LEVERAGING COMMERCIAL SPACE FOR EARTH AND OCEAN REMOTE SENSING

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LEVERAGING COMMERCIAL SPACE FOR EARTH AND OCEAN REMOTE SENSING

Committee for the Assessment of Partnership Options for a Small Satellite System for Collecting Scientific Quality Oceanic and Coastal Data

Intelligence Community Studies Board

Division on Engineering and Physical Sciences

A Consensus Study Report of

The National Academies of
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Acknowledgment of Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

Stephen A. Fuselier, NAS
Sarah T. Gille
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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Richard Crout, who is Supervisory Oceanographer and Head of the Ocean Sciences Branch at the Naval Research Laboratory, and Soroosh Sorooshian, NAE, who is the Director of the Center for Hydrometeorology and Remote Sensing at the University of California, Irvine. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

Contents

Summary

The National Academies of Sciences, Engineering, and Medicine formed the Committee for the Assessment of Partnership Options for a Small Satellite System for Collecting Scientific Quality Oceanic and Coastal Data to address the following objectives within the statement of task:

> The study will provide an independent assessment of the feasibility and implications of creating and exploiting partnerships for developing, deploying, and operating a system of satellites and supporting infrastructure capable of sensing ocean, coastal, atmospheric, and hydrologic data of sufficient scientific quality to enable prediction models and to support near real time applications of national interest. It will identify and describe, to the extent possible, promising options for such a system. The committee will identify and consider potential partners—public and private—for developing such a system or major subsystems, taking into account factors such as:
>
> - What national missions might benefit in a substantial way from access to a small satellite data collection system and how might that mission depend on the frequency and geographic scope of the data collection? Those benefits might be defined broadly to include military, economic, scientific, educational, and environmental benefits.
> - What partnerships among industry, government, and academic institutions might be incentivized to develop the necessary space platform, system integration, launch, communications, test, data distribution, and maintenance functions?
> - Is the existing infrastructure sufficient to support the needed space platform development and manufacture, system integration, launch, communications, test, data distribution, and maintenance functions? What infrastructure components should be enhanced or created in order to reduce the timeline from idea to on orbit? Infrastructure is broadly defined to include industrial manufacturing capability, space system support structures, and communication-information systems.
> - What processes may be employed to enhance the technology development pipeline, standards development, and the identification and adoption of best practices?
> - What is the anticipated time line for the development of the required technology, infrastructure, and processes that will enable the development of the desired satellite systems?
>
> In conducting the study, the committee will review current systems that provide some of the needed system components, as well as systems in various stages of development for future deployment. To the extent possible, the committee will gather and analyze information on anticipated relevant future needs of public and private organizations as well as relevant perspectives of academic researchers.

In fulfilling its charge to the statement of task the committee's approach to the assessment relied on the experience, technical knowledge, and broad expertise of its members. The committee did not attempt to report an exhaustive assessment of every potential partnership option or every available approach to implementation. The committee's first objective was to provide enduring value by identifying and focusing on which government mission areas could most utilize and benefit from commercial New Space capabilities for space access (defined in Box S.1 below). Its second goal was to determine current challenges and future opportunities for redefining space infrastructure in order to become more amenable to sustainable partnerships together with identifying acquisition methods capable of serving multiple stakeholders.

GENERAL OBSERVATIONS

The opportunities discussed in this report derive from the explosive growth of New Space technology serving both the commercial and government sectors (discussed in Chapter 2). SmallSat technology (described below in Box S.1) has dramatically changed the paradigm of how commercial satellites are procured, developed, and launched by government agencies. The technology and associated space development continue to evolve rapidly and are generally referred to as the New Space ecosystem in this report. The intended definition is modeled after the "Silicon Valley" ecosystem[1] where the government is an important partner in creating a healthy and self-sustaining relationship with the commercial sector to provide space products as well as associated innovations of the space business itself. As one might expect there are many new terms associated with such a paradigm shift meaning that the terminology for the discussion in this report of current and future trends require careful and specific definition. For consistency and clarity the committee uses the following terms listed in Box S.1.throughout the report.

BOX S.1
Report Terminology

SmallSat: A small satellite spacecraft with a mass less than -600 kg. Throughout this report, the term "SmallSat" subsumes all of the categories below, except in cases where the specific size or type is relevant.

- **CubeSat:** A spacecraft, with multiple sizes, that adheres to the CubeSat Design Specification (CDS) standard where a single unit (1U) is based on a physical dimension of 10 cm × 10 cm × 10 cm in size and launched into space via a containerized dispenser. Note that a CubeSat can be an aggregation of multiple 1U elements with 3U being a common architecture but with sizes that can be extended to 27U. Generally, sizes above 27U do not have containerized launch capability but need to be accommodated by some other means.
- **Minisatellite**: A small satellite spacecraft with a mass in the range of 100-600 kg.
- **Microsatellite:** A small satellite spacecraft with a mass in the range of 10-100 kg.
- **Nanosatellite:** A small satellite spacecraft with a mass in the range of 1-10 kg.

New Space: A post-millennial, modern approach focused on lowering the barriers of entry to space through increased risk tolerance and innovations in spacecraft development, launch, contracting, and business practices, largely led by new and agile private sector commercial organizations focused on bringing increased and rapid access and affordability to space.

Picosatellites: The term "picosatellite" or "picosat" is usually applied to artificial satellites with a wet mass between 0.1 and 1 kg (0.22 and 2.2 lbs.), although it is sometimes used to refer to any satellite that is under 1 kg in launch mass.[2]

Public Private Partnerships (PPP): As used in this report, PPP is an overarching generic term for an arrangement that can be formed as: (1) a formal PPP agreement between the government and a commercial capability provider—for example to meet government requirements, or for privatization of existing government capabilities or (2) the government buying a commercially marketed capability such as: data products, satellite buses, satellite components, or hosting of payload developed to adapt to existing commercial capabilities.

Traditional Space: The historical space industry or space pioneers, mainly consisting of large government agencies, multinational corporations, and contractor organizations, highly experienced with legacy space systems and practices.

[1] Kushida, K., A Strategic Overview of the Silicon Valley Ecosystem: Towards Effectively "Harnessing" Silicon Valley. 2015. Stanford University.

[2] See https://www.scribd.com/document/367909647/Small-Satellite?.

Within the past decade an ever-growing number of New Space organizations have emerged that are unencumbered by legacy practices and constraints. By reimagining, creating, and continuously improving SmallSat space technology a new and growing space ecosystem is now in place that is capable of serving a broad stakeholder community of both traditional users and new or nontraditional users. For the purposes of this report, traditional users primarily entail government departments and agencies with missions that support intelligence, defense, and civil space that were generally confined to large spacecraft developed by government contractors employing expensive but proven development methods. New or nontraditional users are typically smaller scientific missions, technology maturation programs or other applications that previously were unable to access space often owing to lack of experience or resources. Space access for these users was either unavailable or limited through dependence on traditional space partners.

Current commercial practices are expanding with capabilities including technology and business-driven applications that open the door to a broad and vibrant ecosystem offering a wide range of solutions capable of supporting a growing range of stakeholders. In parallel to traditional approaches, space infrastructure related to manufacturing, such as customized spacecraft buses,[3] instruments, and sensors—including high-resolution imaging and radar systems rivaling the performance of traditional systems—are emerging in both growing volume and with constantly improving capability. On the operational commercial ground stations are now routinely available, as are data management and analytics including cloud computing for data access and archiving. Thus, if properly encouraged and nourished, a broadly capable ecosystem can emerge including new business opportunities for data fusion, analysis, and data-buys, as well as ground/space communications that can equally benefit both traditional and nontraditional user communities.

Although these evolving systems are not yet in a fully transportable commercial technology state—for example, spacecraft systems still lack interoperability—these capabilities and services are still opening a growing range of possibilities for the business of space for all types of users. Public-private partnerships (PPPs) and other innovative procurement approaches can enhance national missions focused on communications, remote sensing, and military intelligence, as well as new mission areas focused on scientific data collection in oceanography, hydrology, atmosphere, climate, monitoring natural and human-made disasters, imaging, navigation—together with yet unknown new and opportunistic applications.

From 2011 to 2020, 75 percent (2,972) of all spacecraft launched worldwide, were SmallSats.[4] Within this period the National Aeronautics and Space Administration (NASA) and Department of Defense (DoD) led the proliferation of SmallSat launches among all government agencies worldwide. Furthermore, commercial organizations launched 2,013 of the 2,972 SmallSats over this 10-year period providing numerous services for developers, as organizations operating the largest number of SmallSats. *Planet* owned 22 percent of all remote sensing SmallSats launched, while *SpaceX* owned 47 percent of all communications SmallSats during these years. Both companies currently fly large constellations in low Earth orbit (LEO).[5] Table 2.2 in Chapter 2 provides a timeline of the commercial capability trends and a development forecast.

In recognition of these new advances, DoD established the Hybrid Space Architecture (HSA), as its leading philosophical framework for evaluating the balance between ingesting commercial systems, or procuring DoD unique systems. The HSA is an integrative infrastructure that was first researched by the Air Force Research Laboratory (AFRL) in 2014 and expanded through work done by United States Space Force (USSF) and intelligence community stakeholders. The goal of this new approach is to move beyond traditional program stovepipes to enable individual government stakeholders to use the framework to

[3] Within the context of this report, a spacecraft bus is an operational spacecraft system without a payload.
[4] SmallSats by the Numbers 2021. Bryce Space and Technology, BryceTech, Alexandria, VA, 2021, http://brycetech.com/reports.
[5] Bryce Space and Technology, 2021, *SmallSats by the Numbers 2021*, BryceTech, Alexandria, VA, available at: brycetech.com/reports.

achieve their unique needs. It is opening new possibilities of benefiting from the combination of traditional space with New Space by taking advantage of the synergies arising from a combined and integrated approach. As discussed in Chapter 3, HSA is a multi-layer system architecture offering the flexibility to integrate capabilities from multiple commercial and government systems to meet a variety of differing and constantly evolving government user needs. While still at an early stage, it has started delivering cost-effective and resilient space capabilities in support of a broad array of national security missions, including science and technology (S&T) and research and development (R&D) efforts (Refer to Box 3.1 in Chapter 3 for specific definitions of S&T/R&D).

HSA is predicated on an expansive utilization of New Space innovations opening the door to potential scientific opportunities discussed in Chapter 4 and new business models discussed in Chapter 5. Government managers when enabled to align their acquisition approaches to this new framework would benefit from new partnerships between the U.S. government and the commercial sector. As SmallSat capabilities develop and the HSA becomes more rooted, users will need to understand the strengths and weaknesses of SmallSat systems to determine their utility in specific missions, particularly for scientific objectives. For ocean science and coastal data missions, while the use of SmallSats to measure ocean variables is a real advantage for some applications, e.g., short-term forecasting via data assimilation in ocean models, not all objectives may be achievable with SmallSats. Combining larger dedicated missions with SmallSat constellations is likely to be the best strategy to monitor the full range of processes occurring in the ocean. Chapter 4 outlines the specific strengths and weaknesses of SmallSats and provides guidance on their potential mission application.

Commercial space and technology providers would also benefit from new business models considering contracting arrangements, mutual responsibilities, and terms and conditions of partnerships, as well as the range and scope of services provided. At the same time, the current lack of integrated commercial services (capabilities that are packaged together to meet the needs of particular missions and contain interoperable components that facilitate greater adaptability between systems) impedes the use of government contracting vehicles to support mission development and operations processes. The private sector and the U.S. government could jointly encourage the integration of commercial services in order to facilitate a better alignment between government mission objectives and commercial capabilities within an acceptable and manageable risk posture.

To achieve a useful ecosystem, the government space acquisition and management cultures need to enable an environment where government managers are capable of reacting quickly and effectively to what will be a rapidly changing environment. In the experience of the study committee members, government managers have, in many cases, preferred greater control; they have been reluctant to risk their program and national security missions by depending on commercial resources or by quickly adapting to changing opportunities within an evolving ecosystem. In addition to discussing the potential risks and perceived challenges of the New Space paradigm, Chapter 5 identifies and discusses the risks associated with varied organizational practices, intellectual property rights, and contracting barriers that inhibit the full benefit that can be derived from the use of innovative commercial capabilities. It is important in the current environment that government managers consider not only technical performance of commercial providers but also the business viability risk. On the positive side, multiple commercial providers are emerging for most products and services that allows for dual source options (e.g. multiple providers) to be considered in the commercial sourcing decision process.

Thus, to fully benefit from the New Space ecosystem, government agencies will need to develop acquisition and procurement practices and approaches that both enable and incentivize managers to partner with commercial services to gain maximum value for their program. There are also benefits to creating an environment that allows partnerships to develop, such as through connecting commercial and government stakeholders to intermediary agents who can broker such partnerships by matching a user's needs to commercial provider capabilities. The outcome of such a brokered partnership would be a "win-win" contractual arrangement benefiting both the provider and user. Stakeholder tools, such as a managed repository of commercial services, could improve stakeholder alignment and accelerate an effective partnership process.

In such a dynamic and evolving environment, flexibility is key, because tools and methods will continue to adapt, grow, and evolve. For a PPP business arrangement to be successful and sustainable it needs to have a contract that protects both parties and enables equitable mitigation options to be exercised to deal with changes in stakeholders' interests. Chapter 5 discusses some adaptable PPP options for the near-term future could include a complete space system solution or a menu of options depending on specific user needs. Example alternate models could include the deployment of commercial space component companies, which would provide different elements of the space system or, in some cases a simple purchase of data. As will be discussed, all of these options are possible and supportable for both traditional and nontraditional stakeholders within the proposed HSA and New Space ecosystem.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are ordered as they appear in each chapter of the report.

Chapter 2: Conclusions and Recommendations

CONCLUSION: The commercial space industry's tremendous growth and rapid evolution have generated high-profile successes, and signs indicate that this trend will continue to accelerate. The U.S. government, including traditional governmental space users, could benefit greatly from less traditional relationships, such as public-private partnerships (PPPs) that enable the adoption of industry's technology and volume manufacturing capabilities.

RECOMMENDATION: The U.S. government should encourage the development of public-private partnerships (PPPs), potentially including anchor tenancies, to promote a new national space ecosystem supportive of industry, government, and academic objectives.

CONCLUSION: Existing interoperability standards are primarily driven by traditional system constructs and impede the government's access to flexible and adaptable commercial services. The U.S. government and commercial stakeholders will increasingly rely more heavily upon integrated commercial services and advancing standards to establish a broad-based ecosystem enabling smoother transition paths among spacecraft development, payload integration, test, launch services, operations management, and data product production. Development and adoption of interoperability standards driven by unique commercial New Space needs and design practices for key systems will increase competition and enable efficient execution and management for a broad range of space mission and operational needs for current and future government users.

RECOMMENDATION: Key systems—those most appropriate for standards—should be jointly developed and actively managed to support the New Space public-private partnerships in way that promote the greatest acceptance and usage on future systems. Standards and best practices could be developed within organizations such as the Air Force Research Laboratory's (AFRL) AFWERX, National Aeronautics and Space Administration (NASA's) Small Spacecraft Systems Virtual Institute (SSSVI) and the Small Payload Rideshare Association (SPRSA) to facilitate the adoption of New Space business product capabilities.

CONCLUSION: A coordinated government effort to promote and oversee existing government programs, together with the exploitation of dual-use technologies (evolving out of the automotive, medical, gaming, and other industries) could enhance the existing technology pipeline and benefit all national space activities. The Air Force Research Laboratory's (AFRL's) AFWERX, National Aeronautics and Space Administration's (NASA's) Small Spacecraft Technology Program (SSTP), the government's Small Business Innovative Research (SBIR) program, and the government's Small

Business Technology Transfer (STTR) program are the appropriate venues for such technology infusion and demonstration.

RECOMMENDATION: The Office of Naval Research (ONR) should take full advantage of opportunities for the infusion of dual-use technologies deriving from participation in existing government technology development programs such as the Air Force Research Laboratory's (AFRL's) AFWERX, the Small Spacecraft Technology Program (SSTP), the government's Small Business Innovative Research (SBIR) program, and the government's Small Business Technology Transfer (STTR) program.

CONCLUSION: The rapid expansion of space systems and operations knowledge throughout the commercial space industry provides numerous opportunities for the Hybrid Space Architecture (HSA) and other U.S. government space initiatives. Clearly stated standards and best practices, in conjunction with procurement mechanisms that address and accelerate decision speed, address mission risk, and align incentives, would allow efficient U.S. government access to these new capabilities. Procurement mechanisms tailored to commercial business models could further support responsive schedules from initiative inception to on-orbit capability.

RECOMMENDATION: U.S. government procurement mechanisms should be tailored to embrace evolving commercial practices and appropriate standards to address and accelerate decision speed, management of mission risk, and alignment of incentives to rapidly enable government space initiatives.

Chapter 3: Conclusion and Recommendation

CONCLUSION: The Hybrid Space Architecture (HSA) shows great potential as a framework for a new space ecosystem integrating timely, traditional and New Space industries to deliver cost-effective and flexible space capabilities in support of a broad array of national missions and objectives. This ecosystem could enable the Office of Naval Research (ONR) to pursue both its technology demonstration initiative and its long-term applications.

RECOMMENDATION: The Office of Naval Research (ONR) should consider the Hybrid Space Architecture (HSA) framework as an opportunity to fulfil its long-term ocean science objectives. ONR should work with U.S. Space Force (USSF) to tailor its HSA-based approach to serve as a pilot program for other U.S. government and nongovernment users.[6]

Chapter 4: Conclusion and Recommendation

CONCLUSION: SmallSats are demonstrating their utility in national civil missions with respect to oceanography, meteorology, hydrology, disaster assessment, and other applications associated with the Earth sciences. When applicable, they complement traditional systems in the Hybrid Space Architecture (HSA) by offering increased temporal and spatial resolution and reduced planning cycles which permit rapid insertion of new technology over traditional approaches. It is expected that SmallSat technology and sensor capabilities, as well as related services, will expand in the future.

RECOMMENDATION: The U.S. government should actively position itself to take full advantage of the evolving and growing capabilities of the commercial space sector to serve the broadest spectrum of

[6] This recommendation was edited after release to the sponsor to direct it to ONR rather than the broader National Oceanographic Partnership Program. This clarifies that the recommendation is aimed at enabling ONR's long-term ocean science objectives.

traditional and nontraditional users, with applications to oceanographic and coastal data as an initial effort to experiment with new process and procedures.

CONCLUSION: SmallSat mission partnerships between the U.S. government and academic institutions have produced high value/low-cost advancements in space science and technology including satellite platforms and payloads, ground segment communications, mission and payload operations, and science data product generation and distribution.

RECOMMENDATION: As part of its ongoing relationship with academic institutions the Office of Naval Research (ONR) should examine emerging advanced sensor and associated technology opportunities that benefit future ocean science objectives and missions.[7]

Chapter 5: Conclusions and Recommendations

CONCLUSION: The technical infrastructure required to support needed services in the New Space ecosystem currently exists or is expected to come into existence if actively enabled through expanding government procurement opportunities. However, the U.S. government space community's current and potential future exploitation of that infrastructure is impeded by lack of familiarity with existing technical capabilities as well as new capabilities evolving out of the rapid growth of the commercial space industry. In the case of the Office of Naval Research (ONR), space science procurement practices are artificially constrained by traditional approaches in ways that limit them from taking full advantage of available New Space opportunities related to the rapid demonstration of the ocean and coastal sensor technologies under development for the National Ocean Partnership Program (NOPP).

RECOMMENDATION: The Office of Naval Research (ONR) together with the National Oceanic and Atmospheric Administration (NOAA), as the joint managers of the National Ocean Partnership Program (NOPP), should explore the broad range of available contractual mechanisms that enable quicker deployment of commercial space capabilities in pursuit of the NOPP technology demonstration objectives. It should empower its acquisition workforce to take full advantage of the rapidly evolving commercial space system opportunities**.**

CONCLUSION: The federal procurement regime—both the statutory and regulatory schemes—provides sufficient flexibility to take advantage of the evolving commercial marketplace and employ innovative approaches such as public-private partnerships (PPP's) and other forms of contractual relationships including Other Transactions Authority [OTA] and Space Enterprise Consortium [SPEC].

RECOMMENDATION: The U.S. government should employ a full range of available contractual mechanisms and actively support the use of innovative business models required to fully engage with both the traditional space and New Space commercial industries. These include a range of options from public-private partnerships (PPPs) and commercial services contracts, as well as newer mid-tier acquisition options in the categories of rapid prototyping and rapid fielding.

CONCLUSION: Currently, no existing mechanism permits forecasting future government needs to proactively inform the commercial space sector such that it can focus and prioritize the direction of its future investments. The National Aeronautics and Space Administration's (NASA's) Rapid Spacecraft Development Office (RSDO) has addressed this forecasting problem related to indefinite

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[7] This recommendation was edited after release to the sponsor to delete reference to the National Oceanographic Partnership Program. This clarifies that the committee is recommending that ONR take this step in support of its own objectives and missions.

delivery/indefinite quantity (IDIQ) satellite bus acquisitions through the development of its *Rapid Spacecraft Catalog* satellite catalogue.

RECOMMENDATION: The Office of Naval Research (ONR) should leverage the National Aeronautics and Space Administration's (NASA's) Rapid Spacecraft Catalog for their current needs and should also work with NASA's Rapid Spacecraft Development Office (RSDO) and the Air Force Research Laboratory's (AFRL's) AFWERX to incorporate their forecasted future needs.

CONCLUSION: The development and adoption of the Hybrid Space Architecture (HSA) framework offers a potential roadmap to establish the timeline of SmallSat system capabilities for national needs. However, the capacity for building SmallSat services can be accelerated by the alignment of commercial SmallSat capabilities to HSA needs—this would reduce the time needed to reach a fully capable space ecosystem. Similarly, market-driven forces and sustained government investment programs could also accelerate technology, infrastructure, and process support responsive to customer and community needs and requirements.

RECOMMENDATION: The U.S. government should incentivize private investment to achieve faster and more integrated outcomes through advanced acquisition strategies such as public-private partnerships (PPPs), establishing Indefinite Delivery Indefinite Quantity (IDIQ) contracts with commercial providers, and anchor tenancy where the government is a stable facilitator for achieving faster and more integrated outcomes.

CONCLUSION: The commercial space sector appears fully capable of meeting the ocean sensor technology demonstration flight and launch needs of the National Oceanographic Partnership Program (NOPP) as presented to the committee. Many of these capabilities are accessible to NOPP today, through a variety of contractual mechanisms. Furthermore, these capabilities are expected to grow and evolve in concert with HSA-driven U.S. Space Force (USSF) and other government procurements over the next five years keeping pace with the NOPP objectives.

RECOMMENDATION: Innovative procurement practices offer substantial benefits, both in cost and the pace of flight, to meet government, and specifically, National Oceanographic Partnership Program (NOPP) requirements. Depending on technology readiness and mission requirements, NOPP should consider the following options:

1. Engage nascent commercial broker capabilities to explore and form appropriate partnerships to match existing and emerging commercial capabilities to achieve desired technical outcomes;
2. Explore existing government programs and consortiums, such as the National Aeronautics and Space Administration (NASA) International Space Station or the Space Enterprise Consortium (SPEC), and other programs that support technology prototyping and rideshare opportunities consistent with desired space flight objectives;
3. Engage a Federally Funded Research and Development Center (FFRDC) or a similar impartial agent as a trusted intermediary between interested government and commercial business entities to identify appropriate PPP mechanisms and structure them to achieve a successful alignment of technical and procurement capabilities; and,
4. Similarly employ an FFRDC or similarly trusted agent to develop guidelines for technical and business engagement to actively bridge existing gaps and new gaps as they occur between government and industry.

1

Introduction

THE CHARGE TO THE COMMITTEE AND THE ASSESSMENT PROCESS

In 2021, at the request of the Office of Naval Research (ONR), the National Academies of Sciences, Engineering, and Medicine formed the Committee for the Assessment of Partnership Options for a Small Satellite System for Collecting Scientific Quality Oceanic and Coastal Data to address the following statement of task:

> In accordance with the rules and procedures of the National Academies, the National Academies will appoint a volunteer study committee of appropriate size and composition. The study committee will consist of National Academy members and other technical experts. Committee members will serve without remuneration; however, they will be compensated for travel and similar expenses related to attendance at committee meetings and other such activities. The study committee will meet as it deems appropriate to hold discussions with the sponsor, hear presentations and otherwise gather relevant information, deliberate, and reach consensus on findings and recommendations.
>
> The committee will produce one report. That report will be reviewed in accordance with the rules and procedures of the National Academies. Following completion of the review, the report will be delivered to the sponsor in printed and electronic versions. The study will provide an independent assessment of the feasibility and implications of creating and exploiting partnerships for developing, deploying, and operating a system of satellites and supporting infrastructure capable of sensing ocean, coastal, atmospheric, and hydrologic data of sufficient scientific quality to enable prediction models and to support near real time applications of national interest. It will identify and describe, to the extent possible, promising options for such a system.
>
> The committee will identify and consider potential partners—public and private—for developing such a system or major subsystems, taking into account factors such as:
>
> - What national missions might benefit in a substantial way from access to a small satellite data collection system and how might that mission depend on the frequency and geographic scope of the data collection? Those benefits might be defined broadly to include military, economic, scientific, educational, and environmental benefits.
> - What partnerships among industry, government, and academic institutions might be incentivized to develop the necessary space platform, system integration, launch, communications, test, data distribution, and maintenance functions?
> - Is the existing infrastructure sufficient to support the needed space platform development and manufacture, system integration, launch, communications, test, data distribution, and maintenance functions? What infrastructure components should be enhanced or created in order to reduce the timeline from idea to on orbit? Infrastructure is broadly defined to include industrial manufacturing capability, space system support structures, and communication-information systems.
> - What processes may be employed to enhance the technology development pipeline, standards development, and the identification and adoption of best practices?

- What is the anticipated timeline for the development of the required technology, infrastructure, and processes that will enable the development of the desired satellite systems?

In conducting the study, the committee will review current systems that provide some of the needed system components, as well as systems in various stages of development for future deployment. To the extent possible, the committee will gather and analyze information on anticipated relevant future needs of public and private organizations as well as relevant perspectives of academic researchers.

To accomplish the assessment, the National Academies assembled a committee of 13 volunteers with relevant expertise to answer the statement of task. The committee met four times over webcast—March 18–19, 2021, April 13–14, 2021, May 12–13, 2021, and May 27, 2021—during which it received an overview from the ONR sponsors and heard presentations by subject matter experts. The committee also met in a closed session to deliberate on its findings and to define the contents of this assessment report.

One important outcome of fact-finding at the first meeting was a clearer understanding from the sponsor on how to interpret the statement of task. In particular, the sponsor was less interested in a prescriptive solution and more interested in a broad framework for creating a sustainable "space ecosystem" capable of solving the near-term sponsor technology demonstration objectives in combination with longer-term development of capabilities to serve naval strategic and tactical objectives at both rapid temporal and large spatial scales. It became clear at the first meeting that the sponsor's interests were broader than ocean science in that a space ecosystem, if appropriately conceived, was capable of serving a broad science user base that could be extended to other government agencies as well as interested external users. At the first and second meetings it became evident that any solution would need to be adaptive as well as integrative in that both the business landscape is rapidly growing and changing while the government needs are also growing and changing through the development of what has come to be known as the "Hybrid Space Architecture" or HSA.

The resulting approach taken by the committee to address the statement of task was to examine the opportunity space afforded by opening the door to public-private partnerships and other programmatic means of taking maximum advantage of the growing commercial sector. The ultimate goal of this approach is to provide an actionable template intended to benefit all stakeholders- a more constructive relationship with a broad range of potential business partners while also stretching the range of potential government users. One discovery by the committee during this process was that the slow pace of space procurement and apparent impediments to change are largely self-inflicted. The current procurement regulations allow faster and broader participation but a positive change of perspective by the relevant procurement authorities need to be aligned with the associated evolution of process. Thus, a key focus of this report is how can we do things better in order to not only create a self-sustaining space ecosystem but provide the best value to all government stakeholders.

In taking this broad view, the study committee did not neglect the specific sponsor issues also represented in the statement of task. Those issues are discussed in appropriate sections of the report and summarized in Appendix 1 as a specific case study, which is intended as a direct conversation of the committee with the ONR sponsor.

Box 1.1 provides just a few examples of the rapid evolution of the space business sector over the time of this report's preparation. Recognizing this rapid evolution, the report is designed to address the emerging and complex physical, administrative, budgetary, and cultural issues in order to recommend an achievable path forward toward promoting an expeditious, multi-faceted, and sustainable use of space. The committee concludes that there is no "one size fits all" solution to the current problems, because different approaches will be optimal for different categories of space actors; and there is no perfect "end state," because roles and relationships in space will perpetually have to adapt evolving methodologies afforded by commercial technology combined with needs driven by scientific opportunity, economics, military requirements and politics. Thus, a key objective of this report is finding ways of harnessing the opportunities of the New Space commercial enterprise that merge the government needs driven by the

HSA. This merger could be both adaptive and sustainable in ways that develop a large and inclusive space ecosystem capable of supporting both the sponsor's immediate needs as well as its broader and expansive long-term objectives.

