Policy Brief

Eyes Wide Open

Harnessing the Remote Sensing and Data Analysis Industries

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Executive Summary

Remote sensing—literally, measurement at a distance—forms the basis for today's weather predictions, informs financial markets, and serves American national security needs. The U.S. 2020 National Space Policy acknowledges its importance, recognizing "that long-term United States national security and foreign policy interests are best served by ensuring that United States industry continues to lead the rapidly maturing and highly competitive commercial space-based remote sensing market."[1]

Given the reported expansion of the remote sensing market, this paper seeks to understand the national security consequences of that expansion, and provide insights and recommendations for policymakers as they navigate this security environment. Using a commercially available dataset, we find that in recent years, the industry has indeed been rapidly expanding, with new companies founded at rates 10 times faster around 2015 compared to a decade earlier. That growth has since slowed from its peak, yet remains historically elevated. The explosive expansion of the U.S. remote sensing commercial market resulted from the confluence of four factors: technology development, especially microelectronics and imaging sensor miniaturization; the rise of cheaper space launch at scale; new funding and business models, including venture capital and data-focused companies complementing imagery-sales companies; and a stable regulatory environment. A less noticed but equally important factor is that the space data analysis market has also grown, with three-fourths of companies having been founded in 2008 or later.

Today, the convergence of those factors has allowed the United States to become the global leader in commercial remote sensing. To maintain and expand U.S. leadership in this market, this paper identifies the following gaps, challenges, and opportunities, along with recommendations for maintaining a competitive, globally preeminent domestic remote sensing market:

Gaps: Infrared and hyperspectral imagery, while more difficult to develop than more common visual-band imagery, promise new applications and capabilities that current commercial imaging services cannot provide.

Very low Earth orbit is likewise underexploited, though technically difficult. Companies are pursuing these new technologies, and orbits, but only a few are operational today. Each of these gaps represents a potential economic and security advantage not seized.

Challenges: The proliferation of satellite constellations adds to the growing number of debris pieces and increases the likelihood of collisions. This growth in debris raises operating costs and degrades benefits. While remote sensing satellites are not uniquely affected, the environment forms a backdrop for new systems. Responsible design and constellation management is critical for continued access to space.

Like the space environment, the strategic environment is shifting. Competing states who dislike the transparency provided by remote sensing satellites openly talk of targeting commercial capabilities. Governments and companies must be prepared for the possibility that those threats become actions.

Opportunities: Much like astronomy uses radio, infrared, visible-band, X-ray, and other sensors to better understand the cosmos, the commercial remote sensing market has the opportunity to lead a similar explosion in a multi-mode understanding of the Earth. The economic and security benefits of that understanding are broad; the challenge will be to make it profitable.

The paper makes five recommendations to close the gaps, confront the challenges, and embrace the opportunities presented, while leveraging market trends to continue building capability within the remote sensing industry. These recommendations help ensure American strategic advantage in the years to come:

1. The U.S. government should expand purchases of products and services from commercial remote sensing companies, while partnering with investor capital to encourage commercial remote sensing innovation.

2. The U.S. government should expand purchases from data analysis companies while partnering those companies with multi-disciplinary government test and experimentation teams to maximize the operational relevance of new data sources.

3. The U.S. government broadly, and the Department of Commerce specifically, should maintain current remote sensing regulations allowing commercial sales of world-leading imagery, but also evaluate the application of location-specific controls to protect allies, partners, and U.S. forces in conflict.

4. The U.S. government should continue basic research investments in sensing technology, and expand the technology transfer of those with commercial applications.

5. Within operational plans, the U.S. government should ensure coordinated options are developed and exercised to respond to reversible and irreversible attacks on commercial U.S. satellites.

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Introduction

Remote sensing has a long history in the United States, but a relatively short commercial one. Throughout that history, it has been linked closely to national security—indeed, the 2020 National Space Policy explicitly says "that long-term United States national security and foreign policy interests are best served by ensuring that United States industry continues to lead the rapidly maturing and highly competitive commercial space-based remote sensing market."[2]

Motivated by the importance of the industry to U.S. national security and the reported explosive growth in the remote sensing arena, this paper identifies the policy, technology, and market trends that together have delivered the industry to where it is today. It also leverages author annotations of the commercially available PitchBook dataset, using company founding dates and operating status to assess the health and relative breadth of the space remote sensing market. Finally, it identifies gaps, challenges, and opportunities in the market, culminating in recommendations for continued U.S. strength in this important mission area.

What Is Remote Sensing?

Remote sensing is measurement at a distance.[3] Using passive sensors like cameras and active sensors like radars, remote sensing spacecraft use the electromagnetic (EM) spectrum to measure activity on Earth and in space. Beyond space-based detectors, remote sensing requires infrastructure to communicate with spacecraft, task them, and receive, process, store, and distribute the data they collect.

Remote sensing applications span various fields, including the terrestrial fields of environmental monitoring, agriculture, forestry, urban planning, and disaster management, as well as the non-earthbound fields of astronomy and space situational awareness. Remote sensing enables the acquisition of valuable data without direct physical contact with the subject, offering an expansive and non-invasive approach to studying and understanding the Earth's surface and atmosphere.[4]

That remote sensing data is the start of a sense-making pipeline, where analysts use tools and algorithms to turn it into useable, actionable information and insights. In the context of national security, remote sensing and the data-to-information pipeline is fundamental to the practice of intelligence, surveillance, and reconnaissance (ISR).

Why Remote Sensing Matters

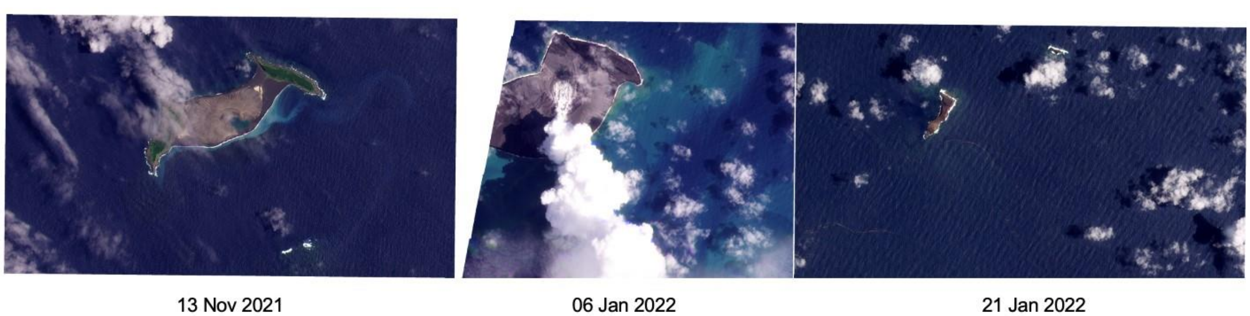
The first pictures from space were taken from a rocket in 1946 and the first satellite was launched in 1957. Early space imaging was the realm of militaries and intelligence agencies, often as the "National Technical Means" by which nuclear treaties were verified.[5] Today, the importance of remote sensing has only grown, delivering value in three ways.

The first way is by enabling scientists, researchers, and others to identify and monitor environmental developments across a broad range of sectors and applications. Satellite remote sensing provides imagery used in commercial maps; similar images can support responses to human-caused (Figure 1) and natural (Figure 2) disasters.[6]

Figure 1: June 06, 2023 destruction of the Kakhovka Dam, Ukraine[7]

Source: Images © 2023 Planet Labs PBC.

