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Earth Science Mission Control Center
Enterprise Emerging Technology Study

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Abstract

The purpose of this study is to identify technologies that could have a significant impact on Earth Science Mission Control Centers (MCCs), and related mission operations when looking out at the 5-15 year horizon (through 2025). The potential benefits of the new technologies will be discussed, as well as the potential need for early research and development, prototyping, or analysis for these technologies. Representatives from four NASA Centers participated in this study – providing multiple viewpoints and mission backgrounds as the ideas were formulated.

Executive Summary

The Earth Science Technology Office (ESTO) conducted a study, which concluded in 2013, that looked at potential common approaches for Earth science mission operations systems supporting missions at multiple NASA Centers. The effort outlined characteristics of a potential Mission Control Center (MCC) enterprise architecture based on currently available technology and modern system design practices. A follow-up study was initiated in early 2014 to add detail to the initial study regarding the impact of emerging information technology, and incorporate more NASA-specific details. As this new study effort began, the study team felt that one needs to better understand the influencing trends affecting mission operations systems design decisions prior to developing new design paradigms. Technology advances represent only one aspect of the rapid change taking place in satellite ground systems and operations. The new study was then refined to focus on the technology and other trends, which will influence the future designs, and not on the system designs themselves. Factors affecting future system design and operations concepts were organized into the five “trending areas” listed here and discussed in more detail in Section 2 of the report.

1. Satellite/Mission Changes

Small satellites are changing the industry. Hosted payloads provide new access-to-space opportunities and coordinated payload and host operations. On-board and ground-based automation is changing how operators interact with their space systems, and the rate, volume and variety of data continues to increase.

2. Computing Technology

Virtualization and Cloud computing affect how we deploy systems, software-defined networking will allow rapid system reconfigurations. Remote access, the use of standards, advanced expert systems, the Internet of Things, and an ever-evolving need for increased security are all affecting how we must build future systems.

3. Architecture Approaches

The debate continues on the most appropriate use of reusable software, Commercial Off The Shelf (COTS), open source software, and mission-specific development approaches. Systems can be designed as combinations of heritage designs, open system approaches, service-enabled

capabilities, and enterprise concept. The need for all operations to be contained within a single physical facility is quickly changing.

4. Operations Concepts

Automation, cross-training, fleet operations, split mission/payload operations, service-based operations, and outsourced mission support are each creating new opportunities to develop new mission operations concepts.

5. Business Models

The traditional approach of a single mission developing its own MCC and staff is still common within NASA, but other approaches are becoming more practical. Multi-mission operations centers may share facilities; multi-mission fleet operations software and teams may share the costs across dissimilar missions. Moving to a broad enterprise approach enables many shared or common services. Outsourcing operations and hosted payload agreements also provide new options.

From the identified trends, the study team developed three future mission use cases and vision concepts addressing trends of significance to Earth science via hosted payloads, small satellites and remotely piloted aircraft. These scenarios are included in Section 3 to illustrate the potential impact of emerging technology on anticipated trends for new Earth science mission concepts.

Based on this follow-on study effort, the study team identified key principles and themes to consider in leveraging emerging technologies to evolve to an efficient and secure Earth science Mission Control Center Enterprise Architecture. These areas are overlapping but they represent the top themes that emerged from the study and should provide opportunities for continued analysis and investment to best benefit the future Earth science missions. The key principles are summarized here:

- **Approach the architecture as a system:** There are many, many factors that together should affect our final mission operations and system design decisions.
- **Use the best of the old and the new while reducing costs:** We cannot simply discard our current infrastructure and capabilities – we must plan to leverage our heritage and move deliberately towards our new goals taking advantage of new capabilities.
- **The only constant is change:** Work with changing technical capabilities to respond to the high rate of change in both space data systems requirements and operations concepts.
- **The architecture must be flexible across many domains:** New systems will combine aspects of multiple existing approaches used in a more versatile open-system approach that leverage appropriate new technologies.
- **Incentivize for new solutions:** Encourage the creation of new flexible systems to meet the growing breadth of common needs across our new missions.

The following represent the key themes that emerged from the study:

- **Lower cost and ubiquitous access:** Innovative MCC concepts and low operations costs can become mission-enabling criteria, especially combined with small satellite and hosted payloads.
- **Internet of Things:** Data from new internet-connected sources (space and ground-based sensors / equipment / facilities) will help inform mission operations planning and execution.
- **Use of Standards:** In-depth analysis and prototyping is necessary to influence and take full advantage of new standards in order to achieve low cost consistency across system development and operations.
- **Accounting for the Rate of Change:** Requirements, cost-points, technology, business models, and operations concepts are all changing rapidly – plan for continuing change.
- **Development of Use Cases:** Mission operations concepts captured in use case scenarios are effective in understanding needs and evaluating new MCC architecture requirements and technology investments.

The goals of the MCC Enterprise Architecture include 1) a common, robust baseline capability across mission operations, comprised of common services and tools to enable reuse and customization, and 2) an interoperable infrastructure enabling process virtualization, automation, and cyber security. The study team recommended three categories of actions to help ensure that the MCC systems continue to evolve and enable efficient, affordable and secure operations of future Earth science missions. They are expanded in Section 4 of the report and listed here:

1. Actively participate in mission operations “Community of Interest” activities to represent Earth science interests. The key benefit of a Community of Interest is to support collaboration, and share knowledge and strategies to address common mission operations challenges. HQ program management for mission operations needs to ensure that Earth science interests are well represented in Agency and international initiatives to address on-going needs to improve space mission operations. Topics of special interest to Earth science include emerging mission operations standards, especially for small satellite data standards, techniques for fleet management of satellite clusters, and system of frameworks concepts.
2. Invest in new technologies to benefit Earth science missions through improved mission operations concepts. A sustainable capability is needed to develop, evaluate and evolve new technologies that would uniquely benefit future Earth science missions’ ability to respond to mission and technology trends. Topics recommended for technology investment opportunities include advancing near real-time mission planning and sensor tasking (to capture transient events); developing expert tools for virtual operations; and techniques leveraging the Internet of Things into space and ground systems (where sensor connectivity will be pervasive).
3. Devise a capability for experimenting and validating advanced mission operations technologies and concepts. Testbeds are recommended for ground-based prototypes and on orbit resources (e.g., an ISS test payload, an end-of-life mission, or a dedicated small satellite). A testbed capability is needed to enable designers to upload and test new flight software or exercise new protocols. Mission planning teams could propose new capabilities, allowing a user to interact

with a live spacecraft without impacting basic spacecraft health. Technology challenges to mature mission operations concepts could be investigated within the recommended test environment, including demonstrating integrated Cloud services, exploring and validating cyber security strategies, rapidly configuring modular MCC components, prototyping a virtual Zero Footprint Control Center, and infusing mission operations improvements into spacecraft and instrument design.

In conclusion, the study team believes it is important to maintain an awareness of industry advancements, new business practices, and new challenges, while supporting Earth science mission teams in accomplishing science goals. The effort put into participating in mission operations strategy groups, tracking technology and promoting the need for NASA-wide collaboration for mission operations advances will help achieve the common goals of providing more science for the science operations community.