BOX 1.1
2021 News Blurbs Suggestive of the Rapid Evolution in New Space

- "Aerospace Corp CEO Sees Space Procurement Change Space." News (8/31, Subscription Publication) reports that Aerospace Corp. CEO Steve Isakowitz said the establishment of the U.S. Space Force and ongoing commercialization of space are creating an environment for change in the national security space sector. Isakowitz predicts companies will not be competing for contracts in the same way as before, as the rapid advancement of space technology will make it easier for newer companies and technologies to plug into programs. Source: https://spacenews.com/aerospace-corp-ceo-sees-winds-of-change-in-space-procurement/.
- The traditional "acquisition model, in which the government dictates the terms of a product or a mission does not work," U.S. Senator Jerry Moran, the leading Republican on the Appropriations Commerce, Justice, and Science Subcommittee, said Aug. 24 at the Space Symposium. "So why is Washington, D.C., still trying to direct industry to comply with government procedures? The power of the private industry can only be fully realized if government does not stand in its way." Source: https://www.spacesymposium.org/speaker/the-honorable-jerry-moran/.
- U.S. Air Force Secretary Frank Kendall announced Aug. 24 that he is reorganizing the office that oversees Space Force acquisition programs. He also is moving to bring the Space Development Agency under the Department of the Air Force sooner than the congressional deadline. Kendall was confirmed by the Senate in late July as the department's top civilian, overseeing both the Air Force and the Space Force. In a keynote speech at the 36th Space Symposium, Kendall said he was "impressed" by how fast the Space Force has progressed since it was established in December 2019. One area that has lagged, however, is procurement, he said. Source: https://spacenews.com/kendall-reorganizes-space-force-acquisition-office-wants-faster-merger-with-space-development-agency/.
- ExecutiveGov (8/20) reported that NASA "plans to partner with commercial companies for the development of future space-based facilities as the International Space Station nears the end of service life." NASA Director of Commercial Spaceflight Phil McAlister said the collaboration with commercial companies would allow NASA to focus more on deep space exploration. Source: https://www.executivegov.com/2021/08/nasa-eyes-commercial-partnerships-for-next-space-station-development/.
- Space News (8/20, Subscription Publication) reported that the U.S. Space Force selected 19 companies at the Space Force Pitch Day last week to "receive $1.7 million Small Business Innovation Research Phase 2 contracts." The Phase 2 contract winners can "continue to apply for follow-on government funding if their projects are successful and attract commercial investors." Source: https://spacenews.com/kendall-reorganizes-space-force-acquisition-office-wants-faster-merger-with-space-development-agency/.
- Space News (8/17) reports that the Space Foundation and KPMG released a report titled "Navigating Space: A Vision for the Space Domain" Tuesday. The report concludes that military organizations will cease to be the dominant players in space and will have to partner with civilian concerns in order to ensure openness in space. The Space Foundation and KPMG said, "A growing number of countries are realigning their defense organizations to recognize the importance of space. Nongovernmental organizations are also crowding into the domain. And that is changing the focus for many military players." U.S. Space Force Chief of Space Operations General John "Jay" Raymond is quoted as saying, "In the long term, space is going to become the most vital domain for national security, surpassing air, land and sea." Source: https://spacenews.com/kendall-reorganizes-space-force-acquisition-office-wants-faster-merger-with-space-development-agency/.
- Space News (10/1) reported that the Defense Innovation Unit has released a new solicitation for "a hybrid space architecture to integrate emergent commercial space sensor and communications capabilities with U.S. government space systems while incorporating best-in-class commercial practices to secure and defend the network across multiple domains." Source: https://www.diu.mil/work-with-us/open-solicitations.
- Satnews (9/2) reported that "Spire Global, Inc. (NYSE: SPIR) has been awarded the next order to provide commercial radio occultation (RO) weather data for the National Oceanographic and Oceanic Administration's (NOAA) operational Numerical Weather Prediction (NWP) models—this order represents the largest volume of commercial weather data purchased to date by NOAA under the Commercial Weather Data Buy Program." Source: https://news.satnews.com/2021/09/02/contract-received-by-spire-global-from-noaa-for-satellite-weather-data-delivery/.
- TechCrunch (7/6) reported that "Satellite imagery startup Satellogic to go public via SPAC valuing the company at $850 million [where] Satellogic already has 17 satellites in orbit, and aims to scale its constellation to over 300

satellites to provide sub-meter resolution imaging of the Earth updated on a daily frequency." Source: https://techcrunch.com/2021/07/06/satellite-imagery-startup-satellogic-to-go-public-via-spac-valuing-the-company-at-850m/?guccounter=1.

- Space News (10/6) reported that "Earth observation company Satellogic expands partnership with Amazon Web Services." "The service has attracted startups and commercial players that don't want to invest in their own ground infrastructure." "Satellogic's imagery and data analytics services starting this week are being offered on GSA Advantage, an online service used by government agencies to buy commercial products and services." Source: https://spacenews.com/earth-observation-company-satellogic-expands-partnership-with-amazon-web-services/.

The committee's approach to the assessment relied on the experience, technical knowledge, and broad expertise of its members. The committee did not attempt to report an exhaustive assessment of every available partnership option or every alternative approach to implementation. The committee's first goal was to provide enduring value by identifying and focusing on which government mission areas could most utilize and benefit from commercial New Space capabilities for space access. Its second goal was to determine current challenges and future opportunities for redefining space infrastructure with the goal of becoming more amenable to sustainable partnerships or other acquisition methods capable of serving multiple stakeholders.

Several of the report's recommendations suggest the value of more rapid, comprehensive dissemination of already-available information. For example, some potential space users are not fully aware of the diverse opportunities for mutually profitable collaboration with other space actors—for them, an improved system of brokerage services could help to match suppliers and customers swiftly and efficiently. Another example: some government contracting offices may not be fully cognizant of the myriad alternative contracting routes already allowable under federal regulations to engage in novel ways with private industry. For such cases, improved training on legally available options together with broadening the perspective on both traditional and nontraditional ways of doing business could incentivize the execution of more creative contracting approaches.

INTRODUCING THE REPORT

Study Motivation

The motivation for this study is the specific need by the Office of Naval Research (ONR) to place specialized sensors in space to collect ocean and coastal data needed to initialize predictive models and to support operations. ONR together with the National Oceanic and Atmospheric Administration (NOAA) are the joint managers of the National Ocean Partnership Program (NOPP), which consists of 19 U.S. government agencies having ocean interests.[1] Thus, the research supported by these sensors extends across many civilian and military scientific interests at a broad range of spatial and temporal scales.

The NOPP has reached the point where further progress requires a rapid technology demonstration phase informed through the placement of nearly a dozen sensors on space platforms capable of supporting performance validation. After this phase, initial operational deployment will require even more space assets under conditions that are likely to require a rapid and adaptive approaches. Traditional acquisition approaches are currently unaffordable and also slow and non-adaptive. Based on the recent developments in commercial space technology and services, it is reasonable to anticipate lower costs and more flexibility in launching next generation of satellites. The question is: how to marshal the nation's growing commercial capabilities in ways that achieve a sustainable space ecosystem capable of delivering space systems meeting the sponsor needs that are faster and lower cost? The approach

[1]For more information see: National Oceanographic Partnership Act – National Oceanographic Partnership Program (nopp.org): https://www.nopp.org/about-nopp/subtitle-e/.

proposed in this report is to form public and private partnerships (PPPs) together with other commercial means to produce "New Space"[2,3,4,5] (refer to Box S.1 for full definition used in this report) driven innovations mostly from the private sector to create an ecosystem leveraging HSA-driven USSF needs in ways that can benefit not only NOPP but also a wide range of other civil and non-government science users.

Background Perspective

Space is hard. The operating environment is harsh and unforgiving, the logistics are complex, and the costs are daunting, even with the incipient New Space technological revolution. But if the United States can combine the emerging smart technologies with an improved organizational and bureaucratic structure, space does not have to be quite as hard as it has traditionally been.

Space is important—providing unique high ground for Position, Navigation, and Timing (PNT), communications, reconnaissance, and other missions that are vital to both the national economy and the U.S. military. This importance will only grow, as new missions driven by HSA objectives and other user needs are adopted for this uniquely enabling environment. Creativity and flexibility will be required, to take maximum advantage of the rapidly-unfolding opportunities.

Space is getting crowded. The coming decade will see perhaps tens of thousands of small satellites launched, mostly by commercial companies, to create and to serve diverse markets. The space ecosystem of the future will surely be hybrid, characterized by an ever-shifting combination of large and small satellites; owned, operated, and launched by both governments and corporations-- performing in different capacities—from routine commercial functions as well as highly classified national security missions.

Last, the opportunities for exploiting space are not evenly distributed. Some traditional and emerging users enjoy ready access to space—constrained, to be sure, by scarce budgetary assets, but not by artificial impediments. Other potential users, however, have been handicapped in accessing space; they have legitimate and important space-related missions, but do not command sufficient market power or political clout to execute those missions on their own.

The Space Technology Ecosystem

The United States Government (referred to in the report as "U.S. government") has been the controlling historical player in the national space ecosystem, through the development, launch, and integrated operation of large, complex, and highly capable, mission-specific satellites. Aside from certain types of commercial communication satellites, spacecraft of this type have generally been low volume one-of-a-kind systems built by a specialized highly skilled workforce, making them expensive and time consuming to craft compared to systems designed and built using commercial assembly-line processes. Traditional users of these systems are primarily government departments and agencies with missions that support intelligence defense and civil space applications. Trusted developers of such systems are generally large corporations or equivalently capable government entities using proven routines and processes embracing all phases of a space mission.

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[2] NewSpace – A. Golkar and A. Salado. Definition of New Space – Expert Survey Results and Key Technology Trends. IEEE Journal on Miniaturization for Air and Space Systems, Vol. 2, No. 1, March 2021.

[3] NewSpace – New business models at the interface of the space industry and digital economy. SpaceTec Partners, Munich/Brussels, Germany. 2016.

[4] Space: Investing in the Final Frontier. Morgan Stanley Research, July 24, 2020.

[5] Martin, Gary L., NewSpace: The Emerging Commercial Space Industry. ISU Space Studies Program, NASA TRS, June 30, 2014.

Intelligence and defense users, and their associated satellite developers have successfully and very capably enabled the full spectrum of contemporary U.S. national security and civil space activities. For example, remote sensing satellites are employed to provide timely warning about enemy missile launches, to monitor compliance with arms control treaties, to detect potentially hostile troop movements, and to assess the effect of combat damage on a particular facility or location. Secure communication satellite technology creates rapid, secure links between headquarters and fielded forces, and among combat units maneuvering rapidly on a remote battlefield. The global positioning system (GPS) satellite constellation serves both commercial and military users allowing aircraft, ships, land vehicles, and individuals to know their location precisely, and they guide many types of weapons to their targets while their timing signal provides a "global digital heartbeat" that synchronizes worldwide telecommunications. Meteorological satellites enable commanders and planners to anticipate local weather conditions, including sea states, which can drastically affect operations. The intelligence community uses satellites to monitor foreign communications and emanations in order to anticipate military, diplomatic, and other developments of critical national interest.

On the civil side, the National Aeronautics and Space Administration's (NASA's) missions include science, technology, and human exploration encompassing both the Earth's local neighborhood and the entire universe together with "planetary defense," which includes scanning the skies for potentially hazardous asteroids and comets. NOAA, in concert with NASA, has the responsibility for monitoring "space weather" while also having the specific responsibility for weather prediction and for monitoring the conditions in the oceans and the atmosphere, promoting optimal uses and stewardship of those resources. Similarly, the United States Geological Survey (USGS) has the responsibility for the Landsat mission including long-term data continuity to inform land managers and policy makers about natural resources and the environment. Satellites also play crucial roles of observation and responding to natural disasters by supporting rescue and recovery operations for stranded individuals and communities. Last, universities, government and private laboratories and other nonprofit entities also routinely turn to space for support of their educational, research, and other missions.

As with aviation in the past and currently with unmanned aerial vehicle (UAV) technology, space exploration is making a transition to greater utilization of commercialization with enough production capacity to enable a corresponding ecosystem to support new uses and capabilities. Thus, the traditional space business is now expanding and broadening towing to the recent rapid growth in space activity within the private sector, where large numbers of mostly small but advanced spacecraft systems are being developed to provide services tailored to specific user needs. In the private sector, emerging space architectures are being designed and fielded through commercial advancements that are launching and operating mass-produced SmallSats for low Earth orbit (LEO) to provide low-cost, low-latency global services in communications and Earth observation including oceanographic and coastal applications.

The explosive commercial interest in SmallSat missions has also catalyzed a rapidly expanding base of suppliers for space hardware, software, and related services. This includes vendors of component level and adaptable spacecraft components (such as solar panels, transponders, data recorders, reaction wheels, star trackers, and propulsion units); standard system elements, fully integrated "standard buses" spanning the CubeSat to SmallSat range; greatly expanded launch services; remote ground station communication services; mission operations software; flight software; and many other key elements required in the overall development and successful execution of a space mission.

There will be inevitable bumps in the road but these significant shifts are real and permanent, not just opening up new opportunities for traditional users but also creating opportunities for entirely new nontraditional users including new or novel users in the space arena. Many of these emerging users have been impeded from accessing space owing to the extreme cost required to develop, build, launch, and operate complex systems designed for specific purposes. This nontraditional or novel segment of users are important potential contributors to the New Space culture where the lower price of admission into space has created pathways allowing many more stakeholders access to what has historically been a mostly inaccessible domain.

In certain cases, these novel users are looking to increase their information pipeline and leverage the New Space environment to fly new sensors and acquire new data streams, for scientific, national security, and other purposes including the HSA. One example is this study's focus on applications related to coastal ocean science and general ocean science. One would expect that as the ecosystem grows and (assuming conditions allow) thrives, many other users can also benefit. Thus, society is on the threshold of an enormous surge in the opportunities to collect unprecedented quantities of global, timely, multispectral data in many scientific disciplines.

Looking to the future, government needs through the HSA and traditional users can open the door as an "anchor tenant"[6] to many broader applications that serve nontraditional users desiring opportunities for cost-effective access to space. In particular, Earth science and ocean science can greatly benefit from the rapidly evolving commercial, New Space marketplace and the lower cost opportunities afforded by SmallSat missions. Likewise, the ever-expanding demand for data globally and the proliferation of data-producing and data-consuming devices will power demand for the type of global connectivity and communications systems that can be implemented best (or only) in space. These systems will require a mix of capabilities consisting of smaller adaptable systems combined with mission unique systems.

Thus, the "new normal" for space missions is expected to be a "hybrid" space architecture (HSA) as mentioned above and further discussed in Chapter 3. The HSA is an information-based architecture that will serve a greatly expanded array of users—including big and small entities and public and private actors. There are many dimensions to hybridity. Primary among them are organizational hybridity (government and commercial cooperation); orbital hybridity; platform hybridity (large, small); number hybridity (distributed LEO vs. monolithic geosynchronous earth orbit [GEO]). This architecture will employ small, inexpensive single-purpose and mission-unique large spacecraft—which will co-exist and operate synergistically. The traditional and New Space communities will co-exist with nontraditional users and, in many cases will benefit from the available data. This report will discuss the expanded ecosystem that will grow out of this hybrid strategy and provide useful guidance on how to leverage the burgeoning commercial space capabilities through a broad array of business models and acquisition strategies to produce high-quality scientific data products.

[6] The term "anchor tenancy" means an arrangement in which the United States Government agrees to procure sufficient quantities of a commercial space product or service needed to meet Government mission requirements so that a commercial venture is made viable. 48 CFR 1812.7000(a) [or NASA FAR Supplement (NFS) 1812.7000(a)].

2

Current and Future Commercial Landscape

INTRODUCTION

Commercial SmallSat Overview

The global space economy accounted for $371 billion in 2020, where $271 billion (73 percent) of those revenues were directly driven by satellite industry services spanning telecommunications and remote sensing ($117.8B), satellite manufacturing ($12.2B), ground equipment ($135.3B) (e.g., satellite TV dishes, network hardware, etc.), and the launch industry ($5.3B).[1] While the remaining approximately $100 billion of economic activity (27 percent) represents nonsatellite industry revenues across U.S. and international government and commercial human spaceflight activities, space missions often rely on capabilities and advancements by commercial industry in all of these segments to support mission objectives. Of the $117.8B of satellite industry services revenues in 2020, $2.6B, or less than 3% were due to remote sensing. In addition, in 2020 only 3% of the total market share of satellites in operation were categorized as "scientific" by the Satellite Industry Association. Government agencies have recognized SmallSats as a disruptive innovation that can provide a means to effectively address their goals. The commercial industry—both New Space and traditional space organizations—have also realized that there is a growing market to address government needs. As a result, there is an interplay between companies looking to identify the capabilities government organizations need to effectively use SmallSats for mission-critical applications, as well as government users searching to identify how commercial industry can address their challenges. These communities need to be responsive to each other in areas where the future state of commercial development for SmallSats, and the capabilities that developers will require from industry, will drive innovations and activities within both groups and the field in general. This interplay is actively driving the current and future ecosystem landscape of SmallSat commercial services and partnerships; the development impactful to future mission principal investigators; and those that would seek to utilize the outcomes of their work.

THE BUSINESS INTEREST AND SCOPE OF COMMERCIAL SMALLSAT ACTIVITY

Over the past 10 years there has been a revitalization of interest in the utilization of space, driven by advances in launch capability, technologies enabling the ability to build spacecraft more rapidly and affordably, and new science and economic opportunities created by observations from LEO, and potentially from geostationary (GEO) and other orbits. SmallSats are significant contributors to this paradigm shift where the trends have been remarkable over this period of time. From 2011 to 2020, 3,968 spacecraft were launched worldwide where, 2,972 (75 percent) were SmallSats categorized as spacecraft less than 600 kilograms. Of these 2,972 SmallSats, 68 percent were operated by U.S. organizations, including *SpaceX*, where 2,013 were commercial SmallSat launches over this 10-year timeframe.

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[1] Bryce Space and Technology, 2021, State of the Satellite Industry Report, June 2021. BryceTech, Alexandria, VA, http://brycetech.com/reports.

Focusing on these 2,013 commercial SmallSat launches, 83 percent were owned/operated by *SpaceX*, *Planet*, *Spire Global*, *OneWeb*, and *Swarm Technologies* (recently acquired by SpaceX in July 2021), while the remaining 17 percent were managed by 124 other commercial operators. In 2020 alone there were 1,202 SmallSats launched; 937 were commercial missions from *SpaceX's Starlink* and *OneWeb* and 174 represented all other SmallSat missions. The remaining 91 SmallSats launched in 2020 were a mixture of government civil/military and nonprofit missions (see Figure 2.1).[2]

Commercial organizations, over the last ten years, have demonstrated on-orbit capabilities of small satellites primarily for technology development, science, remote sensing, and communications missions. While only a small percentage (10 percent in 2020) of SmallSats launched are dedicated to science missions, the capabilities being demonstrated across the commercial space industry show significant potential to assist in discoveries across numerous and diverse scientific disciplines beyond those typically attainable with higher-cost single satellite approaches.

Studies of the Sun-Earth connection, gravity research, and Earth climate science including coastal and ocean science provide just a few of the many examples where constellations, multi-satellite formations, or clusters of small satellites might provide transformative science advancements. Because of the interconnected nature of geoscience subsystems, local dynamic processes do not act in isolation, but often aggregate to influence other subsystems on global scales.[3] Leveraging a multi-satellite approach to collect simultaneous space-based measurements on larger scales can potentially provide insight into how local variations affect distant and seemingly unconnected regions, while also offering answers to rapid temporal changes that would otherwise be missed through single satellite data collections. Furthermore, for some science investigations the potential to add and fuse simultaneous measurements from various phenomenologies, such as VIS/NIR with SAR could provide a richer understanding of the region being investigated, thus increasing its scientific value.

Although some of the commercial missions currently being flown are seemingly unrelated to the scientific examples provided above, the knowledge being gained throughout the commercial industry in building satellite buses, sensors, ground operations and data analysis centers, autonomous operations, inter-satellite connectivity, on-board data processing, and launch and deployment of large numbers of space assets from a single launch vehicle have direct applicability to numerous science mission areas. These commercial organizations are developing and increasing the capabilities of SmallSat systems and subsystems, and at a rapid pace, that can be leveraged by current and future scientists to accomplish their specific missions. As scientists look for new ways to collect data, and new types of data, these emerging capabilities may be able to provide valuable pieces to scientific puzzles. It is expected that as these capabilities continue to increase, scientists will be motivated to leverage these new tools in heretofore unseen ways to gain knowledge within their areas of expertise, thus influencing the future of science missions and their discoveries.

[2] SmallSats by the Numbers Byrcetech. 2021. http://brycetech.com/reports.

[3] Small-Sat Science Constellations: Why and How", 27th Annual AIAA/USU Conference on Small Satellites, SSC13-VI-9, Dyrud et al., DigitalCommons@USU - Small Satellite Conference: Small-Sat Science Constellations: Why and How.

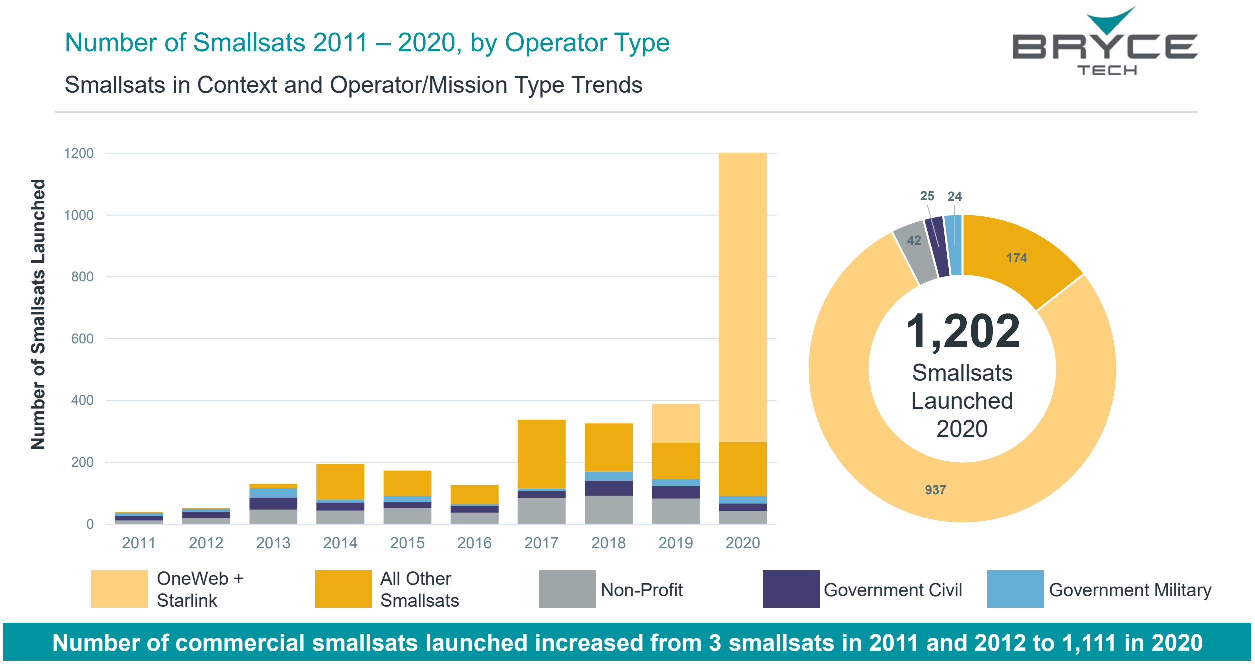

FIGURE 2.1 Number of small satellites launched from 2011 to 2020. As shown, 40 percent of all SmallSats launched in the past 10 years were launched in 2020, dominated by *SpaceX, Starlink* and *OneWeb* satellites. It is clear, within the context of other categories of satellites launched, that SmallSats represented a significant fraction of these missions on an annual basis where SmallSats are defined as satellites with mass less than 600 kg. SOURCE: SmallSats by the Numbers 2021. Bryce Space and Technology, BryceTech, Alexandria, VA, 2021, https://brycetech.com/reports.

Commercial development and deployment of large constellations ought not to be interpreted as stifling competition in the commercial space for data products and technology. These activities are spurring growth in the industry—an industry that is also benefiting from dramatic increases in start-up space company investment. From 2000 to 2020 worldwide there were 1,212 unique investors spanning venture capital firms (52 percent), angel investors (20 percent), corporations (18 percent), private equity firms (6 percent), and banks (4 percent) where $36.7 billion has been invested. In 2020 alone, $7.6 billion has been invested from venture capital, public offerings, acquisitions, debt financing, private equity sources, and other sources (seed/prize/grant, etc.) in the start-up space industry worldwide. Venture capital investment represented 64 percent of the total 2020 start-up space investment. There have also been recent increases in Special-Purpose Acquisition Companies (SPACs)[4] in the space industry. SPACs are publicly traded companies that seek to raise funds and acquire a private company with the intent to go public via a "reverse merger" more rapidly than via an initial public offering (IPO). A number of SmallSat companies have recently gone public via a SPAC.

Although telecommunication needs have been a key industry driver, capabilities for remote sensing are also prominent, and New Space companies are structuring their businesses with future government customers in mind. Over the period from 2011 to 2020, DoD, based on publicly available information, launched the most as a government military organization (77 satellites)[5] with NASA

[4] Bryce Space and Technology, 2021, *Start-up Space: Update on Investment in Commercial Space Ventures 2021*, BryceTech, Alexandria, VA, https://brycetech.com/reports.

[5] Bryce Space and Technology, 2021, *SmallSats by the Numbers 2021*, BryceTech, Alexandria, VA, https://brycetech.com/reports.

launching the largest number of SmallSats in civil space (56 satellites). Government customers may not represent the largest business base today, but demonstrating success with high-profile agencies such as Department of Defense (DoD), NASA, and NOAA, strengthens corporate reputations while broadening community interest in SmallSats and commercial partnerships as a means to advance mission objectives of national priority.

AREAS OF COMMERCIAL SMALLSAT DEVELOPMENT

Commercial development activity for SmallSat missions largely emerged from CubeSat standards developed in the 1990s. The standard subsequently fostered the design of miniaturized components and subsystems for CubeSat spacecraft including GPS receivers, attitude determination and control systems, radios, solar panels, antennas, deployment systems, and other equipment. Considerable progress has been made; however, there is still a long way to go before a spacecraft of any size can be assembled from individual from off-the-shelf components capable of hosting a scientific payload. Individual developers have successfully integrated subsystems into full spacecraft leading to the emergence of commercial companies that assumed this role as a business opportunity. Such companies design and develop full spacecraft buses ready for independent payload integration by the user or the industry spacecraft provider. This provided a means for industry to mature spacecraft through real flight experience, while producing small satellite product lines of increasing sophistication and size ranging from nanosatellites and up. . This allowed developers to conceive focused measurements in their scientific area of expertise, relying upon commercial services for spacecraft and other infrastructure support.

Launch accommodation and integration services have been long-established commercial areas enabling access to space, but the emergence of SmallSats grew these services with new entrants specialized for such payloads across a variety of interface systems on launch vehicles and the International Space Station. Launch brokers have performed a key role largely relieving investigators of managing the complexities of acquiring rideshare[6] launch opportunities compatible with their mission requirements. As the need for greater flexibility in orbit parameters, and the sheer increase in the number of SmallSats looking to procure launch opportunities grew, industry responded with the development of dedicated launch services. Currently, there are 155 organizations working to provide launch capabilities for SmallSats[7]. These companies, while still maturing, have shown great promise to provide rapid and targeted launch services, freeing SmallSats from the primary payload dependencies associated with typical rideshare opportunities.

The rapid growth of SmallSats has also opened new commercial opportunities in ground services spanning spacecraft communications, testing, and data management. Industry is building and expanding ground stations to support global and near real-time monitoring and interaction with SmallSats, largely in support of the growth in constellation missions. Distributed cloud computing infrastructure, integrated with telecommunications, is in active commercial development where users no longer need to build and/or maintain the capability themselves, paying rates directly tied to the level of service and performance desired. Commercial industry has also moved to provide observational measurements as a service for purchase through data-buys, while others are making a business in data curation, fusion, quality control, and analytics. Commercial services for SmallSat vehicle testing are also enabling many new investigation opportunities by eliminating the requirements for mission-specific equipment and facilities. This approach scales well beyond functional testing to areas where detailed expertise is required, including calibration and validation of sensitive payloads, electromagnetic interference (EMI)

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[6] Rideshare: Utilization of a launch vehicle, with excess capacity and performance, by payloads that are not considered part of the primary mission. Rideshare payloads do not drive the launch schedule, or orbit parameters, and need to typically satisfy “do no harm” requirements to minimize risk relative to the primary mission.

[7] C. Niederstrasser. Small Launchers in a Pandemic World – 2021 Edition of the Annual Industry Survey. 35th Annual AIAA/USU Conference on Small Satellites, DigitalCommons@USU, 2021.

and electromagnetic compatibility (EMC), cleanliness, outgassing requirements, environmental testing, coupled loads analysis, and related capabilities.

Miniaturization of instruments and payloads, with their integration into SmallSat flight systems to provide data products, is also rapidly growing within the commercial sector. Commercial SmallSats of minisatellite size are now flying with radars, spectrometers, radiometers, polarimeters, altimeters, and sensors of other types. As mentioned, remote sensing is a growing part of commercial business interest where there is an opportunity to leverage capability advancements, and to influence them, in partnership with leading government and academic institutions. Fundamental research will continue within government laboratories and universities, but commercial organizations[8] are now transitioning proven research observations into systems and information products for a growing customer base.

Typically, the mission developer is responsible for determining how to assess all of these commercial services and how to utilize them to bring a complete mission into successful operation. Determining how to coordinate among commercial and noncommercial entities introduces flight development risks (such as incompatibilities among hardware and software subsystem interfaces) that have to be mitigated via experience, placing new developers at a significant disadvantage toward achieving mission success. As a result, new trends in commercial industry have emerged in the form of integrated services, vertically within a specific company or horizontally among companies that provide a coordination function. These companies utilize the capabilities of other sub-contractor organizations with specific expertise although, the integration of services within the commercial industry is still limited and will necessitate further expansion. Nevertheless, what is clear is that numerous areas once solely the responsibility of the spacecraft developer to manage, now have commercial options to the approach in which missions can be developed. In the grand scheme of spacecraft development many of these commercial areas are not new, but most have not been designed and/or tailored for the properties and principles of SmallSat systems. This is the business opportunity gap that much of the commercial industry has identified in recent years, and will continue to fill as the New Space ecosystem develops.

MARKET AND INDUSTRY TRENDS

Commercial organizations are not only providing numerous services for developers, they are now also the largest operators of SmallSats. From 2011 to 2020, *Planet* owned 22 percent of all remote sensing SmallSats launched while *SpaceX* owned 47 percent of all communications SmallSats. Both of these companies are flying large constellations in LEO. In addition, SmallSats have grown from only 1-2 percent of the total upmass (the payload mass that is carried into orbit) to orbit from 2011 to 2017 to 43 percent in 2020 owing to *SpaceX's Starlink* and *OneWeb* launches.[9] The introduction of commercial mega constellations from *SpaceX* and *Planet* have grown the upmass of SmallSats to orbit significantly when compared to the total mass to orbit. Note that mass, scientific value, and even cost need to be treated as independent variables when assessing how commercialization impacts satellite development as a whole. As previously mentioned, $7.6 billion has been invested into start-up space companies in 2020 alone where 64 percent of that amount represents venture capital investment,[10] and this trend is expected to continue. Thus one needs to consider how scientists may seek to benefit from such market and industry trends.

In the context of assessing partnerships for mission development, it is useful to examine how commercial services and partnering interact. The New Space ecosystem landscape consists of partnerships and commercial services. The context of assessing how these both support the needs of

[8] See SmallSat Alliance for commercial listings: https://smallsatalliance.org/members/.