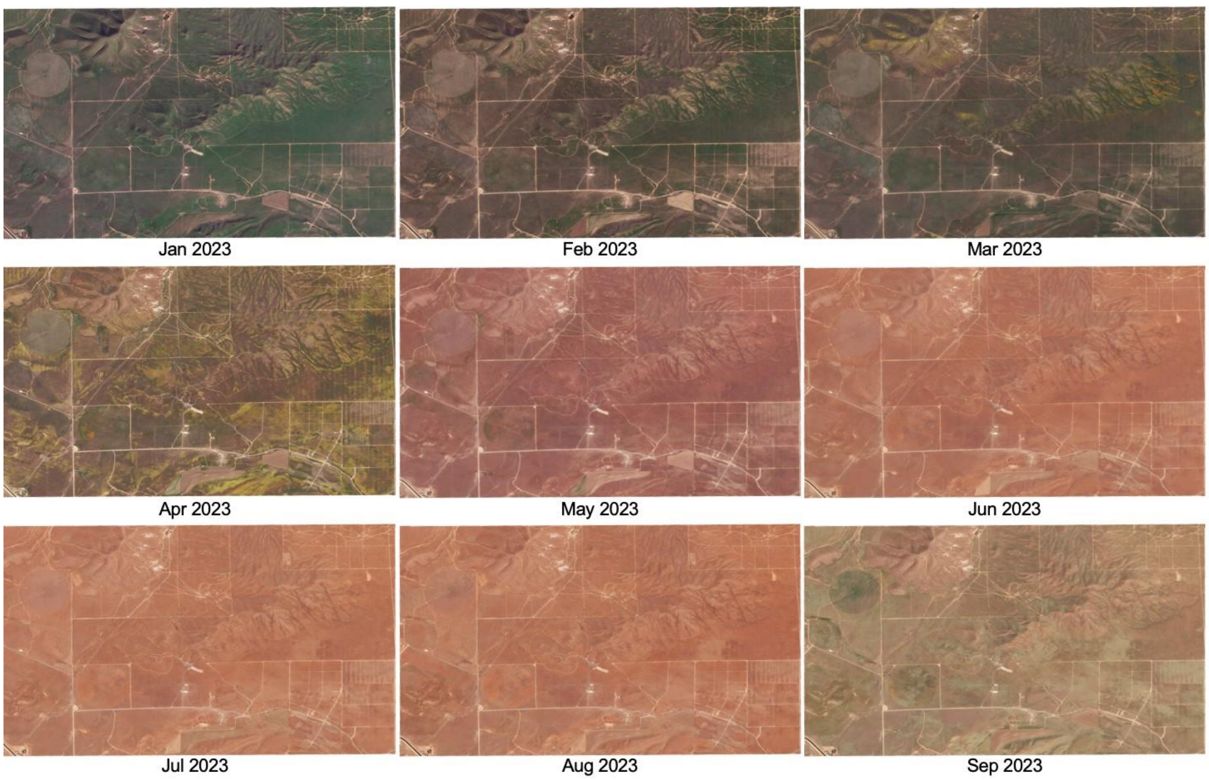
Figure 2: January 14–15, 2022 Hunga Tonga-Hunga Ha'apai Volcanic Eruption, Tonga, Runup and Aftermath[8]



Source: Images © 2021, 2022 Planet Labs PBC.

Remote sensing can also show less destructive natural changes, especially when collected over time. Consider the 2023 California "Superbloom," where a historically wet winter yielded wildflower blooms in the desert (Figure 3). Similar time series support monitoring of plant growth, moisture, and land use with applications in forestry, climate monitoring, water resource management, urban planning, and more. Scientists, planners, and resource managers may rely on mixtures of visible wavelengths and the infrared light that the human eye cannot see. Ultraviolet (UV) measurements, for instance, can provide assessments of ozone, while the combination of all of these wavelengths is used for weather predictions.[9]

Figure 3: April 2023 California "Superbloom"[10]



Source: Images © 2023 Planet Labs PBC.

More complex remote sensing satellites may even "slice" light into thin hyperspectral lines to track emissions, soil composition, ocean ecology, and other factors, by measuring the chemical composition of the land and water beneath them.[11] Such hyperspectral sensors generate enormous amounts of data, but can also generate novel insights. Other radio-detecting satellites provide services from ship tracking to global weather measurements that can't feasibly be collected any other way.

Second, remote sensing plays a vital role in national security. The ability to detect and measure foreign capabilities has clear military and strategic value. Beyond generating images, some military remote sensing satellites use infrared sensors to detect and track missiles. Others, including those in the U.S. Nuclear Detonation (NUDET) Detection System (USNDS), use gamma, neutron, X-ray, and other detectors and sensors to track nuclear explosions around the world.[12]

Finally, the industry itself delivers significant direct revenue and indirect economic returns. The value, both to the economy and to national security, provided by remote sensing satellites is significant. Consider weather data: Even a decade ago, U.S. public and private spending on all weather research and forecasting ran about $5 billion per year, but the public benefit derived was valued at over $31 billion per year, and its value has certainly grown since then.[13] Satellite measurements are a critical element of those forecasts; with space sensing, for instance, no hurricane can appear without warning, and landfall can be predicted increasingly early.[14] Precision agriculture, fundamental to modern farming yields, is reliant on satellite services and becoming even more so.[15]

For these reasons, the United States is rightly motivated to maintain the strength and resilience of the commercial space market.

U.S. Government Policy and Regulation

The 2020 National Space Policy is a guiding U.S. government strategy document for the remote sensing mission area. The policy is broad, directing the use of remote sensing for prediction and science, disaster response, atmospheric and space weather monitoring, and more. Importantly, the policy specifically and repeatedly directs actions to encourage a robust commercial market. These steps include government purchases of commercial imagery and data, reducing the licensing burden to providers, and using open standards and protocols.[16]

The 2023 Space Policy Review does not focus directly on commercial remote sensing—perhaps because the 2020 policy was clear enough.[17] Rather, the review emphasizes two particular capabilities that remote sensing provides. The first is the ability of space-based intelligence to "galvanize collective action," as with the provision of clear and convincing evidence of Russian invasion intent against Ukraine, serving to "expose and frustrate false flag operations, and generate a unified response from the international community," shaping the international response to aggression.[18] The second is the key missile warning and missile tracking (MW/MT) function that supports missile defense and the nuclear deterrence mission.

In both cases, resilience of the remote sensing architecture will be critical[*], and commercial sensors can likely augment exquisite government space sensors but not replace them. Commercial augmentation can reduce the burden on the highest-performance government sensors, focusing the limited bandwidth of the latter on priority collection targets. Government can also purchase commercial imagery to follow-up on collection by intelligence systems, thereby providing unclassified and releasable images. Indeed, given the releasability of commercial data, it may be more useful for non-nuclear deterrence and coalition operations than any government alternative.

[*] This is especially true in the missile warning mission.

History

The requirements in the 2020 National Space Policy are continuations of a history of Executive Branch and Congressional interest in the remote sensing industry. That interest manifests itself in a handful of laws and regulations from the 1980s through the present day.

Legislative action started with the Land Remote-Sensing Commercialization Act of 1984 that sought to privatize the government-owned Landsat satellite. After encountering implementation challenges, Congress passed the Land Remote Sensing Policy Act of 1992, creating the legal framework for the remote sensing industry.[19] The 1992 Act critically included Title II, which provided for the licensing of private remote sensing systems under the U.S. Department of Commerce. Shortly after, companies like the Orbital Imaging Corporation (founded in 1992, later GeoEye), WorldView (1992, later DigitalGlobe), and Space Imaging, Inc. (1994) were formed. (All would eventually be acquired and combined under Maxar in the 2010s.) (Figure 5).[20] The OrbView, QuickBird, and Ikonos satellites from these companies were the forebearers of today's space remote sensing industry, delivering visible band imagery.

To implement the 1992 Act, Congress directed the Secretary of Commerce to establish a licensing and regulatory scheme for land remote sensing by space systems, including a 120-day deadline to review applications.[21] Those regulations included limitations on how quickly imagery could be delivered to non-U.S.-government customers, as well as potential limitations on what resolutions and phenomenologies (types of sensing technologies, such as visible, infrared, or radar) could be sold commercially. The law and the regulations also stipulated that "the licensee shall make available upon request to the government of any country [...] data collected by the system concerning the territory under the jurisdiction of such government on reasonable commercial terms and conditions," with limitations for U.S. national security and foreign policy interests.[22] The regulations also included requirements for government-approved encryption.[23] Policy revisions in 2020 gave greater flexibility for imagery providers, including the creation of a tiering system where lower-performance systems would have minimal limitations, higher-performance systems would be subject to more, and that most license restrictions would be considered temporary and renewable rather than permanent.[24]

The effect of these rules and their implementation is that U.S. commercial imagery providers are now limited mostly by technology in what they sell, rather than being limited by regulation. For instance, when resolution limitations expired in 2023 and were not renewed, one company was able to publicly release a 16 cm resolution image

(Figure 4), which shows features one-third smaller than before. This is a far cry from regulations in 2006 when 82 cm resolution imagery couldn't be released to anyone but U.S. government-approved users for 24 hours.[25] This regulatory change was driven by a recognition that other commercial imagers were approaching American capabilities.[26] As a result, the U.S. government shifted strategies, aiming to "maximize U.S. industry leadership while minimizing the imposition of national security conditions."[27]

Figure 4: Umbra Space SAR Image: 16 cm x 16 cm Resolution

Source: Umbra Space, 2023.

Beyond regulation, the government has also shifted its approach to fostering innovation and market expansion in remote sensing. Throughout the 1990s, the U.S.

government approach focused primarily on setting up a regulatory framework and letting the market develop.[28] Starting in the 2000s, however, this strategy began to evolve into a cycle of government development, commercial adoption, and then public/private partnership. Consider, for example, venture-backed companies such as PlanetiQ (founded 2012) and Spire Global (2012).[29] These companies use so-called radio occultation techniques, monitoring changes in radio signals to understand the atmosphere between a radio emitter (like GPS) and a receiver. The technique itself was pioneered on U.S.-funded interplanetary missions in the 1970s, and further tested with the government-funded GPS-MET mission from 1995 to 1997.[30] The two firms have now commercialized and scaled the technology, fielding dozens of satellites.