Table of Contents

Abstract.....	ii
Executive Summary.....	ii
1 Introduction	1
1.1 Background.....	1
1.2 Vision	1
1.3 Mission	1
1.4 Scope	1
1.5 Goals and Guiding Principles.....	2
1.6 Approach	3
1.7 Applicable Documents	4
1.8 Document Organization	4
2 ESD Ground System Mission Operations Trends.....	6
2.1 Satellite/Mission Changes.....	6
2.1.1 Small Satellites	6
2.1.2 Satellite Constellations.....	8
2.1.3 Satellite Networking.....	8
2.1.4 Commercial Hosted Payloads	9
2.1.5 Rapid Mission Development and Deployment	10
2.1.6 New Mission Types: Refuel, Repair, and Replenish to Extend or Repurpose Missions	10
2.1.7 Onboard Autonomous Tasking	11
2.1.8 Data Requirements	11
2.2 Computing Technology	13
2.2.1 Virtualization.....	13
2.2.2 Cloud Technology.....	15
2.2.3 Software Defined Networking	16
2.2.4 System Monitoring and Automation	17
2.2.5 Security	18
2.2.6 Standards	18

2.2.7	Internet of Things.....	19
2.2.8	Remote/Mobile Access	20
2.2.9	Delay-Tolerant Networking and Other Network Trends	20
2.2.10	Data Analytics	20
2.2.11	Device Consolidation.....	21
2.3	Architecture Approaches	21
2.3.1	Common Software Solutions	22
2.3.2	Increased Use of COTS and FOSS	23
2.3.3	Service-based Capabilities.....	23
2.3.4	Open System Architecture	24
2.3.5	Enterprise Architecture.....	24
2.3.6	“Zero Footprint” Control Center Architecture	24
2.3.7	Advances in System Development Tools and Processes	25
2.4	Operations Concepts.....	26
2.4.1	Changing Support Needs.....	27
2.4.2	Changing Personnel Roles.....	28
2.4.3	Changing Environment.....	29
2.5	Business Models.....	29
2.5.1	“One-Off” Solutions	30
2.5.2	Common Facility.....	31
2.5.3	Common Software	31
2.5.4	Multi-Mission, Incremental Addition.....	32
2.5.5	Multi-Mission Enterprise	32
2.5.6	Multi-Center Commonality Model.....	33
2.5.7	The European Budget Reduction Business Model	33
2.5.8	Outsource.....	33
2.5.9	Hosted Payload	34
3	Scenarios and Use Cases	35
3.1	Hosted Payload Scenario.....	35
3.2	Small Satellites Scenario.....	37
3.3	Airborne Science Locally and Remotely Piloted Vehicle Scenario.....	39

3.4	Use Case Gap Analysis.....	41
4	Summary of Findings.....	43
4.1	Study Findings	43
4.2	Study Recommendations	44
4.2.1	Mission Operations Community of Interest Participation	45
4.2.2	Technology Investments to Improve Earth Science Mission Operations	46
4.2.3	Capability to Experiment and Validate Advanced Mission Operations Concepts	47
Appendix A.	Acronyms	49

1 Introduction

1.1 Background

Advances in ground system technologies have the potential of lowering space mission ground data system development and operations costs, reducing schedules and enabling new operations concepts to increase science return. Many of the technologies exist today – but we need to be smart in how we apply them to our needs. We need to identify those trends for which early study or development funding could increase the likelihood of their use and benefit to our future mission efforts. This study effort extends the FY13 study and report (Ostroy and Slaton, 2013) that identified initial concepts for the future Earth Science Mission Control Center Enterprise. The established vision and mission statements provide the context for this follow on study.

1.2 Vision

A NASA Earth Science Mission Control Center (MCC) Enterprise Architecture, which enables the efficient and secure operations of all current and future NASA Earth Science missions, and enables the delivery of high value science products and mission operations services to Earth Science mission stakeholders, will be the standard operational configuration.

1.3 Mission

The mission of the NASA Earth Science MCC Enterprise Architecture is to provide a common, robust baseline capability to support the functionality and services common across Earth Science mission operations. Key architecture attributes include operational automation and processing virtualization to lower operating costs, an interoperable infrastructure (e.g., standards, network connectivity) to accommodate requirements / system diversity and change, and cyber security. The Enterprise Architecture will provide common services and tools based on open interfaces, and provide data, processes, and computing resources to enable reuse, upgrades, resource sharing, mission customization, and collaboration.

1.4 Scope

Gartner, Inc. has defined strategic technology as an existing technology “with potential for significant impact on the enterprise in the next three years.” (Gartner, Inc., 2013). A strategic technology may also be an “emerging technology” that can have a “significant market disruption in the next 5 years”. This study attempts to look at the existing and emerging technologies to anticipate their progression in the next 5 to 15 years. Technologies that require a long lead-time to invest in, adapt to, and incorporate will be identified for action. Other technologies that fall within the interest or realm of the mission operations center but are expected to advance regardless of early investment activities will be noted but not actively pursued. It is expected that these other technologies will emerge and evolve on their own with no assistance required from ESTO. However, they may indeed find themselves incorporated into or used by a MCC when appropriate to do so.

The primary area of study is the mission control center in the arena of Earth science missions and sensors and platform design that directly affects mission operations. The report recommendations are primarily directed to NASA managers for ESTO technology and the Earth Science Division mission operations. Related areas, including TDRSS and antenna technology, science data processing, algorithms, and big data were considered out of scope of this study.

1.5 Goals and Guiding Principles

Mission Operations are gaining more visibility as a key mission cost element.

- The NASA Technology Roadmap, TA11 (Shafto, 2012) notes that “Demand continues for ground systems which will plan more spacecraft activities with fewer commanding errors, provide scientists and engineers with more functionality, process and manage larger and more complex data more quickly, all while requiring fewer people to develop, deploy, operate and maintain them.”
- The NASA 2014 Technology Capabilities Assessment Team (TCAT) team effort has identified Mission Operations as a key NASA cost element and has completed an initial assessment of the Agency-wide capabilities. TCAT is bringing more visibility to mission operations at the NASA Agency-Level. The TCAT follow-on study team is tasked with considering long-term goals and approaches for more efficient mission operations across all NASA Centers.

The importance of mission operations and the goals of finding more efficient solutions are recognized by other U.S. space organizations and by the international community.

- The “National Defense Authorization Act for Fiscal Year 2014” authorizes appropriations for, among other things, “military activities of the Department of Defense”. Section 822 includes guidance for space programs and, specifically, for satellite control systems. It states:

“DEFENSE ACQUISITION PROGRAMS CONSTITUTING A SPACE PROGRAM. (a) In General.-As part of the certification required by section 2366b(a) of title 10, United States Code, before Milestone B approval of a space system, the milestone decision authority shall perform a business case analysis for any new or follow on satellite system using a dedicated control system instead of a shared control system.(b) Sunset.--No business case analysis is required to be performed under subsection (a) for any Milestone B approval of a space system after December 31, 2019.”

Which is to say: if a mission does not appropriate and implement a shared control system, it will need to justify the “dedicated,” i.e., stovepipe “control system”. Thus, the Department of Defense is providing incentives to procure and implement a shared control system from which it expects to derive a number of benefits.

- The European Space Agency has seen tremendous benefit from a “Common Core” of ground system software for use by all member countries and even their spacecraft manufacturers.

Other government agencies, if not already doing so, may follow suit. Could NASA be next? Would NASA's Earth Science Division be prepared to move to more common or service-based mission operations if a declaration was made similar to the one in the Defense Authorization Act? Are we already moving in that direction as a recognized efficient way to go?