[9] Bryce Space and Technology, 2021, *SmallSats by the Numbers 2021*, BryceTech, Alexandria, VA, https://brycetech.com/reports.

[10] Bryce Space and Technology, 2021, *Start-up Space: Update on Investment in Commercial Space Ventures 2021*, BryceTech, Alexandria, VA, https://brycetech.com/reports.

mission development is qualitatively shown in Figure 2.2 as also influenced by the history of work within this community.[11,12] This diagram represents the evolution over time of the utilization of partnerships and commercial services for SmallSat mission development. The degree of partnerships applied to SmallSat mission development increases in the vertical direction from no partnerships at the bottom to full partnerships at the top. The degree of commercial services applied to SmallSat mission development increases in the horizontal direction from no commercial services at the left to full commercial services at the right. In this manner, the diagram spans the full landscape of partnering and commercial services as applied to SmallSat missions over time.

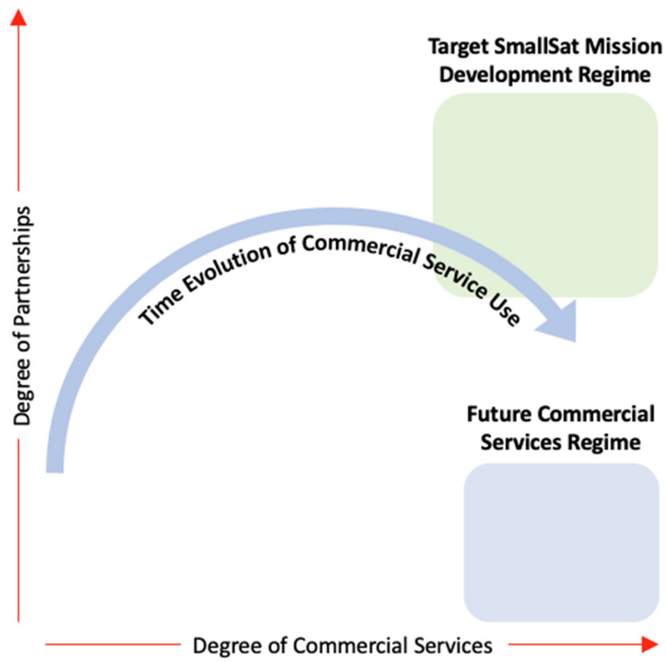

FIGURE 2.2 Ecosystem landscape of degree of partnerships and degree of commercial services reflecting SmallSat mission development over time. The time evolution transition across this landscape represents the ecosystem of the past, current, and future maturation of SmallSat mission development through effective partnerships and commercial services. Early-stage development indicates how SmallSat missions were developed without key partnerships or commercial services or involvement. As time progresses, partnering with organizations that found past success while increasing the use of evolving commercial services have led to the rapid growth and success of SmallSat missions and industry today. This is driving the potential for future establishment of fully commercial services for full end-to-end mission development, operation, and product generation as a service, but this level of product offering does not yet exist. Today, the "Target SmallSat Mission Development Regime" represents the current most effective stage of SmallSat mission development for high-priority and strategic science missions. It is also the regime where most large strategic missions have also found success relying upon a high degree of partnerships with a high degree of commercial services for mission development.

[11] M. Sweeting. Modern Small Satellites – Changing the Economics of Space. Proc. IEEE 106(3), March 2018.
[12] S. Janson. Thirty-Five Years of Small Satellites. 35th AIAA Small Satellite Conference, August 2021.

Moving along the "Time Evolution of Commercial SmallSat Use," historically, most government SmallSat developers produced systems on their own with little commercial services involvement. This harkens back to the early days of university CubeSat mission development focused primarily on student training experiences. To the extent that services procurements occurred, or were even possible, such subsystems were not easily interoperable so the level of expertise of the development team (often at universities) needed to be high. Even when commercial industry produced various system components, the level of reliability was uncertain or initially poor. Furthermore, these institutions typically did not have the financial resources to procure services such as testing, telecommunications, radio frequency licensing and, therefore, performed such work on their own. Nevertheless, missions were launched with various basic objectives, where failures were common except for a few key institutions that found success and leveraged it across subsequent missions. As mission experience grew, both government and academic users looking to gain entrance into SmallSat development often formed partnerships with these institutions. These experiences were oftentimes incubators resulting in the formation of small commercial companies that produced standardized CubeSat/SmallSat kits, as well as key specific subsystems that became de-facto standards for most developers. Numerous technological advances also occurred over this time period based on effective partnerships among government, academia, and emerging industry players. This transition formed the next stage of greater reliability for SmallSat mission development.

With maturation and growing sophistication of the New Space commercial sector came benefits in partnering to leverage both the services and flight heritage products from key industry leaders. Moving toward the "Target SmallSat Mission Development Regime," this highlights the effectiveness of these commercial services partnerships that reduced the burden on new investigators to produce successful flight missions for measurements of interest. This also allowed developers rely more upon industry services and less on prior institutional partnerships if so desired. Indeed, this is the regime of partnerships and commercial interactions that traditionally leads to successful large strategic missions. It also represents, as will be discussed, the target regime for the maturation of SmallSat missions to support observations and measurements of national interest, representing emerging and future trends in time toward providing alternative mission architectures for long-term sustainable science matching previous large strategic missions.

This history shows a progression of past developments influenced by partnerships and commercialization. It also provides a framework to explore a notional timeline for the future development of technology, infrastructure, and processes that can enable a new generation of investigators and missions for government use where commercial services may represent the baseline development approach. The transition across the landscape of partnerships and services accelerated rapidly over the past decade. Indicators are that future market and industry trends are aggressively moving toward full commercial service mission development, in that most investigators will have the ability to outsource nearly all of their mission development to commercial industry with limited additional collaborative partnerships. When observing how various companies are consolidating to provide end-to-end services, and how others are leveraging commercialization through multiple contract mechanisms to include specific capabilities (e.g., launch and testing services) as part of a full mission lifecycle development offering, it is possible fully outsourced mission development will be a viable option for principal investigators in the future.

Considering this landscape, Figure 2.3 illustrates examples of the range of organizations that reside across this ecosystem as well as a potential development path for government investigators aspiring to employ commercial partnerships to help achieve their space-related mission.

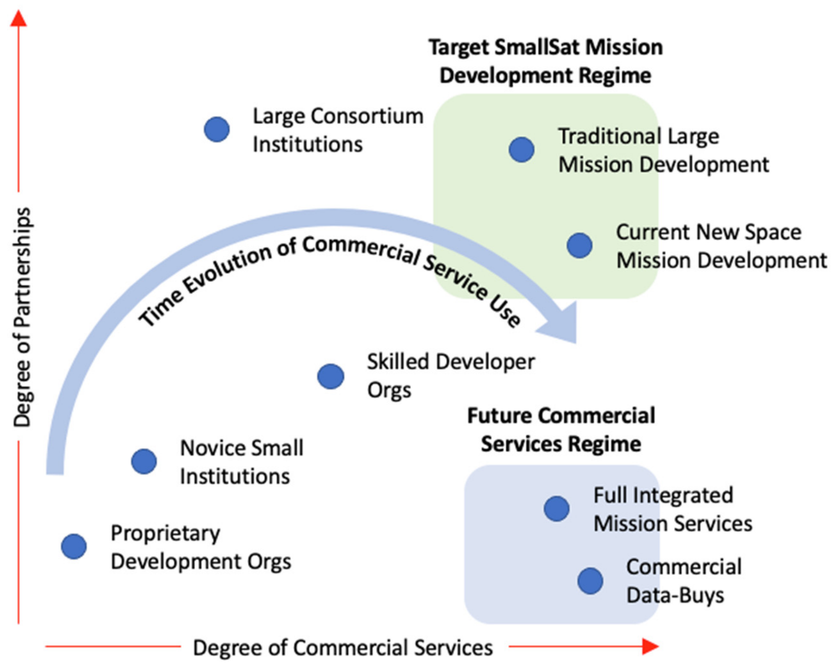

FIGURE 2.3 Development path regime for government investigators seeking to leverage partnerships with industry and other key organizations. The Time Evolution of Commercial Service Use arc represents the transition new government developers may follow to rapidly leverage evolving commercial services to meet government needs. Their business case for reliability and commercial contracting will generally emphasize utilization of commercial services above non-commercial partnerships (driving the curvature of the arrow), but partnering in general will still be important and necessary. The Target SmallSat Mission Development Regime is the ideal region for this development, but there will likely also be government organizations that, due to the nature of their investigations, cannot easily partner with external organizations and will rely entirely on procured commercial services. Reliance on proven commercial products, with innovative procurement mechanisms, to support observations sustained over long time periods, is why most government missions would emphasize commercialization over partnerships with non-commercial entities.

SmallSat development, in terms of these parameters, is evolving using limited partnerships and commercial engagement to the desired end-state of effective utilization of commercial service capabilities to the fullest practical extent. This approach is pitched more toward commercialization than other external partnerships, identifying significant partnering as critical for rapid transition from a level of relative inexperience to mission execution with national strategic importance. There will always be government organizations that will seek to use SmallSats for areas of interest where high levels of partnering may be limited, but even in those instances, commercial services can provide viable benefits. It is unlikely that these government customers would seek to outsource their development completely even as industry capabilities advance. Understanding this range of development helps establish a basis to determine what process enhancements in technology development, standards, and best practices can support the development of government missions.

Even in the context of government mission development striving to have an appropriate balance between commercial services and partnerships, this does not mean that government SmallSat users may only be effective in the target regime. Such users may find specific benefits throughout this landscape depending on their specific objectives. Proprietary development organizations provide opportunities for development of specialized in-house capabilities for SmallSat missions which may be necessary for security or other reasons. Large consortium institutions may promote intra-government partnerships or specific academic partnerships where commercial capabilities are nonessential to meet mission objectives. Companies that provide full integrated mission services may be a rational regime if there are organizations that do not have the capability to develop missions independently, but nevertheless have unique data needs that can be satisfied by outsourcing the full mission development to commercial industry. This may be of particular value when an existing commercial solution exists to meet mission requirements in a manner that would be more affordable than commercial data-buys or other approaches. While the path of SmallSat mission development has progressed in time, and is still evolving, it needs to be stated that the desired end state of the target SmallSat mission development regime may not be the optimal for all circumstances. All of these factors identify and drive market and industry trends in the near-term, affecting how one considers assessment of partnership options for commercial services supporting mission development for government and other interests.

Commercial SmallSat-Related Services

The services provided by the commercial industry for SmallSats are constantly evolving. For the government developer seeking to support high-priority missions, potentially through the integration of experimental payloads to support new measurements, one needs to assess if the commercial infrastructure is sufficiently mature across all services areas to support these goals. This infrastructure spans spacecraft industrial manufacturing, communications, information systems, system integration, launch, testing, and maintenance services. For example, a variety of systems and services need to come together to support satellite launch, especially rideshare launch where multiple satellites are involved. In the broadest sense, multiple satellites are integrated with launch vehicles according to launch windows that accommodate required orbit parameters and timelines. In the past, launch vehicle processing and satellite integration were the majority of commercial services a developer could expect. More and more of these needs are becoming service-oriented capabilities where commercial organizations can support launch vehicle manifest, satellite integration, range safety requirements, mission operations, data return, analysis, and archiving. Today, the breadth of commercial services for SmallSats can be seen at nearly every stage of mission development, yet the maturity of these services can vary widely. Given the rate of change across all commercial services, developers need to constantly monitor progress in these areas while remaining ready to rapidly adopt traditional and new capabilities as they mature.

Spacecraft bus development for SmallSats, ranging from CubeSats under 10 kg through SmallSats up to 600 kg has largely become commoditized by industry based on the intended use. However, plug-and-play standards that support seamless integration of subsystems between vendors remains elusive. There are many organizations that are capable of delivering a complete spacecraft flight system with integrated payloads based on proprietary spacecraft system designs. In general, SmallSat payload development for science missions is still dominated by investigators producing high-performance custom designs that rely on industry components, yet cannot be developed by industry at the required levels of sensitivity and precision. There are exceptions, however, where companies are targeting specific markets (e.g., synthetic aperture radar and visible imagery) developing flight systems that have produced data products of unprecedented resolution for SmallSats. Others are creating data fusion, quality control, and analytics commercial services for integration of SmallSat data, sometimes with other data sources, to produce new tailored products and/or simply making their existing satellite products available via data-buy programs.

Ground services, particularly global satellite communications for SmallSats, provides a means to avoid designing, developing, and maintaining ground communications equipment and staff, where users can establish contracts for levels and quality of services based on need. Various commercial bus providers even support mission operations as a service given their familiarity with the spacecraft design. Cloud computing infrastructure for data management and archiving, supported across a global and distributed data network that can be interfaced to any mission operations center, is growing as a service offering. As space-based networks continue to mature there will be additional services offered to support space-to-space communications within allowable regulatory frameworks.

Launch services have been one of the most rapidly evolving areas where the government has supported access to space through rideshare launches. Now, the number of commercial organizations providing launch opportunities via rideshare, dedicated, and specialized deployments from the International Space Station has grown such that there are rarely bottlenecks for access to space—although launches can be delayed for many reasons and some specialized orbital parameters will always present challenges. Hosted payload[13] services even provide access to GEO, which can be a unique vantage point for certain types of Earth-science measurements. Testing and evaluation capabilities of flight systems are also available to ensure that range requirements are satisfied, including calibration/validation of payload systems, has been extended down to SmallSat spacecraft saving significant capital expenditures for developers that cannot afford to support such infrastructure.

The technical maturity of commercial services across all these areas varies, as highlighted in Figure 2.4. The mission lifecycle begins with the process of defining data requirements and examining existing data sources to determine if they can be met without building anything new. There is a small but growing set of companies offering commercial data products and a much larger set of companies now offering commercial satellite communication capabilities that, if acceptable, can entirely bypass the complexity involved in developing new systems.

If existing products cannot meet the user needs, the process of mission formulation is initiated in which instrument, spacecraft and ground systems are conceptualized and carefully traded to arrive at a system specification and implementation plan that meets the technical and program requirements. The implementation plan needs to address solutions for all of the downstream components of the system including (1) development of the instrument, spacecraft bus, and ground infrastructure; (2) procurement of launch services; (3) integration of bus with the instrument, spacecraft with launch vehicle, and space system with ground infrastructure; (4) development of data calibration, validation, and production software pipelines and (5) development and staffing of mission operations.

Many individual components or sub-systems are becoming available as commercial products or services including spacecraft buses, launch services, RGS services, mission operations, and cloud software hosting. Although systems engineering, integration and production operations are largely the responsibility of the customer today, it is anticipated that commercial providers will become more capable of providing integrated space systems offerings such as full spacecraft and mission integration and even end-to-end data production, calibration, and validation.

Figure 2.4 also illustrates how commercial services evolved independently even though specific relationships and dependencies exist. This implies, in terms of the level of maturity of commercial services to support full end-to-end mission designs that a complete system-level integrated approach does not yet exist. As a result, fully outsourcing complete mission development to a commercial provider is not an option that exists today. The current commercial offerings do not solve all development challenges, but the landscape is rapidly changing where future capabilities in Figure 2.4 are being realized. Infrastructure advancements that could help lead toward full commercial system-level integration capabilities, from mission formulation to on-orbit operations, could begin with systems engineering-based virtual mission design and simulation capabilities tied to hardware in the loop development testbeds emulating relevant measurement environments. There are commercial companies working on such environments where some success has been seen in the development of tools and infrastructure for custom spacecraft avionics, but work to generalize such systems tied into instrument/payload measurement requirements remains open. In the long-term, introduction of commercial services that cover the full range of systems identified in

[13] Hosted Payload: Parasitic utilization of excess capacity on a commercial or government spacecraft platform where resources such as power, communications, and access to space enable the operation of the payload. Hosted payloads are typically scientific instruments, or other spaceborne items that, depending on the hosting platform design, may not impact control, operation, or resources of the spacecraft platform.

Figure 2.4 would reduce the risk of fielding long-term sustained observations, provided such services are integrated, trusted, reliable, and tailorable to specific customer needs.

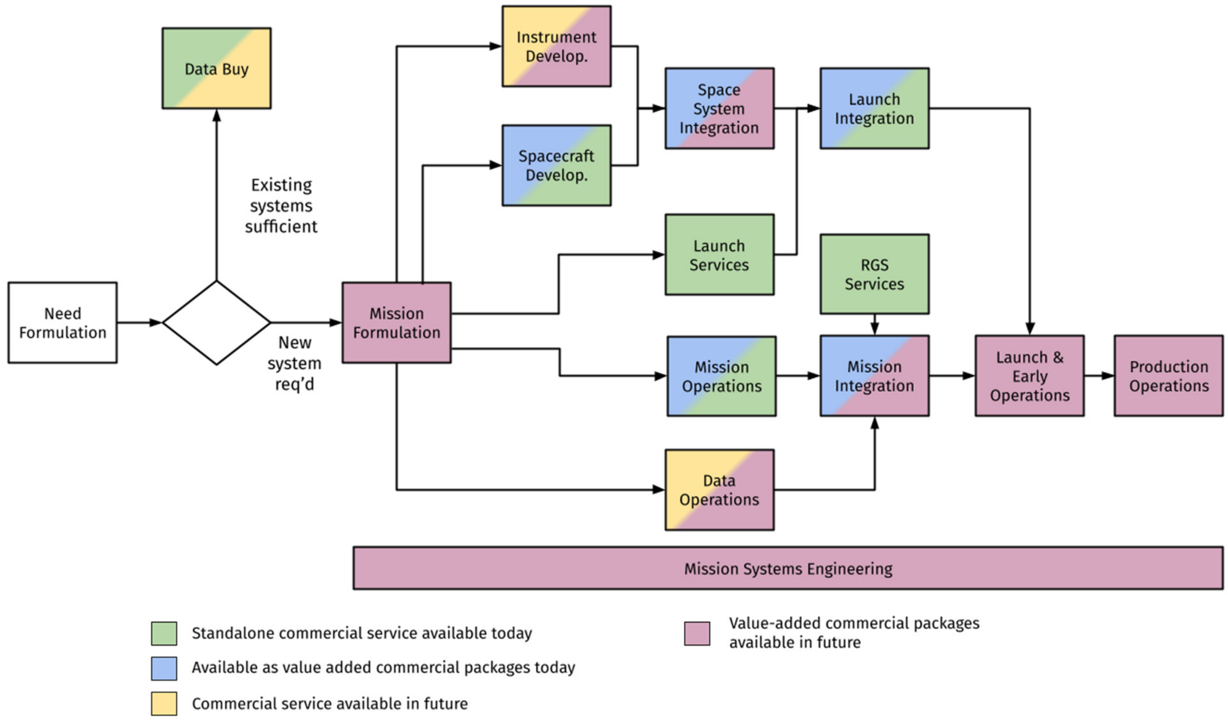

FIGURE 2.4 General process for supporting SmallSat development, launch, and product acquisition. Assessment of commercial services to satisfy customer needs may consist of purchasing existing data products or formulating a new mission to create such products. Currently, the ability to perform commercial data-buys is limited, yet the number of commercial organizations that could support various phases of mission development is rapidly growing. Understanding the state of maturity of commercial options spanning instrument and spacecraft development, system integration, launch services, Remote Ground Station services (RGS) and mission operations is critical toward the use of commercial services to produce flight systems satisfying mission requirements. In this diagram, "standalone" refers to commercial offerings that are standalone products—they do not come bundled or integrated with other mission products; "value-added" packages indicate commercial offerings that address part of a broader, more integrated commercial package consisting of multiple mission segment solutions.

Several commercial providers offer hosted payload opportunities today. In these cases, shown in Figure 2.5, the customer delivers an instrument or payload to the provider who integrates the instrument, launches it, operates the spacecraft bus and delivers data and power to and from the instrument on-orbit. In cases where the mission requirements can be met with a hosted payload solution, it significantly reduces the scope and complexity of mission execution for the customer as many of the components are handled by the host system and are transparent to the user.

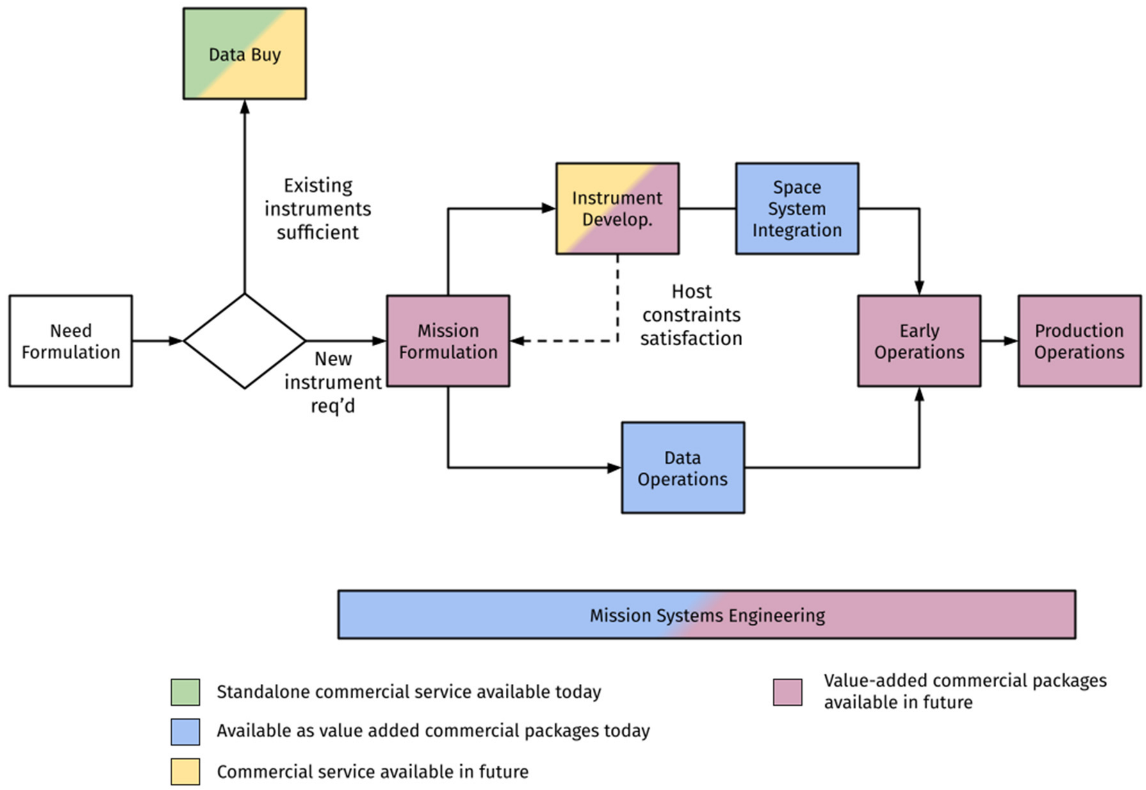

FIGURE 2.5 General process for flying payloads though a hosted payload offering. The hosted payload path is notionally much simpler than the full mission development articulated in Figure 2.4 and there are growing commercial opportunities for hosted payload slots. While there are challenges related to the constraints of the host and complex integration and de-confliction with other payloads, this is an option worth considering for many missions. It is also likely that more value-added service offerings will develop commercially over the coming years.

While the hosted payload solution can be very attractive, there are also limitations. The constraints (mass, volume, power, thermal, data, and pointing) associated with the payload often significantly limit operational capabilities and because there is no existing standard, these may vary significantly across providers. For some instruments driven by aperture/power there may not be solutions that physically fit while for others the mission data allocation or instrument operating duty cycle may become a performance constraint. Additionally, contamination control represents another potential issue for coordination between payloads. If, for example, the primary payload is a communications satellite, then a secondary payload that is a remote sensing satellite may not be able to accept the less restrictive host contamination control plan. Understanding and optimizing to the host constraints is often a significant portion of the *mission formulation* process, and close collaboration between investigators, instrument developers, and spacecraft host organizations are critical to success. Last, constellation hosting slots are still quite rare (*Iridium Next* being a primary exception) so in such cases where a constellation is required, the hosting options may be quite limited. Hosted payload options release the barrier to entry and are worthy of considered in any small instrument mission that can tolerate the host constraints.

COMMERCIAL INFRASTRUCTURE CAPABILITIES FOR SUPPORTING SCIENCE

Successful adoption of commercial services for the development of science-driven missions relies on an assessment of the state of industry infrastructure and technology capabilities. Table 2.1 identifies commercial infrastructure capabilities, in terms of their current technology state and needed near-term technology advances (e.g., open and interoperable standards enabling mass production and common interfaces), that could benefit future science mission development. Later, Table 2.2 will revisit these commercial capabilities adding predictions of future capability trends and the expected timeframe of their development.

Processes exist that can be employed to enhance technology development pipelines across these infrastructure areas. For example, government space agencies, through prizes, challenges and other means, have introduced focused technology programs, in partnership with industry, to create targeted capabilities when a specific mission objective has been identified. More generally, however, incremental/staged programs that mature specific categories of technologies from early-stage development through flight validation have been very effective when commercial industry participates in the process.

Examples include the National Oceanographic Partnership Program (NOPP) and NASA's Earth Science Technology Office (ESTO) which matures instrument and information systems technologies with low readiness through a series of development steps to achieve flight system validation. While every stage of this process is competitive, it provides a regular and sustained mechanism for investigators to advance key technologies for infusion into flight missions. As investigators team with commercial industry it also provides a valuable vector for both partner to gain increased experience with SmallSats.

Developing technologies to support the transitions described in Table 2.1 requires government, academia, and industry to assess the value added in these future capabilities with incentives for all to partner in their development. Satisfying the needs of any one customer would be insufficient. The main incentive is the understanding that SmallSats have demonstrated high-quality science measurements, which can be performed rapidly and affordably, and that greater interoperability and standards can grow the diversity of investigators creating new business opportunities to fly missions of national interest.

COMPARING COMMERCIAL SERVICES MISSION DEVELOPMENT AGAINST ALTERNATIVE APPROACHES

Most SmallSat missions thus far have not been flown in support of long-term sustained observations for operational missions of national interest. One reason has been concerns about reliability and, yet, despite these concerns, several SmallSat constellations have demonstrated remarkable reliability. Two examples are the *Planet* SkySat constellation, which has accumulated multiple failure-free years on orbit and the original *Iridium* constellation, which represents an early success in a commercial constellation as it was a technological achievement. Commercial services are now emerging that will allow developers to produce these highly reliable systems, especially for constellation-based measurements, but customers need to apply diligence in vendor selection and management as there remains significant variability in process and quality. It is also assumed that these developers will benefit from the nonrecurring engineering (NRE) investments made by industry leading to products and services that are affordable and possess long-term reliability.

TABLE 2.1 Commercial Infrastructure Technology Capabilities and Near-Term Needs to Enable National Priorities in Science

SmallSat Commercial Capability	Current Commercial Technology State	Desired Commercial Technology State
Spacecraft Manufacturing	Customized spacecraft buses with limited mass production capability	Open and interoperable standards enabling high-volume production and common interfaces
Instruments and Sensors	High-resolution visible and radar systems flown, with constellations providing global coverage, yet often uncalibrated	Highly-calibrated platforms with the capability to integrate research sensors (beyond imagers) into existing spacecraft systems
Data Management and Analytics	Cloud computing for data access/archiving with emerging capability for data fusion, analysis, and data-buys	Distributed multi-institutional platforms integrating well-conditioned data sources with AI/ML for near real-time analytics/forecasting
Ground/Space Communications	Emergence of ground station wide-area telecom services with limited space network-based capability	High-capacity, availability, and reliable ground and space-borne global data access and standards for real-time heterogeneous information exchange integrated with cloud computing data management systems
Mission Operations	Services largely equivalent to existing systems within most institutions with proprietary capabilities for constellation management	Open platforms for distributed mission operations, autonomous commissioning, autonomous spacecraft operations, and constellation support; propulsion and advances in deorbit techniques and tools to manage space debris
Launch Accommodation	Standardized adapters for CubeSats up to SmallSats, and hosted payloads spanning rideshare through dedicated ground and air launch vehicle systems	Standards to reduce customized interfaces and promote launch manifest flexibility definition of launch envelope for noncontainerized satellites advances in propulsive SmallSat technology for rapid and multi-spacecraft precision deployment and orbital injection;
Test and Evaluation	Various standard test vector and data analysis capabilities (e.g., shock, vibe, thermal, EMI/EMC, contamination monitoring and control and other capabilities) consistent with launch vehicle, safety, and other mission requirements	Standards and tools for on-orbit flight system verification and validation (V&V), and broader development of NIST-traceable commercial sensors
Mission Systems Engineering and Integration	Concurrent systems engineering capability with de-coupled tools for integrated mission design of limited fidelity	Fully integrated high-fidelity environments for concurrent design, integration, calibration, and operational commissioning
Cloud-Based Architecture	Well-established commercial services including public, private, hybrid, and government options	Advanced in capability to integrate legacy digital active archive center (DAAC) and other data systems with commitment to preserve scientific data in perpetuity

NOTE: Various infrastructure-related topics supporting SmallSat mission development are listed allowing comparison of the current state of commercial capability versus technology needs to support future scientific mission development.

Figure 2.6 revisits the ecosystem landscape showing how overall mission development risk is influenced by the degree of partnerships versus degree of commercial services during mission implementation. It provides a qualitative assessment of the trade-offs in mission development approach across these parameters. While the emphasis is on overall mission development risk, the kinds of development risks that can be encountered include development and use of custom subsystems that are unproven, personnel turnover, lack of use of industry proven capabilities, reliance on commercial subsystems with little to no known flight heritage, development inexperience, and even lack of oversight where a high degree of past mission experience and success is assumed. Mitigation of these kinds of risks can vary based on the degree of partnerships and commercial services used where more tends to be better.

Many new developers experience such risks when much of the entire mission is developed in-house. Even for the most experienced organizations, avoidance of proven commercial services and limited partnerships introduces higher risks because all of the “corporate memory” and expertise for product and mission development is centrally located within the organization. A loss of any key individual directly impacts the overall team until a replacement is found. Increasing the level of partnerships can not only protect against skill loss or turnover, but also opens the door for wider diversity of participation, potentially leading to more creative solutions.

Continuing along the time evolution of commercial services use, the greater use of commercial services, assuming collaboration with proven organizations, provides the strongest balance especially when developing first-of-a-kind missions of national or strategic importance. Experienced commercial teams and other strategic partners can be fully leveraged representing the most desired state for SmallSat mission development with lower overall mission development risk. This enables a balance among commercial services and developer-driven innovations specific to key measurements of interest. As always, extensive partnerships bring inherent communication risks that need to be actively managed across institutional interfaces. This is true when government organizations deliver subsystems to industry for system integration activities or when government and industry collaborate throughout all phases of mission development.