To complete the cycle of development, adoption, and partnership, Congress passed legislation in 2017[*] which directed NOAA to field microsatellite constellations to collect weather data.[31] Importantly, the same law also directed NOAA to accept and plan for commercial weather data "including public-private partnerships, for obtaining [...] space-based weather observations" and to establish standards for those data sources. The current strategy appears more sustainable over the long run as government supports technology advancement and benefits from commercial ability to deliver at scale, while companies have an anchor customer during market downturns.

[*] The Weather Research and Forecasting Innovation Act of 2017.

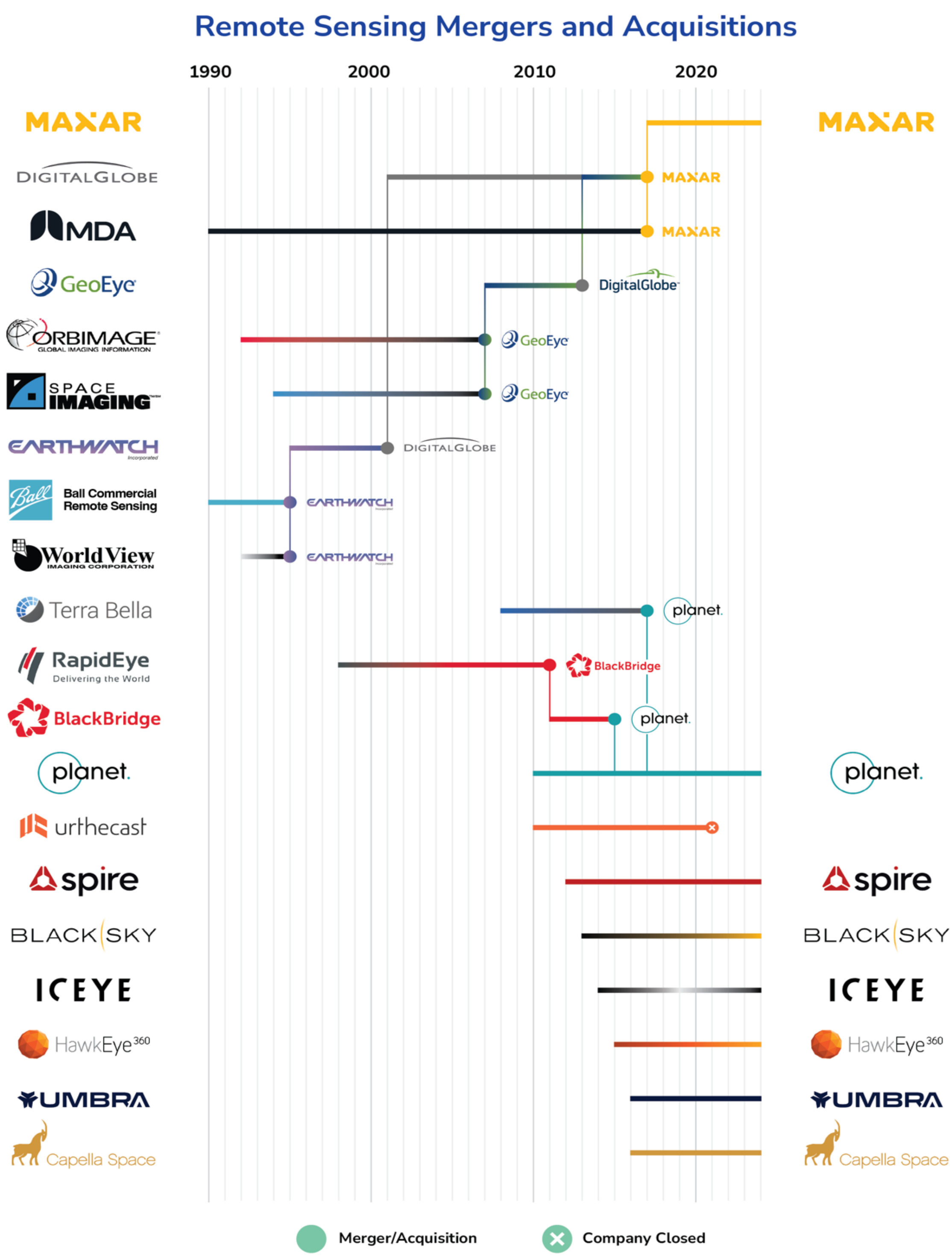
Industry and Technology Trends

The 1992 Land Remote Sensing Act created the U.S. commercial remote sensing industry. Figure 5 shows the founding of three companies, WorldView, Space Imaging Corporation, and Orbital Imaging Corporation, around the law's passage. Multiple launch failures, coupled with still-maturing technology and a relatively limited commercial market for imagery, led to major consolidation, especially in the 2000s.[32]

Another early player founded abroad, RapidEye, would be absorbed into what is today's Planet Labs PBC. The others would eventually merge into Maxar. The 2010s, however, saw a change from consolidation to rapid expansion. While causation is difficult to attribute, four technical, financial, and regulatory events happened around this time:

1. Satellites and electronics shrank, while sensors improved;
2. Launch availability increased;
3. Venture capital poured in, accelerating the other trends; and
4. Regulation remained stable and workable, before loosening further.

Figure 5: Selected Remote Sensing Corporate Foundings, Mergers and Acquisitions



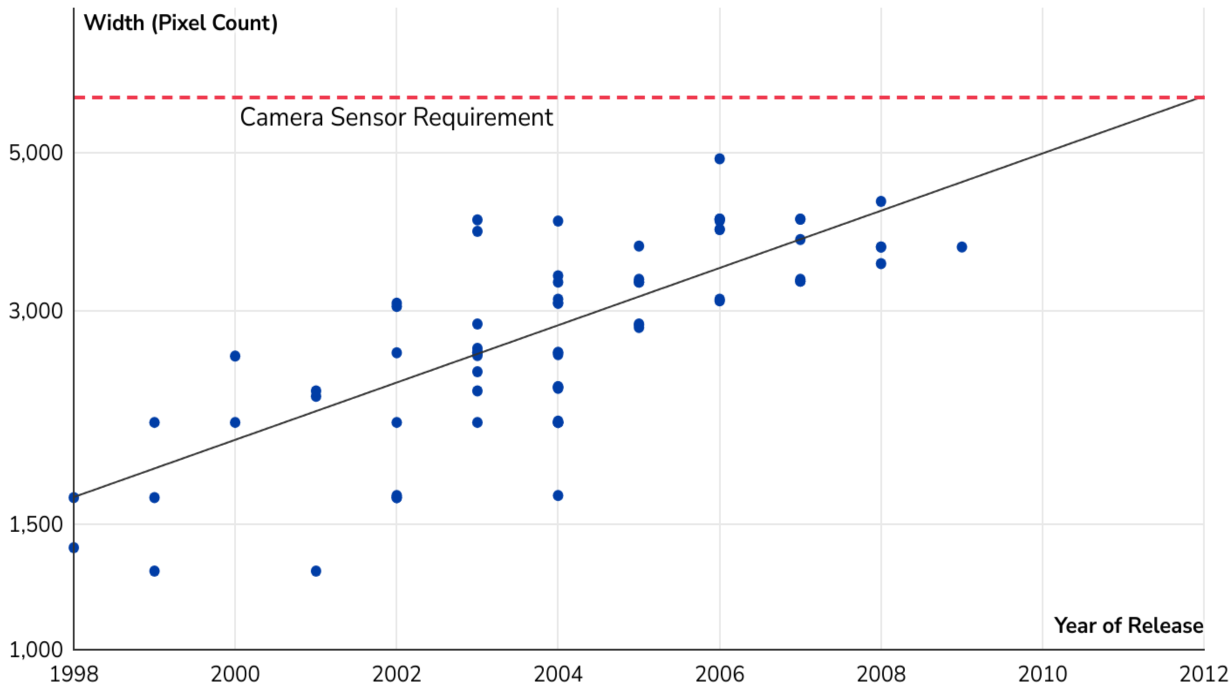
Source: Dates via Crunchbase and company websites.[33]

Contributing Factors

By 2010, miniaturization was in full swing, with the commercial chip market continuing to deliver better processing capability (compute) per unit mass and, importantly for satellites, improved compute per unit of power.[34] For remote sensing, both compute and image sensor capability are important. Figure 6 shows the consistent growth in camera sensor size over time.[35] Sensitivity and resolution likewise progressed. For instance, consider the case of Planet Labs: If we estimate the camera technology needed to provide global daily coverage with a moderately-sized (approximately 100-satellite) constellation, we find a commercially available camera sensor of sufficient size should have just entered the market between their founding in 2010 and their first launch in 2013, as shown with the Camera Sensor Requirement in Figure 6.[36]

Just as compute was getting faster, smaller, and more efficient, their satellite hosts were shrinking. At the same time, imaging sensors were growing and improving. The breadbox-sized cubesat platform was invented in 1999 primarily as a teaching tool, but by 2007 multiple launches with cubesats were occurring. While most of the industry did not embrace cubesats immediately, the diminutive form factor did signal the workability of smaller satellites.[37] Planet Labs is one notable industry exception; they recognized not only the workability of the small platform but its market advantages: cheap products, rapid technology refresh, good-enough performance, and the ability to accept a launch failure or two.[38]