The community is embracing the view that smarter and lower-cost ground data systems and operations result in lower overall mission costs and enable a greater emphasis on science. The guiding principles of this study are to identify trends to be considered or applied as we progress towards newer architectures and systems that:

- Create flexibility so as to:
 - Accommodate diversity rather than one-size fits all (i.e., provide options to choose from within a trade space that is constrained to a common baseline)
 - Allow for the continual evolution of capabilities without sacrificing the heritage architecture and capabilities
- Infuse extensibility so as to:
 - Increase the value of mission operations capabilities more than just reducing the initial implementation cost (e.g., to be able to extend mission life).
- Provide incentives to:
 - Leverage a common baseline rather than dictating standard solutions (i.e., encourage, enable and reward collaboration, sharing, leveraging best practices, while avoiding vendor and product lock-in)

1.6 Approach

The study was conducted by first identifying multiple factors affecting the ground systems and mission operations. A series of meetings were held with the members of the study team from NASA Ames Research Center, the Jet Propulsion Laboratory, the Langley Research Center, and Goddard Space Flight Center. Although the initial goal of the meetings was to create a list of potential new technologies that could benefit mission operations, it became clear that the potential for change in mission operations approaches comes from more than just technology. Over the next several years there is the potential for major changes in the area of requirements, business models, operations approaches, and more. For this study it was therefore decided to look at Earth Science Division ground system mission operations trends from the perspectives shown in Figure 1:

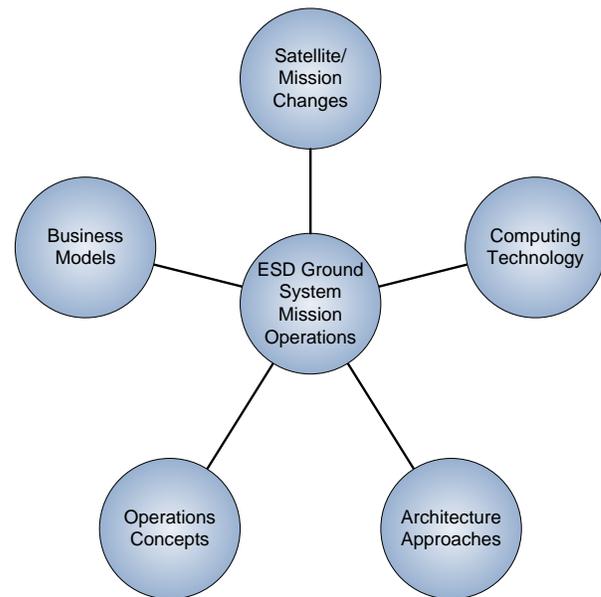


Figure 1 -- Technology and operational drivers influencing MCC design and evolution.

1. **Satellite/Mission Changes**
How is our mission set evolving? How are the functional requirements for future mission operations changing?
2. **Computing Technology**
What new technologies can be applied to our new mission operations system to reduce cost and risk or increase system capabilities?
3. **Architecture Approaches**
How should we assemble the parts for a broader mission operations capability in the future? Are common solutions, enterprise approaches, or stand-alone systems the best answer?
4. **Operations Concepts**
What new operations approaches may become viable as we have smarter and faster space and ground capabilities, fleets or satellite, and a pressing need to increase science data return?
5. **Business Models**
What new competitive business models are evolving as we look at smallsats, hosted payloads, commercial mission operations services, and creative system licensing?

Table 1-1 shows how these categories were expanded into specific topics for investigation.

1.7 Applicable Documents

- [1] J.H. Ostroy and B.K. Slaten, "Next Generation Enterprise NASA Earth Science Mission Control Center Architecture," Aerospace Corporation Report No. ATR-2013-00118, April 30, 2013.
- [2] Gartner, Inc., 2013. Gartner Identifies the Top 10 Strategic Technology Trends for 2014. <http://www.gartner.com/newsroom/id/2603623>, 8 October 2013.
- [3] "What Will 2022 Look Like? The IEEE CS 2022 Report," <http://www.computer.org/portal/web/computingnow/2022-Report> Feb. 2014.
- [4] "National Defense Authorization Act for Fiscal Year 2014," <http://www.gpo.gov/fdsys/pkg/CPRT-113HPRT86280/pdf/CPRT-113HPRT86280.pdf>.
- [5] M. Shafto et al., Modeling, Simulation, Information Technology & Processing Roadmap Technology Area 11, Section 2.2.4.5, p. TA11-24, April 2012, http://www.nasa.gov/sites/default/files/501321main_TA11-ID_rev4_NRC-wTASR.pdf.

1.8 Document Organization

Section 1 of this document provides the background, purpose, and forward-looking fundamentals on which the study was conducted. Section 2 examines the trends in various arenas from technology and architecture to mission operations and business models and discusses key high-priority areas for investigation. Section 3 provides several use-case scenarios to show how the use of these new

Table 1-1 Study Evaluation Parameter Space

Satellite/Mission Changes	
<ul style="list-style-type: none"> • Small Satellites • Satellite Constellations • Satellite Networking • Commercial Hosted Payloads 	<ul style="list-style-type: none"> • Rapid Mission Development & Deployment • New Mission Types • Onboard Autonomous Tasking • Mission Data Requirements
Computing Technology	
<ul style="list-style-type: none"> • Virtualization • Cloud Technology • Software Defined Networking • System Monitoring & Automation • Model-based Capabilities • Security 	<ul style="list-style-type: none"> • Standards • Internet of Things • Remote/Mobile Access • Disruption Tolerant Networking • Data Analytics • Device Consolidation
Architecture Approaches	
<ul style="list-style-type: none"> • Common Software Solutions • Use of COTS and FOSS • Service-based Capabilities • Open System Architecture 	<ul style="list-style-type: none"> • Enterprise Architecture • Zero Footprint Control Center • Advances in System Development Tools and Processes
Operations Concepts	
<ul style="list-style-type: none"> • Changing Support Needs • Changing Personnel Roles 	<ul style="list-style-type: none"> • Changing Environment
Business Models	
<ul style="list-style-type: none"> • One-Off Solutions • Common Facility • Common Software • Multi-mission, Incremental Addition • Multi-mission Enterprise 	<ul style="list-style-type: none"> • Multi-center Commonality • European Budget Reduction Business Model • Outsource • Hosted Payload

technologies could be applied to future mission concepts. Section 4 provides a summary of the findings, conclusions, and recommendations from this survey.

2 ESD Ground System Mission Operations Trends

To plan for the future of efficient mission operations, one must understand the evolving trends from multiple viewpoints ranging from mission requirements to technology to new operations concepts and business models. The following sections discuss trends as organized into the following categories:

1. Satellite/Mission Changes
2. Computing Technology
3. Architecture Approaches
4. Operations Concepts
5. Business Models

2.1 Satellite/Mission Changes

Advances in miniaturization, on-board computing capabilities, power, materials, and commercial involvement are rapidly changing what satellites and their payloads may look like in the coming years. The mission operations efforts may need to change dramatically to support the variety of space missions now being envisioned.

The following paragraphs highlight some of the important areas in which capabilities and requirements are evolving rapidly, including:

- Small satellites
- Satellite Constellations
- Satellite Networking
- Commercial Hosted Payloads
- Rapid Mission Development and Deployment
- New Mission Types: Refuel, Repair, and Replenishment
- Onboard Autonomous Tasking
- Mission Data Requirements

Table 2-1 shows why these missions were chosen and how we see them as disruptive in the current MCC environment.

2.1.1 Small Satellites

Small satellites (smallsats) are generally described as spacecraft with a total mass under 200 kg. There are a various common classes of small satellite from the femtosatellite with a mass in grams to a minisatellite with a mass approaching 100 kg. Cubesats are a specific realization in this class with masses generally on the order of 1 kg to 10 kg. The user community sees this class of satellite as a new opportunity to apply less sophisticated, less complex, and smaller-in-scope design configurations to address science data collection challenges in new ways with a considerable savings in terms of both cost and schedule. Additionally, fleets of small satellites can enable concepts not possible with one large

Table 2-1 - Evaluation Parameter Space for Satellite/Mission Changes

Study Case	Reason for Choice	Disruptive Nature
Small Satellites	Moving from academic demonstration to science and technology operational missions	Mission operations stressor due to mission cadence, comms and ops support stressor due to number of active satellites
Satellite Constellations	Government and private sector both designing satellite constellations for missions	Need to scale operations support from 10s of satellites to 100s of satellites
Satellite Networking	Satellite fleets being designed with cross communications capabilities	Flexible support drives the need for mission operational and data systems standards
Hosted Payloads	Commercial entities actively seeking to host science payloads to supplement normal business	Change to mission operations and data streaming models; government not in control of all data links and spacecraft bus
Rapid Mission Development & Deployment	Modular spacecraft as an architecture paradigm	Drives the need for MCC innovation and standards
New Mission Types	Satellites may be able to be revived and repurposed	Implies indefinite MCC support needs/repurposing
Onboard Autonomous Tasking	Migration of MCC functions to the spacecraft	MCC expert knowledge and decisions migrated to space
Data Requirements	New satellite/mission needs imply data systems support changes	Increased data volume, velocity, & variety; low-latency data product generation; data provenance & security

satellite. A small satellite fleet could be spread out spatially (sensors, instruments) and/or temporally for measurements and observations.

