and in cloud shadow. Both Landsat and Sentinel-2 with their large optics and apertures can capture sufficient light to achieve high SNR. Improvements in sensor sensitivity enable the smaller optics that fit into smallsats to achieve suitable SNR values so long as the spatial resolution is kept larger than ~10 meters. Achieving suitable SNR from the optics of cubesats is doubtful, though this is quite achievable with larger classes of smallsats.

While the number and width of spectral bands is important, without radiometric calibration of the data sensed in those bands, satellite images are little more than pretty pictures. For many applications (e.g., land cover mapping, agricultural analysis, or monitoring any form of change in state over time) radiometric calibration of the sensors is critically important and needed to support robust spectral and temporal analysis. Proper radiometric calibration enables one to derive conclusions from satellite observations with confidence, by avoiding the many factors that can introduce noise or uncertainty. Calibration of Landsat and Sentinel imagery is rigorously performed and backed up by USGS and ESA science programs. DigitalGlobe also has a rigorous calibration program and regularly reports their calibration methods and results at scientific conferences. However, many of the existing and planned commercial smallsats and cubesats do not have robust calibration programs and actually rely on Landsat and Sentinel-2 imagery for calibration, requiring substantial post-collection spectral collaboration. Scientific grade concurrent observations from Landsat 8 and Sentinel-2 are currently necessary to extract full value from small and cubesat commercial observations. In theory, there is nothing preventing a future smallsat from incorporating scientific grade calibration, though this can be a cost driver; evaluation of future Landsat design approaches should consider this along with its associated costs in the trade space.

Radiometric calibration of the sensors is also dependent on being able to regularly compare sensor measurements against a calibrated source. This can be achieved by using on board lamp calibration, which increases the number of moving parts and complexity of the space system or by undertaking appropriate satellite maneuvers that enable the satellite to scan cooperative ground targets or objects of known reflectance such as the moon and stars. As these cross calibration techniques have been refined over the years it may not be necessary for advanced on board lamp calibration, which would help reduce costs.

Aerosols and water vapor in the atmosphere have potentially the largest impact on the light being observed by a satellite. They absorb different parts of the incoming sunlight, and again absorb portions of the light reflected back into space. Removing these effects is known as atmospheric compensation. The most accurate approach is to measure these atmospheric components directly by incorporating the appropriate spectral bands in the sensor (albeit these can be at lower spatial resolution than the primary sensor bands). This is the approach taken on DigitalGlobe's WorldView-3 satellite, which incorporates an 11-band "Clouds, Aerosols, Vapors, Ice, and Snow" (CAVIS) sensor to make these atmospheric measurements. However, as long as the main sensor includes red, green, blue and near-IR bands whose absolute spectral response is well calibrated, techniques exist to estimate the atmospheric effects with reasonable accuracy. Lower resolution coastal aerosol and cirrus bands also provide significant value to determine atmospheric effects and the existence of high-altitude clouds.

Spatial Accuracy

For imagery to be useful in mapping applications, it must be registered to the ground. Landsat, Sentinel and DigitalGlobe systems all include star sensors and gyroscopes which allow for precise measurements of the satellite location and orientation. Conversely, smallsats and cubesats tend to have poor intrinsic geometric accuracy (on the order of 100 meters) because they typically cannot afford the cost to include higher accuracy star sensors or gyros. This can be compensated by registering cube and smallsat imagery to a suitably accurate layer, so long as the image has enough non-cloudy pixels over land. Such global accurate base layers now exist and this registration process can be automated, especially for wider swath widths. The resulting accuracy will depend on sensor viewing angle, digital elevation model accuracy and sensor stability. For primarily nadir-pointing sensors, the first two will have limited impact. As long as the ground pixel size of the sensor is greater than 10 meters, the geometric stability of the sensor is also likely to have little effect, so overall accuracies of ~10 meters should be achievable without including the more advanced star sensors and gyroscopes.

Pricing and Licensing

U.S. Government civilian satellite data and European Sentinel-2 data are distributed to the public at no charge and without licensing restrictions. Commercial imagery usually has use and sharing restrictions which are spelled out in a license to use the imagery. Commercial satellite operators also usually charge for access to their imagery. Like Landsat, all Sentinel-2 imagery is made public and hosted at cost in commercial cloud (Amazon Web Services [AWS] and Google), as well as on many commercial services.