As the ecosystem landscape evolves toward a capability for full commercial services for mission development, this can increase certain risks in that nearly the entire mission development has been ceded to commercial industry, meaning the ability to perform innovative measurements of national interest may be limited to the capabilities represented by the current state-of-the-art of commercial organizations. This can create a ceiling in mission capability. A potential mitigation factor here would be for commercial providers to be contractually incentivized to develop and maintain strong R&D activities in addition to sustaining their standard production capabilities. Forming strong long-term working relationships with innovators in academia and industry would also serve to infuse new technologies and best practices into industry improving existing product lines with new capabilities over time.

Future Trends in Commercial Development for Science Missions

There has been significant growth and establishment of commercial flight systems over the past ten years. This has resulted in an expansion of measurement capabilities from innovative miniaturized instruments, an increase in the design trade space of measurement opportunities, and a greater diversity of options for access to space. Commercial industry has always influenced the success of large mission development, but now that SmallSats can provide viable alternatives to produce results at the same, or even improved, quality levels of traditional missions the role of legacy and the New Space industry will grow in significance in the coming years. Table 2.2 shows some future trends in SmallSat development where industry, government, and academia can partner to fully establish such capabilities within the next 10 years for scientific measurements for a wide range of applications.

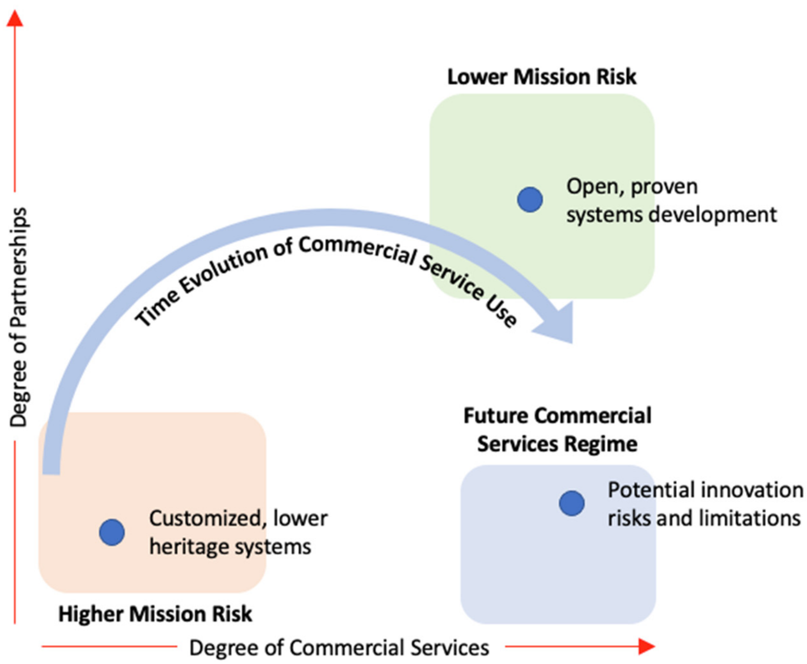

FIGURE 2.6 Trade-offs in mission development approach based on ecosystem landscape of degree of partnerships and commercial services applied. SmallSat mission development risk may be higher when developed primarily in-house without significant use of industry standard and proven subsystems. Mission development risk was lowered over time by pursuing proven subsystem partnerships through organizations that had experienced prior mission success (In the early days of CubeSat/SmallSat development government organizations often partnered with universities that flew successful missions as a means to bootstrap government capabilities). The region of Lower Mission Risk represents the strongest balance between the use of effective partnerships and commercial services in an environment where such service capabilities are still evolving. Nevertheless, this only works when both the partners and the commercial organizations are strong with proven track records of success. Indeed, success here breeds further success and lessons learned can be integrated into commercial service practices which may build a strong reputation leading to additional work. This represents the desired state for SmallSat mission development when sustained observations are of primary interest as these partnerships and commercial services can be established through long-term contracting mechanisms. As the ecosystem advances toward ceding most mission development to industry, risk increases again given less direct involvement and oversight if commercial organizations choose to protect aspects of their technical development or rely upon third-party contractors as part of the flight system delivery.

Managing partnerships to achieve these advances means requirements will need to be established with appropriate roles agreed upon among government, industry, and academia. Mechanisms exist for industry to directly commercialize capabilities emerging from government and academia in areas such as instrument and sensors whereas in others, such as launch accommodation, industry needs to continue to lead. Broadening of government management understanding and acceptance of commercial capabilities and opportunities are needed for commercial industry to positively impact SmallSat mission developers; to institute new partnerships for focused technology development; to develop the relevant infrastructure components; and, to do so in a manner that is reliable and sustainable. This also requires balancing decision-making and risk in an actively changing environment.

TABLE 2.2 Commercial Capability Trends and Development Needs Forecast for Infrastructure-related Topics Supporting SmallSat Mission Development

SmallSat Commercial Capability	Capability Future Trend	Capability Need Forecast
Spacecraft Manufacturing	SmallSats for sustained observations	0–5 years
Instruments and Sensors	Multi-instrument and smart sensor systems producing data products indistinguishable from legacy systems	0–5 years
	Large deployable systems	0–5 years
Data Management and Analytics	Multi-instrument constellation data fusion and analytics	0–5 years
	Distributed and near real-time data interaction and processing	5–10 years
	Commercial data-buy of raw and finished data products	0–5 years
Ground/Space Communications	Laser communications, space-to-space telecom, Gb/s global telecommunications, secure networks	5–10 years
Mission Operations	Cooperative synergies among large and small missions	0–5 years
	Reconfigurable constellations	5–10 years
	High-performance/reliability propulsion systems	0–5 years
Launch Accommodation	Fully responsive launch	0–5 years
	Propulsive-SmallSat deployments to arbitrary orbital planes	0–5 years
	Plug-and-play hosted payload accommodation	5–10 years
Test and Evaluation	Parametric and/or spot testing of complete product-line systems in-lieu of component and full system test and evaluation	5–10 years
Mission Systems Engineering and Integration	Fully distributed and concurrent engineering environments supporting design, build, assemble, integration, test, commissioning, calibration, and operations	5–10 years
Cloud-Based Architecture	Commercial systems fully compatible with legacy science data systems, DAACs, and integrated (perhaps with customization) into government mission operation centers (MOCs)	5–10 years

NOTE: This table identifies areas where commercial development is needed to benefit government science mission capability and provides a time frame for when that capability could be developed and used. Although it categorizes and indicates that infrastructure exists to support the range of capabilities for mission development from spacecraft manufacturing through cloud-based architecture for data management, all of these capabilities need continued enhancement over the next 5–10 years to enable a robust commercial ecosystem to reduce the time from concept development to operations and data return. Many of these capabilities, spanning technology, infrastructure, and processes, are on-track to be available as fully vetted commercial services within 5 years, while others may need 5–10 years to come to full fruition.

Coordination will still be required to transition these capability advancements into operational use by developers. Organizations, such as DoD's Small Spacecraft Coordination Activity (SSCA) and NASA's Small Spacecraft Systems Virtual Institute (S3VI) provide forums for the commercial community to interact with government and academic developers to identify needed capabilities for SmallSat science missions. NASA's Small Spacecraft Coordination Group (SSCG) and DoD's SSCA also provide internal coordination functions within their agencies to support decision making on how New Space activities can enable their scientific and defense related programs.

Technology Pipeline Development

The enhancement of the SmallSat technology development pipeline may be supported via a number of approaches. The first and most traditional model is to embed technology development resources into existing programs of record. This involves setting aside some amount of resources to enable targeted investments in those technologies that are specifically important to that program.

The second and most targeted approach is direct investment from end users such as military and civil space organizations. For instance the AFRL funds SBIR and SSTR research and technology development opportunities through the AFWERX program. Similarly the NASA Science Mission Directorate (SMD) funds and operates the Small Spacecraft Technology Program (SSTP) to create, mature, and demonstrate needed technologies for NASA's SmallSat science and exploration missions. SMD also sponsors multiple competed technology programs for mission and instrument development on the order of $100M annually. Finally, other governmental agencies participate in SmallSats use mechanisms like the SBIR programs to seed and mature SmallSat Technologies.

A third, less direct but very important means of technology investment for SmallSats, comes in the form of dual use technologies. For instance, the telecommunications industry invests billions of dollars annually to create small, low powered, yet highly capable electronic devices and sensors. Many devices and system elements, such as computer processors are naturally radiation tolerant and, with appropriate radiation test methodologies, have the potential for dual-use in space applications. The automotive and biomedical industries produce highly reliable, robust systems, which can also be similarly tested and adapted to SmallSat systems. Additionally, SmallSats are utilizing cameras, IMUs, altimeters, processors etc. derived from cellphone technologies. The gaming industry is constantly improving the speed of processors that can be used to support artificial intelligence/machine learning (AI/ML) software applications on SmallSats, enabling potentially new and unique mission concepts with greater capabilities than currently available. Due to the rapid pace of technology development and the large number of agencies and organizations involved, duplication of efforts is common. Therefore, in order to achieve coordination and oversight, a better method of communication between government procurement agencies could prove beneficial for impacting acquisition strategies, development of best practices, sharing of acquisition mechanisms, and other areas.

Standards Development

Standards have been highly instrumental in enabling the SmallSat revolution. For instance, the invention of the Poly Picosat Orbital Deployer (PPOD) allows CubeSats to be manifested and deployed from a wide number of launch vehicles. The PPOD provides known, stable interfaces to both the spacecraft and the launch vehicle. It has extensive testing and operations campaigns behind it and it is now considered a safe, low risk system for accommodating CubeSats. The standard is published and widely available for all developers and designers to reference, and it has been adopted by many in the SmallSat community. Similar standards could be developed for areas like orbital safety and the minimization of light pollution for astronomers from orbiting spacecraft. However, the successful adoption of these standards hinges on how they are created. Top-down dictates are generally considered less likely to find wide-spread acceptance and use versus those developed by end users and then shared with the community. In other cases, an organic standards process is not possible and government involvement will be required.

One example of standards applied to the development and procurement of complex space systems by the Defense Department is a concept called the Evolutionary Acquisition for Space Efficiency (EASE).[14] This concept was introduced by the USAF in 2012 to deal with the high cost of satellites but, also, to foster innovation in satellite acquisition. EASE was adopted by Congress as a means of allowing DoD to acquire expensive satellite systems through fixed price, block buys spread over multiple years rather than through single-year procurements that had become prohibitively expensive. An important part of the EASE concept was the addition of a Capability and Affordability Improvement Program (CAIP) in the satellite program's budget. CAIP provided funding for the acquisition of new, enhanced components to be added to the satellite systems for each launch, nominally every 2 years. Any company could compete for CAIP funding. The contract award for the core system required the industry producer to share their integration standards enabling others to design components and sensors to be added to the original satellite system.

This CAIP concept could also be extended beyond a core satellite system to an entire constellation. Overarching integration standards would allow all systems launched for a particular mission to integrate their operations into a coherent "whole". Another benefit of broader integration standards would be for data integration. Today, each satellite system provides data for their specific system's ground processing, making it challenging to integrate the information across a large number of systems. If data standards could be introduced, this data integration process would be much easier and would better enable new data analytic techniques such as machine learning. In this case, government would either have to develop these standards or, as done with EASE, contract the standards development out to industry as part of their task.

Not all areas benefit from standardization. Part of the success of standards, is identifying the key technological areas that will benefit and enable the advancement and usage of small satellites. Blanket adoption of standards across all systems could stifle innovation meaning that collaboration between government and industry is necessary to determine which areas would benefit the most from standardization. The government can help facilitate the usage of standards by incentives to industry and including them in contractual agreements for future procurements. A clear value proposition to support standards needs to be made for commercial industry to adopt and incorporate them into existing and future products or services.

Technology and manufacturing standards are typically accomplished by professional societies through organizing groups of stakeholder representatives. Societies like the Institute of Electrical and Electronics Engineers (IEEE), the Society of Automotive Engineers (SAE), and the American Institute of Aeronautics and Astronautics (AIAA) can be encouraged to organize industry groups to first identify areas and systems that would benefit from standards and then to proceed with their formulation. The government can also develop guidelines for using those standards in procurement practices.

Another key element of standards lies in their communication and promulgation. Standards need to be readily available to existing and new entrants, and they need to also include a process for testing, updating and improvement as situations and needs evolve. The wide distribution of standards will assist equal access to the space technology marketplace. Similarly, where standards are needed but not available, a well-trusted, independent group needs to be identified to coordinate and facilitate new standards creation and disseminations.

[14] See https://acqnotes.com/acqnote/careerfields/evolutionary-acquisition-space-efficiency-ease.

BEST PRACTICES AND LESSONS LEARNED

The nature of New Space allows for a large number of new entrants to contribute and participate in space operations using SmallSat platforms. However, in contrast to larger, more established aerospace organizations, these new entrants usually do not have the advantage of depth and experience to guide them as they develop their missions. Therefore, the SmallSat community tends to be a more collaborative one. To encourage more collaboration, lessons learned along with best practices need to be identified, vetted, and clearly communicated throughout the community. This can be achieved through activities and organizations such as NASA's Small Spacecraft Systems Virtual Institute,[15] which provides a number of resources, tools, and lessons learned to the community.

Opportunities to collaborate across organizational boundaries is another way for new entrants to quickly benefit from the experiences of others, for example, NASA has been actively collaborating with USSF, NSF, and NOAA. Barriers to such collaborations need to be minimized to the extent possible, and collaborations need to be encouraged and rewarded. Collaboration environments and tools also need to be provided and made available to assist with this goal.

Finally, there exist benefits and challenges in adoption of new business models to best leverage SmallSat commercialization and partnerships. While Figure 2.6 highlights the risk trade in maturing mission development based on the degree of commercialization and partnerships, Chapter 5 will highlight how specific commercial capabilities across services, mission operations, technology development and data-buys, may benefit government users pending the details of how various business arrangements are structured. Assessment of these risks, in the context of the state of technology development enabling these capabilities, and their forecasted readiness over a period of years as shown in Table 2.2, directly impact how government users could phase in appropriate technologies and capabilities to meet mission objectives. Thus, the maturation rate of these capabilities will also impact decision making regarding development and readiness/adoption of the HSA. As will be describe in subsequent sections, the HSA could, under appropriate contract mechanisms, also serve as an enabling capability to provide standardized services for government mission development across a variety of commercial services.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSION: The commercial space industry's tremendous growth and rapid evolution have generated high-profile successes, and signs indicate that this trend will continue to accelerate. The U.S. government, including traditional governmental space users, could benefit greatly from less traditional relationships, such as public-private partnerships (PPPs) that enable the adoption of industry's technology and volume manufacturing capabilities.

RECOMMENDATION: The U.S. government should encourage the development of public-private partnerships (PPPs), potentially including anchor tenancies, to promote a new national space ecosystem supportive of industry, government, and academic objectives.

CONCLUSION: Existing interoperability standards are primarily driven by traditional system constructs and impede the government's access to flexible and adaptable commercial services. The U.S. government and commercial stakeholders will increasingly rely more heavily upon integrated commercial services and advancing standards to establish a broad-based ecosystem enabling smoother transition paths among spacecraft development, payload integration, test, launch services, operations management, and data product production. Development and adoption of interoperability standards driven by unique commercial New Space needs and design practices for key systems will increase competition and enable efficient

[15] See https://www.nasa.gov/smallsat-institute.

execution and management for a broad range of space mission and operational needs for current and future government users.

RECOMMENDATION: Key systems—those most appropriate for standards—should be jointly developed and actively managed to support the New Space public-private partnerships in way that promote the greatest acceptance and usage on future systems. Standards and best practices could be developed within organizations such as the Air Force Research Laboratory's (AFRL) AFWERX, National Aeronautics and Space Administration (NASA's) Small Spacecraft Systems Virtual Institute (SSSVI) and the Small Payload Rideshare Association (SPRSA) to facilitate the adoption of New Space business product capabilities.

CONCLUSION: A coordinated government effort to promote and oversee existing government programs, together with the exploitation of dual-use technologies (evolving out of the automotive, medical, gaming, and other industries) could enhance the existing technology pipeline and benefit all national space activities. The Air Force Research Laboratory's (AFRL's) AFWERX, National Aeronautics and Space Administration's (NASA's) Small Spacecraft Technology Program (SSTP), the government's Small Business Innovative Research (SBIR) program, and the government's Small Business Technology Transfer (STTR) program are the appropriate venues for such technology infusion and demonstration.

RECOMMENDATION: The Office of Naval Research (ONR) should take full advantage of opportunities for the infusion of dual-use technologies deriving from participation in existing government technology development programs such as the Air Force Research Laboratory's (AFRL's) AFWERX, the Small Spacecraft Technology Program (SSTP), the government's Small Business Innovative Research (SBIR) program, and the government's Small Business Technology Transfer (STTR) program.

CONCLUSION: The rapid expansion of space systems and operations knowledge throughout the commercial space industry provides numerous opportunities for the Hybrid Space Architecture (HSA) and other U.S. government space initiatives. Clearly stated standards and best practices, in conjunction with procurement mechanisms that address and accelerate decision speed, address mission risk, and align incentives, would allow efficient U.S. government access to these new capabilities. Procurement mechanisms tailored to commercial business models could further support responsive schedules from initiative inception to on-orbit capability.

RECOMMENDATION: U.S. government procurement mechanisms should be tailored to embrace evolving commercial practices and appropriate standards to address and accelerate decision speed, management of mission risk, and alignment of incentives to rapidly enable government space initiatives.

3

Hybrid Space Architecture and the Pathway to a New Space Ecosystem

INTRODUCTION

Integrating the new commercial space industry's capabilities with traditional space mission capabilities is desirable because there are complementary benefits. As a first step in this direction, the government is working toward an architecture that is resilient by design, known as a Hybrid Space Architecture (HSA). The HSA is an information-based architecture that supports the integration and aggregation of emergent New Space small satellite capabilities with traditional U.S. government and allied space systems. This framework also embraces orbital diversity and encourages platforms to go to the best orbit to achieve their mission. The HSA also assumes that a mission is achieved through multiple platforms providing constituent components of a system-of-systems, not the historical model where mission and platform were often synonymous. In addition to enhanced capability and cost savings through partnership, the natural synergies that are provided among the HSA, operational, and science and technology (S&T)/research and development (R&D) communities will be a significant driver in shaping an space ecosystem that provides utility to a broad range of space users. It achieves this by:

- Distributing risk: Increasing satellite population provides strength in numbers and diversity
- Allowing rapid innovation: Incorporating rapid insertion of new technologies as they mature
- Improving interoperability: Allowing interoperability among U.S. government, allied, and commercial space systems, and
- Fostering PPPs: Enabling U.S. and allied governments to benefit from capabilities in the commercial sectors

The HSA relies on individual agents performing specific roles where their products and services are integrated together and can be tailored for a variety of stakeholder needs. It is anticipated that the HSA will provide an initial impetus to create an ecosystem capable of supporting a spectrum of traditional and nontraditional stakeholders. Traditional stakeholders are those that are structured vertically with everything owned and managed under one line of control. Nontraditional stakeholders, on the other hand, are not sufficiently large, scoped, or funded to have everything "in-house." This requires a model where nontraditional stakeholders can participate through a "pay as you go" approach without necessarily acquiring ownership or control of large, capital-intensive infrastructure elements. However, the ecosystem will require the development of business cases and partnerships in order to incorporate the broad range of capabilities from private industry. If these incentives are successful, the initial efforts can be expanded to incorporate new users who traditionally could not independently be served by the legacy architecture because of high costs and significant time-to-completion burdens. Many of those new users are science-based organizations of the federal government. Their ability to integrate into the expanding ecosystem will provide new sensors and systems and lay the foundation for the next segment of information growth. This chapter describes how HSA is facilitating the initiation of the New Space ecosystem through integrating legacy systems and new commercial capabilities.

TRADITIONAL SPACE ARCHITECTURE

The legacy space architecture currently utilized by the U.S. government was originally developed primarily to support high-level government strategic users. Historically space was an expensive domain with a high barrier to entry, requiring significant capital to field a capability. Thus, only high-priority user needs could be serviced. These users include the National Reconnaissance Office (NRO), Department of Defense (DoD), National Aeronautics and Space Administration (NASA), and National Oceanic and Atmospheric Administration (NOAA) and other government organizations. The typical architecture was based on roughly 10-year planning cycles, mission-unique system and satellite designs, and a significant amount of investment in each system. That approach resulted in highly reliable systems, one-of-a-kind technology, and special purpose missions. This approach is often referred to as mission-based. Examples of the mission-based systems are the Geostationary Operational Environmental Satellite (GOES); the Landsat series of spacecraft; and the GPS or Advanced Extremely High Frequency (AEHF) constellations on the DoD side. This approach is not adaptable to government users requiring shorter planning cycles, having smaller budgets or special requirements.

Hybrid Space Architecture

A New Space ecosystem opens the door to the consideration for a multi-layer system architecture that would aggregate multiple information sources, whether they be from traditional space, SmallSat systems, commercial services, or foreign partners to collectively enhance the information pipeline to the end user, while supporting increased on-orbit capability and overall resiliency. This multi-layer system architecture is called the HSA**.** The HSA is not a prescriptive solution but rather a broad architecture framework with the flexibility to integrate capabilities from multiple systems to meet a variety of differing user informational needs.

The HSA has the potential to dramatically contribute to the missions of a broad array of national security users and other government stakeholders through the development of an ecosystem that will utilize PPPs which will enable different components to the architecture. This new architecture will also provide a clear leap forward for nontraditional or new users who previously had limited access or no access to the data provided by traditional systems.

FULLY ENABLING THE HYBRID SPACE ARCHITECTURE

As outlined in the previous chapter, commercial systems are becoming increasingly more capable in a broad array of applications including Earth observation data collection, providing inter-satellite communications, supporting an increase in cadence of launch of SmallSats, and providing ground network services. At its core, the HSA is a framework that enables the integration of these emergent commercial space systems with the more traditional government and allied capabilities. Such an architecture will leverage satellite systems and services that are: (1) large and small; (2) government and commercial; (3) U.S. and allied; and (4) in various, diverse, and layered orbits.

Several essential elements will allow the HSA to benefit to a broad set of users. These elements include: (1) embracing all sources of information (U.S. government, allied, non-allied [e.g. Brazil, Sweden] and commercial); (2) maximized interoperability and interconnectivity; (3) a variable trust framework for integration and aggregation of information sources; and (4) autonomy at multiple levels of the architecture, such as automation of scheduling and packet network routing through diverse communication paths. Instead of a single satellite or a distributed homogeneous constellation providing a single source or type of data, this information-centric approach utilizes all available information sources from multiple satellites or constellations, as well as terrestrial sources of information, and integrates them to meet mission-specific needs. Furthermore, because the hybrid approach provides a variety of communications paths, information can be delivered via various routes, providing inherent resilience. Various trades involving such parameters as orbital regimes, number of satellites, altitudes, data delivery rates/deadlines, inclinations, spacing/phasing, sensor types, performance, and sensing frequency are necessary to meet specific mission needs.

This open framework enabling the ingestion of multiple sources of information, will provide many important benefits including improving the architectural resilience in the face of increasingly technically capable adversaries. Strength in numbers and diversity distributes risk, and provides graceful degradation, which will mitigate "the inherent vulnerability associated with small numbers of high-value assets in the current architecture."[1] This will enable missions to be completed despite interruptions in service. A variable trust approach to provide a networking framework for rapid and secure data exchange among systems will be required. This framework makes decisions and takes actions based on the trust of the derived data sources—ensuring the security and integrity of all data and services.

TECHNOLOGIES KEY TO A SUCCESSFUL HSA

With the growth and diversity of the space community significant capability is coming on line through allied and commercial sources. The previous space architecture was designed to be single source to the terrestrial user and was not scalable to meet the need of resiliency and capacity. The HSA model provides the ability to deploy dedicated capability while taking advantage of opportunistic sources. To fully realize the benefits of an HSA, a number of key technologies are required in order to integrate the distributed set of inputs into a coherent set of timely data products. In many cases, these technologies exist in other industries or applications, but may still require adaptation prior to integration and full-scale operations.

An HSA, by definition, consists of heterogeneous sensors and platforms supported by a variety of diverse infrastructure elements, all targeted toward a particular customer or business case, but rarely the same requirement. At the point of first contact, where the sensor acquires the raw data or phenomenology (and because there is inherently a large volume of raw data being ingested) in certain cases there is a need for robust data processing resources and capabilities at the "edge" (e.g., processing on the satellite). This need is driven partially by the large amount of data being collected, not all of which is germane to the objectives of the specific mission. Therefore, the sensor element of the architecture, or the edge, requires the capability to distill the relevant data that is needed from other less valuable data sources. A similar example can be given to users of mobile photography whose default picture taking setting reduces the raw photo to a sharable size. For some users the ability to store the raw image is available but comes with greater constraints. However, if all users shared the raw image it would unnecessarily create a significant network data volume burden.

The costs and inherent delays associated with transmitting large amounts of raw data to the ground for analysis and then to upload actionable commands is inefficient and open to exploitation by adversaries and other risks. Therefore, some level of onboard processing to reduce the amount of critical data to be transmitted to the ground. Thus, transmission, radio communications, and associated power requirements can be reduced.

With the availability of robust data processing in space, advanced technologies like autonomous operations, tipping and cueing, event detection, and artificial intelligence/machine learning (AI/ML) technologies are envisioned. Each of these technologies provide added flexibility and mission resiliency, but all are enabled by the ability to analyze large amounts of data as close to the sensor as possible.

To complement the robust onboard processing capability described above, multi-path and adaptive secure communications are required. Coordinated data collection and observational events

[1] See https://assets.ctfassets.net/3nanhbfkr0pc/43TeQTAmdYrym5DTDrhjd3/a37eb4fac2bf9add1ab9f71299392043/Space_Industrial_Base_Workshop_2021_Summary_Report_-_Final_15_Nov_2021c.pdf.

require certain sets of engineering information and data, for example, timing and relative location of sensor platforms, as in a swarm or constellation, to be shared within the greater space-based network. Similarly, as different elements of the various heterogeneous system need to interact, specific data sets are required to be distributed and exchanged with these external networks. Passing information across system interfaces will naturally require a collection of standards and protocols in order to efficiently move information through the HSA and eventually to the end user. The adoption of a set of standards that enables this cross-platform exchange and coordination will also facilitate the seamless addition of novel assets or systems or the deletion of obsolete nodes and elements.

A NEW ECOSYSTEM ENABLED BY THE HSA

Evolution of technical capabilities is rarely static; improvements, increased efficiencies, and novel ways of achieving mission goals are continuously developing. However, exactly how this evolution occurs is not entirely predictable. Much of the early research is still trial and error and requires specific results as a demonstration of performance and acceptability.

S&T/R&D practitioners who experiment and test to evaluate and explore novel technologies are the most fundamental type of users. A second type of user is the one that transitions from the more basic S&T/R&D to the operational user. Here, the system is tested further under varying conditions and environments, and is upgraded for integration and adoption by operational users. The operational user requires a stable, reliable, and robust set of capabilities to meet mission needs.

As illustrated in Table 3.1 below, in this new architecture, the operational user sits on top using mission-directed space assets, which collect timely and important data. The next layer consists of test and integration users using assets supporting the development of systems potentially transitioning to the operational level in the future. These users are evaluating systems that may significantly add to the data base collected by the operational users. The lowest level consists of S&T/R&D users developing and testing technology in the exploratory and discovery phases of the information. All users will benefit from the HSA, with S&T/R&D users able to more rapidly respond to changing national priorities, by leveraging the existing architecture. Table 3.1 also depicts two important factors: (1) Operational users require high reliability and risk avoidance—naturally, these systems inherently come at a higher cost, and have a low pace of change. (2) S&T/R&D users work to keep pace with advancing technologies in support of national priorities—their pace of change is much higher than operational systems.

As depicted in Table 3.1, reliability and risk avoidance for DoD operational users are much higher than for S&T/R&D users, but pace-of-change of technology insertion is the opposite. S&T/R&D users are interested in the creation of new or novel capabilities, and therefore, consider such capabilities as test articles or laboratories. While the outcome of these tests is intended to inform and migrate up the technology readiness level ladder toward an operational capability, they are not always predictable.

Test and integration users mature the immature technology and adapt or modify it to be compatible with the operational mission. Operational users, on the other hand, demand technological stability, predictability, and a higher pace of change (e.g., adaptability and flexibility of systems), in order to meet mission objectives. A system can be considered operational when sufficient testing has been completed to demonstrate an appropriate level of reliability. To satisfy a capability requirement, users of future space architectures will need to be able to take advantage of the following resources: (1) traditional satellites; (2) SmallSats; (3) various launch services (rideshare and dedicated); (4) hosted payloads on government or commercial satellites; and (5) commercial data services. From a national security space system perspective, each of these resource options supports user needs, but individually they are only part of a possible larger ecosystem. For example, the systems-orientated approach provided by the HSA is necessary to develop on-orbit capability to increase the information opportunities to users whether that information is data or a service.

Through its multi-system integration, the HSA shows great promise in benefiting critical government national missions, while at the same time providing broader opportunities for S&T/R&D

teams to inject innovations at a more rapid pace, ensuring new technologies and sensor phenomenologies can be brought to bear as they mature. Technology developers need not tackle the creation of needed infrastructure required to field a given technology. As an example, if a company is developing an innovative sensor to test, they can leverage the production of space vehicles, and the common communications architecture being developed with the HSA to rapidly field their sensor and enable their investment to focus on their payload, rather than having to fund and develop the entire effort. This allows the technology development efforts to be more efficiently focused on the improvements of that capability. In addition, there are increasing opportunities to take advantage of commercial satellites to host government-developed payloads—decreasing cost and increasing overall system resilience. This enterprise integration of national, allied, and commercial systems will result in efficiencies and operational synergies beneficial to all government users.

TABLE 3.1 HSA User Hierarchy

Reliability	Risk Avoidance	Cost	Pace of Change	Level of Trust	DoD Users of Space Assets
High	High	High	Low	High	Operational Users
Medium	Medium	Medium	Medium	Medium	Test and Integration Users
Low	Low	Low	High	Low	S&T/R&D Users

NOTE: Three primary DoD user categories are shown that all reap benefits of an HSA. One end of the spectrum shows space assets supporting operational users, typically driven to high reliability systems with risk avoidance. This combination almost always drives cost upward. Because DoD operational systems are typically required to be very mature before fielding, the technological pace of change can oftentimes be slow. The opposite end of the spectrum pertains to S&T/R&D users who are typically developing one-off systems with lower reliability. These technology systems can typically tolerate more risk, and are typically less costly than highly mature systems. Because these systems are not being developed for DoD operational fielding, these less mature systems can advance technology at a much more rapid pace.