Figure 6: Camera Width (in pixels) vs. Year[39]



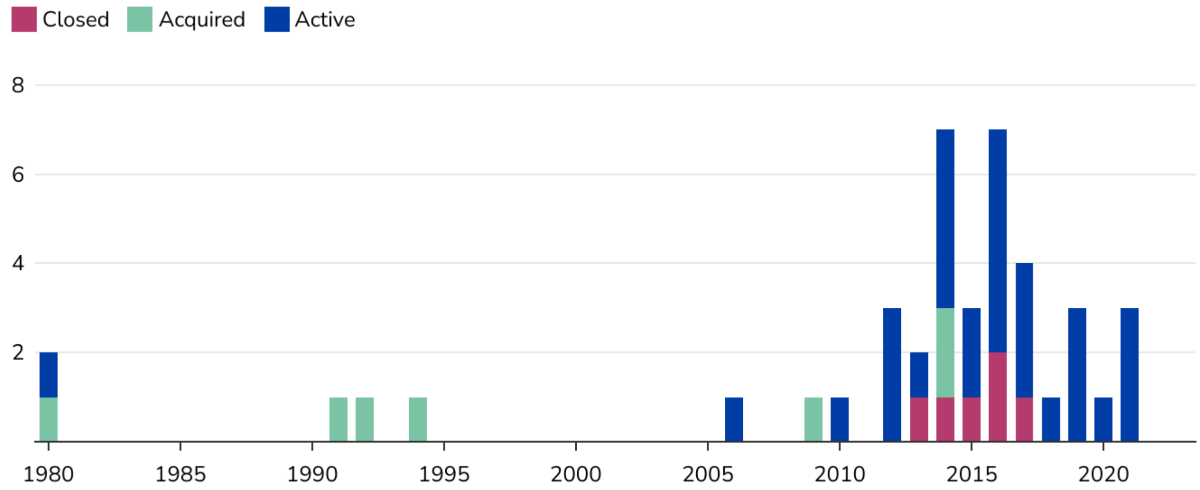
Source: Vitaly Lunyov, "Digital Camera CCD Development History."

The second contributing factor—namely, the rise of cheaper space launch at scale—came as SpaceX's early difficulties gave way to success, including the first launch of their now-workhorse Falcon 9 rocket in 2010.[40] Their launch rate would ramp up in the following five years, and with lower costs and the start of their rocket reusability research (which would pay off later), there was a new and viable niche for smaller spacecraft in larger quantities.[41]

Third, an influx of venture capital entered the market around 2014, ramping up significantly through at least 2022.[*, 42] Especially in light of decreased government research and development spending following 2013's budget sequestration, venture capital was both a lifeline and an accelerant to the technology trends.[43] The effects are seen in the growth in the number of companies founded in these years of increasing venture investment (Figure 7).[44]

* See Appendix: Methodology Details for more detail on PitchBook data.

Figure 7: Remote Sensing Company Founding Dates and Status[*, 45]



Source: PitchBook Data, Inc.

A final factor in the expansion of the commercial remote sensing market was the stability of the Department of Commerce remote sensing licensing rules, with NOAA as the licensing authority.[46] With few changes after 2006, companies could build and execute plans not subject to rapidly changing regulations that might push them out of business. Companies may have preferred moderately looser standards but those in place were workable.[47]

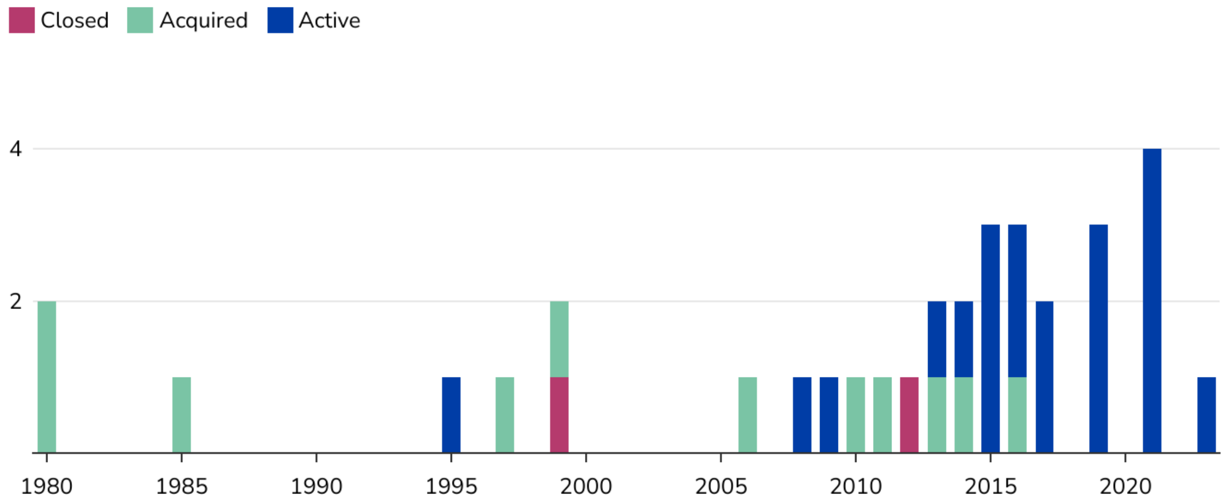
Trend Consequences

These factors, and the industry growth that came alongside them, had consequences for the industry itself. Those consequences and changes include diversification of business models and of satellite designs.

Business model diversifications included the stand-up of data-focused businesses. These companies take space data and generate actionable insights while imagery-focused companies operate the satellites that capture and deliver actual pictures from space. Data-focused companies that sell information, not just pixels, saw similar growth trends as their more hardware-focused counterparts (Figure 8).[48] Venture capital likely supported data analysis company growth as it did with remote sensing. The steady trends in growth, however, point to the importance in increasing data availability and quality, alongside lower computing and storage costs.

[*] Note: Companies founded in or before 1980 are combined into the 1980 histogram bin.

Figure 8: Space Data Analysis Company Founding Dates and Status*, [49]



Source: PitchBook Data, Inc.

Additionally, the deluge of data provided by newer, large constellations that image the world multiple times daily (high revisit rates) provide a more exploitable dataset than higher-resolution, tasking-driven images can. These high-revisit rates and broad coverage are a boon to data analysis companies as they allow for retrospective looks over vast areas rather than needing to prospectively forecast what will be interesting in order to plan future image collections.

The increasing availability of storage and compute also makes a data analysis business more viable. The expertise required for each business is different, and so the split and specialization of the two business models also simplifies talent management. This differentiation lets remote sensing companies set the foundation for a data analysis market, creating more opportunities for cross-company collaborations, investments, innovation, and distributed workloads.

Importantly, growth in the data analysis market is at least as important as growth in the broader remote sensing industry. Figure 8 shows that company foundation rates have grown, and today more than three in four data analysis companies in the PitchBook dataset were founded in 2008 or later. Progress in satellites is limited by the physical constrains of sensors, satellites, and launch vehicles. Data companies do not have such limits, and are instead constrained by the simpler, far cheaper, and more

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* Note: Companies founded in or before 1980 are combined into the 1980 histogram bin.

accessible terrestrial storage and compute, making them potentially attractive to investors.

Diversification includes more than different business models. It also covers the proliferation of both large and small satellites, and an increase in the types of sensors (or sensor *phenomenologies*).

In terms of size, different companies have sought out different niches. Maxar, for instance, has typically built build larger satellites to deliver high optical resolution, but their relatively larger size (1,000s of kg per satellite) and the attendant cost means the company is able to produce and launch fewer of them. As newer companies challenged their market share, Maxar began a move to greater numbers of smaller platforms (750 kg per satellite), though still prioritizing resolution over total quantity.[50] Planet, on the other hand, has expanded its constellation of much smaller satellites (5 kg per satellite) that offer lower resolution but daily world coverage.[51] Both approaches provide commercial value.[52]

At the same time that satellite size diversified, new sensing phenomenologies began commercial development and deployment. Historically, more 'legacy' companies—like those which would become Maxar, and the *New Space* company Planet—deployed visible band imagers.[*], [53] Especially after 2012, companies monitoring different phenomenologies were founded. Spire Global, which uses very small satellites to monitor radio emissions for ship tracking, weather measurement, and more, is one early example.

Figure 9 shows this expansion in phenomenologies: Maxar and its predecessors began their commercial space imagery enterprises in 1992, and Planet's effort began in 2010. Beginning two years later and accelerating around 2016, companies covering other phenomenologies were founded in quick succession. Many new companies brought new sensor types, some of which had previously been the domain of governments, such as radiofrequency (RF) sensing satellites and synthetic aperture radar (SAR) satellites providing high-resolution images during the day, at night, and in all weather conditions. Other phenomenologies that are rare even for governments to field are either in orbit commercially today, or planned for the near future. Hyperspectral satellites capable of thinly slicing light into narrow wavelengths to measure chemical composition and more are examples of the former, while the latter group includes non-Earth imaging (NEI) and LIDAR platforms.