Findings

None of the current smallsat or cubesat satellite systems deployed to date have the technical capabilities required by the thousands of researchers, government agencies, NGOs, and commercial companies who rely on Landsat continuity for research and operational decision making. While the smallsats and cubesats may exceed Landsat capabilities in spatial resolution and/or revisit time, none of these satellites currently have sensors with the needed spectral bands, calibration stability, or swath area required by the tens of thousands of US Landsat users. Equally important, unlike Sentinel and Landsat, none of the commercial providers offer imagery worldwide without use restrictions and at no cost, an important consideration for researchers and agencies relying on Landsat and Sentinel to support operational decisions. Conversely, Landsat and the Copernicus Program's Sentinel-2 multispectral bands are very similar and can be used in combination with one another. However, only Landsat provides moderate resolution thermal imaging capabilities.

Enhanced Capabilities for Future Landsat Missions

While currently on-orbit smallsats and cubesats are incapable of meeting current Landsat user requirements, decisions regarding future Landsat capabilities must be made within the context of current and emerging technology advancements, as well as changes anticipated in the rapidly evolving market for both government and commercially provided satellite imagery. As Figure 3 illustrates, the number of commercial earth observing satellites is projected to quadruple over the next 10 years.

As the U.S. Government considers requirements for future Landsat systems, the existence of Sentinel-2 and the proliferation of commercial systems offer opportunities for technology innovation and synergies, yet also present challenges in ensuring Landsat data continuity while also avoiding competition with operational, commercial capabilities which have become available in the last decade. The following sections summarize four of the most promising options, in order of priority, and lists the pros and cons of each.