Benefit of the HSA to Traditional Users

Below are examples of legacy space systems users that can benefit from the new capabilities afforded by the HSA:

- **U.S. Strategic Commanders** - may utilize proliferated SmallSats with higher revisit rates that have a better chance of being in the right place at the right time to make data collections. Commanders will also benefit from the possibility of sharing unclassified commercial data to communicate the gravity of national or international issues and emergencies with the government, allies, and adversaries.
- **U.S. Intelligence Community** - may exploit higher revisit rates, allowing it to inform intelligence based on change detection. Adversaries in previous times could deny or deceive U.S. understanding of their capabilities and actions by hiding them during times when intelligence assets were overhead. With the HSA, this deny/deceive approach becomes more challenging as the gaps between the government-only systems (government, allied, and commercial) are dramatically reduced. Further, information operators, such as those charged with influencing

adversary perceptions and actions before and during a conflict, will also benefit from the ability to use unclassified commercial space products.

- **U.S. Strategic Forces -** may benefit from the improved resilience, deterrence, and stability that comes from constellations with more breadth and depth than the current highly vulnerable, highly concentrated architecture.

The inherently more affordable SmallSats and small launchers being developed by the New Space community will make holding space assets in strategic reserve much more practical. In the cases of air, sea, or ground warfare, the military ensures its force structure has additional assets to fill gaps caused by attrition or to surge capability to create decisive effects. The distributed nature of the HSA allows it to be incrementally updated with new technologies and capabilities as they mature.

Opportunities for Nontraditional Users

With an HSA, rapid access to space may be a future option for many government users who were excluded from participation owing to the cost associated with developing and fielding space capabilities. They range from tactical operators to the S&T/R&D community and may have specific data requirements, sensor designs, or even prototypes they would like to launch on short timelines. For those users traditionally underserved by current space assets, the HSA will be a major step forward. Some of these users include:

- *U.S. Tactical Military Forces:* These forces have traditionally relied on surface or airborne platforms for tactical intelligence, surveillance, and reconnaissance (ISR) and command and control. The HSA will provide many new opportunities in support of ISR, command and control, positioning, navigation, and timing (PNT); weather; missile warning; and tracking missions. Space systems show promise in providing high-bandwidth information access to move ISR and other data rapidly to mobile forces. Reducing information latency is critical to tactical forces as they conduct high-tempo operations. *Starlink*, *Project Kuiper*, and *OneWeb* are current examples of existing or planned commercial services capable of providing low-latency high-bandwidth (i.e., 100 megabits) communication capabilities for both consumer and military users. *SpaceX* has already launched over 1,600 LEO SmallSats, with a constellation able to provide individual users with such high bandwidth communications.
- *DoD and Intelligence Community Scientists:* this new architectural approach will enhance scientific study of military operating locations, including ocean and coastal areas.
- *Military Logistics:* The U.S. military is constantly moving large volumes of materiel to support its global operations and would benefit greatly from the fine tracking capability that could come from employing Internet of Things (IoT) services based on satellite technology. New Space companies are working to deploy and operate constellations of IoT-related satellites. Swarm,[2] is an example of this type of technology. Such an approach offers the potential to further improve military logistical capabilities..

[2] For more information, see https://swarm.space/our-technology/.

EVOLVING THE HSA FOR A BROAD SPECTRUM OF USERS

Technical Challenges

The HSA could be the basis of a national space ecosystem servicing not only top-level military users, but a broad spectrum of other users, including those in DoD, civilian agencies, universities, and private industry. The primary challenges of the HSA are the complexity inherent in this type of architecture since it requires a variable trust framework and the ability to perform data fusion and network automation. Until recently there weren't enough sources to pursue this type of approach in space.

There are many architectural elements involved, starting with the on-orbit sensors and stretching all the way through the network and communications layers through analytical engines to the ground and ultimately the end user. In order to enable and grow all of the various elements of such an ecosystem, efficiencies and economies of scale need to also be exploited. Rapid development approaches as well as advanced design and manufacturing techniques, such as model-based design and testing, additive manufacturing, digital engineering, and agile software development methods will be required. Further, towing to the large number of elements within the architecture that will be required to be interoperable and integrated, standards and common interfaces will be essential to allow the various elements to work together effectively.

For data management needs within the ground segment, advanced secure cloud-based services will be essential to the synthesis of disparate data streams and the associated analysis and routing of large amounts of data. These technologies are developing sufficiently in the commercial sectors for the capabilities needed to create a robust HSA, but custom algorithms, standard interfaces, and unique applications will certainly be required to achieve a successful overall architecture.

The deployment and maintenance of the various elements of the HSA will also require a timely, robust launch capability. Fielding of new sensor packages with advanced capabilities obviously relies on the ability to place these new nodes into the appropriate operational space environment. Further, as on orbit assets fail or become obsolete, replacement spacecraft will be required to be launched and deployed. Because neither of these scenarios have predictable timelines, the ability to launch on demand becomes critical. Significant launch delays could result in diminished coverage or capabilities. However, in contrast to traditional single sensor packages, marginal losses of nodes in the HSA can be overcome with the redeployment or retasking of other deployed elements. Ultimately, the ability to rapidly launch and replenish on orbit assets introduces a key element of flexibility and agility and provides the HSA with the ability to quickly react to changing or unanticipated scenarios.

Partnership Challenges

HSA as a driver of a New Space ecosystem could shift the paradigm for a broad spectrum of traditional and nontraditional users. At the heart of the HSA is the ability to aggregate sources of information at different trust levels. Because of the rapid growth of unclassified, space-based information sources from commercial (U.S. and allied) there are many ways to ingest these products at varying trust levels to benefit both military and civilian missions. In some cases, they may merely highlight where a higher trusted source might look, or in other cases, they may ingest data from global science monitoring campaigns. Data and information aggregation can happen using multiple sensors across the full trust spectrum. Not all sensors would be required for the same action but they can inform decision-making based off the trust of the platform.

The ecosystem could change the paradigm for a broad spectrum of current and New Space users. To achieve this potential, however, these individuals/agencies will need to form new and strong relationships and partnerships with the commercial space industry. For traditional users, this will require a significant culture shift. DoD and Intelligence Community, in particular, are used to partnering with traditional large defense contractors to build and field specialized capabilities.

Another challenge for new users is that many do not have the knowledge and understanding of what it takes to field capabilities and operate in space that has typically been in domain of the traditional space. These new users will need to learn how to field a space-based capability and to develop the partnerships necessary to achieve their goals, or find commercial partners that can supply all or part of the necessary components. Today, there is no “one-stop shop” option for access to space. Chapter 5 discusses some approaches to make access to New Space capabilities easier in the future.

Aggregated stovepipe investments for traditional space have been shown to be more expensive than pivoting to the solutions offer by the HSA. These new approaches offer the potential to reduce costs, increase access, and add resiliency but they will require a willingness to partner with new providers and explore new approaches to providing the needed capabilities. The HSA approach is not precluded by current acquisition rules; however, there will be cultural challenges. Trust in new partners, the ability to experiment with new approaches, the willingness to be flexible, and a greater acceptance of risk will be required to take advantage of the New Space community as it rapidly evolves.

The HSA can lay the foundation to support government and commercial partnerships in a manner that will enable solutions to the challenges laid out above. The HSA will leverage advances coming from both the public sector and private industry, while creating underlying standards would aid new entrants into this field by reducing the required amount of infrastructure. A successful HSA will provide well-validated solutions to common mission development and operational challenges, as well as a community of experts, who can enable a long-term and sustainable ecosystem spanning civil, intelligence and defense interests. Commercial organizations need to realize the benefits of the HSA as it will define a common architecture into which they can design and produce products across broad agency areas of common interest. As no one entity will have the ability to develop and maintain the HSA partnerships will have to be formed, and agreements produced, to direct and sustain its usage, but given the scale and complexity of its objectives, it will necessarily rely upon the government and its resources.

GOVERNMENT AS ANCHOR TENANT FOR THE NEW ECOSYSTEM

For a broad spectrum of users to take full advantage of the capabilities that the new ecosystem offers, commercial companies will need government investments and sponsorship to grow what is currently a small wedge of business. While the commercial space industry is enjoying considerable private investment today, it will need reliable customers for the long term. The government will need to be one of the key customers of the capabilities offered by the envisioned space ecosystem. With government support, New Space companies can continue to flourish through PPPs, ensuring that the United States will maintain a lead in the commercial space economy. It will ensure that critically important government needs are met through cost-effective and resilient architectures of the New Space ecosystem and that the entire spectrum of users is able to access the capabilities provided by space systems.

CONCLUSION AND RECOMMENDATION

CONCLUSION: The Hybrid Space Architecture (HSA) shows great potential as a framework for a new space ecosystem integrating timely, traditional and New Space industries to deliver cost-effective and flexible space capabilities in support of a broad array of national missions and objectives. This ecosystem could enable the Office of Naval Research (ONR) to pursue both its technology demonstration initiative and its long-term applications.

RECOMMENDATION: The Office of Naval Research (ONR) should consider the Hybrid Space Architecture (HSA) framework as an opportunity to fulfil its long-term ocean science objectives. ONR should work with U.S. Space Force (USSF) to tailor its HSA-based approach to serve as a pilot program for other U.S. government and nongovernment users.[3]

[3] This recommendation was edited after release to the sponsor to direct it to ONR rather than the broader National Oceanographic Partnership Program. This clarifies that the recommendation is aimed at enabling ONR's long-term ocean science objectives.

4

Science and Applications

INTRODUCTION

The acquisition of new scientific data usually involves the development of new sensor and processing technologies. A key tenant of the Hybrid Space Architecture (HSA) is that the demand for new data will drive innovation, and broaden the spectrum of space technology, which allows entry of new players as part of the New Space ecosystem. As discussed in this chapter, and further examined in Chapter 5, a healthy and growing New Space ecosystem driven by the HSA and other government needs, when enabled by incentivized commercial partnerships, offers the potential benefits of lower cost and faster response at every level of the space system business. This ranges from basic parts to integrated systems as well as “bundles” including turnkey support all the way through launch services. A healthy SmallSat ecosystem will not only permit an increased pace of scientific development and exploration but will also open the door to new players, including nontraditional users, to populate the information layers within the architecture. Thus, there can be a natural synergy with mutual benefits between the HSA and enabled science stakeholder communities.

Science, until now, has generally relied on traditional mission-unique architectures to provide either a singular mission flight opportunity or aggregated sensors as part of a large dedicated mission. While some missions will still require a traditional system approach, SmallSats introduced through commercial opportunities and partnerships can provide more flight opportunities and faster access at lower cost for science applications. Advanced technologies and sensor innovations within on-going programs have demonstrated that high-quality data can be obtained in many applications at lower cost and faster cadence. Thus, a healthy and well-managed ecosystem will benefit the science user and allow ideas to more quickly and efficiently transition to deployed government or commercial constellations capable of collecting information required by national and local decision makers.

EMPLOYING SMALLSATS FOR EARTH OBSERVATION

Remote sensing of the Earth and of other planetary bodies is performed by satellites whose orbital characteristics differ with regard to the temporal, spatial, and spectral resolutions imposed by the mission objectives. As related in the 2016 National Academies report *Achieving Science with CubeSats*,[1] a LEO satellite provides high spatial resolution imaging but poor temporal coverage (unlike a geostationary satellite that provides diurnal—or better—temporal coverage but reduced spatial resolution). To date, most SmallSats in LEOs have been developed for technological development and surface imaging purposes rather than for scientific applications that require accurate and reliable calibration of the data products[2] but the situation has been evolving and growing on many commercial and technology fronts as illustrated in Figure 4.1 for the 2011–2020 time span.

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[1] National Academies of Sciences, Engineering, and Medicine, 2016, *Achieving Science with CubeSats: Thinking Inside the Box.* Washington, DC: The National Academies Press, doi:10.17226/23503.

[2] R.M. Millan et al., 2019, Small satellites for space science: A COSPAR scientific roadmap, *Advances in Space Research*, 64, 8,1466–1517.

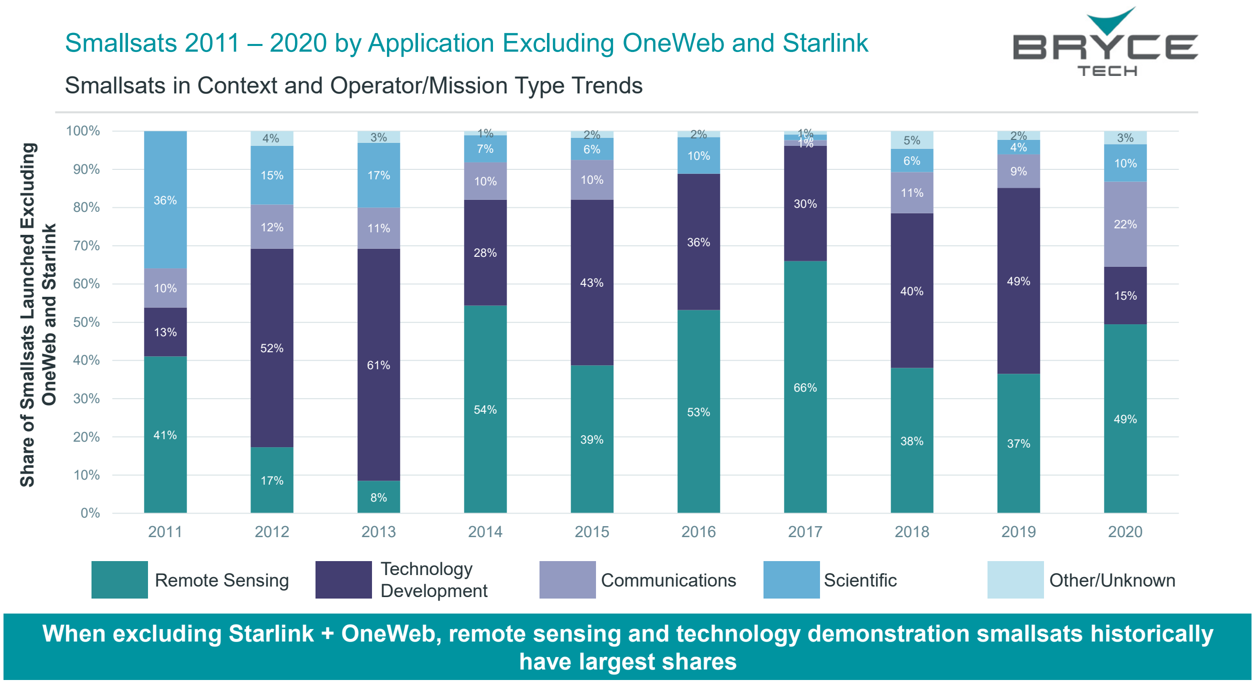

FIGURE 4.1 Number of SmallSats by application excluding the 126 SmallSats launched in 2019 and the 937 SmallSats launched in 2020 by Starlink and OneWeb as communication satellites. Of the 265 SmallSats launched in 2020 shown above, while only 10 percent are scientific, 49 percent perform remote sensing and are considered, in aggregate, to have similar potential to support science investigations. Remote sensing is expected to continue to be a growing segment. It is also expected that the science segment will grow with many applications that overlap between the two segments. SOURCE: Bryce Space and Technology, 2021, *SmallSats by the Numbers 2021*, BryceTech, Alexandria, VA, 2021, https://brycetech.com/reports.

Observing the Earth system and its evolution is a great challenge considering the multitude of processes occurring in the atmosphere, hydrosphere, biosphere, and solid Earth, and their complex mutual interactions on a broad range of spatial and temporal scales. For more than three decades, NASA and other space agencies worldwide have launched multiple large and small traditional space missions in different orbital inclinations and altitudes, carrying a large variety of instruments for monitoring weather patterns; atmospheric dynamics and composition; ocean circulation and sea state; climate change and variability; land and marine ecosystems; land use change; water; energy and carbon cycles; solid Earth rotation and deformations; gravity and magnetic fields; as well as other processes.

The contributions of all of these missions have been invaluable and fundamental to understanding the Earth system and its evolution under natural and anthropogenic force at an individual discipline science level and also at an integrated Earth system science level. The system science approach producing a diverse range of data products is becoming ever more important, especially to feed models developed to predict/project future changes and their associated societal impacts. Thus, the Earth science community is now positioned to fully benefit from the added data opportunities afforded by smaller, faster, and less-expensive missions based on advanced technology miniature sensors flown on SmallSats.

However, while the potential for a higher volume of SmallSat missions including constellations for science (in particular Earth and heliophysics science) is enormous and promising, it is recognized that they do not replace larger missions but rather complement them. SmallSat missions allow new approaches and new measurements that can be transitioned from conception to flight on shorter time scales. The potential benefits are substantial in many cases, owing tolower cost but also a faster and potentially broader scientific set of results, shorter development times, and more frequent mission opportunities combined with the capability of fielding satellite constellations.

All of the above are important benefits of SmallSat technology, but the ability to deploy multiple satellites either on the same orbit or in different orbital planes is a true game-changer by allowing observations with increased spatial and temporal coverage. Satellites in different orbital planes improve both the spatial coverage of the Earth surface and the frequency of data acquisition, while satellites in the same orbital plane essentially increase the temporal resolution. Closely spaced satellites also allow for the possibility of making nearly simultaneous measurements at multiple viewing geometries. Almost all areas of Earth science can benefit from such SmallSat constellations including weather forecasting, climate monitoring, detection and tracking of natural and human-induced disasters, water resources management, urban and coastal zones surveys, and so on. Several examples are discussed in the rest of this chapter.

Long-Term, Sustained Measurements for Climate Monitoring

SmallSats allow for new opportunities to reduce uncertainties in forecasting Earth's climate future through the use of multi-satellite constellations that are affordable, persistent, and upgradeable. The ability to launch up to hundreds of SmallSats over relatively short time periods, at reasonable cost, now means that data gaps common to traditional large, single spacecraft approaches, with multi-day revisit times, can be mitigated. While the impact of short revisit times with SmallSats is phenomenon-dependent, the true benefit of this approach is the ability to achieve accurate sustained measurements over long time periods. Using platforms that can support multiple instruments, or varying single instrument spacecraft with multiple instrument types, these approaches also allow for new products to be generated through data fusion techniques as well leading toward a capability that can help resolve long-standing questions in several fields of climate science. Furthermore, the technology used to sustain continuous observations introduces benefits for science including autonomous observation tasking, real-time data collection and analysis, large-scale satellite intercalibration to reduce aggregate measurement biases, and improvement of simulation models. This is particularly beneficial in oceanography, where the impact of rapidly changing phenomena (e.g., small eddy formation) can have a significant effect on longer-term processes (e.g., ocean circulation heat transport). As another example, constellations of SmallSats can provide more frequent sampling of extreme weather conditions. Frequent measurements of ocean surface winds and latent heat flux by the Cyclone Global Navigation Satellite System (CYGNSS) constellation prior to the rapid intensification phase of tropical cyclones can significantly improve the prediction of both their inner core wind structure[3] and their track.[4] More frequent measurements over land can also provide valuable predictive information. CYGNSS measurements of soil moisture are able to track sub-daily water cycle dynamics, which significantly improves global land surface models.[5] This is also true for many other areas in Earth observation, such as hydrology and coastal zone change monitoring.

[3] Cui, Z., Z. Pu, V. Tallapragada, R. Atlas, C. S. Ruf (2019). A Preliminary Impact Study of CYGNSS Ocean Surface Wind Speeds on Numerical Simulations of Hurricanes. Geophys. Res. Ltrs, DOI:10.1029/2019GL082236.

[4] M.J. Mueller, B. Annane, M. Leidner, L. Cucurull (2021). Impact of CYGNSS-Derived Winds on Tropical Cyclone Forecasts in a Global and Regional Model. Monthly Weather Review, DOI: 10.1175/MWR-D-21-0094.1.

[5] Kim, H., V. Lakshmi, Y. Kwon, S. V. Kumar (2021). First attempt of global-scale assimilation of subdaily scale soil moisture estimates from CYGNSS and SMAP into a land surface model. Environ. Res. Lett. DOI:10.1088/1748-9326/ac0ddf.

Improved Temporal Sampling

The revisit time provided by a SmallSat constellation in LEO will scale with the number of satellites (designated as "N" in this discussion), provided their orbits are properly phased. N satellites can revisit N-times more frequently than a single satellite reducing the 3-day revisit time typical of many medium swath width polar orbiting imagers to 3 hours with a constellation of 24 satellites. As a specific example, the mean revisit time for measurements by the Global Navigation Satellite System Reflectometry (GNSS-R) bistatic radar on a single SmallSat in the CYGNSS constellation is ~2 days. This is reduced to ~7 hours for the full constellation of 8 spacecraft.[6] The spatial coverage provided by a single spacecraft can be similarly improved upon with a constellation. The spatial coverage over time provided by CYGNSS is illustrated in Figure 4.2. Coverage by the full constellation over a single 95 minutes orbit is shown on the left and coverage over 24 hours. (about 15 orbits) is shown on the right. Notably, the dense daily spatial coverage includes multiple samples per day within ¼ × ¼ degree grid cells, with a mean time between samples of 7.2 hours.

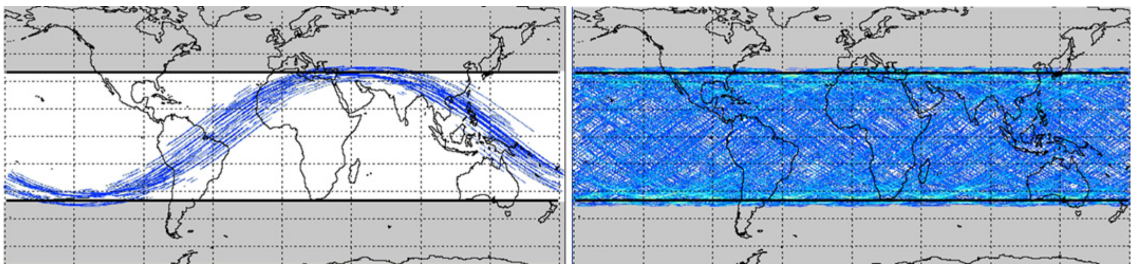

FIGURE 4.2 Spatial coverage provided by the 8-satellite CYGNSS constellation after 95 minutes, or one orbit (left) and after 24 hours (right). The mean revisit time of samples within its coverage range of +/– 38 degrees latitude is 7 hours. SOURCE: C. Ruf, P. Chang, M.P. Clarizia, S. Gleason, Z. Jelenak, J. Murray, M. Morris, S. et al. 2016,.*CYGNSS Handbook*, Ann Arbor, MI, Michigan Pub.

Rapid refresh, low revisit time measurements are necessary to resolve short time scale dynamics, e.g., extreme precipitation events, tropical cyclones, and flooding. While archival records of well-sampled extreme weather events can be useful for process studies and other retrospective analyses, there is significant value in the near real time availability of extreme weather observations for operational uses. Providing near real time data requires low data latency, the time between when an observation is made and when the data products generated with it are available to a data user. This requires the appropriate satellite-to-ground communication infrastructure. It is noteworthy that there are also low data latency needs with larger traditional space sensors observing both extreme weather and more typical weather conditions, and the supporting communication infrastructure, such as networks of ground stations, already exists. Two significant differences in the case of SmallSat constellations are (1) the number of satellites that would need to be supported by the ground network with a large-N constellation; and (2) the relatively limited uplink and downlink capabilities of a SmallSat's onboard data communication system (scientific sensors oftentimes do not reduce data in ways discussed in Chapter 3). In order to take full advantage of the unique temporal sampling capabilities of large constellations of Earth-observing SmallSats, it will be important for the communication infrastructure to be in place to support low data latency for near real time data delivery.

[6] See http://dx.doi.org/10.1175/BAMS-D-18-0337.1.

Faster Turnaround from Conception to Operational Flight Systems

The application of SmallSat technology to science applications not only directly benefits the science community but also allows a faster and more adaptive response to changing national priorities as well as evolving commercial sector capabilities. The commercial sector has been rapidly advancing capabilities to ease the transition of a broad segment of the scientific community to fly their own missions for application-specific purposes. It is now possible for a scientist to conceive and develop high-quality instruments for a measurement of interest, to work with commercial organizations to test and integrate the payload into a commercial SmallSat spacecraft bus, and to launch the mission in approximately 4 years and the expectation is that the development time will become even shorter as the ecosystem matures.

Many success stories exist today in Earth observation where high-quality measurements have been made. For example, the RainCube and Temporal Experiment for Storms and Tropical Systems Demonstration (TEMPEST-D) missions developed a Ka-band (35.75 GHz) precipitation radar and a 5-channel millimeter wave radiometer (89 to 182 GHz) for cloud and precipitation processes, respectively. Although these were both rapidly developed technology flight validation instruments, both missions successfully produced science measurements of high precision and quality from these platforms. They deployed from the International Space Station with a separation time allowing for coincident measurements to be performed and to produce new products through data fusion. Figure 4.3 shows one such product from Typhoon Trami on September 28, 2018, where the 165 GHz brightness temperature (horizontal) has been combined with the radar reflectively profile (vertical) producing a 3D perspective on the typhoon. This is an example of how such methods and techniques, once proven in space, can form the basis for large constellation measurements to address science questions of national priority

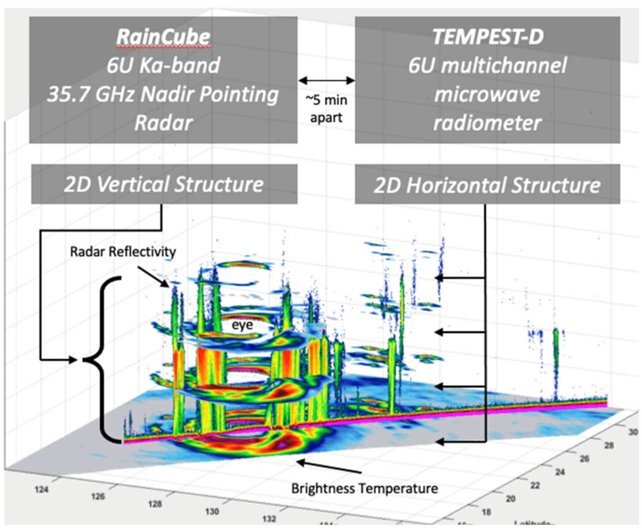

FIGURE 4.3 TEMPEST-D and RainCube Data. These missions image Typhoon Trami on September 28, 2018, from the International Space Station (ISS) orbit. This represents a new data product where the 5-channel radiometer measurements from the TEMPEST-D mission are fused with the Ka-Band vertical profile from the RainCube mission to provide a 3D view into Typhoon Trami. These spacecraft were deployed into a 51.6-degree inclination LEO orbit from the ISS with a separation of 5 minutes at time of image acquisition. The radiometer brightness temperatures and radar reflectivity capture the observed stratiform rain, ocean surface reflectivity, and convection in the vicinity of the eye of the typhoon. SOURCE: Jet Propulsion Laboratory, California Institute of Technology.

Missions such as TEMPEST-D and RainCube, sponsored by NASA's Earth Science Technology Office (ESTO), were developed under a program focused on validation of new sensor technologies where investigators worked toward mission requirements that would allow for opportunistic science. The products from such technology demonstration missions need not be limited to science investigations. Commercial organizations are now advancing the deployable radar antenna technology demonstrated on RainCube for future science measurements as well as nonscience applications where radar measurements can be applied to situational awareness, surveillance, and other areas. The recent selection by NASA of the Investigation of Convective Updrafts (INCUS) as an Earth Venture Mission (EVM-3) is such an example.

Government organizations are also increasingly looking to industry for data-buy opportunities where measurements of commercial interest can be utilized for science applications. NOAA operates a Commercial Weather Data Pilot (CWDP)[7] demonstration project tasked with evaluating commercial weather-related data products to assess their quality and potential impact (latency, quality, and reliability) on numerical weather forecast models. As part this demonstration in September of 2021, *Spire Global* received a contract from NOAA to purchase commercial radio occultation data for satellite weather data delivery. These data will be assimilated into numerical weather prediction models to reduce uncertainties in weather forecasting and will be shared with international meteorological organizations as well as the government.

ENABLING CAPABILITIES OF SMALLSAT CONSTELLATIONS

SmallSats Can Provide High-Quality Science Observations

Educational objectives with the goal of increased access to space drove many of the early CubeSat design approaches in what was originally a bottoms-up development paradigm. The decision to seek standardization had a major positive impact on the growth and success of CubeSats[8] with adoption of the concept of the standardized "U" unit of size, the partitioning of satellite sub-systems into U and ½-U stacked volumes resulting in a simple and consistently reproducible configuration. The ubiquity of the 3U CubeSat, and the development of standardized PPOD deployment interfaces, have been internationally embraced and have played a major role in the popularity of CubeSats as well as being the starting point of what we now call the New Space ecosystem.

Education-oriented missions still exist at universities and have grown significantly in number, but development of CubeSats and SmallSats by the private sector and federal government agencies has fundamentally shifted the focus of the missions and the complexity and quality of the scientific payloads they carry. Complete low-cost spacecraft are now available allowing the focus to be on the science payload. There is also significant payload technology development under way with an emphasis on reduced size, weight and power without compromising data quality.

This has increased the engagement of segments of the scientific community who previously worked only with large traditional space missions. Two examples of current private sector SmallSats delivering scientifically valuable measurements are the constellation of GNSS Radio Occultation (GNSS-RO) satellites flown by *Spire Global* and the *X-Band Synthetic Aperture Radar* (SAR) satellites flown by *Capella Space*.[9] *Spire Global* currently has approximately 100 operational CubeSats on orbit, most carrying GNSS-RO payloads. They produce integrated refractivity and propagation bending angle

[7] Contract Received by *Spire* Global From NOAA for Satellite Weather Data Delivery. Satnews, September 2, 2021. https://news.satnews.com/2021/09/02/contract-received-by-spire-global-from-noaa-for-satellite-weather-data-delivery/.

[8] SmallSats by the Numbers 2021. Bryce Space and Technology, BryceTech, Alexandria, VA, 2021, https://brycetech.com/reports.