One key impact for mission operations and ground systems of having many small satellites is the area of data communications. The small satellites and ground stations need a new architecture to support an ever-increasing demand for data capacity despite the satellite bus being generally power-limited in its design. The possibility of having dozens of small, low-powered satellites all requesting the same expensive ground antenna resources at the same time is clearly problematic. Mission operations are affected because the scale of operational support can range from a single user with a laptop up to providing fleet management support for dozens or even hundreds of satellites and their sensors. The business model hinges on the satellites being cheaper to build, launch, and operate – and must assume that many smallsat missions are planned to last only several months and not up to a decade or more like some traditional satellite systems. Many smallsats may even be manufactured for future use, allowing for rapid configuration when needed, but also requiring new thoughts on operations concepts as satellites are put into operations on short notice or even launched and not immediately activated.

There is visible trend of a need for a satellite-to-ground and low-cost ground-to-ground mission architecture for single and constellations of small satellites, especially without swamping the resources for the traditional NASA ground networks. One vision for a future business model is to extend the Global Educational Network for Satellite Operations (GENSO) concept to a network of high-speed, interconnected ground stations that the satellite owner can subscribe to for services. Although much emphasis has been put on standardizing the various small satellite form-factors, we will be in trouble if we do not have consistent ways to recognize and process the data streams to and from the small satellites. Will these include the CCSDS telecommunications and operational recommendations? Will they be based on the traditional IP network standards, TDM, or something new? Picking several standards would be better than no standard. Could we even standardize (like Europe does) operational functions such as memory dumps, stored command loads, etc. to reduce operational overhead and complexity, especially when there is a relatively rapid cadence to small satellite missions? These types of standards will facilitate making ground services into commodity items with reduced cost and greater reliability and flexibility.

2.1.2 Satellite Constellations

The small satellite trend is enabling new concepts for satellite constellations. A satellite constellation is composed of a number of heterogeneous, homogenous, or ad hoc satellites operating under the same center or mission. Constellations are in operation today and are found in both the government-owned satellites such as TDRS and GPS and in private sector constellations providing telecommunications or imaging services. The future has the possibility of needing to scale the current fleets from tens of satellites to hundreds of satellites that need to be monitored and controlled. This includes both active satellites and satellites placed in holding orbits.

The technology challenges lie in the fleet management for clusters of satellites where the goal is to reduce the overhead and bring commonality to the NASA fleet through ground access scheduling, mixed public/private provider access, minimal scheduling overhead/real-time scheduling, leveraging public/private assets. Satellite users may demand more direct access to their data which could even lead to the concept of developing a dynamic spot market for ground station access and data connectivity.

2.1.3 Satellite Networking

Satellite networking can take on several variations that are not mutually exclusive domains but may be interconnected. Satellites may use inter-satellite communications to sustain data transmission within the members of the satellite cluster or constellation. Satellites may also utilize satellite networking between constellations of satellites. The simplest case is a network that involves communications with a single satellite through a space relay satellite. With satellite networking, satellites must route communications to/from the ground access point(s) to/from the targeted satellite with “routers” on the satellites. In this mode, sensors, instruments, and even the satellites themselves become addressable nodes on the integrated space/ground network. This effectively can make the intersatellite communications an extension of the Internet. The satellite network is not required to use Internet concepts as part of its internal telecommunications design and the internetworking can be sustained as a network of space communications satellites for satellite-to-satellite communications (a physical

internet in space) and satellite-to-ground communications. In this case, the satellites are analogous to a wire communications link without integrated networking support. For NASA, this raises the question of what will the next TDRS (or the next, next TDRS) require to make it efficiently support networked satellites and instruments? For ground systems, the ability to communicate with one's satellite may not be limited to when it is in view of a specific ground station. In addition, Delay- (or Disruption-) Tolerant Networking (DTN) will allow for more communications paths and may require the ground to better handle non-real-time data receipt of delivery.

Cubesats are already "upsetting the apple cart" and providing a forcing function to do operations and mission science faster and at a significantly lower cost. With their rapid advancement comes great breakthroughs but also some key concerns. Standardization of the form-factor is very helpful, but more work is needed in the area of standardized component interfaces and space-ground communications. Will traditional CCSDS framing be used or will they move to internet protocols or something new? As the government gets off of the UHF bands, data rates will increase dramatically, but so will contention for scarce ground station resources. Might there be a new communications service with space-based omni receivers and relays, similar to an Iridium for small satellites?

NASA should work to be involved with other government agencies to establish clear small satellite-oriented data and communications standards including spectrum allocations, encoding standards, and space-ground data formats.

2.1.4 Commercial Hosted Payloads

In our current context, a commercial hosted payload is a NASA-sponsored science instrument that resides on a host satellite as a "customer" to that host's primary mission. At this time, hosted payload opportunities are most numerous on commercial telecommunications satellite hosts.

In a hosted payload model, the science instrument taps into services that may be negotiated (such as power) as well as the host's telecommunications architecture for telecommand and telemetry data transmission support. A link between the NASA and host ground systems provides the indirect connectivity between the instruments and the NASA science operations center. Public/private partnerships are common in this model.

In this model, mission payload operations are concerned with payload data operations, instrument scheduling, and science data processing. The host contractor organization and not the science instrument owner manage the host spacecraft. Satellite health and safety responsibility, including orbit and attitude management, belongs to the commercial hosting provider. NASA contracts for launch services through the host, for satellite engineering services, and for data delivery.

This commercial service model implicitly requires that services be procured from the commercial vendor. The government instrument designers may need to modify their designs to be compatible with the host's form factors, resource envelopes (power, thermal, pointing tolerance, etc.), data transmission architecture and the host's ground access methods.

NASA support systems and mission operations concepts must account for the significant split in responsibilities when an instrument is on a hosted payload. How should NASA-specific orbit or landmarking products be generated? What is the operations protocol for dealing with spacecraft or instrument anomalies? With the understanding that the host's payloads have priority over the NASA payloads, is there a greater risk tolerance or a lower threshold for acceptable data collection (95% instead of 99% for example)? How will I&T and early testing work if NASA is not involved in the spacecraft development effort? While some of these issues are being worked on NASA hosted payload missions such as TEMPO, all issues are by no means settled at this early adoption stage.

2.1.5 Rapid Mission Development and Deployment

One goal of spacecraft designers is to achieve the ability to rapidly assemble existing modular parts into a launch-ready vehicle in minimal time (days to weeks) with a readily available MCC. In this mode, satellites and operations cannot be too dissimilar from spacecraft to spacecraft.

In a related technology, small satellite designers are looking at fractionated spacecraft that are composed of standard modules that are stored either on ground or on orbit and can be reconfigured to form desired spacecraft for a short mission. At the end of the mission, the segments separate and are available for a new mission. These spacecraft designs will require “plug and play” capabilities both in the electromechanical systems and in the software and operational systems. To be successful, a high degree of standardization will be required in the space segment and in the ground segment.