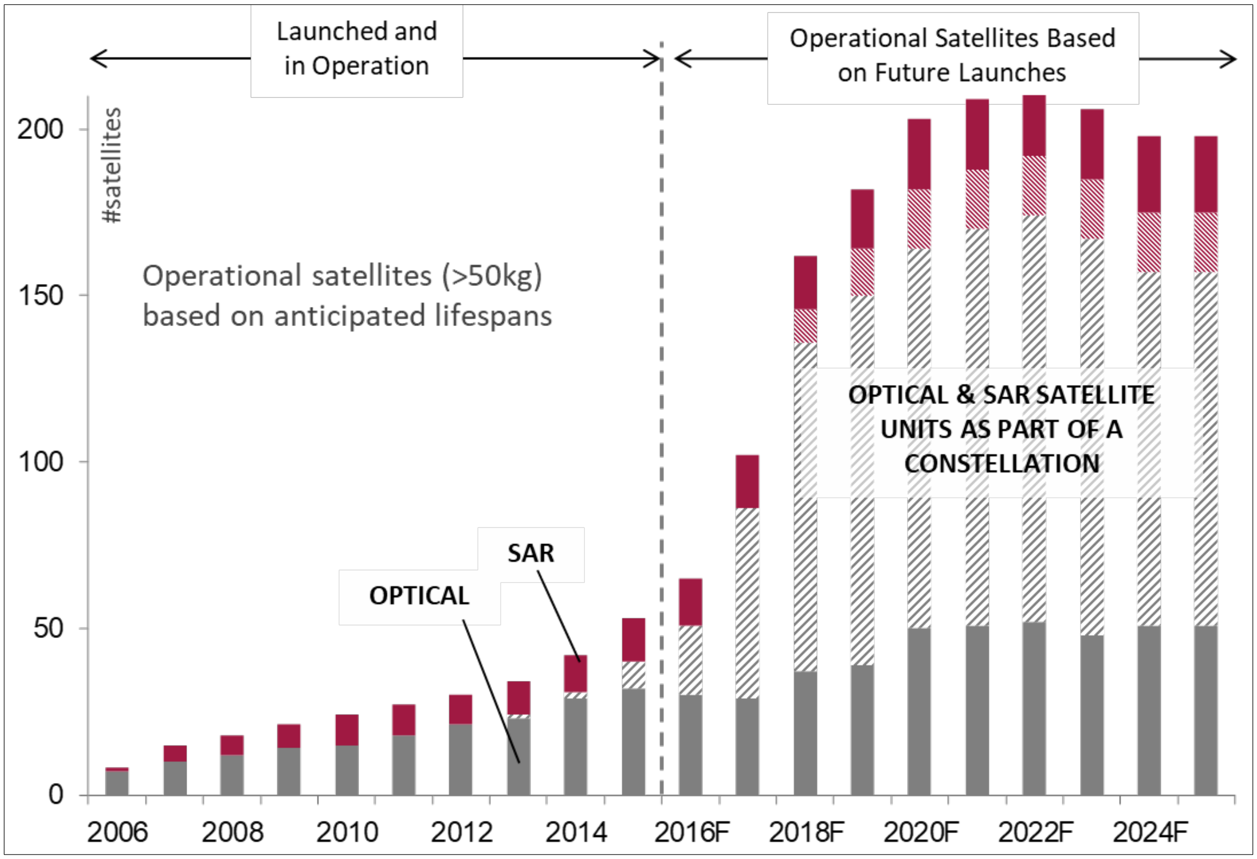

Figure 3: The projected growing supply of high and very high resolution satellite imagery. (Source: Euroconsult)

Option 1: Maintain Current Landsat Capabilities at Lower Cost

It would be unconscionable for the next Landsat to not take advantage of rapidly emerging and increasingly proven technical innovations which could greatly reduce costs while maintaining continuity. Opportunities definitely exist for substantial size, weight, power and cost savings through adoption of newer technologies, especially in sensors and overall spacecraft electronics. Advances in microelectronics and sensors—driven both by consumer electronics and by U.S. Government sponsored developments—have enabled new classes of space missions. While none of the deployed systems to date have capabilities that envelope those required for Landsat continuity, there are many viable elements (both at the component level and the system design approach level) that can be applied to drive a cost effective Landsat successor.

With microelectronics performance continuing to improve along with decreasing size, weight, and power, the drivers for satellite size are ultimately its payload(s) and those systems that scale to accommodate the payload (e.g., power, maneuvering). For passive electro-optical remote sensing, this is driven by telescope aperture, which in turn drives weight, though for resolutions in the Landsat class this does not by itself drive weight above the smallsat class.

A secondary driver is focal plane complexity. Sensors to collect all bands through SWIR to match the Landsat 8/9 Operational Land Imager (OLI) are relatively easy to obtain. Silicon based detectors collect in the visible portion of the spectrum, while those based on MerCad-Telluride (HgCdTe) can collect short-, mid-, or even long-wave infrared. Sensor costs have been declining dramatically. For example, the WorldView CAVIS sensor (including telescope) was built for a few tens of millions of dollars, leveraging the same scanning detectors as Landsat 8 and capturing a total of 11 spectral bands from visible through short wave infrared. To assure suitable determination of surface reflectance either additional CAVIS bands at lower resolution could be added to Landsat.

Imagery for a Landsat continuity mission with suitable radiometric and geometric accuracy should be achievable using smaller satellites at a lower cost than a Landsat 8/9 OLI sensor assuming the pixel size is kept to 10 meters or above and the sensor remains nadir pointing. Other changes that could reduce costs and size are the reduction in the complexity and accuracy of the star sensors used for accurate georeferencing and on-board lamps used for some calibration.

The thermal IR sensor on Landsat is unique and the lack of a thermal capability would be a significant loss to global earth observation continuity. However, including thermal infrared imagery on a smallsat with OLI-like performance is likely to considerably increase the cost of the sensor as well as size, weight and power for cooling the sensor. Technology advances have reduced the size, weight, power and cost of satellite buses, which create much more opportunity for disaggregating sensors in a cost-effective manner (e.g., separate OLI and Thermal Infrared Imaging Sensor [TIRS] spacecraft). This is particularly helpful when the refresh rate requirements of the different sensing modalities are not the same (e.g., higher frequency refresh on some bands than others, particularly if the thermal does not become the driving case). Therefore, the option of flying the OLI-like and TIRS sensors on separate but coordinated platforms is now a viable alternative.

Pros: Lower costs without losing continuity of measurements coupled with the potential of higher refresh rates, which would be extremely valuable for agricultural and drought monitoring and emergency response applications. Multi-satellite constellations are more resilient to individual component failures; they degrade gracefully (e.g., degraded revisit) rather than losing capability entirely, as would be the case with a single satellite. The disaggregation of the sensors allows launching TIRS sensors consistent with their expected life-cycle and sustaining a continuous record.