[9] See http://www.capellaspace.com.

information from which atmospheric profiles of temperature and humidity can be derived. The quality of the *Spire Global* GNSS-RO data products has been assessed by the UK Met Office,[10] with a finding that its impact on forecast quality generally comparable to that of GNSS-RO measurements made by larger, traditional spacecraft. As a result, both the European Centre for Medium Range Weather Forecasting (ECMWF) and NASA's Commercial SmallSat Data Acquisition (CSDA) Program have both initiated data-buys for scientific purposes. In addition, a data quality evaluation effort is under way by NOAA's Commercial Weather Data Pilot (CWDP).[11] *Capella* launched its first SmallSat satellite carrying a SAR payload in 2020. It currently has three operating on orbit and have plans for more. It has publicly released data that demonstrates well-registered SAR images with ~50 cm spatial resolution.[12]

Similar examples of government funded CubeSats carrying high quality scientific payloads are the previously mentioned TEMPEST-D (Figure 4.4) and RainCube instruments. Both were launched in 2018 and have successfully demonstrated the quality and scientific value of their measurements. In the case of TEMPEST-D, scientists from the NASA Precipitation Measurement Mission (PMM) satellite intercalibration team were engaged to perform a similar data quality assessment as they do for large satellites that are part of the PMM constellation. Their results demonstrate comparable data quality for TEMPEST-D with regard to precision, calibration accuracy, and overall uncertainty.[13] Both the RainCube and TEMPEST-D science payloads are included in NASA's recent Earth Venture Mission-3 mission, INCUS, which consists of a constellation of three SmallSats. Notably, INCUS mission execution will be led by an academic institution, Colorado State University.

On a slightly larger scale, the CYGNSS mission is an example of a constellation of eight identical ~25 kg SmallSats in circular LEO orbit.[14,15] While government funded, the CYGNSS mission is also led by an academic institution, the University of Michigan, which had full control over all aspects of mission execution both pre- and post-launch. Each spacecraft carries a four-channel bistatic radar receiver tuned to measure GPS navigation signals scattered back into space from the Earth surface and the constellation has been operating continuously since March 2017.[16,17,18] Scattering from the ocean can determine surface wind speed,[19] sea level,[20] and ocean microplastic concentration.[21]

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[10] See https://doi.org/10.1002/qj.3872.

[11] See https://www.space.commerce.gov/wp-content/uploads/2020-06-cwdp-round-2-summary.pdf.

[12] See https://www.capellaspace.com/capella-unveils-worlds-highest-resolution-commercial-sar-imagery/.

[13] See doi:10.1109/TGRS.2020.3018999.

[14] Li, W., E. Cardellach, F. Fabra, S. Ribó, A. Rius, "Assessment of Spaceborne GNSS-R Ocean Altimetry Performance Using CYGNSS Mission Raw Data," Trans. Geosci. Remote Sens., doi: 10.1109/TGRS.2019.2936108, 2019.

[15] In a circular LEO orbit, using a satellite draft CYGNSS does not carry propulsion and maintains the satellite constellation spacing differential drag in the upper atmosphere.

[16] Ruf, C.S., C. Chew, T. Lang, M.G. Morris, K. Nave, A. Ridley, R. Balasubramaniam, "A New Paradigm in Earth Environmental Monitoring with the CYGNSS Small Satellite Constellation," Scientific Reports, doi: 10.1038/s41598-018-27127-4, 2018.

[17] Ruf, C. S., S. Asharaf, R. Balasubramaniam, S. Gleason, T. Lang, D. McKague, D. Twigg, D. Waliser, "In-Orbit Performance of the Constellation of CYGNSS Hurricane Satellites," Bull. Amer. Meteor. Soc., 2009-2023, doi: 10.1175/BAMS-D-18-0337.1, Oct. 2019,

[18] Li, W., E. Cardellach, F. Fabra, S. Ribó, A. Rius, "Assessment of Spaceborne GNSS-R Ocean Altimetry Performance Using CYGNSS Mission Raw Data," Trans. Geosci. Remote Sens., doi: 10.1109/TGRS.2019.2936108, 2019.

[19] Ruf, C.S., C. Chew, T. Lang, M.G. Morris, K. Nave, A. Ridley, R. Balasubramaniam, "A New Paradigm in Earth Environmental Monitoring with the CYGNSS Small Satellite Constellation," Scientific Reports, doi: 10.1038/s41598-018-27127-4, 2018]. Scattering from the ocean can determine surface wind speed (Ruf et al., 2019).

[20] Li, W., E. Cardellach, F. Fabra, S. Ribó, A. Rius, "Assessment of Spaceborne GNSS-R Ocean Altimetry Performance Using CYGNSS Mission Raw Data," Trans. Geosci. Remote Sens., doi: 10.1109/TGRS.2019.2936108, 2019.

[21] Evans, M. C., C. S. Ruf, "Towards the Detection and Imaging of Ocean Microplastics with a Spaceborne Radar," IEEE Trans. Geosci. Remote Sens., doi: 10.1109/TGRS.2021.3081691, 2021.

With RainCube, its first light measurements of precipitation profiles verified scientific functionality (Figure 4.5)[22] and coincident measurements with TEMPEST-D during simultaneous overpasses of Hurricane Dorian have demonstrated that CubeSats can be viable tools for space-borne meteorology.[23]

Scattering from land can determine near-surface soil moisture[24] and scattering from inland water bodies allows the water boundaries to be mapped for flood inundation imaging,[25] river width and streamflow determination,[26] and the generation of wetland water masks under heavy vegetation.[27] An example CYGNSS land and inland water body image over the Amazon basin is shown in Figure 4.6.

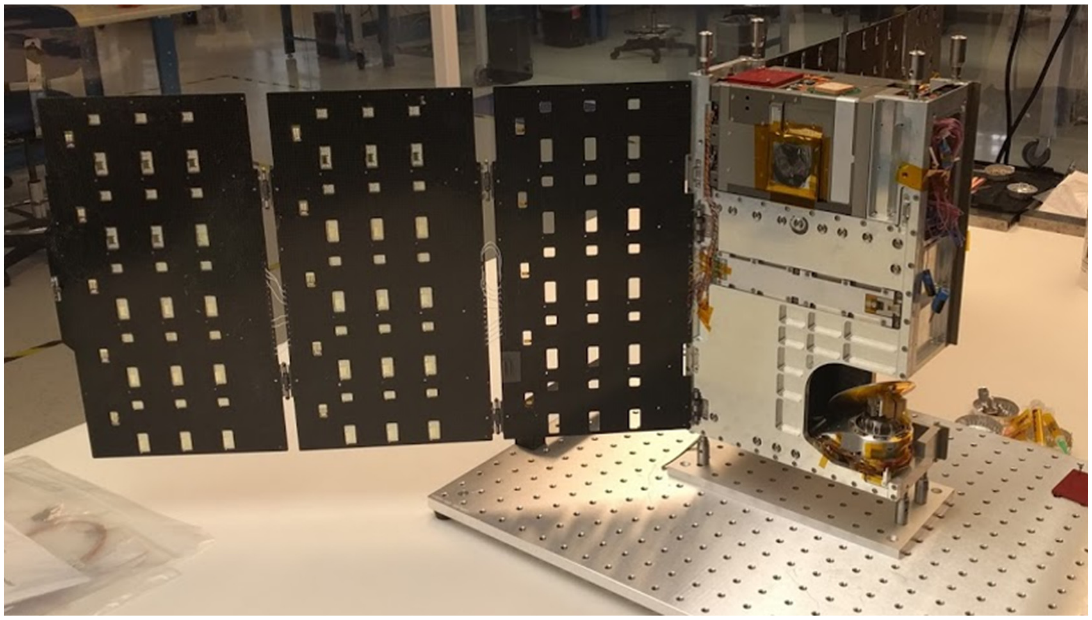

FIGURE 4.4 TEMPEST-D Instruments. Tempest-D flight model radiometer instrument and XB1 spacecraft bus for self-compatibility testing at BCT. SOURCE: TEMPEST-D Team, Colorado State University. Courtesy of TEMPEST-D collaboration.

[22] See doi: 10.1109/IGARSS.2019.8898687.

[23] See https://doi.org/10.1175/BAMS-D-19-0146.1.

[24] C. Chew and E. Small, 2020, Description of the UCAR/CU soil moisture product, *Remote Sensing*, doi: 10.3390/rs12101558.

[25] C. Chew, J.T. Reader, and E. Small, 2018, CYGNSS data map flood inundation during the 2017 Atlantic hurricane season, *Scientific Reports*, doi: 10.1038/s41598-018-27673-3.

[26] A. Warnock and C. Ruf, 2019, Response to variations in river flowrate by a spaceborne GNSS-R river width estimator," *Remote Sens.*, 11(20):2450, doi: 10.3390/rs11202450.

[27] C. Gerlein-Safdi and C. Ruf, 2019, A CYGNSS-based algorithm for the detection of inland waterbodies, *Geophys. Res. Ltrs.*, doi: 10.1029/2019GL085134.

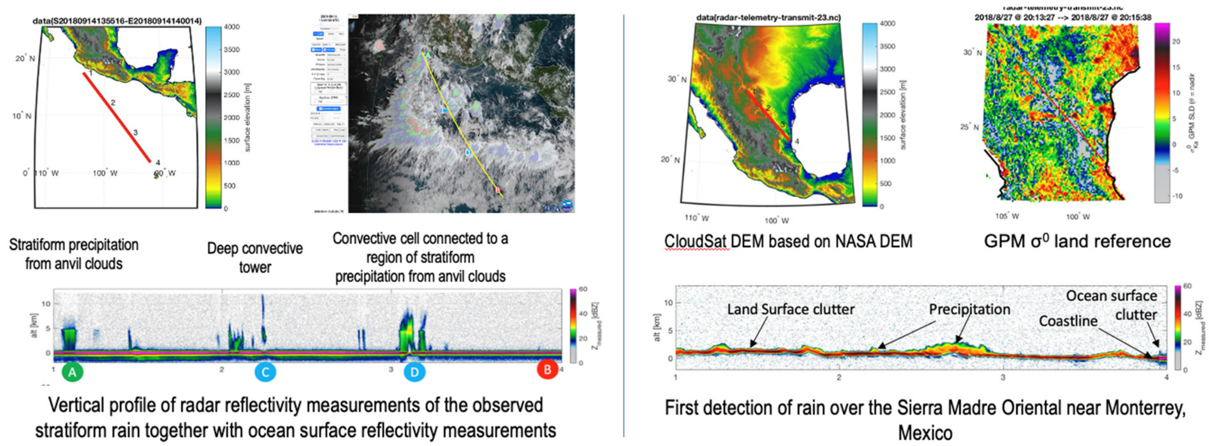

FIGURE 4.5 RainCube Ka-Band Data. RainCube's precipitation profiling radar first light showing detection of widespread oceanic stratiform rain, convective cell, and deep convective tower on September 14, 2018, off the south coast of Mexico and Guatemala (left) and first detection of rain over the Sierra Madre Oriental near Monterey, Mexico (right). Source: Jet Propulsion Laboratory, California Institute of Technology. SOURCE: Courtesy of NASA/JPL-Caltech.

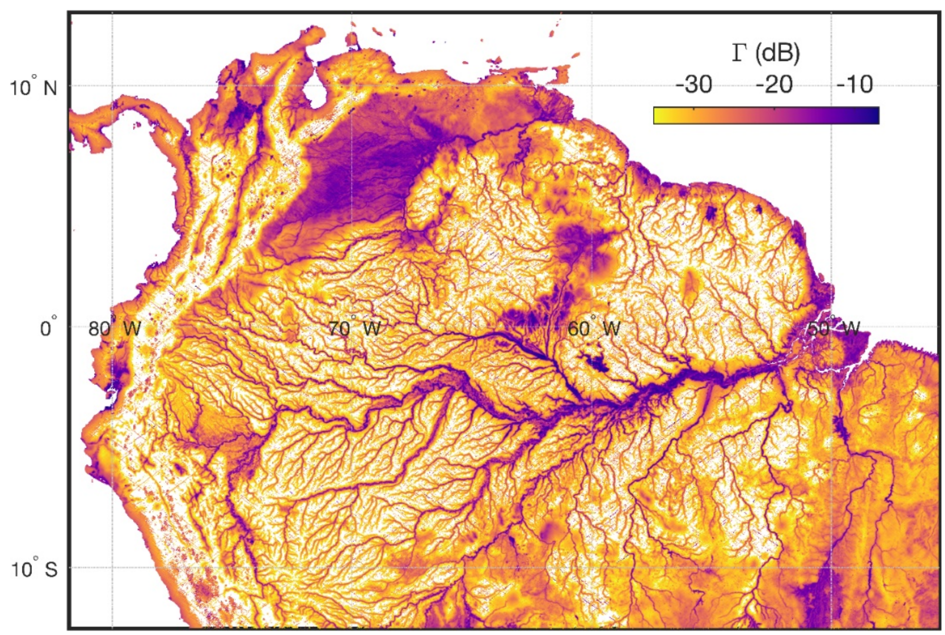

FIGURE 4.6 CYGNSS Image of the Amazon Basin Data over the period March to December 2017. CYGNSS measures reflected GPS signals and the scattering is enhanced by smooth water surfaces. This highlights the many Amazon River tributaries. Attenuation by the vegetation canopy is negligible in most areas. SOURCE: C.S. Ruf, C. Chew, T. Lang, M.G. Morris, K. Nave, A. Ridley, and R. Balasubramaniam, 2018, A new paradigm in Earth environmental monitoring with the CYGNSS small satellite constellation, *Scientific Reports*, doi: 10.1038/s41598-018-27127-4.

SMALLSAT TECHNOLOGY APPLIED TO SCIENTIFIC MISSIONS

Earth Science Applications

Oceanography

Oceans cover more than 70 percent of the Earth and have been an important focus of U.S. Navy, NOAA, and NASA, as well as nearly every space agency throughout the world for more than three decades. Numerous missions carrying a broad variety of increasingly sophisticated sensors routinely measure sea surface temperature, sea surface salinity, surface winds and waves, surface currents, sea ice, sea level, and ocean-color. These data allow improved knowledge of the role of the oceans on climate, on climate variability (e.g., El Niño Southern Oscillation [ENSO] events); climate change (e.g., the oceans store more than 90 percent of the anthropogenic heat accumulated in the climate system[28]); on the air-sea interactions and their impacts on weather and extreme events; and on short scale ocean dynamics, on marine ecosystems, and so on. Most of these data are assimilated in different kinds of ocean models for improved process understanding, forecasting purposes, and operational oceanography (i.e., estimates of 3-D ocean variables for current ocean state, short-range predictions and ocean re-analyses), benefiting marine industries, service providers, government agencies, as well as the science community.

The majority of the oceanographic missions to date have been medium-to large platforms with several sensors onboard such as the altimeter satellites of the Jason series which carry a radar altimeter plus a radiometer and tracking systems needed for the measuring sea surface height at the required 1 cm accuracy. For certain types of applications, however, SmallSats could satisfy many of the future needs in oceanography.[29] To study ocean phenomena, which can spatially and temporally change from hours to weeks/months, SmallSats offer near real time coverage of any area of the oceans can do so with multiple types of platforms. For example, satellites carrying different sensors can provide diverse observations of the same target, of particular relevance to monitoring vulnerable coastal zones changes under natural and anthropogenic forcing.[30,31] The wide variety of remote sensing modalities included on the NASA A-Train,[32] and the resulting breadth of scientific investigations they were able to support, are an excellent example of this. In addition, constellations of SmallSats in different orbital planes, similar to the GPS constellation, can provide permanent global coverage.

A specific example of a U.S. oceanography community is the NOPP, which represents the ocean interests of 19 government organizations, including the ONR, NOAA, NASA, and USGS.[33] NOPP may be a good model of how the science community can operate under the New Space ecosystem. Currently NOPP can be viewed as a cooperative association of common interests to pool resources and to promote common goals. Under joint ONR and NOAA leadership NOPP has developed nearly a dozen sophisticated sensors to measure coastal ocean parameters. These sensors will collect data to initialize prediction models and to support Navy operations. However, good science practice requires a test and evaluation process before those sensors can be fielded as part of an operational system. The advent of commercial organizations that have the capacity to offer affordable, precise, and repeatable testing, is

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[28] Dahlman and Lindsey, Climate Change: Ocean Heat Content. NOAA. August 17, 2020. https://www.climate.gov/news-features/understanding-climate/climate-change-ocean-heat-content.

[29] Guerra A.G.C., Francisco F., Villate J. Angelet F.A., Bertolami O. and Rajan K., On Small Satellites for Oceanography: A Survey, Acta Astronautica, 127, 404-423, https://doi.org/10.1016/j.actaastro.2016.06.007, 2016.

[30] Benveniste J. et al., Requirements for a Coastal Hazard Observing System, OceanObs'19 Community White Paper, Frontiers in Marine Science, 6, 348, 2019, DOI: 10.3389/fmars.2019.00348, 2019.

[31] Ponte R. et al.: Towards comprehensive observing and modeling systems for monitoring and predicting regional to coastal sea level, OceanObs'19 Community White Paper, Frontiers in Marine Science, 6, 437,2019, DOI: 10.3389/fmars.2019.00437, 2019.

[32] See https://atrain.nasa.gov/.

[33] See National Oceanographic Partnership Program—Promoting Partnerships for the Future of the Ocean, Coasts and Great Lakes (https://www.nopp.org/).

emerging as a means to reliably support such services at large-scale for the SmallSat instrument community.

Hydrology

For more than two decades, the hydrological science community has been using data provided by space-born sensors. Combined with hydrological modelling or used in isolation, they offer an alternative to the ground-based observations. This is especially valuable for developing nations where in situ networks are declining or are even nonexistent (e.g., in Africa). Different space-based observing systems have allowed measurements of the parameters of the terrestrial water balance, either directly (e.g., precipitation and water storage change) or indirectly (e.g., evapotranspiration and river runoff). Some traditional larger missions have been specifically designed for measuring these parameters (e.g., Tropical Rainfall Mapping Mission [TRMM] and Global Precipitation Measurement Mission [GPM] for precipitation and Gravity Recovery and Climate Experiment ([GRACE/GRACE-Follow On] for water storage change). It is also the case for soil moisture, another important hydrological parameter (e.g., Soil Moisture Active/Passive [SMAP] and Soil Moisture and Ocean Salinity [SMOS] missions). More recently, the CYGNSS constellation of SmallSats has also been shown able to measure soil moisture.[34] The more frequent, sub-daily, revisit time provided by the constellation has been shown to improve upon the multi-day temporal sampling by a single satellite when assimilated into a Land Surface Model.[35]

Evapotranspiration is not observed directly but is derived from different remote sensing techniques, in combination with modeling. This is also the case for river runoff. High-precision radar and laser satellite altimetry developed since the early 1990 to study ocean dynamics and climate-related sea level is now routinely used to monitor lakes and large river-level changes. River runoff can be derived from space-based river elevation via modeling approaches and/or calibration with in situ data but the coarse resolution of space observations greatly limits this application to large river systems. Moreover, the revisit time of current altimetry missions, of at best 10-days for the Jason mission series, does not match the desired daily or sub-daily temporal resolution required for river discharge estimates used for water resource management and flood forecasting.[36] One way of increasing this revisit time can be achieved by launching SmallSat constellations. For example, a constellation of 10 SmallSats in the same orbital plane of a 10-day repeat orbit, would allow a daily revisit time of a large number of rivers on Earth and a data latency of a few hours as needed for water resource management and water-related disasters forecasting. Such SmallSat constellations distributed through different orbital planes would also increase the spatial coverage toward a larger number of river systems and offer an invaluable complement to the upcoming wide-swath altimetry Surface Water and Ocean Topography (SWOT) mission (launch in 2022).

Atmosphere

Measurements of the atmosphere from space have, for decades, played a central role in the study of atmospheric physical processes, the detection of atmospheric gaseous and particulate composition, and

[34] H.V. Kim and V. Lakshmi, 2018, Use of Cyclone Global Navigation Satellite System (CyGNSS) observations for estimation of soil moisture, *Geophys. Res. Ltr.*, doi: 10.1029/2018GL078923; C. Chew and E. Small, 2020, Description of the UCAR/CU soil moisture product, *Remote Sensing*, doi: 10.3390/rs12101558.

[35] H. Kim, V. Lakshmi, Y. Kwon, and S.V. Kumar, 2021, First attempt of global-scale assimilation of subdaily scale soil moisture estimates from CYGNSS and SMAP into a land surface model, *Environ. Res. Lett.* 16(2021):074041, doi: 10.1088/1748-9326/ac0ddf].

[36] McCabe, M. F., M. Rodell, D. E. Alsdorf, D. G. Miralles, R. Uijlenhoet, W. Wagner, A. Lucieer, R. Houborg, N. E. C. Verhoest, T. E. Franz, J. Shi, H. Gao, E. F. Wood. The future of Earth observation in hydrology. Hydrol. Earth Syst. Sci., 21, 3879–3914, DOI: 10.5194/hess-21-3879-2017, 2017.

the monitoring of upwelling radiant energy spectra. Measurements of atmospheric profiles of temperature, humidity, liquid and ice clouds and precipitation, and of latent and sensible heat fluxes at the surface are regularly used operationally for numerical weather forecasting. Long-term measurements of many atmospheric state variables play a central role in the detection, characterization, and prediction of global and regional climate change. Observations of most of these atmospheric variables have been demonstrated by CubeSat and SmallSat payloads. Most mature among them are measurements made of atmospheric temperature and humidity profiles by constellations of GNSS-RO sensors.[37] Measurements of wind speed and of latent and sensible heat flux at the ocean surface have been made by constellations of GNSS-R sensors.[38] More recent measurements have been made by the TEMPEST-D millimeter wave spectrometer/imagers, the RainCube precipitation radar, and the Radiometer Assessment using Vertically Aligned Nanotubes (RAVAN) Earth radiance radiometer. Large N constellations of these SmallSat atmospheric sensors will significantly reduce the revisit time of global observations. This will provide improved initialization of numerical weather forecasts in support of scientific studies and will also allow short-term extreme weather events to be better tracked and imaged in support of situational awareness for disaster management.

Monitoring and Providing Operational Support for Natural and Human-Made Disasters

SmallSat constellations dedicated to surveying major disasters would be a ground-breaking application of this new technology, in ways that can serve Earth observation needs with extremely high societal relevance. For about two decades, space agencies and space system operators have implemented the International Disaster Charter[39] to provide high-resolution satellite imagery to civil security organizations and the United Nations to facilitate the implementation of field operations. As soon as a major disaster occurs anywhere on Earth the charter is activated. It consists of programming the acquisition of optical or radar images of the disaster area using all available in-orbit satellites. The detailed mapping of the impacted area and survivors' identification is crucial for rapid and efficient field rescue.

Natural hazards, "such as earthquakes, volcanic eruptions, tsunamis, wildfires and hydro-meteorological extremes (e.g., cyclones, floods, storm surges, landslides triggered by heavy rainfall or floods, heat waves and droughts)" as well as human-made hazards (e.g., air and sea pollution) have strong negative effects on the environment and human societies. Hydro-meteorological hazards are the most frequent disasters and are intensifying with time as a result of climate change and related global warming. Satellite observations are "increasingly used to support disaster monitoring, mitigation, adaptation, and risk management. The space-based observing systems have several advantages compared to in situ networks. Since they are not affected by the hazards occurring at the surface of the Earth," space-based observing systems provide important advantages compared to in situ networks. They collect consistent data over different special and temporal scales and provide important information on dangerous and/or remote areas. The satellite observations provide a synoptic view of natural hazards, allowing improved

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[37] N.E. Bowler, 2020, An assessment of GNSS radio occultation data produced by Spire, *Quarterly. J. Royal Meteo. Soc.*, 146(733):3772–3788, doi: 10.1002/qj.3872.

[38] C. Ruf, S. Gleason, and D.S. McKague, 2018, Assessment of CYGNSS wind speed retrieval uncertainty," *IEEE J. Sel. Topics Appl. Earth Obs. Remote Sens.*, doi: 10.1109/JSTARS.2018.2825948; J.A. Crespo, D.J. Posselt, and S. Asharaf, 2019, CYGNSS surface heat flux product development, *Remote Sens.*, doi: 10.3390/rs11192294; Z. Cui, Z. Pu, V. Tallapragada, R. Atlas, and C.S. Ruf, 2019, A preliminary impact study of CYGNSS ocean surface wind speeds on numerical simulations of hurricanes, *Geophys. Res. Ltrs.*, doi: 10.1029/2019GL082236.

[39] See https://disasterscharter.org/.

understanding of the underlying processes and their complex interactions, as well as of their associated risks.[40]

BENEFITING FROM INTERNATIONAL OPPORTUNITIES

The New Space ecosystem can be considered to have worldwide impact. Of the 2,972 SmallSats operated worldwide from 2011 to 2020 United States operators, including *SpaceX*, have led the way with 68 percent of these missions. The next largest single operator of SmallSats is China at 8 percent, followed by the UK, Japan, Russia, and Germany with percentages ranging from 2 to 4 percent.

As part of its future Earth observation program, the European Space Agency (ESA) has recently developed a new initiative called ‘Scout’ consisting of SmallSats that add scientific value to data from current larger missions of the ESA Earth Explorer program and the Copernicus Sentinel missions.[41]The objective is to demonstrate the capability of SmallSats to deliver value-added science, either by miniaturization of existing technologies or by developing new sensing techniques. The Scout missions consist of several small spacecraft orbiting in constellation, and developed within three years (from kick-off to launch) for a maximum cost of 30 million euros (budget including space and ground segments, launch and in orbit commissioning). Four mission concepts are currently under the study Earth System Processes Monitored in the Atmosphere by a Constellation of CubeSats[42] (ESP-MACCS) for measuring upper troposphere composition and aerosols, Hydrological Global Navigation Satellite System (HydroGNSS) dedicated to soil moisture, freeze/thaw cycle of permafrost, wetlands inundations and biomass; Twin Anthropogenic Greenhouse Gas Observers (TANGO) for monitoring methane and other greenhouse gas-emissions; and NanoMagSAT for measuring the Earth magnetic field and ionospheric environment.

The distribution of SmallSat launches across nations from 2011 to 2021 is examined in BryceTech (2021).[43] While the United States, Russia, India, and China have accounted for the large majority of launches worldwide throughout the decade, several trends are noteworthy. The percentage of launches in the United States has grown significantly, due primarily to the increasing number of commercial *Starlink* and *OneWeb* launches. In addition, over the past decade the percentage of Russian launches has generally decreased while the percentage of Indian and Chinese launches has increased. The Japan Aerospace Exploration Agency (JAXA) space agency and Japanese universities also develop technological demonstration satellites for both industry applications and natural disaster monitoring.

Evolving the Space Science Paradigm

Considering space science in the broadest sense as a source of data and information leading to knowledge, the goals of both traditional and nontraditional science programs are fundamentally aligned to the information-driven goals of the HSA. This alignment bodes well for science benefitting from a partnership within the HSA New Space operational framework. Chapter 5 will discuss options for how science users can best benefit from this partnership when considering the early current state of the ecosystem and then the maturing state as it evolves and grows and changes in response to government needs in combination with business pressures.

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[40] Excerpts of this paragraph are taken from Guest Editorial: International Space Science Institute (ISSI) Workshop on Geohazards and Risks Studied from Earth Observations, https://link.springer.com/article/10.1007/s10712-020-09617-1.

[41] See https://www.esa.int/Applications/Observing_the_Earth/Earth_observing_missions.

[42] See https://www.esa.int/ESA_Multimedia/Images/2020/11/ESP-MACCS.

[43] Bryce Space and Technology, 2021, *SmallSats by the Numbers 2021*, BryceTech, Alexandria, VA, https://brycetech.com/reports.

No matter how good this initial alignment seems the HSA will be the dominant government driver of the ecosystem. Sciences users will need to be creative, agile, and adaptive to the government-business partnership as it constantly adapts its contracting approach evolve over time to what will be divergent and convergent pressures driven by the HSA needs of the primary government users. Most of the infrastructure capabilities and processes required to sustain high-quality SmallSat constellation science measurements such as onboard processing capability, ground operational support, cybersecurity, supply chain security, safety and mission assurance, and interoperability standards, will run in parallel with those of the HSA (see Chapter 3).

Some required capabilities are unique to science measurements and will almost certainly evolve as the ecosystem grows and as the performance expectations become more demanding and specific. In particular, the introduction of methods allowing data to be shared openly with the international community will grow in importance as a means to manage the increasing number of on-orbit systems. In this regard, policies with associated agreements (both business and political) supporting international collaborations will be required when considering the potential to sustain flight measurements over a period of decades without loss of continuity in the data record.

There are also some measurements that are better suited for, if not only possible by, traditional large satellites that may not align perfectly with the HSA. One such class of measurements is those at sufficiently long electromagnetic wavelengths for which diffraction limited optics define the spatial resolution. Passive microwave radiometers and incoherent scatterometer radars are two examples. In such cases, very large apertures are required to provide adequate spatial resolution, and larger satellites can more readily accommodate them. There is significant technology development under way in the area of High Compaction Ratio (Mission Volume/Launch Volume) technology, especially in ultra-compact, deployable antennas, so this may become less of a limitation over time. A second class of measurements better suited to large satellites are those involving many different types of sensors observing the same volume of the atmosphere or area of the surface at the same time. Multi-frequency, multi-polarization, multi-look angle, active/passive, or other types of simultaneous measurements are extremely useful for constraining the allowable states of the observed body and for supporting fundamental process studies in Earth system science.

Yet even in this context, technology advancements continue in ways that science related business contracts will need to recognize and adapt. The Hyper-Angular Rainbow Polarimeter (HARP) CubeSat technology demonstration mission, sponsored by NASA ESTO, performed the first hyperangular cloudbow retrieval from space. HARP demonstrated the ability to characterize aerosol particles and measure "properties of cloud particles including their thermodynamic phase (ice or water) and the size of cloud water droplets."[44] This polarimeter instrument measures more than 120 unique viewing angles simultaneously through four visible wavelengths and three unique polarization states and represents a prototype for future designs that will be supported on larger spacecraft platforms (Figure 4.7).

A multi-sensor platform necessarily requires more size, weight, power, and data rate accommodation, making a larger satellite bus necessary. One attractive side benefit of the miniaturization of SmallSat sensors is that the required size of a "large" satellite capable of supporting many sensors has decreased significantly. Indeed, this strategy is being considered for future polarimeter SmallSat constellation designs that may carry multiple HARP-like instruments on a single, albeit smaller, spacecraft platform.