The U.S. Operationally Responsive Space (ORS) has had a goal of going from concept to construction to launch to mission operations in seven days by making many assumptions about the vehicles, choice of instruments, orbits, etc. Their approach would allow only about two days to configure a ground system – again with many assumptions having been made in advance.

These concepts require operational space and ground networks that can readily accommodate additional satellites on a rapid cadence. This implies many concepts similar to fleet operations, especially for the fractionated spacecraft concepts. The networking business model requires an existing ground and satellite infrastructure that can accommodate similar satellites and missions.

The forcing function of extremely short schedule cycles creates opportunities for ground system innovations that could benefit missions of all types. Standards will play a large role in responding to many of the challenges.

2.1.6 New Mission Types: Refuel, Repair, and Replenish to Extend or Repurpose Missions

In current satellite operational concepts, satellites are decommissioned when they exhaust their fuel or suffer a serious system malfunction that impedes their ability to collect useful data or perform their intended operational function. NASA is currently investing in technologies whereby satellites can be serviced with fuel and modular components to extend their life. The ability to repair a satellite on-orbit has been demonstrated with the Space Telescope. Replenishment and repair have been demonstrated with other missions.

In the future, we see a trend for more robotic servicing missions, perhaps refueling and modular replacement. For ground systems, we may see that mission life can be extended indefinitely. We will also need to support these special missions with new technologies, including video downlink, close approach sensors, and new unmanned tool manipulation capabilities.

2.1.7 Onboard Autonomous Tasking

Part of having a low-cost ground mission control infrastructure is migrating traditional ground operations functions to the spacecraft. This means that certain guidance, navigation, and propulsion functions are performed onboard the spacecraft with little to no operator intervention or approval. Additionally, goal-oriented onboard mission planning and re-planning and adaptive real-time mission responsiveness to events is done to support instrument operations. To accomplish this, satellite subsystems and sensors will determine real-time items of interest to record and downlink based on knowledge-derived rules. Once this is done, there will be the complementary initial science data pre-processing performed in the satellite to reduce constraints due to limited data downlink bandwidth and contact opportunities.

This capability requires advancements and evolution in the algorithms required to process the data on board. This includes the expert systems to know how to operate the spacecraft autonomously and learn from operational experience. Mission operations must evolve into accommodating planned activities as well as “known unknown” activities. This implies some form of ad hoc mission planning heuristics. This may also require learning to accept a selection of reduced data sets in place of acquiring all of the “raw” data sets. The business model must trade the additional, higher up-front development costs for the on-board software enhancements with the out-year lower operational costs for a single satellite and/or the ability of one control center to control many more satellites than currently possible.

A complexity added to the ground system may be the validation of spacecraft states given that some of the decision processes have been moved on-board. Model-based systems on the ground could be re-synched to current states at the start of every contact and then propagated forward based on known scheduled activities.

2.1.8 Data Requirements

In the earlier sections, a number of data implications for future ground systems have been mentioned. In this section, we examine several key data issues and new requirements for future ground systems.

a) Data Volume, Velocity, and Variety

Data trends for satellite science instruments indicate nothing but a steep increase for the future. This can come from a single satellite with instruments requiring large storage, aggregate data gathered across a fleet of satellite instruments, or thousands of addressable sensors across constellations of small satellites or ground-based in-situ sensors. In this future environment, ground resources will need to be increased, shared, leased, or more tightly scheduled as more uplink and downlink times are requested. This is analogous to the current issues with airport runway schedules and flight capacities in the transportation sector or similar sectors where the infrastructure capacity is constrained but the user access demands keep growing significantly each year. Coupled with the

constrained capacity, “The Internet of Things” and “The Web of Things” whereby in situ sensors are located everywhere with ubiquitous coverage giving many addressable devices and nodes on the network will stretch telecommunications capacities and delivery mechanisms. Just as in the ground commercial consumer market, we expect that devices that are integrated will define the space instrument future, coordinating and sharing large volumes of data. Furthermore, we expect that the current strategy of collecting or distributing “everything everywhere” change to an “access everything from anywhere,” with more consolidated data storage and more data access services.

We anticipate that space communications architectures of the near future will look for optical transmission techniques to surpass the current radio techniques. This changeover will require new ground-based communications equipment (optical terminals) resulting in new interfaces to the MCCs. We also expect that the large number and variety of sensors everywhere will have multiple data formats with a large amount of aggregated data. Taken together, we see that missions must be well defined, selective, and bounded on data for downlink or ingest rather than “sending all” to prevent overloading or resource exhaustion. The collection of disparate data from a variety of sensors could define a mission, as well as ad hoc circumstances. The future business model will include more selling, leasing, booking, scheduling of uplink/downlink resources, including private resources. The mission funding may need to anticipate that provider will make data and apps for the data available for a fee. The mission must accommodate both planned and ad hoc circumstances of data transport and availability.

Implications for the mission control centers may include more extensive use of public Cloud resources to simplify large-volume data storage and distribution, clean separation of science data and satellite health data, service-based data management and access, and higher processing capabilities within the control center.

b) Low-latency Product Generation and Analysis (sensor to scientist and back)

The increased availability of data from multiple sources in real-time will increase the level to which dynamic tasking of missions becomes possible. In addition, expectations will continue to grow that data collected by NASA’s Earth science missions is available in shorter and shorter amounts of time – with some data analysis efforts requiring near real-time data accessibility to enable spacecraft tasking, capture transient events (e.g., tornadoes), support severe storm warnings, report lightning strikes, etc. This tighter and tighter cycle of data collection, transmission, processing, distribution and analysis will place new burdens on the ground systems and some mission operations concepts for both satellite control and for data acquisition and distribution.

c) Data Provenance

We anticipate that an increasingly important issue for Cloud-based data delivery with data originally sourced from many places is the data provenance. Data provenance is the principle of identifying and ensuring the ownership and sourcing of the data is as the customer expects or as advertised by the provider. For NASA missions, it is essential that the integrity of the data be unquestioned as data is collected, shared, analyzed, refined, and updated (and this cycle is repeated). NASA currently does a good job of appending time-tags and sourcing metadata to collected raw scientific data. As

we move to public/private methods of data delivery or hosting on non-government data stores, it is important that the history of its evolution be traceable as data is shared, massaged, and productized.

Data provenance provisions may require additional metadata be appended with its origins which also adds to the overall transmission bandwidth. The mission operations database management will need to explicitly account for provenance. This may be more appropriate and significant for science data processing than engineering data, at least for that engineering data not part of the science ancillary data needs. The mission business model will need to incorporate data provenance into the provision of an operations center.

2.2 Computing Technology

In addition to basic mission support requirements changes, there are supporting technology trends that will affect the design decisions on future ground station systems. In this section, we look at certain key technology trends with potential benefits for ground station support:

- Virtualization
- Cloud
- Software Defined Networking
- System Monitoring and Automation
- Model-Based Capabilities
- Security
- Standards
- Internet of Things
- Remote/Mobile Access
- DTN
- Data Analytics
- Device Consolidation

Table 2-2 shows why these computing technology capabilities were chosen and how we see them as disruptive in the current MCC environment.

2.2.1 Virtualization

As we have seen in consumer applications, computers, storage, networks, systems, and enterprises have become virtualized. There is no reason to believe that this trend will not hold for Mission Control Centers in the future. In fact, many NASA control centers have already moved in this direction. With virtualization, each type of physical device can be overlaid with a set of virtual instantiations.

The use of virtual machines (VMs) allows for simplified system integration and replication. Since an entire configuration and environment is virtualized, vendors or even other missions or NASA Centers, can provide pre-configured VMs that are ready to install and run.