Cons: Requires extensive and precise design work up front to rigorously demonstrate how a thermal free flyer in formation with the OLI type sensor can still achieve the required degree of synopticity. For example, it would require a study to show the ability to achieve geometric calibration through registration against a base layer, etc.

Recommendation: The U.S. Government should aggressively investigate rapidly emerging and increasingly proven technologies which could greatly reduce the cost of Landsat missions. Included in this investigation should be consideration of smaller satellites with Landsat 8/9 OLI-like performance and free flyer thermal missions to maintain continuity in Landsat thermal measurements. As a test, it is recommended that the U.S. Government consider placing a thermal sensor on a dedicated free flyer companion satellite to one of the existing European Sentinel-2 systems. Additionally, it is recommended that a study be undertaken to determine if additional CAVIS bands or input from a suitable auxiliary lower resolution satellite, could be used to reduce costs associated with sensors for radiometric calibration.

Option 2: Adopt the Sentinel Model for Cost Savings and Increased Temporal and Spatial Resolutions

Sentinel-2 has established a new standard for Earth observation systems. Its spectral resolution is also similar to Landsat, however with the notable lack of the thermal bands. Sentinel-2 has been designed as a four-satellite acquisition (e.g. a four satellite buy with two satellites in orbit at any one time), thereby reducing development and acquisition costs per satellite. Sentinel-2 costs are estimated at $250-300 million per satellite versus Landsat 8's $855 million cost. Sentinel-2 is also part of a larger coordinated program of satellite constellations, including Sentinel-1 C-band SAR (similar to and improving on the Canadian MDA Radarsat constellation) and Sentinel-3 low resolution daily global imaging (similar to and improving on NASA's Terra/Aqua MODIS and NOAA's Suomi-NPP/JPSS VIIRS). Sentinel-2 has set expectations for future public satellite systems, while drawing close to the spatial resolution that currently separates public imagery from commercial grade imagery.

Landsat 10 could be a constellation of new US. instruments and satellites built to the Sentinel-2 technical specifications. Alternatively, the U.S. could seek to reduce costs by leveraging the existing production run of Sentinel-2 instruments and satellites, either by licensing the technology or ordering additional Sentinel-2 satellites from the current manufacturers. The U.S. Government could then apply the savings to producing a free-flying medium-wave/thermal imager that provides the current Landsat capability not present in the Sentinel-2 program. In any of these cases, the new Landsat 10 constellation should be placed in orbits that add to the coverage provided by Sentinel-2, e.g., a coordinated constellation of Sentinel-2A, 2B and Landsat 10A, 10B satellites could provide global coverage with semi-weekly imaging at the equator.

> **Pros:** Reduces costs and ensures consistent data collection between Landsat and Sentinel-2 systems; greatly enhances the current revisit rate which is very valuable to agricultural and drought monitoring and emergency response applications.
>
> **Cons:** Cedes U.S. leadership in moderate resolution earth observation, which would probably result in a risk of loss of Congressional support; U.S. lacks control over cost and design.
>
> **Recommendation**: Too many critical U.S. research and operational programs rely on U.S. leadership in moderate resolution earth observations for the U.S. to cede its leadership in moderate resolution earth observations to the European Copernicus Program. Maintaining U.S. homeland, food and environmental security are all dependent upon the Landsat program. However, the U.S. should continue to work closely with the EU better harmonize the Landsat and Sentinel data sets, obtain economies of scale where possible, and share lessons learned. The Copernicus approach of building multiple satellite constellations at once and launching them over time should especially be investigated to reduce development and acquisition costs per satellite.