For some applications (e.g., measurement of sea level change at an accuracy of 0.5 mm/year or better) it is very challenging to use SmallSats. On the other hand, the use of SmallSats to measure some ocean variables is a real advantage (e.g., short-term forecasting via data assimilation in ocean models). Therefore, combining larger dedicated missions with SmallSat constellations is likely to be the optimal strategy to monitor the full range of processes occurring in the ocean.

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[44] From https://userpages.umbc.edu/~martins/laco/harp.htm.

FIGURE 4.7 HARP wide field-of-view imaging polarimeter CubeSat flight validation mission demonstrating multi-angle aerosol and cloud property measurements from space. This technology was matured from an airborne system into a space-borne version where a long data capture of 400 images over Lake Titicaca in South America were post-processed into a pushbroom image. Similar images taken by the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on the Aqua and Terra satellites are also shown confirming the atmospheric and land features seen in the HARP data. Lake Titicaca serves as an excellent clean air vicarious calibration source for this polarimetric imager given the lake's high altitude providing excellent visibility of the sun's reflection off the surface and polarization from to the atmosphere. SOURCE: HARP Team, University of Maryland Baltimore County. https://esi.umbc.edu/hyper-angular-rainbow-polarimeter/.

To summarize, in view of their shorter development phase, lower cost, increased temporal resolution, and other benefits, SmallSats are of growing relevance in various fields of the Earth sciences. However, they would not entirely replace larger missions owing to the inherent technical limitations that have been discussed. Thus, they need to be used for specific science applications, in complement with larger dedicated missions, or under conditions where they provide a unique measurement capability that a single large platform cannot perform. Fortunately, the business approaches discussed in Chapter 5 are amenable to supporting the HSA goals and can also be adapted in ways that can support both the HSA and science users.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSION: SmallSats are demonstrating their utility in national civil missions with respect to oceanography, meteorology, hydrology, disaster assessment, and other applications associated with the Earth sciences. When applicable, they complement traditional systems in the Hybrid Space Architecture (HSA) by offering increased temporal and spatial resolution and reduced planning cycles which permit rapid insertion of new technology over traditional approaches. It is expected that SmallSat technology and sensor capabilities, as well as related services, will expand in the future.

RECOMMENDATION: The U.S. government should actively position itself to take full advantage of the evolving and growing capabilities of the commercial space sector to serve the broadest spectrum of traditional and nontraditional users, with applications to oceanographic and coastal data as an initial effort to experiment with new process and procedures.

CONCLUSION: SmallSat mission partnerships between the U.S. government and academic institutions have produced high value/low-cost advancements in space science and technology including satellite platforms and payloads, ground segment communications, mission and payload operations, and science data product generation and distribution.

RECOMMENDATION: As part of its ongoing relationship with academic institutions the Office of Naval Research (ONR) should examine emerging advanced sensor and associated technology opportunities that benefit future ocean science objectives and missions.[45]

[45] This recommendation was edited after release to the sponsor to delete reference to the National Oceanographic Partnership Program. This clarifies that the committee is recommending that ONR take this step in support of its own objectives and missions.

5

Benefits and Challenges of New Business Models

INTRODUCTION

Government managers are faced with both opportunities and challenges in understanding the benefits of the commercial marketplace and how to best achieve/establish mutually acceptable “win-win” business arrangements. This chapter provides insight such arrangements, and discusses the benefits, challenges, and mitigations for using commercial commodity-based capabilities that are capable of meeting the unique needs of the HSA, while also being extensible to the needs of both traditional and nontraditional users.

As discussed in Chapters 3 and 4, the National Oceanographic Partnership Program (NOPP) can benefit from evolving government procurement practices that emphasize the use of commercially developed capabilities, such as those for the Hybrid Space Architecture (HSA), to meet government user space mission needs (see Appendix B). If properly structured and incentivized, there is the potential to develop and then expand a space ecosystem that will broaden the technological options for a large pool of both traditional and nontraditional government users. The nature of commercial services within a public-private partnership (PPP) contractual relationship is that a market needs to exist for such services outside of the unique government customer and, accordingly, the market sets the price for the service rather than the government “making the market”. If circumstances demand, however, commercial services can generally be customized to meet unique government customer needs at an added cost.

PPP business arrangements offer many options within existing Federal Acquisition Regulations (FAR), including contracting for a wide range of commercial space services and capabilities to enable data-buys, technology maturation, mission needs and operational support. In addressing ONR current and future needs for sensor technology demonstration and oceanographic science, the anchor tenant and commercial services models may offer the greatest potential benefit as they leverage accelerating commercial investment in the development of flight technology, ground systems and infrastructure.

The business relationship for a PPP can be either (1) a formal agreement between the government and a commercial capability provider to meet mission-specific government requirements, or to privatize existing multi-mission government capabilities or (2) a government procurement of commercially marketed capability such as data products, satellite buses, satellite components, or payload hosting.

New Space commercial growth has the potential to provide government managers with opportunities to leverage the private investment in these capabilities to meet their needs at a lower cost. However, there are also potential risks and challenges, both perceived and real, presented by a confusing array of commercial capabilities with various levels of maturity, reliability, unique tailoring, lack of flexibility and underlying business stability. Reciprocally, commercial providers and the investors in these companies in most cases find working with the government as a trusted partner in a commercial business arrangement to be equally challenging.

THE CHANGING COMMERCIAL LANDSCAPE

The established government organizational culture for space systems is generally oriented toward a low tolerance to risk, an approach tending to exclude nontraditional product and service acquisition practices as well as product-driven investment strategies that are common in the commercial space sector. It is understandable that government managers would be reluctant to put their program and high-priority missions at risk by dependence on a commercial resource, especially in places where the marketplace has many new players and is changing rapidly at a pace that is out of sync with traditional space procurement practices. In the early stages, the challenge was even greater with the emergence of commercial providers that, in many cases, were limited to one or two suppliers who were considered fragile at best and unproven and/or untrusted at worst.

Rapid and sustained growth in the commercial sector is dramatically changing this situation as a New Space ecosystem takes hold offering services from multiple providers competing in nearly every segment of the space business including commercial launch, SmallSat buses, and communications services. Commercial space practices are changing the procurement dynamic by allowing for multiple suppliers and competitive pricing for both individually purchased capabilities and through the bundling of such capabilities. The growth of the New Space ecosystem is mitigating many of the risks associated with commercial sources and opening the door to potential use of such systems for high priority missions. As the HSA has recognized, costs have fallen to the point that previously unaffordable approaches such as redundant satellites or a constellation of satellites may be an appropriate means of reducing mission risk. It is also becoming possible to implement multiple procurements covering a range of cost, capability and risk levels such that the aggregate outcome is better than a single large procurement, even if some elements fail.

On the business side, commercial providers typically develop capabilities as a commodity to address a broad range of customer needs in a very competitive marketplace. In many cases product pricing is based on having a production line of standard capabilities and/or delivering standard services with limited ability to customize or make late changes. Government managers on the other hand, have traditionally developed mission-unique capabilities, and in most cases, have cost reimbursable business arrangements to accommodate changes. Thus, in terms of cost and schedule, there can be real risk reduction benefits to working with commercial providers, to be traded against other risks such as sustained technical availability and having firm enough requirements early in the program development cycle to avoid costly scope changes.

For a PPP business arrangement to be successful and sustainable it needs to have a contract that protects both parties and enables equitable mitigation options to be exercised as needed to manage the partnership as it changes and evolves. A workable business relationship functions best when the customer requirements, the capabilities of the commercial provider/agency partner, and resource risks are fully understood, contractually recognized and accepted from both a benefit and risk perspective. Given the emerging commercial suppliers, one mitigation option would be to engage multiple sources for the commercial capabilities with the goal of reducing the availability risk while also ensuring competitive pricing.

Brokers can also play an important intermediary role in helping to forge partnerships between the public and private sectors. The role of these intermediaries can also be expanded to match the needs of a user (or users) to appropriate New Space commercial options and capabilities. For example, rapidly emerging commercial hardware/software technologies, satellite constellations, sensor hosting opportunities (on both free flyers and space stations), launch vehicles, ride shares, and operational support services, create a complex landscape where a trusted intermediary can be very valuable for identifying, characterizing, and accessing such capabilities. Thus, the use of brokers could greatly benefit government managers in the understanding and leveraging of these capabilities.

Although other business arrangements exist, historically there are three major models typically used for government engagement of commercial services specific to space acquisition: (1) privatization, (2) anchor tenant/agency partnerships, (3) commercial services and products. These are discussed below.

It should be noted that the below examples are not isolated cases but can be merged in different ways that benefit the government.

Privatization

Privatization, also referred to as "outsourcing," is a model where a private entity takes over government assets, provides service for the government as well as commercial customers resulting in a reduction of the government share of infrastructure overhead costs. Government initiatives to privatize and outsource launch capacity and communications services are part of a wide-ranging three-decade outsourcing trend across the government including DoD. Commercialization of the Delta and Atlas launch vehicles in the 1980's are an excellent privatization example where industry took over the government launch facilities, expanded services for non-government satellites, invested in upgrades and maintenance of these facilities, with the net result of reducing government space infrastructure costs. NASA's privatization of the Alaska Satellite Facility (ASF) is a second example, enabling non-government satellites to use these capabilities and the government to buy services as needed rather than pay full infrastructure and maintenance costs. NASA's experience using ASF and a few other commercial ground stations, provided a template to expand their use and attracted private investment by multiple providers in commercial ground stations. This successful transition led the way for the current use of commercial ground stations to provide the Near Earth Network (NEN) tracking and communications services currently supporting NASA and DoD missions in addition to a large customer base of commercial satellites.

Anchor Tenant/Agency Partnerships

In the anchor tenant/agency partnership model the government commits to buy or fund a significant amount of a private/partner agency developed capability and provides an upfront payment or funding commitment that is used to supplement and also possibly incentivize the partner investment. Data-buys, satellite in-orbit servicing, International Space Station crew and cargo delivery are examples where the government committed to, and in many cases made, advanced payment for products and services that supplemented private investment in the development of commercial capabilities aligned to government needs.

Anchor tenant/agency partnerships are not without challenges; both partners need to commit and then sustain that commitment. This is challenging, with the potential for the government to change priorities, or as in the example of the U.S. Air Force (USAF) Hosted Payload Service (HOPS) contract changes in leadership and commitment to using commercial services. The commercial partner has an equal challenge to develop a reliable capability and sustain a competitive position in the marketplace such that they remain a reliable provider to the government. As illustrated by the launch vehicles, ground station, imaging data-buys and International Space Station crew and cargo partnerships, these challenges are not insurmountable and, if recognized and addressed in the formation of the partnership, can provide a faster schedule combined with significant initial as well as operational cost savings.

Commercial Services, Products, and Data-Buys

This model of utilizes commercial services and products developed through private investment developing capabilities and providing services to the government as one of many customers. Growing engagement of the private investment community combined with increased demand by non-government customers is driving the New Space ecosystem in many new ways that are making products and services increasingly affordable. Direct procurement of Earth remote sensing data by the image from commercial sources is one such example. Advances in SmallSat technology combined with increasing demand for data by private corporations as well as state and local governments is driving significant growth in the number and capability of commercial Earth Remote Sensing satellites and opportunities for government data-buys. The NRO contract for subscription services for *Planet's* satellite and *Maxar's* Digital Globe imagery offers a similar example of meeting a government need with a data buy from commercially developed and operated satellites. Other commercial Earth remote sensing data sources such as *Spire Global's* weather and oceanographic data, and emerging Synthetic Aperture Radar/Multispectral Sensor constellations also offer the potential for meeting a subset of the oceanographic and Earth science data needs (discussed in Chapter 4) in a far more cost effective and timely manner than traditional methods.

In closing this discussion there are hybrid versions of the above acquisition approaches with the NASA data-buy for the *SeaWifS*, and the Commercial Resupply Services for Space Station provided by *SpaceX* and Northrop Grumman serving as such examples. These are anchor tenant contracts that created highly successful partnerships under a Space Act Agreement. In the case of *SeaWifS*, Orbital Sciences Corporation (OSC) leveraged the up-front payments for oceanographic data to be collected when the satellite was operational to offset their development private capital needs. *SeaWiFS* launched in 1997 and successfully provided oceanographic data for five years. The project was paid for by the upfront funding and remained operational for an additional seven years—providing both a continued data source for the global ocean biogeochemistry research community and a greater return on investment to OSC. Additional examples on the civil space side are NASA's Commercial SmallSat Data Acquisition program that buys data from providers such as *Spire Global* and *Planet*, and NOAA's Commercial Weather Data Pilot including *Geo Optics* and *Spire Global* data-buys.

Technology Development and Mission Services

For Standard Satellite Buses and Mission Services, the NASA Goddard Rapid Spacecraft Development Office[1] (RSDO) Rapid Spacecraft Catalogue was developed in the 1990's as a streamlined procurement vehicle. The RSDO successfully demonstrated that adapting payloads to leverage existing satellite bus designs, versus developing a mission-specific bus using traditional contracting mechanisms, provides both a significant cost and development timeline reduction. In addition to an enabling contract structure based on a competitive fixed price starting point, the RSDO office put into-place a mission design environment and engineering support tools for payload developers to use for both evaluation and selection of standard buses from the catalog. The *Rapid Spacecraft Catalogue* (current version is referred to as *Rapid IV)* while managed by NASA has been used by other agencies to successfully reduce the government development time and cost of missions. The first mission, launched in 1996, using the *Rapid Spacecraft* process was the Quick Total Ozone Mapping Spectrometer (TOMS) satellite, a replacement for the TOMS satellite; that was lost due to a launch vehicle failure. The replacement using a backup TOMS sensor was ready for launch about 13 months. Repositories of information, like this catalog and associated standardization approaches could help government stakeholders and also enable brokers who are working to forge PPPs to connect to resource offerings from commercial industry.

The original RSDO concept was developed to specifically support traditional government missions and, while a forerunner to the current New Space commercial paradigm, was not fully aligned to the reduced cost and schedule opportunities afforded by the emergence of multiple commercial satellite bus product lines. The recent inclusion in the latest *Rapid IV* catalog of emerging New Space commercial satellite bus product lines expands this concept by providing the opportunity for rapid and cost-effective platforms to support HSA objectives as well as NOPP and other government payload technology demonstration flights. Many of the commercial satellite bus providers also offer full mission integration and on-orbit operations services—further simplifying the technical and business arrangements needed to support payload technology development and operational mission needs. Some of these providers also

[1] See https://rsdo.gsfc.nasa.gov/about.html.

offer custom solutions based on commercial products and services. *Spire Global,* for example, provides CubeSat configurations, payload hosting, data, and cloud-based data analytics capabilities tailored to meet specific customer needs. *Rocket Lab* and *Loft Orbital* are also developing a complete payload to orbit service that in many cases is capable of integrating a customer's payload onto their standard bus, conducting systems tests, launches, and, if needed, providing mission operations services[2] and payload data delivery to the customer.

In addition to these services, there is the option for procuring standard components and payload hosting opportunities. The growth in the commercial satellite industry especially the large constellations has fueled commercial technology investments in mass production of star trackers, reaction wheels, magnetics, flight computers, GPS receivers, communications receivers/transmitters, propulsion and other subsystem capabilities that enable a reduction in cost and development time for both commercial and government "make your own" users.

The Government Accountability Office (GAO) found that "using commercial satellites to host government payloads may be one way DoD can achieve on-orbit capability faster and more affordably."[3] Commercial satellites, hosted payloads, the International Space Station, or one of the future commercial space stations, are consistent with the GAO finding and may provide faster and lower cost opportunities for payload technology demonstrations and operational missions. Similarly, a USAF Commercially Hosted Infrared Payload (CHIRP) was hosted on a SES-2 Communications Satellite and was estimated by GAO to save $300 million versus using a government satellite. As part of its Responsive Environmental Assessment Commercially Hosted (REACH) program, an *Iridium Next* launch in 2017 hosted 64 USAF operational sensors on 32 satellites that continuously monitor and measure radiation with the GAO estimate of savings at $230 Million over a dedicated USAF mission. The GAO also pointed out in their report that "DoD's use of commercial satellites to host defense payloads would benefit from centralizing data"[4] so that future procurements take full advantage of lessons learned.

This above discussion is an indicator of the potential offered by what is a dynamic and constantly changing New Space ecosystem offering a continuously evolving menu of commercial services that requires monitoring. NASA's October 2020 State-of-the-Art Small Spacecraft Technology report (NASA TP-2020- available 5008734)[5] provides insight into many of the existing capabilities of both privately and government funded commercially SmallSat component, buses, launch, and mission services available to meet government mission needs.

BENEFITS AND CHALLENGES OF NEW BUSINESS MODELS

The breadth of commercial capabilities is rapidly growing and evolving making it challenging for government program managers to gain information on their varying states of technical and business maturity needed to make cost-benefit trades against risk. Table 5.1 indicates the benefits and risks for a broad range of commercial capabilities and business arrangements to draw upon that could potentially satisfy government space program needs including needs related to oceanographic data collection and other science applications. The benefits to the government by employing commercial capabilities are very real. They reduce cost, schedule, and/or ensure technology currency but it is important to balance these benefits against the potential risks, which can be both real and perceived. The real risks are related to organizational practices, Intellectual Property (IP) rights and other factors unique to each partnership and the perceived risk are largely cultural.

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[2] Not all solutions are necessarily equal due to possible mission unique needs such as contamination, electromagnetic self-compatibility and other special requirements.

[3] See https://www.gao.gov/assets/gao-18-493.pdf.

[4] See GAO-18-493 (July 2018): https://www.gao.gov/assets/gao-18-493.pdf.

[5] See https://www.nasa.gov/sites/default/files/atoms/files/soa2020_final3.

TABLE 5.1 Benefits and Risks in Using Commercial Services

COMMERCIAL CAPABILITIES	BUSINESS ARRANGEMENT	POTENTIAL BENEFITS	CHALLENGES/RISKS	POTENTIAL MITIGATIONS
DATA-BUYS· (Earth Remote Sensing Data)	Government anchor tenant for buying data commercially developed new source(s)	• Government can specify requirements • Potential cost savings in the long term	• Delivery of less data or quality than paid	• Shared risk/cost benefit via contract terms
	Government buys from existing or new commercial source(s)	• Flattening the cost of acquiring data over time As needed buy of established and characterized source	• Orbit/spectrum/S/N etc. may not be optimum • Sensor/data calibration insight • Provider sustainability • Data transparency/open science	• Invest in tools to minimize impact and/or calibrate • Dual source
TECHNOLOGY DEVELOPMENT (Orbital Development Test and Validation)	Government buys Commercially Hosted Payload and Support Services on Free Flyer or a Space Station	Potential for significantly lower cost and risk for orbital test/validation and operational	• Coordination and matching of orbit/schedule/data security/accommodations/technical resources is difficult and where match found result may not be optimum • Host sustainability	• Ensuring government requirements are well defined, and potential providers' capabilities are well understood • Understanding potential host in mission conceptual phase to design payload to make optimum use of host capabilities • Cost/Risk/Benefit Tradeoff
	Government integrator buys commercially bus(s)	Potentially lower cost with potential for reduced schedule and technology risk	• Potential capability availability and/or reliability risk—rapidly becoming less of a challenge as commercial bus availability grows	
	Government buys commercial Bus/Payload Integration/Launch Service	Potentially lower cost with potential for reduced schedule and technology risk • Can be government payload team led	• Benefits and risks highly dependent on maturity of commercial capabilities, firm requirements and provider sustainability	
MISSION (Operational Mission Capabilities)	Government buys from commercial spec hardware production lines for government missions	Potentially lower cost with potential for reduced schedule and technology risk	• Design performance and qualification details in some cases treated as proprietary	• Mission risk posture and supplier contract specific agreements that provide government access to data can mitigate risks
	Government Integrator/ Operator and buys commercial Satellite Buses < 500kg Satellites and Constellations			
	Government buys commercial developed and	• Potentially lower cost with potential for reduced	• Stakeholder flexibility, understanding and	• Trade-offs of risk versus business arrangements

COMMERCIAL CAPABILITIES	BUSINESS ARRANGEMENT	POTENTIAL BENEFITS	CHALLENGES/RISKS	POTENTIAL MITIGATIONS
	operated Mission - Satellite or Constellation	schedule and technology risk • Potential for a Fee for Service business arrangement • Can be government payload/end user team led program	agreements of mission risk tolerance - Deployment schedule - Quality - Lifetime	pricing such as commercial terms where government pays for service or paying for additional insight into development
	Host government Operational Payload on a commercial Satellite/ Constellation	• Potentially lower cost with potential for reduced schedule and technology risk • Can be government payload/end user team led program	• Orbit / deployment schedule may not be optimum • Provider sustainability	• Dual source
SERVICES (Operational Services)	Government buys dedicated Launch	• Government controls orbit and launch date	• Higher cost –than rideshare	• The increasing number of launch providers may drive dedicated launch prices down over time.
	Government buys Shared Ride Launch	• Dependent on class of satellite, shared ride can be significantly lower cost than dedicated launch vehicle	• Finding a rideshare opportunity, compatible orbit and launch schedule needs, and managing on-time payload delivery schedules	• Mission flexibility of orbit and deployment schedule needed
	Government buys Ground Station Network services	• Fee for service business arrangement cost savings	• Provider sustainability • Potential Operational schedule conflicts	• Dual source
	Government buys Tracking/Collision Avoidance Services	• Fee for service business arrangement cost savings	• Provider sustainability	

While Congress has mandated its preference for commercial solutions where commercial services could meet mission needs, there is still insufficient incentive for the government manager to use commercial services or products. In the experience of the committee, although there has been a maturation of commercial services, many government managers still perceive that using commercial solutions as an unacceptable mission (and career) risk due to the lack of control over performance, quality and sustainability.

Historically, government space system development and mission management have pushed the technological and operational envelopes making cost reimbursable contracts the typical business arrangement to manage scope changes in requirements as the system design was development and matured. The emergence of New Space commercial providers for capabilities, such as a satellite bus, ground stations, data relay communications, and launch purchased as a fixed price commodity, opens the door to many potential benefits but also requires a change in development discipline, as scope and technical changes after contract signing can be impactful.

Challenges

Historically, space organization risk tolerance, culture, stability of needs/funding, and variations in service/product acquisition practices have made it more difficult for commercial providers to do business with the government. An essential goal of commercial business models is maximizing stakeholder return-on-investment. The New Space commercial industry is pursuing an increasing number of space-based systems applications, with business plans based on credible, but unvalidated, market demands. The commercial providers seek to find the optimum product and service mix that support the underlying differences in customer needs, at competitive price points and within an acceptable business risk tolerance. The typical model for achieving this is providing a set of standard products or service delivery models that take advantage of shared infrastructure and economies of scale that, based on customer capability, can be integrated to meet their specific need. Although this model appears attractive, injecting the government into the customer mix presents additional, but not insurmountable challenges for commercial providers.

Commercial Provider Performance

The current suite of commercial capabilities are provided by corporations that range from large and traditional, to small startups. The large amount of available private and investment funds are spawning new and innovative commercial space startups with innovative products and services at an unprecedented rate. Service sustainability is one of the more noteworthy risks when relying on innovative but inexperience commercial providers of space products and services. Retaining key personnel and the need to remain commercially competitive and are all part of the sustainability risk equation when considering the ability to meet government mission commitments. Although less of a risk with large companies, it clearly is a concern with startups who are trying to develop their business base and investment support. Thus, it is important in the current environment that government managers consider not only technical performance of commercial providers but also the business viability risk. On the positive side, multiple commercial providers are emerging for most products and services that allows for dual source options to be considered in the commercial sourcing decision process

Government Customer Culture

Few, if any, legislative or regulatory mandates or prohibitions impede government from the procurement of commercial services. Congress currently mandates that agencies acquire commercial items when they are available to meet government needs. There is sufficient latitude within and outside of the FAR to provide contracting structures to support a long-term sustainable activity. The challenge is overcoming cultural and traditional processes that are not used to new ways of doing business. As discussed earlier in this chapter, the RSDO *Standard Bus Catalog* is a pioneering example *Rapid IV* catalog of space procurement strategies where the culture shift has begun, offering standard “Commercial off-the-shelf” components, buses, and service capabilities with the potential for reduced costs, controlled technology risk, and faster schedules to meet government space mission needs.

The transition from relying principally on a government controlled and managed capability to a hybrid of government and commercial capability or buying a complete commercial service is a major cultural shift and an evolving business model. Although government use of commercially available space capabilities is increasing, and has to-date enjoyed some major successes, challenges remain for providers attempting to meet the government’s needs while remaining competitive in the commercial marketplace, especially where price is dependent on efficiencies of scale.

Incorporating government unique requirements into design, production process control or services can potentially demand a significant amount of upfront effort impacting commercial competitiveness in terms of time to market as well as driving up the development and production/delivery cost. Commercial satellite buses and components are developed, optimized, and qualified to meet requirements driven by the market at a level of quality achieved at the lowest practical price point using adapted commercial and mass production processes. In this business model, it will be challenging to meet low volume mission-unique requirements or to supply unique services without incurring increases in overhead or production costs.

Government Requirements and Funding Stability

Stable funding facilitates agency efforts to fulfil their requirements. Unfortunately, experience teaches that agency priorities, approved budgets, program schedules, and leadership commitments to using commercial services are vulnerable to change. This challenge affects not only the government program managers but also the external supplier community, and especially, emerging commercial providers. Moreover, investors may be reluctant to support a business dependent upon revenue from potential government contracts, especially if it is limited to a few programs or a single agency's needs.

The ability of the government to follow through on initiatives and estimates of government revenues factored into business plans is a very real and heavily discounted risk by private investors. Familiarity with the history of federal procurement, and innumerable GAO reports, is a reminder that the government consistently underestimates the cost and schedule of major system developments although there are some counter examples discussed earlier such as where the USAF realized significant benefits for CHIRP and REACH.

Some programs have successfully emphasized the need for a close alignment between the different cultures coming together in partnership (e.g., commercial sector verses public sector), government mission needs, and commercial capabilities in order to be successful. For example, the USAF Hosted Payloads Solutions (HOPS) was a government/commercial provider relationship that did not live up to the expectations of the commercial partners or the sponsoring USAF program office and was discontinued after the initial 5 year contract. Based on a forecast of USAF stakeholders' requirements, 14 companies were selected to provide payload hosting services on the HOPS IDIQ-based contract. Post-award, no USAF payloads used the HOPS contracting vehicle; being attributed to shifting alignments between mission needs that reprioritized budgets and hosting opportunities. It was also the result of cultural mismatches between providers and program managers in combination with USAF Space Systems Command (SSC) leadership changes. Notably, both NOAA and NASA used HOPS to secure hosted payload opportunities. The HOPS paradigm is also consistent with ONR's desire for leveraging New Space capabilities across agencies. NOAA's Argos Advance Data Collection system used HOPS to develop a contract to be hosted on a General Atomics Orbital Test Platform and NASA used it for hosting the Tropospheric Emissions: Monitoring of Pollution (TEMPO) sensor on a *Maxar* geostationary communications satellite. As noted in the GAO reports for HOPS and CHIRP, if ONR decides to initiate a hosted payloads or in fact any multi-user PPP, it will be important to ensure cultural buy-in from the stakeholders together with consistent leadership guidance and recognition of potential funding challenges.

Contracting Mechanisms

Sufficient exists within and outside the FAR to enable contracting structures to support a long-term sustainable New Space activity driven by government needs. Culture change is difficult, and government users need to be open to consider alternatives to their traditional processes and embrace opportunities afforded by new ways of doing business. It is difficult to overstate the flexibility that federal agencies currently enjoy with regard to choosing acquisition strategies and contractual vehicles. The

Defense Acquisition University's (DAU's) Contracting Cone[6] offers a useful graphic with embedded descriptions of different contracting mechanisms. This tool is particularly helpful in demonstrating the breadth of options and highlighting innovative and evolving non-FAR-based options, such as other transactions authority (OTAs), a longstanding feature of the Space Act. The FAR and the Space Act Agreements provide the ability for the government to procure commercial products, data and services structured as partnerships, cooperative agreements, and commercial service procurement contracts.

OTAs, like the Space Enterprise Consortium (SPEC), allow the government to work with a qualified pool of commercial companies and academia to develop prototypes or research. This gives the government greater speed, flexibility, and access to a more diverse set of companies that might not be eligible or lack the experience to propose under traditional procurement contract solicitations. The OTA consortium acts as a "broker" to minimize barriers and to encourage partnering and collaboration on proposals that maximizes each company's strengths which benefits the government. In turn, the companies have access to the government to not only showcase their technologies or capabilities but also gain knowledge of future government mission needs.

Business arrangements within these structures can be tailored to meet specific government and commercial provider needs to serve a single agency or multiple agencies. They can support joint development of commercial capability using both the commercial provider and government technologies with appropriate intellectual property licensing agreements. They can also provide for government anchor tenant commercial service buys with either firm deliverables or IDIQ contracts. They can work with one provider, as was the case for *SeaWiFS*, or multiple providers, such as the USAF HOPS Hosted Payload contract and the NASA *Rapid Spacecraft Catalog*.

IDIQ contracts—particularly multiple award IDIQ's—currently dominate the federal procurement landscape. The growth and popularity of the multiple-award IDIQ contract since the 1990's is understandable. On a task-by-task basis, the government dramatically reduces its transaction costs and procurement lead times by only competing tasks among a pre-qualified pool of contractors within a specific market sector. Moreover, with the flexibility the agency enjoys to craft and negotiate tasks with its preferred vendor(s), the task negotiations process is streamlined because the "umbrella contract" or the IDIQ itself avoids the need to reinvent the contracting wheel for innumerable FAR-based terms and conditions.

Of course, the many benefits associated with adopting a more commercial approach to contracting are, in part, offset by (or balanced against) an alteration of the allocation of risk inherent in conventional FAR-based contracts. For example, commercial services contracting typically require the government to rely on contractors' existing quality assurance systems rather than a more conventional government inspection and testing regime. Moreover, the government sacrifices significant flexibility in managing its contractual relationships by giving up its familiar power to unilaterally modify its contracts. These trade-offs are further amplified when the government employs innovative, non-FAR contractual vehicles such as OTA's. Within this context, the FAR provides the capability to add contract clauses to address specific insight, reviews, and approvals to commercial contracts where the provider is open to these arrangements.