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[*] "New Space" refers broadly to the set of companies developing low-cost, space-related products and services to meet commercial needs and not just traditional government requirements.

Figure 9: Remote Sensing Phenomenologies and Orbits[54]

<table>
<tr><th>Phenomenology</th><th colspan="2">Selected LEO Companies</th></tr>
<tr><td>RF/Sounding</td><td colspan="2">Spire Global (2012)</td></tr>
<tr><td>Radar/SAR</td><td colspan="2">Umbra (2015) & Capella (2016)</td></tr>
<tr><td>“Thermal” Infrared (IR)</td><td>Hydrosat (2017)</td><td rowspan="2">VLEO
Albedo (2020)</td></tr>
<tr><td>Visible Band (VIS)</td><td>Planet (2010) &
Maxar (1969/1992/2017)</td></tr>
<tr><td>Ultra Violet (UV)</td><td colspan="2" rowspan="3">Government Missions</td></tr>
<tr><td>X-Ray</td></tr>
<tr><td>Gamma Ray</td></tr>
<tr><td>LIDAR</td><td colspan="2">NuView (2022)</td></tr>
<tr><td>Multispectral</td><td colspan="2">Muon (2021)</td></tr>
<tr><td>Hyperspectral</td><td colspan="2">Orbital Sidekick (2016)</td></tr>
<tr><td>Non-Earth Imaging (NEI) &
Space Situational Awareness (SSA)</td><td colspan="2">Turion (2020)</td></tr>
</table>

No/Limited Commercial Exploitation
New Commercial Phenomenologies
Legacy Commercial Phenomenologies

Source: Dates via Crunchbase and company websites; phenomenology via author analysis.

Notably, the expansion of remote sensing constellations has been driven entirely by Low-Earth Orbit (LEO) missions. This is partly common sense: LEO missions provide much higher resolution and signal strength, ground antennas can be smaller, space radiation is relatively lower, and launch is much cheaper and more plentiful. With the onward march of Moore's law in storage, processing, and cameras (e.g., Figure 6), it is possible to design constellations that can affordably provide imagery on a high cadence.

Interestingly, while they have yet to launch, some companies are even venturing into the Very-Low-Earth Orbit (VLEO) regime from 100–400 km altitude, rather than the more typical 400+ km that most other LEO missions occupy.[*] This orbit promises low-cost approaches to high-resolution images. Governments have flown test missions there, but most missions have generally avoided those altitudes.[†, 55]

While most commercial remote sensing work is done at LEO, there are critical remote sensing missions often accomplished at higher altitudes, such as geosynchronous Earth orbit (GEO). These critical missions are challenging, though not impossible, for commercial vendors to service for technical and policy reasons. Consider, for example, the nuclear missile warning mission, executed in part by the Space Based Infrared System, or SBIRS.

Strategic missile warning systems like SBIRS must be nuclear hardened and highly reliable, which drives up costs. To mitigate these costs, many operate at GEO where only a few are required for global coverage. Operating tens of thousands of miles above the Earth helps coverage, but it also means surviving a harsher radiation environment, communicating over those vast distances, and seeing missiles from great distances—a technically challenging task for companies, but not impossible.[56]

Policy and legal limitations pose a greater challenge to commercialization and rightly so. Protecting the homeland is an inherently governmental function—if companies were tasked with operating nuclear missile warning satellites and failed in the mission, addressing the failure through contract law mechanisms would be an unsatisfying remedy.

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[*] As with many boundaries in space, definitions for VLEO differ slightly by organization.

[†] VLEO is difficult because of the propulsion and pointing control needed to counter drag, and the atomic oxygen at those altitudes tends to erode spacecraft surfaces.

Gaps, Challenges, and Opportunities

The dramatic proliferation of commercial remote sensing has created new opportunities for remote sensing and data analysis entrepreneurs along with national security leaders.

Despite these dramatic changes, there are still several gaps and challenges that industry and government might address to seize new opportunities for the economy and the nation's security. These include two phenomenology gaps, an orbital gap, and a pair of general challenges as the remote sensing industry progresses.

Gap 1: Infrared Phenomenology

There is limited commercial capability in infrared imagery, particularly long-wave (thermal) infrared, but that is changing. While the DOD has long invested in infrared sensors, and long used GEO-based infrared satellites for missile warning purposes, commercial infrared imagery provides a new opportunity.[57] Indeed, companies such as SatVu, Albedo, and Hydrosat are working toward satellites to meet that opportunity.[58] The thermal gap provides the opportunity for 'deeper' data: the ability to directly measure temperature allows analysts to indirectly calculate power generation and consumption, track fires, monitor industrial activity, and more. At the same time, producing infrared imagery presents challenges: Cooling requirements for most infrared imagers increase the expense and complexity of satellite designs, while the physics of infrared light's longer wavelengths means that the resolution of a given size of telescope runs 10–40 times worse than if used for visible light applications.

Gap 2: Hyperspectral Imagery

Hyperspectral imagery—the simultaneous collection of multiple narrow, contiguous wavelengths of light—is an emerging area for commercial collection. As with infrared, it has multiple companies (e.g., Planet, Orbital Sidekick) pursuing it.[59] Hyperspectral data at sufficient resolution has military and intelligence applications, while even low spatial resolution data can identify and track climate-relevant emissions and ocean health. For industry, hyperspectral data can help identify minerals and provide agriculturally relevant data on moisture content and plant and soil health. The science community has led, flying a handful of U.S. missions with spatial resolutions from 30 to 90m, alongside a small set of international missions. Opportunities, however, exist: Finer spatial resolution, more satellites and sensors, and a wider variety of orbits could benefit customers, especially as most of the previously flown U.S. missions have now ended.[60] While airborne alternatives do exist, operating costs, revisit rates, overflight restrictions, and other factors lend support to space-based solutions.

Though the technology itself is more complex than a basic visible band camera, it is not new, as American missions have gathered such data since 2000. More difficult is the management of the data volume generated: While visible band imagery takes 2-dimensional images, the addition of a spectral band creates a 3-dimensional 'data cube' that has to be downlinked, stored, and processed. Solving data management challenges in storing, downlinking, and processing the vast amount of data involved—and doing it profitably—remains the primary challenge in this area.

Gap 3: Very Low Earth Orbit (VLEO)

While the benefit of moving to GEO, HEO, or MEO orbits is difficult to discern for resolution-driven remote sensing products, so-called very low Earth orbit (VLEO) options are attractive. Their proximity to the ground increases resolution and signal strength, while reducing launch cost and the orbital lifetime of associated space debris.[61] For satellite operators themselves, the tradeoff is a reduction in sensor field of regard and the data download time available in a given pass, while fuel requirements and space environment effects (especially atomic oxygen erosion/damage) increase significantly. A company that can successfully operate in VLEO may provide uniquely high-resolution products while dramatically reducing one of the major risks of mega-constellations: debris. This is because the drag at such low altitudes means any debris reenters the Earth's atmosphere quickly, giving it little time to collide with other orbital objects.

Challenge 1: Debris Generation

Space debris and large constellation management are challenges for the commercial space industry, and remote sensing companies are not immune. As customers demand faster revisit rates and better resolution, the straightforward solution is more satellites and larger optics. This increases the likelihood and consequence of a collision between satellites, respectively.[62] Companies can manage this risk through the purchase of insurance, as is done in many terrestrial industries. However, space insurance is historically subject to wild boom-and-bust cycles, and the proliferation of low-cost, proliferated satellites makes insuring in LEO difficult.[63]

Unlike cars, however, spacecraft collisions affect more than just the immediately surrounding environment, as each collision seeds orbit with even more debris. To mitigate that risk, properly managing maneuvers, conducting collision avoidance, and executing post-mission disposal to a high degree of reliability will pose a challenge, especially since a business model where any one satellite is considered disposable means that companies may be willing to accept lower reliability. Further exacerbating the challenge is the fact that the risk of collision to any particular satellite or constellation is small, which may lead companies to discount the risk; in the aggregate, however, the risk is growing over time.

Challenge 2: Geopolitical Context

Commercial satellites, especially those with potentially outsized roles in a conflict, may become targets for state actors. Looking at the war in Ukraine, remote sensing companies provided proof of massed Russian forces before an invasion and evidence of troop movements, bombings, and violence against civilians after it.[64] Not only is this imagery relatively cheaper for governments than building their own satellites, but it is by its nature unclassified and shareable. There are export control considerations to make, however, to ensure such American-built capabilities are not used against allies and partners.[65] Even with these controls, industrial and cyber-enabled espionage by nation states will remain a risk that threatens to allow U.S. and allied assets to be used against friendly forces.