Option 3: Improve Landsat Spatial and Temporal Resolution

In the recent LAG study, *Analysis of Non-Federal Landsat User Requirements* (https://www.fgdc.gov/ngac/meetings/april-2016/landsat-user-requirements-analysis-ngac-june-2016.pdf), Landsat users identified improved spatial and temporal resolution as the most important improvements needed for Landsat 10. Savings realized from options 1 or 2 above could be used to improve Landsat 10 spatial resolution to 10 meters global semi-weekly coverage at the full Landsat spectral range including 10 meter thermal. Shorter intervals between observations would require a constellation of multiple satellites, and planning to acquire 4 to 6 satellites from inception of the program would significantly reduce development and acquisition costs per satellite. This constellation would maintain U.S. leadership in public, global Earth observation. It is important, however, that such an approach not attempt to replicate what commercial firms are doing or plan to do, as this would place the Government in direct competition with private enterprise, contrary to US space policy which directs that the U.S. Government will "…focus United States Government remote sensing space systems on meeting needs that can not be effectively, affordably, and reliably satisfied by commercial providers…" (https://fas.org/irp/offdocs/nspd/remsens.html). Rather, such an approach should seek to complement what the commercial industry is doing.

Pros: Increased spatial and temporal resolution which has been identified as a Landsat 10 requirement by multiple Landsat users. Increased compatibility with Sentinel-2.

Cons: Going to higher spatial resolution tends to drive up costs, particularly if there is a desire to maintain the same swath width, as the number of pixels in the focal plane will increase proportionally, which drives both electronics cost and optical/mechanical complexity. Significantly higher spatial resolution on a Landsat system could be interpreted as competing with the commercial sector, contrary to U.S. Space Policy. It is not clear that this is the best place to be making investments when the private sector is already providing high resolution data, i.e., is it cheaper for those applications which need higher resolution/revisit data.

Recommendation: The Landsat 10 ground sample distance be set to 10 meters or larger, so as to increase compatibility with Sentinel sensors, ensure wider swath widths, increase coverage, and reduce overlap with commercial providers.

Option 4: Improve Landsat Spectral Resolution

If costs are lowered, multispectral non-thermal temporal and/or spatial resolution improved through the above options, and continuity maintained in thermal measurements, then the possibility exists for development of a moderate spatial resolution hyperspectral system flown in constellation with the multispectral and thermal Landsat systems. Super- or Hyperspectral imagery would enhance the Landsat record by providing the ability to more accurately identify and monitor phenomena on the Earth's surface.

Conversely, if it is found acceptable to cede leadership in global land imaging to the EU (Option 2 above), the U.S. Government could acknowledge that Sentinel-2 now provides Landsat-like global coverage in the visible to short wave infrared, and instead seek to provide a new complementary Earth observation capability, e.g., develop a medium-wave to thermal infrared multi-spectral instrument, or explore hyperspectral imaging.

Pros: Demonstrates U.S. space leadership by providing a new valuable capability freely available to the public.

Cons: Additional development and operational risk. Risk of competing with new commercial spectral-imaging constellations (planned but not yet operating).

Recommendation: The U.S. Government should investigate the benefits and costs of increasing Landsat spectral resolution.

Opportunities for Public-Private Partnerships

Each of 7 successful Landsat missions has resulted from a collaboration between public and private organizations in that the government (currently NASA and USGS) defines its requirements and awards contracts primarily with private companies to provide the satellite and rocket. Following launch, the Government (currently USGS) operates the satellite and ground station, often using personnel contracted from private companies. However, this type of collaboration does not meet the typical model of public-private partnership where the private partner puts some resources at risk which are offset by expected commercial revenue and lower costs to the Government.

Several public/private partnership models exist which, if applied to the Landsat program, have the potential to reduce costs to the Government by offsetting some of those costs with commercial revenue. Fundamental to these models is the concept that the Government does not make freely available the same product that the contractor is trying to commercialize, as otherwise there is no offsetting commercial revenue opportunity, and the Government ends up bearing the full cost of the program. Therefore, to be successful, a substantially large demand for the commercial product must be projected to exist. Two models are discussed here.

"NextView" or "EnhancedView" Model

The National Geospatial-Intelligence Agency (NGA) has acquired commercial high resolution satellite imagery over the past decade under what is known as the "NextView license." NGA pays a commercial data provider an annual fee (what is known as a "Service Access Agreement" or SAA) in exchange for having the ability to use data available via the EnhancedView contract, including the ability to task a percentage of the provider's capacity (roughly half). NGA can use that data within the U.S. Government. It can also share it (with some limitations) with allies, coalition partners, and first responders, but it is not allowed to make the data openly available to the public.