Table 2-2 Evaluation Parameter Space for Computing Technology

Study Case	Reason for Choice	Disruptive Nature
Virtualization	Use of virtual machines are commonplace technologies	MCC can switch support modes by changing the current virtual machine; new method for packaging and distributing software
Cloud Technology	Enabling technology for “anytime, anywhere” access to data and virtualized applications	MCC data, applications, and services are dynamic; modular mission architectures; security is a fundamental concern
Software Defined Networking	Decoupling the network control functions from the data flow functions to bring greater efficiency	Real-time adaptable networking control, especially between government and private networks; standards driven interfaces for network control
System Monitoring & Automation	A natural result of the desire to reduce the budget impacts of mission operations	Brings in the ability for support through machine learning and smart instruments to bring value added to minimal operations crews
Model-Based Capabilities	Models of mission and subsystem entities permit developing new operational efficiencies	Validation of command and operational sequences prior to attempting execution
Security	Major issue in considering new ways of designing the MCC, especially with Cloud-based technologies and commercial networks	Converting from closed government systems to commercial and open standards based systems will present many security challenges to MCC design
Standards	Standards are part of NASA’s operating mode through CCSDS and other organizations	There is a need for new standards to support the evolving data communications and architecture concepts; small satellite data standards
Internet of Things	Next step in the evolution of the Internet’s capabilities and operating modes	Smart devices adding value to data and providing services distributed anywhere there is connectivity
Remote/Mobile Access	Ned to support “anytime, anywhere” access on a variety of platforms	Movement away from fixed consoles and infrastructure; operators utilize personal computing platforms.
Delay/Disruption Tolerant Networking and Other Trends	Need to support intermittent connectivity, high channel error rates, and long delay-bandwidth products; support commercial data distribution channels	Need be able to provide ad hoc connectivity over commercial and government networks; intermix science data with commercial telecom data
Data Analytics	Open Data initiative, open standards, and data sharing require these capabilities	Need for long-term planning and management data, tools, and products
Device Consolidation	MCC hardware and software eventually need upgrades and replacements	Compatibility issues with new hardware and software due to rapid pace of change in the commercial world

The use of system servers, each with multiple virtual machines, has become common. A knowledgeable staff can now address early concerns about system performance and complexity. Some work is still needed in how to best handle commercial products in a VM environment, especially if the product is serving multiple VMs for different purposes. The COTS industry is also still addressing this area in how they establish their pricing rules. In addition, one needs to be careful on how systems are configured to provide robustness for both processing and data storage requirements.

Virtualization is quickly becoming a standard method for software packaging, distribution, and integration. Future mission operations systems will clearly continue the current trends and adhere to new common practices as they mature.

2.2.2 Cloud Technology

A logical extension of the realization of bulk data storage, the ubiquitous Internet, and the desire for access “anytime, anywhere” is the evolution of Cloud-based storage and user applications. Cloud-based storage also provides a means for automatic back up of data to provide greater reliability in the enterprise. Clouds may be local/private, public, or hybrid. Additionally, Cloud-based solutions allow a “many-to-many” data flow architecture where many sources of data, both on orbit and on ground, can place their data products over the communications networks into the Cloud for the many users of that data, again, both on orbit or on the ground. The movement of data storage from a specific disk storage location to a virtualized location also carries the risks of unauthorized access and modification, loss of data provenance, and premature distribution of data to non-project personnel and computing systems. Despite these risks, government and private sector entities appear to be moving rapidly to embrace Cloud-based solutions.

This trend implies that the infrastructure for future mission operations will need to become more dynamic and responsive to mission needs. As mentioned earlier, we envision that satellites and instruments will be configured as addressable nodes on a network like any other device. From this, we expect that mission operations will become more efficient users of resources with equipment and MCCs not necessarily being physically present at a specified location. However, it remains true that mission operations will need some recourse or assurance regarding failures or outage protection. The improved business model should show that the mission requires less hardware acquisition. The mission may lease resources from a virtual provider on an as needed basis rather than a permanent equipment acquisition.

Cloud Computing supports the virtualization of services. Just as in the consumer market, we expect there to be several government Cloud computing and networking services. Large Cloud services providers will be available commercially. NASA may develop its own private Cloud, or hybrid Cloud of services available to NASA clients. The progression is seen toward a loosely integrated suite of services with commonly shared services, commonly shared infrastructure, and common anomaly reporting system across all systems. More and more apps will be available on mobile devices to take advantage of services, data products, and remote monitoring capabilities. In this future, we see NASA potentially using both private and hybrid Clouds, the acquisition of systems as a service, and Software Defined anything technologies to support mission operations.

This will result in a mission architecture that is modular, with less-coupled subsystems, systems, and networks. Here, architecture can be defined, configured, and implemented virtually with no local physical infrastructure. This should result in mission operations that exhibit more efficient use of resources with equipment and MCCs not necessarily physically present. In fact, an entire system could be defined and leased from a set of service providers. The mission business case should include less hardware acquisition. NASA may lease resources from a virtual provider or NASA may build its own Cloud. This will lead to more leasing and less acquisition of physical resources. Leasing of software, system, and network resources from service providers. Once virtualized, components can also be virtually joined and configured to create a Software Defined anything, for example a computer suite, storage, network, system, or MCC. This leads to a companion question of “What systems or parts of systems are suitable for a Cloud?” All or only the non-real-time aspects? At the same time, the instrument controllers must be able to communicate with a plethora of devices that are local, remote, portable, mobile, and transient.

In this future networked environment, does Cloud networking apply to satellite networking? Here, we assume that some form of integrated Cloud services will not only be desired but also required in the future. The question now becomes how NASA, and other government agencies, manages it properly with multiple input ports (public and private), back up, data distribution, security measures, data provenance, data integration (multiple DTN delayed packets), etc. In the Cloud computing and networking environment, satellite ground station designers may be able to treat a physical control center room like a schedulable conference room – simply reconfigure the data access for different groups. This design philosophy can help manage external access to data streams and support “zero footprint” control centers. Additionally, especially on the space segment side, the introduction of Software Defined Networking technology can be the next logical abstraction to Software Defined radios. How telecommunications designers integrate the networking layers with the Level 1 and Level 2 radio or optical hardware and protocols of the radio. Also, how will the designers bring in the routing layers, etc. so that the telecommunications device will have everything below the application layers in the same logical “box”?

2.2.3 Software Defined Networking

The goal of Software Defined Networking (SDN) is to achieve greater performance and efficiency by decoupling the networking control functions from the data forwarding functions in the protocol architecture. Key concepts in SDN are

- Allowing the networking control to be completely programmable
- Allowing network administrators to have immediate flow control to react to changing conditions
- SDN appears to applications as a common, generalized switch
- Management of network resources is programmable through common interfaces
- SDN uses open interfaces that are vendor neutral.

Having NASA missions move their communications architecture design to a SDN based approach will have several advantages for these missions:

- Programmable network control implies that both ends of the communications link can be more adaptable in responding to network issues such as congestion and availability. This will also enhance the ability to rapidly switch between government-controlled networks and private networks without costly reconfiguration efforts.
- A common-use mission control facility could be immediately reconfigured to match the network and security requirements of a specific mission. Each mission could have its networking and security configurations stored and the proper files loaded prior to each support period. In this way, one could move towards an approach much like a common conference room, where missions sign up for blocks of time and the room is configured accordingly.
- Common, open interfaces mean that the SDN interfaces will be standards-driven. This will give long-term stability to the interfaces and the ability to have rolling upgrades to ground segment hardware and software, and space segment software to sustain longer mission lifetimes.

2.2.4 System Monitoring and Automation

As we go to more efficient ground systems, it is implicit that higher degrees of automation will be required to support operations. This implies the development of appropriate smart sensors, analytic tools, and augmented reality devices to assist users. For example, a rapidly evolving automation technology is machine learning, which is moving beyond smartphone speech recognition and search engines to ‘virtual personnel assistants’ to support decision-making. Such techniques are envisioned to operate by building a model from example inputs and using the model to examine data and predict outcomes or suggest solutions.