Furthermore, as countries continue to develop indigenous remote sensing satellites and commercial systems continue to proliferate abroad, protection against their capabilities in an event of a crisis or conflict will become more challenging.[66] Commerce Department regulations recognize this challenge, and to empower American industry, have jettisoned the old strategy that “attempted to control [risk in] perpetuity.”[67]

Additionally, countries prosecuting conflicts may view satellite imagery as a threat, if not a legitimate target in war. Russia, for example, has threatened the use of force against commercial satellites, such as those that captured imagery of Russian forces in and around Ukraine as well as evidence of active combat, mass graves, and the destruction of civilian buildings and infrastructure.[68] Thus far, publicly revealed actions against satellites appear to be limited to regular jamming-like attacks. A physical, irreversible attack on satellites, however, could raise the stakes.[69] While there is wide international support to ban certain types of anti-satellite testing, there is not yet support for outright bans on weapons that could damage or destroy a satellite.[70] Following Russian threats against satellites, the United States promised a response if American commercial infrastructure were targeted.[71] While proliferated commercial constellations improve resilience to physical attack, it does not prevent adversaries from using other tools, such as cyber capabilities, to further their goals.

Opportunity: Multi-Phenomenology and Multi-Disciplinary

Historically, commercial satellite capabilities have been limited: a handful of satellites that operated in and near the visible band. The rise of new phenomenologies and orbits present a unique opportunity for collaboration.[72] Combining diverse orbits and sensors offers the ability to sense and understand the world at a deeper level. For instance, the combination of hyperspectral imagers with high-resolution visible-band imagery may provide insight into methane emissions.[73] Other techniques may create 3-D imagery from multiple 2-D satellite images.[74] Some capabilities, such as distributed aperture sensing and its gains in resolution, *require* combinations of distributed sensors. The governments and companies that can first take advantage of these new capabilities will have a competitive edge—but there must be a path to commercial profitability.

Collaboration, however, necessitates the creation of multi-disciplinary teams of experts from various fields, including engineering, operations, and data analytics. Done well, this collaborative approach will improve the timeliness and depth of data for military and civilian applications, offering enhanced situational awareness and reconnaissance capabilities.[75] Importantly, increases in multidisciplinary collaboration offer the possibility for truly game-changing innovations, providing asymmetric national security advantages against adversary nations.[76] Commercially, this also means investment in data analysis companies should be considered at least as important as support for remote sensing companies.

Recommendations

The United States has benefitted from a combination of factors leading to a robust space remote sensing market: stable and light regulation, government and venture capital investment, and the combination of a capable workforce and the advancing technology. To keep the market robust while allowing American companies to deliver cutting-edge capabilities that simultaneously benefit the U.S. economy as well as protect national security, we recommend the following:

1. **The U.S. government should expand purchases of products and services from commercial remote sensing companies, while partnering with investor capital to encourage commercial remote sensing innovation.**

   The United States derives great national security and economic advantage from its domestic remote sensing *and* data analysis industries, and its expansion into new orbits and new phenomenologies represents a (almost) unique American commercial capability. Critically, the country must encourage the continued health and growth of the market via the twin tracks of investment and purchases in order to continue to best reap those advantages.

   For the health of the market, government activity should help the industry through cyclical downturns, while providing time for new businesses to mature and enter the market to ensure competitiveness. This can be best achieved if the government acts as an anchor tenant that is willing to buy products once a company can deliver them.[77] The DOD and the broader Intelligence Community (IC) should heed the example of the National Reconnaissance Office (NRO) Strategic Commercial Enhancements contracts, which connect new remote sensing providers to national security customers. This lets users test their products while supporting commercial technology development.[78]

   For continued growth and innovation in the market, anchor tenancy is helpful to build venture investor confidence. The use of limited grants like small business innovation research (SBIR) funding can help, but space systems are expensive. While these capped awards can show interest, more resources are necessary. In this area, organizations such as the DOD's Office of Strategic Capital would be likely leaders in this activity, helping focus and encourage private venture capital.[79]

2. **The U.S. government should expand purchases from data analysis companies while partnering those companies with multi-disciplinary government test and experimentation teams to maximize the operational relevance of new data sources.**

   The United States benefits when new data analysis companies bring novel ideas to bear to national problems. The same companies can benefit from the deep knowledge base that resides within government defense, intelligence, and science communities.

   Furthermore, with multiple new data companies and types of sensors, there are opportunities for the DOD and the broader government to build new operational constructs combining datasets. It will take creative teams of experts to find some of the most innovative solutions. Much as it has done for experiments with autonomy and uncrewed systems, the DOD should charter experimentation teams to test ways to use new satellite capabilities and deliver operationally relevant capabilities. Newer phenomenologies like hyperspectral and "thermal" infrared, and new orbits like VLEO, lend themselves well to this government-commercial teaming arrangement.

   Such a team should maintain close personal and organizational links to acquisition teams, operational teams, and the test community, and interact closely with the remote sensing companies. The teams should be chartered to deliver new capabilities relevant to government customers. By building expertise, use cases, and a government demand signal for multi-modal sensing, the United States will be better positioned to leverage nascent commercial technologies and further encourage their development. The government can also act as an anchor customer for novel data products, bridging the gap between a viable technology and a commercially profitable one. In doing so, the government can enhance American economic competitiveness, but more importantly deliver national security insights that might not be commercially attractive.

3. **The U.S. government broadly, and the Department of Commerce specifically, should maintain current remote sensing regulations allowing commercial sales of world-leading imagery, but also evaluate the application of location-specific controls to protect allies, partners, and U.S. forces in conflict.**

   The current remote sensing market growth grew during an era of stable regulation. Loosened licensing provisions in 2020 and the Commerce

Department's move permitting the scheduled expiration of many of those resolution restrictions in 2023 should further ease the burden placed on commercial sensing providers. This low burden allows U.S. companies to compete on quality *and* quantity rather than cost, which may slow the rise of similar capabilities in unfriendly nations that otherwise possess lower labor and capital costs. Especially as other less-than-friendly nations improve their commercial capabilities, holding back U.S. companies is undesirable. Under the Commerce Department, NOAA's current regulations recognize that fact. Nevertheless, the growing capabilities of space-based remote sensing, and its geopolitical relevance, require caution to mitigate the risk to the United States and its allies and partners.

4. **The U.S. government should continue basic research investments in sensing technology, and expand the technology transfer of those with commercial applications.**

   The U.S. government has long invested in applied research to improve sensors; DOD has driven infrared sensor development; NASA and the scientific community have developed exquisite hyperspectral systems; and radio occultation was developed on interplanetary missions and is now used to sense terrestrial weather. To keep a national advantage, such investments should continue, especially in sensors lacking the kinds of robust consumer markets seen in visible band sensors. Working with companies to reduce size, weight, power, and cost can provide a dual benefit: While the government advances technology, industry makes it easier and cheaper to use. Careful tuning of export control and export licensing measures will be required to enable U.S. companies to use these technologies alongside allies and partners. However, with appropriate measures in place, this is a feedback loop to be encouraged.

5. **Within operational plans, the U.S. government should ensure coordinated options are developed and exercised to respond to reversible and irreversible attacks on commercial U.S. satellites.**

   The U.S. advantage in space is no secret to adversaries. Its commercial advantage is likewise well-known and worth preserving. To preserve the U.S. ability to leverage commercially-provided remote sensing systems in crisis, or in conflict should it occur, requires pre-crisis communication with industry and a strong, credible disincentive for attacks on those systems.

Conclusion

The United States has a broad set of space remote sensing companies, and a sensing market far different than existed a decade ago. While the explosive growth appears to have ebbed, the United States still possesses a major national security advantage. The threads of law and regulation, technology development, and new business models have set the stage for this advantage. Policymakers have the opportunity to continue to encourage growth for this still-nascent industry.

How the U.S. government chooses to invest in new technologies and orbits, how they deal with the challenges of space debris and geopolitics, and how they take advantage of the newest entrants into the space sensing market will determine the path forward for the next decade. By investing in the commercial remote sensing market, serving as an anchor tenant, and teaming with industry for both technology development and pre-crisis preparation, the United States can continue to translate its economic advantage into national security strength, and vice versa.

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Disclaimer

The conclusions and opinions expressed in this research paper are those of the authors and do not necessarily reflect the official policy or position of the U.S. government, the U.S. Department of Defense, the U.S. Space Force, or the Air University. Any and all errors are those of the authors alone.

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Appendix: Methodology Details

The goal of this publication is to capture the history and current status of the remote sensing and data sub-sector of the broader space economy, given its relevance to policymakers and the national security community.