Training, expertise, and support are critical to agency experimentation with innovative contracting techniques. Government users are already experimenting with innovative contracting techniques such as the USAF AFWERX,[7] a nontraditional scheme to transition commercial capabilities to more rapidly fulfill government needs. There is also NASA's Entrepreneurs Challenge that invites entrepreneurs to compete for initial funding (up to $90,000) and then take part in follow-on activities awarded through its Small Business Innovative Research program.[8] Both of these approaches are attempts to more effectively engage commercial companies. They are also both experiments and it is too early to know if they will be successful. Even if they are not, the resulting lessons learned will be important in the

[6] See https://aaf.dau.edu/aaf/contracting-cone/.
[7] For more information see https://www.afwerx.af.mil.
[8] See https://www.nasa.gov/press-release/nasa-launches-entrepreneurs-challenge-to-identify-innovative-ideas.

design of follow-on efforts. Meanwhile they signal a willingness to industry that the government is committed to developing more agile and innovative procurement methods. For example, to the extent that innovative vehicles, such as OTA's, are not FAR-based contracts (and so are not constructed using the extensive suite of standard remedy-granting contract clauses found in FAR Subpart 52.2), the contracting parties' rights are negotiable. How these agreements address critical issues that allocate common risks, such as flexibility to modify the agreement, quality assurance, liability and insurance, and termination rights will dramatically alter the parties' relationship and the pricing of the services.

CONCLUDING THOUGHTS

The emergence and rapid expansion of the commercial space sector, with appropriate contract vehicles can serve the development of the HSA and also open the door to a growing ecosystem providing for the needs of government science as well as nontraditional users. There are sufficient provisions within the current FAR and contracting practices to support creative and mutually beneficial PPP's. Given the emergence of multiple providers for most commercial products and services along with the growing examples of real cost savings to the government, the mechanisms can be put in place to mitigate the potential risk of PPP's so that win-win outcomes are possible for all stakeholders.

DoD and the government civil space agencies are successfully using hosted payloads, Earth Remote Sensing constellation data-buys and commercial SmallSat technology that could also be used meet ONR technology development and mission data needs. For example, there are commercially available services to help ONR facilitate sensor demonstrations and space qualification using the International Space Station capabilities. In addition, PPP's for commercially high-repeat cycle constellations acquiring oceanographic data flying either ONR sensors or through data buys from sensors jointly defined, could meet both commercial market and ONR mission needs. The increasing commercial investment in these constellations provides another opportunity for ONR.

Examining and potentially using the current USSF, NRO, NASA, and NOAA contract vehicles or developing an ONR commercial contracting model that leverages lessons learned from these business models could be a good starting point to enable access to commercial data and technology. In addition, past partnerships, such as the HOPS may provide lessons learned in terms of leadership, cultural, and fiscal challenges toward building successful commercial partnerships.

It is clear that there are potentially significant cost and schedule benefits for the government, including NOPP, to leverage the HSA in concert with commercially developed capabilities to meet a wide range of technology, development, and operational requirements. The breadth and continued emergence of commercial capability offerings, make the understanding their suitability of creating effective partnerships a daunting task for government managers. On the other hand, the broad scope of the government civil and defense space programs, funding challenges, and organizational contracting practices present a reciprocal challenge for industry. A trusted agent can be a bridge between these two challenges. Having a trusted agent or broker establish a clearing house to maintain a "catalog" of available and emerging capabilities, and also emerging government needs, could significantly improve access to commercial capabilities for government managers and clarify the government market needs for commercial capabilities providers.

Finally, the New Space ecosystem envisioned in this report is a place where the creativity and innovation of the commercial space sector is enabled to grow and prosper but is also harnessed to provide important services of high value to the government. As discussed in this chapter, there are potentially significant cost and schedule benefits for the government, including NOPP, that are worth harnessing to leverage the HSA in concert with commercially developed capabilities to meet a wide range of technology, development, and operational requirements. While the breadth and continued emergence of commercial capability offerings make understanding their suitability for creating effective partnerships a potentially daunting challenge for government managers, the broad scope of the government civil and defense space programs, funding challenges, and organizational contracting practices present a reciprocal challenge for industry. The substantial potential benefits for the government and its commercial partners justify finding a way to bridge these challenges through a broker or some other acquisition approach capable of enabling a trusted partnership.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSION: The technical infrastructure required to support needed services in the New Space ecosystem currently exists or is expected to come into existence if actively enabled through expanding government procurement opportunities. However, the U.S. government space community's current and potential future exploitation of that infrastructure is impeded by lack of familiarity with existing technical capabilities as well as new capabilities evolving out of the rapid growth of the commercial space industry. In the case of the Office of Naval Research (ONR), space science procurement practices are artificially constrained by traditional approaches in ways that limit them from taking full advantage of available New Space opportunities related to the rapid demonstration of the ocean and coastal sensor technologies under development for the National Ocean Partnership Program (NOPP).

RECOMMENDATION: The Office of Naval Research (ONR) together with the National Oceanic and Atmospheric Administration (NOAA), as the joint managers of the National Ocean Partnership Program (NOPP), should explore the broad range of available contractual mechanisms that enable quicker deployment of commercial space capabilities in pursuit of the NOPP technology demonstration objectives. It should empower its acquisition workforce to take full advantage of the rapidly evolving commercial space system opportunities.

CONCLUSION: The federal procurement regime—both the statutory and regulatory schemes—provides sufficient flexibility to take advantage of the evolving commercial marketplace and employ innovative approaches such as public-private partnerships (PPP's) and other forms of contractual relationships including Other Transactions Authority [OTA] and Space Enterprise Consortium [SPEC].

RECOMMENDATION: The U.S. government should employ a full range of available contractual mechanisms and actively support the use of innovative business models required to fully engage with both the traditional space and New Space commercial industries. These include a range of options from public-private partnerships (PPPs) and commercial services contracts, as well as newer mid-tier acquisition options in the categories of rapid prototyping and rapid fielding.

CONCLUSION: Currently, no existing mechanism permits forecasting future government needs to proactively inform the commercial space sector such that it can focus and prioritize the direction of its future investments. The National Aeronautics and Space Administration's (NASA's) Rapid Spacecraft Development Office (RSDO) has addressed this forecasting problem related to indefinite delivery/indefinite quantity (IDIQ) satellite bus acquisitions through the development of its *Rapid Spacecraft Catalog* satellite catalogue.

RECOMMENDATION: The Office of Naval Research (ONR) should leverage the National Aeronautics and Space Administration's (NASA's) Rapid Spacecraft Catalog for their current needs and should also work with NASA's Rapid Spacecraft Development Office (RSDO) and the Air Force Research Laboratory's (AFRL's) AFWERX to incorporate their forecasted future needs.

CONCLUSION: The development and adoption of the Hybrid Space Architecture (HSA) framework offers a potential roadmap to establish the timeline of SmallSat system capabilities for national needs. However, the capacity for building SmallSat services can be accelerated by the alignment of commercial SmallSat capabilities to HSA needs—this would reduce the time needed to reach a fully capable space ecosystem. Similarly, market-driven forces and sustained government investment programs could also accelerate technology, infrastructure, and process support responsive to customer and community needs and requirements.

RECOMMENDATION: The U.S. government should incentivize private investment to achieve faster and more integrated outcomes through advanced acquisition strategies such as public-private partnerships (PPPs), establishing Indefinite Delivery Indefinite Quantity (IDIQ) contracts with commercial providers, and anchor tenancy where the government is a stable facilitator for achieving faster and more integrated outcomes.

CONCLUSION: The commercial space sector appears fully capable of meeting the ocean sensor technology demonstration flight and launch needs of the National Oceanographic Partnership Program (NOPP) as presented to the committee. Many of these capabilities are accessible to NOPP today, through a variety of contractual mechanisms. Furthermore, these capabilities are expected to grow and evolve in concert with HSA-driven U.S. Space Force (USSF) and other government procurements over the next five years keeping pace with the NOPP objectives.

RECOMMENDATION: Innovative procurement practices offer substantial benefits, both in cost and the pace of flight, to meet government, and specifically, National Oceanographic Partnership Program (NOPP) requirements. Depending on technology readiness and mission requirements, NOPP should consider the following options:

1. Engage nascent commercial broker capabilities to explore and form appropriate partnerships to match existing and emerging commercial capabilities to achieve desired technical outcomes;
2. Explore existing government programs and consortiums, such as the National Aeronautics and Space Administration (NASA) International Space Station or the Space Enterprise Consortium (SPEC), and other programs that support technology prototyping and rideshare opportunities consistent with desired space flight objectives;
3. Engage a Federally Funded Research and Development Center (FFRDC) or a similar impartial agent as a trusted intermediary between interested government and commercial business entities to identify appropriate PPP mechanisms and structure them to achieve a successful alignment of technical and procurement capabilities; and,
4. Similarly employ an FFRDC or similarly trusted agent to develop guidelines for technical and business engagement to actively bridge existing gaps and new gaps as they occur between government and industry.

6

Concluding Statement by the Committee

There are four core findings in this report from which the conclusions and recommendations derive in addressing the statement of task.

1. The tremendous growth in commercial space business activity over the past decade has fundamentally changed the landscape for development, opening new doors to the employment of space systems. A New Space ecosystem is rapidly evolving and will happen with or without government participation.
2. For military and intelligence programs, the initial phases of the Hybrid Space Architecture (HSA) represent a working framework for the government use of space to serve multiple information and intelligence needs. The HSA will ingest information from both traditional and nontraditional space system elements meaning that the government can substantially benefit from utilization of the growing commercial space ecosystem. Moreover, by taking a strategic approach to procurements the government can add vitality and focus to the ecosystem by providing growth opportunities and business vectors congruent with government needs.
3. Within the government, a broad set of both traditional and nontraditional users in both the military and civil space user community can greatly benefit from the growing New Space ecosystem. With appropriate training of government managers, incentives, and acquisition strategies it will be possible for all players to participate with faster and lower cost outcomes.
4. Consistent with the above 3 findings, ONR and NOAA as managers of NOPP, and the extended oceanographic science community stands to directly benefit through access to New Space opportunities. In the near term, the approaches discussed in this report open the door to rapid and lower cost technology demonstration flight opportunities. In the longer term, growth of the space ecosystem will also open the door to rapid access, constellations and other approaches capable of serving navy and other government applications.

This report arrives at the conjunction of user needs and business capabilities such that the future is hard to predict beyond seeing the commercial sector continue to explosively grow and evolve. Growth and sustained prosperity are not the same, however, so there is a place at the table for the government that needs to be both recognized and acted upon in ways that encourage growth serving the full and diverse range of national interests. Such an approach can be both direct through the acquisition process and also indirect through the implementation and adjudication of standards that open the door to greater commercial participation and greater interchangeability of services within the desired public-private marketplace.

The traditional government space architecture is typically mission-based and predicated on serving individual agency needs. With some notable exceptions involving multi-agency objectives, defense and intelligence-related missions generally occupy on one side of the user equation with civilian-related missions driven by NASA, NOAA and USGS on the other side. A mission-based architecture is characterized by long planning and investment cycles (typically more than 10 years), highly resilient and dependable satellites that are large and few-of-a-kind, large budgets, and a relatively small collection of large corporations to provide the needed systems. It is not an ecosystem in the sense of this report because it is not diverse and, while robust in a mission sense, it is not self-sustaining due to the asymmetry of continuing government investment without a matching level of business investment.

The burgeoning commercial space industry demonstrates that this traditional approach is not the only way to manage and grow the nation's space enterprise. Numerous companies, including a few large ones, have built impressive space capabilities in satellite construction, launch services, and associated infrastructure that are creating a multi-faceted and resilient space ecosystem. The nation can benefit by integrating traditional government-based capabilities with the commercial-based approach in ways that grow and sustain the larger ecosystem.

An important step in this direction is the HSA which is an information delivery system, capable of ingesting data from multiple platforms in ways that can supply coherent and relevant information to government decision makers. Although the initial intent of the HSA is to support traditional users, in particular the intelligence community and military missions, it is a flexible architecture fully capable of supporting a broad range of traditional and nontraditional government users. as well as non-government users. Thus, HSA opens an important door to utilization of the commercial space ecosystem that, if appropriately supported and incentivized, could not only benefit government users but also provide the same benefits for a broad range of nongovernment users such as universities, private foundations, and privately financed science.

Last, it is worth comparing the changing environment of space usage with the evolution of aviation over the past century. While aviation differs from space in many ways, the current aviation ecosystem benefits the nation by supporting a wide range of users, from corporations building large airliners to all sorts of mid-size and small companies building a variety of special airplanes and airframes. Moreover, aviation is experiencing its own exciting "New Aviation" transition between the growth of UAVs, autonomous systems, and electric means of air mobility. The associated ecosystem is undergoing growth and change, but its well-developed infrastructure and manufacturing base maintains a ready supply of parts, generates new systems and services, and promotes standards incorporated within a healthy commercial base that provides these services and capabilities at an affordable cost.

The following conclusions and recommendations are not presented in the order they appear in the report but are correlated with the five statement of task elements. This approach is intended provide useful and actionable advice in a way that benefits the broadest range of users and stakeholders.

Task 1: *What national missions might benefit in a substantial way from access to a small satellite data collection system and how might that mission depend on the frequency and geographic scope of the data collection? Those benefits might be defined broadly to include military, economic, scientific, educational, and environmental benefits.*

CONCLUSION: The Hybrid Space Architecture (HSA) shows great potential as a framework for a new space ecosystem integrating timely, traditional and New Space industries to deliver cost-effective and flexible space capabilities in support of a broad array of national missions and objectives. This ecosystem could enable the Office of Naval Research (ONR) to pursue both its technology demonstration initiative and its long-term applications.

RECOMMENDATION: The Office of Naval Research (ONR) should consider the Hybrid Space Architecture (HSA) framework as an opportunity to fulfil its long-term ocean science objectives. ONR should work with U.S. Space Force (USSF) to tailor its HSA-based approach to serve as a pilot program for other U.S. government and nongovernment users.[1]

[1] This recommendation was edited after release to the sponsor to direct it to ONR rather than the broader National Oceanographic Partnership Program. This clarifies that the recommendation is aimed at enabling ONR's long-term ocean science objectives.

CONCLUSION: SmallSats are demonstrating their utility in national civil missions with respect to oceanography, meteorology, hydrology, disaster assessment, and other applications associated with the Earth sciences. When applicable, they complement traditional systems in the Hybrid Space Architecture (HSA) by offering increased temporal and spatial resolution and reduced planning cycles which permit rapid insertion of new technology over traditional approaches. It is expected that SmallSat technology and sensor capabilities, as well as related services, will expand in the future.

RECOMMENDATION: The U.S. government should actively position itself to take full advantage of the evolving and growing capabilities of the commercial space sector to serve the broadest spectrum of traditional and nontraditional users, with applications to oceanographic and coastal data as an initial effort to experiment with new process and procedures.

Task 2: *What partnerships among industry, government, and academic institutions might be incentivized to develop the necessary space platform, system integration, launch, communications, test, data distribution, and maintenance functions?*

CONCLUSION: SmallSat mission partnerships between the U.S. government and academic institutions have produced high value/low-cost advancements in space science and technology including satellite platforms and payloads, ground segment communications, mission and payload operations, and science data product generation and distribution.

RECOMMENDATION: As part of its ongoing relationship with academic institutions the Office of Naval Research (ONR) should examine emerging advanced sensor and associated technology opportunities that benefit future ocean science objectives and missions.[2]

CONCLUSION: The commercial space industry's tremendous growth and rapid evolution have generated high-profile successes, and signs indicate that this trend will continue to accelerate. The U.S. government, including traditional governmental space users, could benefit greatly from less traditional relationships, such as public-private partnerships (PPPs) that enable the adoption of industry's technology and volume manufacturing capabilities.

RECOMMENDATION: The U.S. government should encourage the development of public-private partnerships (PPPs), potentially including anchor tenancies, to promote a new national space ecosystem supportive of industry, government, and academic objectives.

Task 3: *Is the existing infrastructure sufficient to support the needed space platform development and manufacture, system integration, launch, communications, test, data distribution, and maintenance functions? What infrastructure components should be enhanced or created in order to reduce the timeline from idea to on orbit? Infrastructure is broadly defined to include industrial manufacturing capability, space system support structures, and communication-information systems.*

CONCLUSION: Currently, no existing mechanism permits forecasting future government needs to proactively inform the commercial space sector such that it can focus and prioritize the direction of its

[2] This recommendation was edited after release to the sponsor to delete reference to the National Oceanographic Partnership Program. This clarifies that the committee is recommending that ONR take this step in support of its own objectives and missions.

future investments. The National Aeronautics and Space Administration's (NASA's) Rapid Spacecraft Development Office (RSDO) has addressed this forecasting problem related to indefinite delivery/indefinite quantity (IDIQ) satellite bus acquisitions through the development of its *Rapid Spacecraft Catalog* satellite catalogue.

RECOMMENDATION: The Office of Naval Research (ONR) should leverage the National Aeronautics and Space Administration's (NASA's) *Rapid Spacecraft Catalog* for their current needs and should also work with NASA's Rapid Spacecraft Development Office (RSDO) and the Air Force Research Laboratory's (AFRL's) AFWERX to incorporate their forecasted future needs.

CONCLUSION: Existing interoperability standards are primarily driven by traditional system constructs and impede the government's access to flexible and adaptable commercial services. The U.S. government and commercial stakeholders will increasingly rely more heavily upon integrated commercial services and advancing standards to establish a broad-based ecosystem enabling smoother transition paths among spacecraft development, payload integration, test, launch services, operations management, and data product production. Development and adoption of interoperability standards driven by unique commercial New Space needs and design practices for key systems will increase competition and enable efficient execution and management for a broad range of space mission and operational needs for current and future government users.

RECOMMENDATION: Key systems—those most appropriate for standards—should be jointly developed and actively managed to support the New Space public-private partnerships in way that promote the greatest acceptance and usage on future systems. Standards and best practices could be developed within organizations such as the Air Force Research Laboratory's (AFRL) AFWERX, National Aeronautics and Space Administration (NASA's) Small Spacecraft Systems Virtual Institute (SSSVI) and the Small Payload Rideshare Association (SPRSA) to facilitate the adoption of New Space business product capabilities.

CONCLUSION: The technical infrastructure required to support needed services in the New Space ecosystem currently exists or is expected to come into existence if actively enabled through expanding government procurement opportunities. However, the U.S. government space community's current and potential future exploitation of that infrastructure is impeded by lack of familiarity with existing technical capabilities as well as new capabilities evolving out of the rapid growth of the commercial space industry. In the case of the Office of Naval Research (ONR), space science procurement practices are artificially constrained by traditional approaches in ways that limit them from taking full advantage of available New Space opportunities related to the rapid demonstration of the ocean and coastal sensor technologies under development for the National Ocean Partnership Program (NOPP).

RECOMMENDATION: The Office of Naval Research (ONR) together with the National Oceanic and Atmospheric Administration (NOAA), as the joint managers of the National Ocean Partnership Program (NOPP), should explore the broad range of available contractual mechanisms that enable quicker deployment of commercial space capabilities in pursuit of the NOPP technology demonstration objectives. It should empower its acquisition workforce to take full advantage of the rapidly evolving commercial space system opportunities.

CONCLUSION: The federal procurement regime—both the statutory and regulatory schemes—provides sufficient flexibility to take advantage of the evolving commercial marketplace and employ innovative approaches such as public-private partnerships (PPP's) and other forms of contractual relationships including Other Transactions Authority [OTA] and Space Enterprise Consortium [SPEC].

RECOMMENDATION: The U.S. government should employ a full range of available contractual mechanisms and actively support the use of innovative business models required to fully engage with both the traditional space and New Space commercial industries. These include a range of options from public-private partnerships (PPPs) and commercial services contracts, as well as newer mid-tier acquisition options in the categories of rapid prototyping and rapid fielding.

Task 4: *What processes may be employed to enhance the technology development pipeline, standards development, and the identification and adoption of best practices?*

CONCLUSION: The rapid expansion of space systems and operations knowledge throughout the commercial space industry provides numerous opportunities for the Hybrid Space Architecture (HSA) and other U.S. government space initiatives. Clearly stated standards and best practices, in conjunction with procurement mechanisms that address and accelerate decision speed, address mission risk, and align incentives, would allow efficient U.S. government access to these new capabilities. Procurement mechanisms tailored to commercial business models could further support responsive schedules from initiative inception to on-orbit capability.

RECOMMENDATION: U.S. government procurement mechanisms should be tailored to embrace evolving commercial practices and appropriate standards to address and accelerate decision speed, management of mission risk, and alignment of incentives to rapidly enable government space initiatives.

CONCLUSION: A coordinated government effort to promote and oversee existing government programs, together with the exploitation of dual-use technologies (evolving out of the automotive, medical, gaming, and other industries) could enhance the existing technology pipeline and benefit all national space activities. The Air Force Research Laboratory's (AFRL's) AFWERX, National Aeronautics and Space Administration's (NASA's) Small Spacecraft Technology Program (SSTP), the government's Small Business Innovative Research (SBIR) program, and the government's Small Business Technology Transfer (STTR) program are the appropriate venues for such technology infusion and demonstration.

RECOMMENDATION: The Office of Naval Research (ONR) should take full advantage of opportunities for the infusion of dual-use technologies deriving from participation in existing government technology development programs such as the Air Force Research Laboratory's (AFRL's) AFWERX, the Small Spacecraft Technology Program (SSTP), the government's Small Business Innovative Research (SBIR) program, and the government's Small Business Technology Transfer (STTR) program.

Task 5: *What is the anticipated timeline for the development of the required technology, infrastructure, and processes that will enable the development of the desired satellite systems?*

CONCLUSION: The development and adoption of the Hybrid Space Architecture (HSA) framework offers a potential roadmap to establish the timeline of SmallSat system capabilities for national needs. However, the capacity for building SmallSat services can be accelerated by the alignment of commercial SmallSat capabilities to HSA needs—this would reduce the time needed to reach a fully capable space ecosystem. Similarly, market-driven forces and sustained government investment programs could also accelerate technology, infrastructure, and process support responsive to customer and community needs and requirements.

RECOMMENDATION: The U.S. government should incentivize private investment to achieve faster and more integrated outcomes through advanced acquisition strategies such as public-private partnerships (PPPs), establishing Indefinite Delivery Indefinite Quantity (IDIQ) contracts with commercial providers, and anchor tenancy where the government is a stable facilitator for achieving faster and more integrated outcomes.

CONCLUSION: The commercial space sector appears fully capable of meeting the ocean sensor technology demonstration flight and launch needs of the National Oceanographic Partnership Program (NOPP) as presented to the committee. Many of these capabilities are accessible to NOPP today, through a variety of contractual mechanisms. Furthermore, these capabilities are expected to grow and evolve in concert with HSA-driven U.S. Space Force (USSF) and other government procurements over the next five years keeping pace with the NOPP objectives.

RECOMMENDATION: Innovative procurement practices offer substantial benefits, both in cost and the pace of flight, to meet government, and specifically, National Oceanographic Partnership Program (NOPP) requirements. Depending on technology readiness and mission requirements, NOPP should consider the following options:

1. Engage nascent commercial broker capabilities to explore and form appropriate partnerships to match existing and emerging commercial capabilities to achieve desired technical outcomes;
2. Explore existing government programs and consortiums, such as the National Aeronautics and Space Administration (NASA) International Space Station or the Space Enterprise Consortium (SPEC), and other programs that support technology prototyping and rideshare opportunities consistent with desired space flight objectives;
3. Engage a Federally Funded Research and Development Center (FFRDC) or a similar impartial agent as a trusted intermediary between interested government and commercial business entities to identify appropriate PPP mechanisms and structure them to achieve a successful alignment of technical and procurement capabilities; and,
4. Similarly employ an FFRDC or similarly trusted agent to develop guidelines for technical and business engagement to actively bridge existing gaps and new gaps as they occur between government and industry.

Appendixes

A

Addressing the National Oceanographic Partnership Program Challenge of Conducting a Technology Demonstration

Following from the core findings discussed in Chapter 6, the advice in this appendix is based on three premises:

1. The commercial New Space business model is sound and will continue to grow in directions that will create a self-sustaining ecosystem that, with properly structured contract mechanisms can benefit both traditional and nontraditional government users.
2. The Hybrid Space Architecture (HSA) is foundational to future USSF space acquisitions and represents a driving need for space hardware large enough to make the government and important and ultimately an essential player within that ecosystem.
3. The growing ecosystem will be extensible such that it will provide opportunities for new users with innovative ideas residing both inside and outside of the government.

From the perspective of the statement of task, this report recognizes an existing space ecosystem capable of supporting most of ONR's current needs and also predicts a growing future space ecosystem capable of also supporting ONR's projected future needs. Based on the committee's work in preparing this report and their collective experience, the pursuit of HSA's allocation of system of system requirements across USSF, IC, commercial, and allies represents a legitimate way to cost share, build resiliency, and increase performance. Unfortunately, full benefits not likely to be realized within a timeframe capable of fully satisfying ONR's near term technology demonstration window. This estimate is based on the annual congressional budget cycle, assuming it takes another 3 years to sort out the differences in opinion amongst the current players and to secure the necessary funding for the HSA. It will likely take another 2 years to put procedures in place and to secure the funding needed to sufficiently influence the services available within the ecosystem.

Despite these constraints, the committee concludes that the technical capabilities exist today to be able to fly NOPP's sensors in a technical demonstration mode through free flying satellites, hosted payloads and/or other government Agency capabilities such as NASA's International Space Station. Given the current private investment interest and abundance of commercial SmallSat providers and operators, it is projected that the ecosystem will grow sufficiently that the National Oceanographic Partnership Program (NOPP) should readily be able to meet its projected future sensor flight needs through commercial providers of either single satellites or constellations. Just as the ecosystem will grow and evolve so will the contractual methods and types of products offered. Thus, the commercial partnership of the future is likely to be a hybrid in itself consisting of flying advance sensors provided through ONR, commercial turnkey approaches to fly and operate sensors and direct data-buys. The committee sees two challenges for ONR to accomplish this: (1) using systems engineering and management know-how to manage commercial suppliers in a rapidly evolving ecosystem, and (2) navigating the breadth of commercial offerings available within a few years, assuming the sensors could be ready.

ONR leadership commitment to an execution-focused team for facilitating between instrument projects and commercial and/or other government organizations, such as NASA for access to the International Space Station, would be a first step. As noted in this report, ONR's challenges are not unique especially in understanding the breadth and pedigree of the commercial industry capabilities. ONR as well as the rest of the government space organizations would benefit from something like a space Federally Funded Research and Development Center (FFRDC). There would also be significant value in regular facilitated government/industry engagements (conferences, pilot projects, etc.), both formal and informal, to foster better communication, standardization and understanding of capabilities—something ONR could lead. Another option would be a trusted commercial broker that maintained an up-to-date source of commercial capabilities and pedigree data, acting as a clearing house, that could potentially also be employed to broker services. As the HSA matures, a Space FFRDC and/or commercial broker services could also facilitate access to information and capabilities to be employed as part of the HSA.

B

Acronyms

AEHF	Advanced Extremely High Frequency
AFRL	Air Force Research Laboratory
AI	artificial intelligence
AIAA	American Institute of Aeronautics and Astronautic
ASF	Alaska Satellite Facility
B	Billion
CAIP	Capability and Affordability Improvement Program
CDS	CubeSat Design Specification
CHIRP	Commercially Hosted Infrared Payload
COTS	Commercial Orbital Transportation Services
CSDA	Commercial SmallSat Data Acquisition
CWDP	Commercial Weather Data Pilot
CYGNSS	Cyclone Global Navigation Satellite System
DAAC	digital active archive center
DARPA	Defense Advanced Research Projects Agency
DAU	Defense Acquisition University
DoD	Department of Defense
ECMWF	European Centre for Medium-Range Weather Forecasting
EMC	electromagnetic compatibility
EMI	electromagnetic interference
ENSO	El Niño–Southern Oscillation
ESA	European Space Agency
ESP-MACCS	Earth System Processes Monitored in the Atmosphere by a Constellation of CubeSats
ESTO	Earth Science Technology Office
FAR	Federal Acquisition Regulations
FFRDC	Federally Funded Research and Development Center
GAO	Government Accountability Office
GEO	geosynchronous earth orbit
GNSS-R	Global Navigation Satellite System Reflectometry
GNSS-RO	Global Navigation Satellite System Radio Occultation

GOES	Geostationary Operational Environmental Satellite
GPM	Global Precipitation Measurement
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
HARP	Hyper-Angular Rainbow Polarimeter
HOPS	Hosted Payloads Solutions
HSA	Hybrid Space Architecture
HydroGNSS	Hydrological Global Navigation Satellite System
IDIQ	Indefinite Delivery, Indefinite Quantity (contract)
IEEE	Institute of Electrical and Electronics Engineers
INCUS	Investigation of Convective Updrafts
IoT	Internet of Things
IP	Intellectual Property
IPO	initial public offering
ISR	intelligence, surveillance, and reconnaissance
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
KSAT	Kongsberg Satellite Services
LEO	low Earth orbit
ML	machine learning
MOCs	mission operation centers
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering, and Medicine
NEN	Near Earth Network
NOAA	National Oceanic and Atmospheric Administration
NOPP	National Oceanographic Partnership Program
NRE	Nonrecurring Engineering
NRO	National Reconnaissance Office
ONR	Office of Naval Research
OTA	other transactions authority
PMM	Precipitation Measurement Mission
PNT	positioning, navigation, and timing
PPOD	Poly Picosat Orbital Deployer
PPPs	public-private partnerships
R&D	research and development
REACH	Responsive Environmental Assessment Commercially Hosted
RGS	Remote Ground Station
RSDO	Rapid Spacecraft Development Office

S&T	science and technology
S3VI	Small Spacecraft Systems Virtual Institute
SAE	Society of Automotive Engineers
SAR	Synthetic Aperture Radar
SBIR	Small Business Innovative Research
SMAP	Soil Moisture Active Passive
SMD	Science Mission Directorate
SMOS	Soil Moisture and Ocean Salinity
SPAC	Special-Purpose Acquisition Company
SPEC	Space Enterprise Consortium
SPRSA	Small Payload Rideshare Association
SSC	Space Systems Command
SSCA	Small Spacecraft Coordination Activity
SSCG	Small Spacecraft Coordination Group
SSTP	Small Spacecraft Technology Program
STTR	Small Business Technology Transfer
SWOT	Surface Water and Ocean Topography
TANGO	Twin Anthropogenic Greenhouse Gas Observers
TEMPEST-D	Temporal Experiment for Storms and Tropical Systems Demonstration
TEMPO	Tropospheric Emissions: Monitoring of Pollution (sensor)
TOMS	Total Ozone Mapping Spectrometer (satellite)
TRMM	Tropical Rainfall Measuring Mission
UAV	unmanned aerial vehicle
USAF	U.S. Air Force
USGS	United States Geological Survey
USSF	United States Space Force
V&V	verification and validation