These enhancements require that mission designers provide architectures that have built automation into operations that is flexible and expandable. Mission operations systems will need to provide operator’s access to “what if” scenarios and modeling for operations and mission planning. This is the way to enable mission operations with less staffing and more automated (lights out) operations. The ground operations business case would expect to reduce costs with more automation and less staffing.

Development of mission or subsystem models allows for a range of new mission operations efficiencies. Detailed models of the space system’s expected behavior can be used to identify potential system anomalies. The models can be used to validate planned commanding sequences prior to uplink. If the model is aware of current actual states, it could be used to look ahead at potential issues or could identify the required subset of commands needed to get from the current state to the intended final state. In addition to its data assessment use, it could be used to generate high-fidelity simulated data streams.

A key concern in the past has been that the model must be close to perfect, and may be at least as hard to test and validate as the actual flight systems. Mitigation approaches include incorporating modeling approaches in the system engineering process from the earliest days of system design, and using modeling for small, very bounded subsystem efforts. Over time, proven bounded models (e.g., solar panels, solid state recorders, etc.) may become trusted and used as building blocks for future large-scale mission models.

2.2.5 Security

Security is always an issue in any mission operations architecture and will be a much larger challenge in the future as threats become more sophisticated and technology like Cloud storage open up new security boundaries. The security system must provide protection and resistance to assets, systems, data, and services. Usually, security concerns override all other categories.

Areas to be secured within the mission architecture include the uplink/downlink, ground systems, space assets, networks, etc. Mission software must be (statically) analyzed not only for aberrations but also for security vulnerabilities. We expect that to meet security concerns, the mission operations core areas will not be public Cloud based or outside the control of the mission. To complement this, authorization and authentication policies must be developed and incorporated for the missions. The business proposition for the mission must provide provisioning for security assessment services.

2.2.6 Standards

Data system standards have been essential for space mission system interoperability and efficient system design for decades. The Consultative Committee for Space Data Standards (CCSDS) has existed since 1982 and has the support of civilian space agencies around the world. The Object Management Group's Space Domain Task-Force (OMG/SDTF) is supported primarily by commercial companies and has also created standards in support of mission operations. The CCSDS and OMG teams often work together and the recent XML Telemetry and Command Exchange (XTCE) standard is being published by both organizations. The Open Geospatial Consortium's Sensor Web Enablement (OGC SWE) members are specifying interoperability interfaces and metadata encodings that enable real time integration of heterogeneous sensor webs into the information infrastructure. Recently CCSDS and OGC have initiated discussions to leverage SWE and SensorML, as well as Sensor Planning Service (SPS) for sensor operations.

In the past, the emphasis of the standards work for mission operations had been on the space-ground link. RF modulation, encoding, and packet structure standards were all developed. Over the past decade, efforts have started to also focus on mission operations services and data formats to simplify rapid system integration and cross-agency interoperability. These efforts are expected to continue and should simplify the development of multi-agency missions and could allow for the sharing of resources (antenna, network, etc.) in support of spacecraft emergencies or even routine operations. In addition, some of the standards allow for functions to be packaged as services which can run either on-board or on the ground. The service-based standards will allow for a wide range of new operations concepts (See Figure 2).

Cubesats are a specialized case of smallsat which adhere to form-factor standards. A lot of work is needed to select standard space-ground and data format standards to allow for rapid development of cubesat support systems and very low cost.

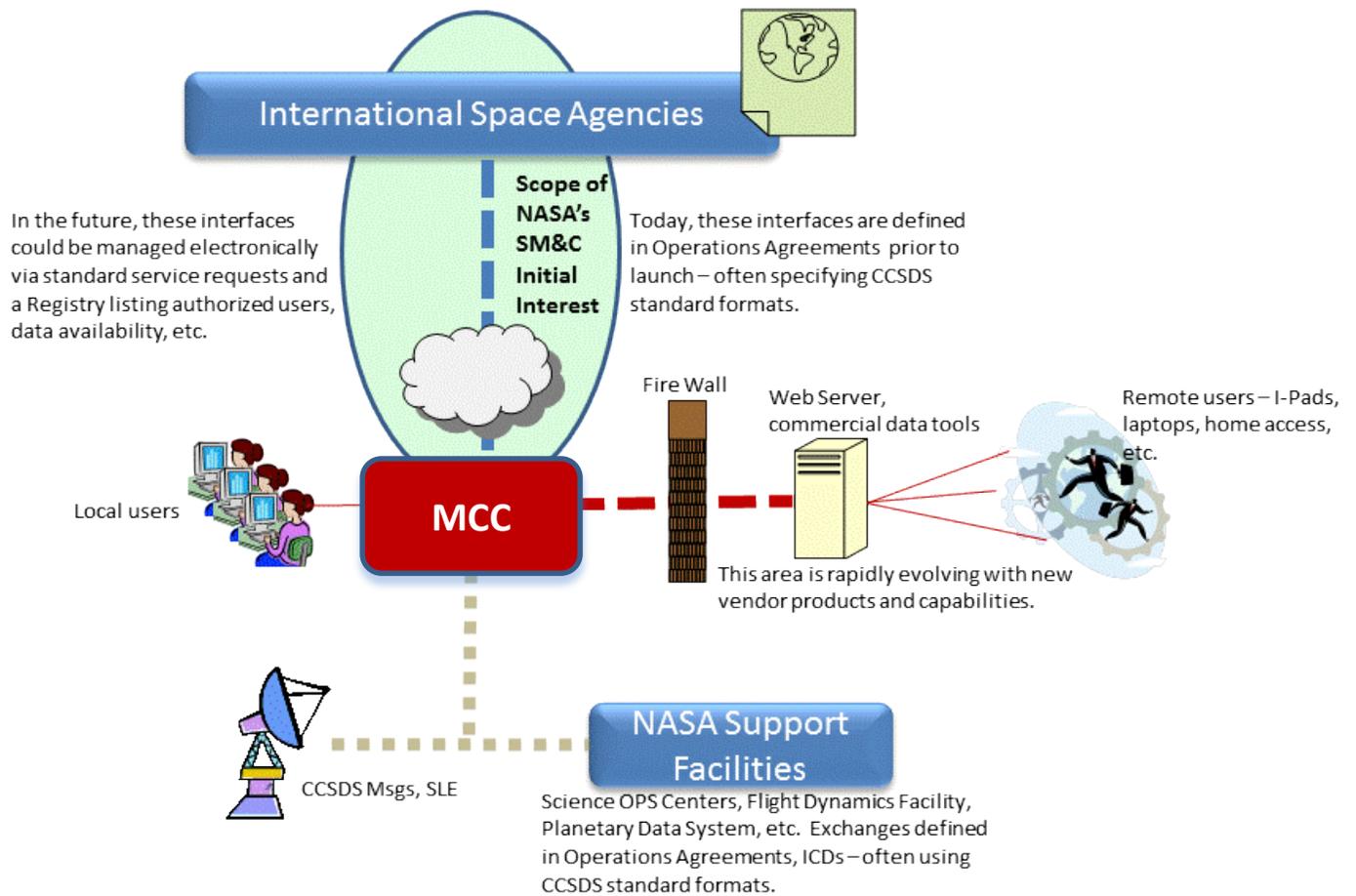


Figure 2. Spacecraft Monitoring and Control (SM&C) standards now in development will change how we work with our international partners and will enable new mission operations approaches leveraging web services.