This analysis leverages PitchBook, which provides rich information about corporate financial and investment fund activity for public and private companies. This insight into corporate finance allows fine-grained analysis of various industries and companies, along with a view into how those industries change through investments and mergers and acquisitions. PitchBook provides industry assignments for companies covered within their dataset, which we use to select companies relevant to the space economy. The authors then assigned each of the 543 companies in the "Space Technology" vertical to appropriate sub-sectors.[80] The company assignments were based on the authors' professional knowledge and a detailed review of the company description from PitchBook, company websites, and news reports.[*] For example, the following criteria were used to assign companies to remote sensing and data sub-sectors:

Primary Question	Secondary Question/Note	Sub-sector "Tag"
Does the company produce satellites or leverage data produced by satellites?	Does the company build satellites that monitor the Earth for their own missions/data sales?	"Remote Sensing"
Does the company manage or analyze data from satellites?	Note: This is typically mission data, as C2-Management companies use data to control satellite constellations.	"Data"

Companies could belong to multiple sub-sectors or none at all. The authors also noted key information about the sensors that remote sensing companies used, such as

[*] Additional criteria were used to assign companies to other sub-sectors. For further detail, please contact the authors.

whether they primarily used hyperspectral sensors, Lidar, or IR/multispectral cameras.[81]

Once companies were assigned, data related to each company's founding date, operating status, and merger activity was acquired from PitchBook. In this publication, there are 42 companies assigned to remote sensing, and 33 assigned to data.

There are limits to the data. While a data aggregator like PitchBook is unlikely to identify every space company, our ultimate goal is to provide analysis and trending of key corporate metadata including foundation year, business status, acquisition status, and investment health. Using manual annotation of companies provides a human check on the relevance of a company to the analysis. Further boosting confidence in the data and analysis, the team found that other research, commercial datasets, and internal sampling showed similar trends.[82]

Additionally, given the developing nature of the space economy, companies may grow or shrink their product portfolios. The data represents a current snapshot of the space economy to maximize usefulness to policymakers and the national security community today. Future work should continue or expand the annotation process to ensure continued accuracy.

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[34] While smaller chips packed with more transistors are better for nearly all users of computing chips, this is not true in space. The radiation environment that satellites operate in means that larger chips with larger feature sizes are typically preferred. In general, larger features mean that a particle of radiation hits fewer transistors as it passes through a chip, and those larger features also require higher energy radiation to 'flip' to an incorrect state. That said, older generation chips, and especially those with sufficient radiation testing, are expensive since the market is miniscule compared to the consumer computing industry. Even then, the use of moderately lower orbits for *New Space* companies compared with many of Maxar's (Polar Geospatial Center, Maxar satellite constellation, October 3, 2023, https://www.pgc.umn.edu/guides/commercial-imagery/maxar-satellite-constellation/) can help mitigate radiation somewhat, and enable the use of cheaper, commercial-grade chips

[35] For camera sensors, pixel size and total number of pixels are not inherently better and the relationship between sensor and optics is important. However, if you are interested in covering large portions of the Earth at reasonable resolutions, it helps to have a large camera sensor chip with a large number of appropriately sized pixels.

[36] Their constellation at 475 km altitude gives them a near-daily global revisit rate with 130 satellites. Their cameras take images of 24.6 km (swath widths) at resolutions of 3.7m. While their 91mm optics may theoretically allow sub-3m resolution, even 3.7m requires approximately 6,600 pixels and pixel width (pitch) of about 5.5 microns. That matches well with their design documentation. See: Planet, Planet imagery product specifications, May 2019, pg. 13, https://assets.planet.com/docs/combined-imagery-product-spec-final-may-2019.pdf; Christopher R. Boshuizen et al., "Results from the Planet Labs Flock Constellation," 28th Annual AIAA/USU Conference on Small Satellites, n.d., pg. 3, https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3016&context=smallsat.

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Vitaly Lunyov, "Digital Camera CCD Development History," Riddle HQ , n.d., https://web.archive.org/web/20151105073645/https://www.riddle.ru/?page=articles%2Fccd. Source data ends in 2009. While some CMOS (complementary metal oxide semiconductor) sensors may have been available in slightly larger sizes, CCDs (charge coupled devices) still offered better performance and were more widely used in the professional imaging community at that time.

Indeed, while we can't confirm it, there is a strong circumstantial case that Planet's sensor was released *in* 2010, right on schedule. Planet describes their sensor as an industrial CCD, and their technical documentation describes a 6600 x 4400 pixel array (Christopher R. Boshuizen et al., "Results from the Planet Labs Flock Constellation," 28th Annual AIAA/USU Conference on Small Satellites, n.d., pg. 3, https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3016&context=smallsat). While no documentation confirms it, this description fits closely with the now-discontinued Kodak KAI-29050 CCD, with the same dimensions and pixel pitch. That sensor was announced around 2010 with engineering units available the same year and production units in early 2011 (Steve Huff, "Press Release: New Kodak 29MP Sensor...HMMMM," Steve Huff Hi-Fi and Photo | Hi-Fi Audio Reviews, November 7, 2010, https://www.stevehuffphoto.com/2010/11/07/press-release-new-kodak-29mp-sensor-hmmmm/). The earliest datasheet our team has found dates from 2013 but is version 2.0 (TrueSense Imaging Inc., "Kai-29050 Image Sensor — 1st Vision," 1st Vision, January 16, 2013, https://www.1stvision.com/cameras/sensor_specs/KAI-29050LongSpec.pdf).

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[42] Ryan Brukardt et al., “Space: The Missing Element of Your Strategy,” McKinsey & Company, March 27, 2023, https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/space-the-missing-element-of-your-strategy.

[43] Committee for a Responsible Federal Budget, “Understanding the Sequester,” n.d., https://www.crfb.org/understanding-sequester.

[44] Different sources may put the start date at various years between 2010 and 2012 (e.g., Crunchbase vs. PitchBook Data, Inc., the latter of which is plotted here). Nevertheless, the current tapering off is seen in both datasets. Trends in revenue, profitability, and other financial metrics are planned for future research, but out of scope for this document.

[45] Defined as companies which use satellite data from other companies to generate information and insight. This is likely to undercount the true number, as companies that perform data analysis that includes satellite imagery may not be fully captured in PitchBook Data, Inc.’s Space Technology vertical.

[46] National Oceanic and Atmospheric Administration, “Licensing of Private Land Remote-Sensing Space Systems,” Federal Register, April 25, 2006, https://www.federalregister.gov/documents/2006/04/25/06-3841/licensing-of-private-land-remote-sensing-space-systems.

[47] See Section 1, “Major Substantive Issues Raised by Public Comment”: National Oceanic and Atmospheric Administration, “Licensing of Private Land Remote-Sensing Space Systems,” Federal Register, April 25, 2006, https://www.federalregister.gov/documents/2006/04/25/06-3841/licensing-of-private-land-remote-sensing-space-systems.

[48] Notably, this growth becomes uneven after 2017, though it is unclear whether this is driven by investment trends, pandemic effects, or other factors. It does correlate with a temporary leveling off in venture investment. https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/space-the-missing-element-of-your-strategy.

[49] Defined as companies which build and/or operate their own satellites for remote sensing missions.

[50] WorldView Legion, eoPortal, August 6, 2020, https://www.eoportal.org/satellite-missions/worldview-legion#eop-quick-facts-section.

[51] Growth in the smaller market appears robust. The launches of sub-10kg satellites, for example, have grown by more than a factor of 10 from 2010–2012 to 2021–2023. While those are on the very small end of satellites, and many are for educational purposes, in a given year two-thirds of those are launched for companies. While our team has not done a full quantitative evaluation of all remote sensing satellite launches, the entire launch market as a whole shows similar growth in satellites larger than 10kg.

See: Erik Kulu, "Nanosatellite Launches," NewSpace Index, n.d., https://www.nanosats.eu/img/fig/Nanosats_years_black_2023-12-31_large.png; Erik Kulu, "Nanosatellite Launches by Organisations," NewSpace Index, n.d., https://www.nanosats.eu/img/fig/Nanosats_years_organisations_black_2023-12-31_large.png.

[52] Interestingly, recent trends at both companies show convergence: Planet has acquired and is building larger systems (https://www.planet.com/products/hyperspectral/), while Maxar is building smaller satellites with greater coverage capability (https://www.eoportal.org/satellite-missions/worldview-legion#providing-intra-day-revisit).

While most trends in commercial remote sensing satellites are for smaller LEO satellites, there is at least one company going the other way: massive commercial satellites to take advantage of upcoming large launch vehicles like SpaceX's Starship and Blue Origin's New Glenn. See: Michael Sheetz, "K2 Space, a Startup with Spacex Veterans Building Monster Satellites, Raises $50 Million," CNBC, February 13, 2024, https://www.cnbc.com/2024/02/13/startup-k2-space-raises-50-million.html.

[53] Many of these companies do offer near-infrared (NIR). While providing important data, especially for measuring things like plant growth, NIR it is not vastly different to visible band light, and doesn't offer the significantly different information that longer-wavelength infrared, like so-called "thermal IR," can offer.

[54] Note that Maxar's founding date is based off of the founding date of Macdonald, Dettwiler and Associates Corporation (MDA). 1992 and 2017 mark significant merger dates for Maxar, though Maxar did go by the name "Maxar Technologies" until 2017.

[55] "SLATS (Super Low Altitude Test Satellite) / Tsubame," eoPortal, October 19, 2012, https://www.eoportal.org/satellite-missions/slats#overview. VLEO is a subset of low Earth orbit.