A variant on this model, which was used in the original NextView contracts, has the Government co-fund the development of the satellite(s) in exchange for lower cost during operations. This approach trades off the timing of funding (more up front) for lower total cost over lifetime.

Both variants of this model work because the commercial provider is then free to monetize its data with non-NGA customers. The revenue earned in this fashion enables the provider to offset the cost to the government, so NGA pays less than it would have for a dedicated system. As a rough data point, the non-NGA revenues from DigitalGlobe, the current EnhancedView contractor, exceed the value of the SAA.

An analogue of this for Landsat (or a similar program) might be to enable the Government to share data freely with the research and public agency communities, but any commercial application would need to procure data from the contractor. However, the demand for Landsat imagery is overwhelmingly derived from the research and public government sectors, and it is unclear if a large enough commercial demand exists to support this model, especially when Sentinel-2 data is freely available and can be substituted for Landsat imagery in many applications.

Pros: The advantage of such an approach are that costs to the U.S. Government could be reduced due to investments from private industry and having private industry efficiency aid in the launch and management of the satellites which should further reduced costs.

Cons: The disadvantage of this approach is that it is unlikely that the U.S. Government would be able to convince a private company to agree to terms unless substantial restrictions were placed on the distribution of Landsat data to public agencies and research organizations which would invalidate many of the Landsat benefits and run counter to the goals of the Sustainable Land Imaging program.

"Pay for Superior Data" Model

This public-private model would entail the U.S. Government contracting with the private sector to build and launch a constellation of sensors with specified resolutions, calibration standards, and spatial accuracies set by Government requirements. The contractor would then have the option of selling higher quality data into all markets. In this approach, the contractor would build a system that would collect data that exceeded the requirements for Landsat continuity, but would provide a Landsat requirements-compliant subset of this data to NASA/USGS to be freely distributed. The contractor's system could exceed Landsat requirements in any of a number of ways (e.g., higher spatial resolution, more spectral coverage, more temporal revisit, higher calibration standards, spatial accuracy, etc.). For example, the Landsat requirement for spatial resolution could be 30 meters with the contractor superior spatial resolution at 10 meters or higher. The contractor would have commercial rights to the full-capability data, which it could monetize because what NASA/USGS shared freely was fundamentally a different product and so would not cannibalize the commercialization opportunity.

This approach in principle is sound as long as there is sufficient demand for the superior data collected by the contractor's system and it is differentiated from the freely distributed Landsat data by enough to be valued by the market and enable the contractor to earn a return and, thus, close its business case. In 2002-2003, NASA conducted several formulation phase studies for a variant of this model for the Landsat Data Continuity Mission (LDCM). However, the approach failed in the original LDCM because the bidders and NASA were unable to come to agreement on terms that enabled the bidders to close their business cases, but this was due to specifics (i.e., allocation of risk and economic terms) rather than an intrinsic flaw in the model. Circumstances, markets, and technologies have changed which may make this model now more viable. For example, the company UrtheCast is building and planning to launch a constellation (UrtheDaily) of satellites in 2020 to provide global daily large swath width coverage with 5 meter GSD and spectral bands similar to those of Landsat-8 and Sentinel-2 (except for the thermal band). There may be an opportunity to license the rights to a lower resolution 20 meter data version of the products and provide these to the Landsat community. U.S. Government development efforts could then be focused on providing a companion TIRS constellation.

Pros: The advantage of this approach is that the U.S. Government would gain most by the efficiencies of private industry, while maintaining Landsat continuity. It also preserves public/open availability of Landsat-quality data.

Cons: This approach is dependent on the contractor's ability to develop a business model that closes based on the "upper tier" of data quality which is difficult. Another disadvantage of the approach is that it can intrinsically increase the cost of system by requiring increased capabilities, and makes the system incumbent to the requirements of a private party, and not just the Government.

Recommendation: The U.S. Government should conduct a market study to determine if sufficient demand exists to support exploration of the creation of a public-private partnership where the contractor provides two or more tiers of data - one meeting U.S. Government Landsat technical requirements for open and free distribution, and others that provide "superior" data which is sold to users, thereby creating a sufficient revenue stream to offset at least some of the costs of building and operating the system. If this model is pursued, the government must ensure that there is an equitable balance of risk between the Government and its private sector partner.

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