[56] Technical requirements, like radiation hardness, nuclear survivability, and continuous global coverage all at high reliability rates, would be challenging at commercial price points using commercial parts. A company would also need to attain certification for their systems prior to use in the nuclear warning architecture. Operating the satellites themselves, which tends to be part of the attractiveness of commercial offerings, would be an even higher hurdle given the responsibilities and consequences of the mission.

It is important to note, however, that commercial communications satellites do operate at GEO, also using the strategy of building a handful of very expensive spacecraft. Further, the Missile Defense Agency, in partnership with the Space Development Agency, is attempting to launch a more proliferated constellation of satellites into lower orbits to enhance missile tracking capabilities using satellites. Each of these technical and cost factors are challenges to expanding the mission sets accomplished by commercial vendors—but not impossible hurdles. See: "MDA, SDA Confirm Successful Launch of the Hypersonic and Ballistic Tracking Space Sensor and Tranche 0 Satellites," U.S. Department of Defense, February 15, 2024, https://www.defense.gov/News/Releases/Release/Article/3677785/mda-sda-confirm-successful-launch-of-the-hypersonic-and-ballistic-tracking-spac/.

[57] A. Rogalski, “History of Infrared Detectors,” *Opto-Electronics Review*, vol. 20, no. 3 (2012), pg. 279–308, https://doi.org/10.2478/s11772-012-0037-7; Antoni Rogalski, “Infrared Detectors: An Overview,” *Infrared Physics & Technology*, vol. 43, no. 3–5 (June 2002),pg.187–210, https://doi.org/10.1016/s1350-4495(02)00140-8; Dr. James “Ralph” Teague and David Schmieder, “The History of Forward-Looking Infrared (FLIR),” DSIAC, October 2021, https://dsiac.org/state-of-the-art-reports/the-history-of-forward-looking-infrared-flir/.

[58] SatVu, “About Us,” SatVu, April 6, 2023, https://www.satellitevu.com/about-us; Winston Tri, “Things Are Heating Up!” Albedo, April 29, 2022, https://albedo.com/post/things-are-heating-up.

Hydrosat, “About,” n.d., https://www.hydrosat.com/#solutions.

[59] A. McCullum, J. Torres-Pérez, and Z. Bengtsson, “ARSET — Hyperspectral Data for Land and Coastal Systems,” NASA Applied Remote Sensing Training Program (ARSET), 2021, part 1, slide 12, https://appliedsciences.nasa.gov/join-mission/training/english/arset-hyperspectral-data-land-and-coastal-systems; Keith Cowing, “NASA JPL Imaging Spectrometer Ready for Tanager 1 Integration,” *SpaceRef*, September 18, 2023, https://spaceref.com/space-commerce/nasa-jpl-imaging-spectrometer-ready-for-tanager-1-integration/; Orbital Sidekick, “Technology,” Orbital Sidekick, n.d., https://www.orbitalsidekick.com/technology.

[60] A. McCullum, J. Torres-Pérez, Z. Bengtsson, “ARSET — Hyperspectral Data for Land and Coastal Systems,” NASA Applied Remote Sensing Training Program (ARSET), 2021, part 1, slide 20, https://appliedsciences.nasa.gov/join-mission/training/english/arset-hyperspectral-data-land-and-coastal-systems. Part 1, slide 20, describes 3 U.S. missions, two of which are aboard the International Space Station. As the ISS orbits at 51.6 degrees inclination (NASA, “International Space Station,” NASA, October 2, 2023, https://www.nasa.gov/reference/international-space-station/), that means it does not overfly any latitudes greater than 51.6 degrees N or S. Only EO-1 Hyperion flew in a polar, sun-synchronous orbit, permitting full global coverage.

[61] An important issue, but one not directly applicable to national security, is the impact on astronomy. For the ground-based astronomy community, VLEO satellites would be a mixed bag: fewer satellites in view, but brighter and more likely to spoil the view. See Olivier R. Hainaut, “Large Satellite Constellations and Their Impact on Astronomy,” Olivier Hainaut Personal Page, European Southern Observatory, https://www.eso.org/~ohainaut/satellites/. See also Olivier R. Hainaut and Andrew P. Williams, “Impact of Satellite Constellations on Astronomical Observations with ESO Telescopes in the Visible and Infrared Domains,” *Astronomy & Astrophysics*, vol. 636 (2020) A121, https://doi.org/10.1051/0004-6361/202037501.

[62] Or the aforementioned lower orbits.

[63]Noor Zainab Hussain and Carolyn Cohn, “Focus: Launching into Space? Not so Fast. Insurers Balk at New Coverage,” *REUTERS*, September 1, 2021, https://www.reuters.com/lifestyle/science/launching-into-space-not-so-fast-insurers-balk-new-coverage-2021-09-01/; Federal Aviation Administration,

Commercial Space and Launch Insurance: Current Market and Future Outlook, 2002, https://www.faa.gov/about/office_org/headquarters_offices/ast/media/q42002.pdf.

[64] Malachy Browne, David Botti, and Haley Willis, "Satellite Images Show Bodies Lay in Bucha for Weeks, Despite Russian Claims," *The New York Times*, April 4, 2022, https://www.nytimes.com/2022/04/04/world/europe/bucha-ukraine-bodies.html; Obtained by *The Washington Post*, "File: Russian Forces Near Ukraine," Wikimedia Commons, December 3, 2021, https://commons.wikimedia.org/wiki/File:Russian_forces_near_Ukraine,_2021-12-03_(crop).jpg.

[65] Graeme Wood, "A Suspicious Pattern Alarming the Ukrainian Military", *The Atlantic*, March 18, 2024, https://www.theatlantic.com/international/archive/2024/03/american-satellites-russia-ukraine-war/677775/.

[66] Josef S. Koller, "The Future of Ubiquitous, Real-time Intelligence — A GEOINT Singularity," Aerospace Corporation Center for Space Policy and Strategy, April 8, 2019, https://csps.aerospace.org/papers/future-ubiquitous-real-time-intelligence-geoint-singularity.

[67] "NOAA Eliminates Restrictive Operating Conditions from Commercial Remote Sensing Satellite Licenses," Office of Space Commerce, August 7, 2023, https://www.space.commerce.gov/noaa-eliminates-restrictive-operating-conditions-from-commercial-remote-sensing-satellite-licenses/.

[68] Maxar Technologies, "New Documentary on Ukraine Underscores the Importance of Maxar's Commercial Satellite Imagery and Capabilities," Maxar Blog, March 2, 2022, https://blog.maxar.com/earth-intelligence/2023/new-documentary-on-ukraine-underscores-the-importance-of-maxars-commercial-satellite-imagery-and-capabilities.

[69] Josh Rogin, "Opinion | A Shadow War in Space Is Heating Up Fast," *The Washington Post*, November 30, 2021, https://www.washingtonpost.com/opinions/2021/11/30/space-race-china-david-thompson/.

Lucas Laursen, "Satellite Signal Jamming Reaches New Lows," *IEEE Spectrum*, July 25, 2023, https://spectrum.ieee.org/satellite-jamming.

[70] Jeff Foust, "United Nations General Assembly Approves Asat Test Ban Resolution," *SpaceNews*, January 30, 2023, https://spacenews.com/united-nations-general-assembly-approves-asat-test-ban-resolution/. Note that among the countries that voted against the UN resolution are Russia and the People's Republic of China—two countries which have demonstrated such capabilities in the past.

[71] Kari A. Bingen, Kaitlyn Johnson, and Zhanna Malekos Smith, "Russia Threatens to Target Commercial Satellites," CSIS, November 10, 2022, https://www.csis.org/analysis/russia-threatens-target-commercial-satellites. Note: The Q&A from CSIS addresses this point but provides other strong insight into the space threat environment; Steve Holland and Susan Heavey, "White House Vows Response If Russia Attacks U.S. Satellites," *REUTERS*, October 27, 2022, https://www.reuters.com/world/white-house-vows-response-if-russia-attacks-us-satellites-2022-10-27/.

[72] Eric Hamilton, "What Is Multi-Messenger Astronomy?," University of Wisconsin-Madison News, n.d., https://news.wisc.edu/what-is-multi-messenger-astronomy/. Similar collaborations in astronomy, *multi-messenger astronomy*, are enabling major advances in the science community.

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[80] The 'Space Technology' was used by our team to generate candidate companies prior to manual review. The use of labeled verticals improves comparisons between industries over other methods. See: "What Are Industry Verticals," PitchBook Data, Inc., https://pitchbook.com/what-are-industry-verticals.

[81] The full list of labels were: 1: VLEO | 2: Hyperspectral | 3: RF-RO | 4: Meteorology | 5: SAR/Radar | 6: RF | 7: Lidar | 8: IR/Multispectral | 9: EO only, [Blank].

[82] E.g., Erik Kulu, “Satellite Constellations,” NewSpace Index, n.d., https://www.newspace.im/. Erik Kulu, “Nanosats,” Nanosats Database, n.d., https://www.nanosats.eu/.