2.2.7 Internet of Things

Future mission operations systems will require knowledge from more sources than just the spacecraft's telemetry stream. Data from other satellites, from ground-based sensors, from ground equipment and facilities and more will help inform the mission operations efforts when developing and executing mission operations plans. The concept of the "Internet of Things" (IoT) is expected to become commonplace and ground systems will need to be able to routinely and dynamically utilize data from many sources. In the IoT, participating entities are smart devices and not merely addressable data sources and sinks. The entities will be able to add value to the data and provide services beyond the mere bit stream. This will lead mission designers to consider new approaches to both spacecraft design and ground system design.

The availability of many data sources introduces concerns over data security, multiple communications paths and networks, data provenance, and data reduction and comprehension.

2.2.8 Remote/Mobile Access

As we have mentioned several times in this study, we expect that the mission operations paradigm of the future will include “anytime, anywhere” access as routine operating mode. This will be driven both by the available technology to support such a model and the expectations of future mission operators based on their everyday experience. The days of designing mission operations around a fixed console or even a desktop workstation are coming to an end. Operators will be expecting to utilize multiple platforms from workstations through smart phones to access data and commanding interfaces. The users will be expecting these remote/mobile devices to provide the same user experience, with some tailoring for platform size, whether the user is in the official control area or at a remote site. As we have mentioned many times, with these remote access modalities, data security and data provenance controls must be built into the architecture. NASA needs to be planning for remote and mobile access modalities as normal parts of mission operations and not as exceptions.

2.2.9 Delay-Tolerant Networking and Other Network Trends

Over the past generation, the means for packaging data for transmission have changed drastically and we expect that to continue to be the case. Spacecraft started with the standard IRIG telemetry frame formats for point-to-point transmission. Later, NASA evolved the NASCOM 4800 bit block format for transmission through the NASA-controlled networks. Eventually communications designers looked to TCP/IP and CCSDS standards to bring a more Internet look and feel to the process. One of the major issues with the Internet-type protocols is their inefficiency when dealing with channels having intermittent connectivity, high error rates, and/or long delay-bandwidth products. New approaches such as Delay Tolerant Networking (DTN), also known as Disruption Tolerant Networking, provide protocols that allow efficient data transmission over space communications networks having one or more of the problem characteristics. As time progresses, these protocols move from the demonstration to adoption stage and the MCC needs to embrace them.

A non-traditional space communications protocol set also needs to be considered when working with commercial entities, especially in the Hosted Payload (HPL) context. For example, the HPL telecommunications satellite and service operators are used to using Multi-protocol Label Switching (MPLS) networks instead of CCSDS-based networking protocols. Additionally, the HPL satellites generally transmit the data using DVB-S2 and DVB-RCS modulation formats. As NASA investigates partnerships with commercial providers, these commercial standard interfaces may cause compatibility issues.

2.2.10 Data Analytics

Data Analytics is the logical analysis and discovery of meaningful patterns in data. This is a concern because with the Open Data Initiative, open standards, and greater connectivity, data sharing will be more prevalent. Consequently, more data analysis will occur with more users (e.g. crowdsourcing), most likely with tools that are commercially available, or developed on an ad hoc basis. As we have seen in other contexts, smaller and simpler analytic tools for personal and mobile use will be readily available.

Given that these trends are currently happening in the consumer market, it makes sense for the mission designers to build a long term plan to store and manage the evolution of data, analytic tools, and data products into the mission architecture. With this in place, it will be common for data assessment to take place outside of a physical control center. This also implies a business model to provide services to store and manage analytic tools and data products, and their evolution.

2.2.11 Device Consolidation

Most of us have encountered the problem of replacing a well understood component such as a WiFi router that is several years old, and then finding that the latest models have features, configurations, and options that not only far surpass the original device's abilities, but we are also not sure that the new device is compatible with the other devices in the system. To make matters worse, the original model device that we are replacing is no longer available from any manufacturer. While this is annoying in the home environment, it can be a major hurdle for maintaining the computing equipment in the mission control center. Not only is device obsolescence a fact of life in our current world of rapidly evolving technology, multiple devices are now bundled into a common platform so that replacing an existing device is not as simple as a one-for-one replacement within a few years of that device's original manufacture. With this type of consolidation and pace of technology change, how does the mission architect plan for rolling upgrades and provision spares? NASA needs to develop and incorporate a strategy for planned obsolescence and device change into mission planning cycles.

2.3 Architecture Approaches

The architecture and development approaches need to look to the consumer markets for trends that will be enablers for space mission architectures. How many of today's buzzwords were even known 5 years ago? New systems will use a combination of approaches. We expect that these concepts will be key enablers for the future:

- Common Software Solutions
- Increased Use of COTS and FOSS
- Service-based Capabilities
- Open System Architecture
- Enterprise Architecture
- "Zero Footprint" Control Center Architecture
- Advances in System Development Tools and Processes

Table 2-3 shows why these architecture approaches were chosen and how we see them as disruptive in the current MCC environment.

Table 2-3 Evaluation Parameter Space for Architecture Approaches

Study Case	Reason for Choice	Disruptive Nature
Common Software Solutions	Meet the budget realities that will only be more constrained in the future	Need for enterprise approaches to MCC implementation and adoption of standards
Use of Commercial Off The Shelf (COTS) and Free and Open Source Software (FOSS)	New paradigms for mission control applications software development and distribution	Ability to import applications from other domains, need for application security review, plan for software obsolescence
Service-Based Capabilities	Entity design based on functions provided and services rendered	Ability to upgrade or add new capabilities to entities without reconfiguring the entire system
Open System Architecture	Standards-based architecture from the ground to the space-based instrument	Architecture becomes vendor agnostic, use of well-defined application interfaces
Enterprise Architecture	Mission control centers and applications software are becoming commoditized	Turnkey applications software, mission operations become a System of Frameworks
Zero Footprint Control Center Architecture	Availability of virtual, Cloud-based applications and data access	Mission operations software and data access becomes an “appliance” application
Advances in System Development Tools and Processes	New ways of interacting with personal computing devices and the applications they enable	Significant computing ability in a personal device, Cloud-based data access, “citizen scientist” participation, integration with the Internet of Things

2.3.1 Common Software Solutions

Given the large percentage of the overall, multi-year mission budget that is dedicated to system maintenance and operations, it is not surprising that sponsoring agencies are now expecting mission architects to avoid one-off systems that must be created from scratch to support the mission. Architects are encouraged to design missions with software reuse from past missions. It is even acceptable now to design missions with commonly used, low-cost COTS software. We envision that future architectures will only be permitted to develop unique solutions when it can be shown that software reuse or a standard product is unavailable.

To assist in this development, we expect that new space data standards by CCSDS, OMG, and OGC could either simplify or complicate development efforts. For example, the GSFC Core Flight Software is becoming to be seen as a standard product within the Agency and it is being adopted at JSC and ARC for testbed and other activities (e.g., Advanced Avionics for Exploration testbed). Since this will also be flight certified, it becomes a natural platform to build upon for the space segment. Having such a common space system core software helps designers to specify the needs of standard ground system software. As with other applications, the question will not be ‘can a standard product supply the needed capability’ but which products will stand the test of time and be viable over the mission duration?

The mission design community needs to expand its horizons beyond only the space mission design products for consideration in the mission architecture. The designers need to be aware of the autonomy and automation tools evolving from other industries such as industrial process control that can be utilized with little or no modification in the satellite mission architecture environment.

Finally, NASA missions must consider multi-mission enterprise solutions for their mission architectures. The functions required to support science missions are really very similar from mission to mission. Mission support software will need very little tailoring to support each mission. Proper design techniques will make the software easy to configure for multiple missions and permit a cost savings in software development and in operator training.

2.3.2 Increased Use of COTS and FOSS

The increased use of Commercial Off The Shelf (COTS) and Free and Open Source Software (FOSS) in the mission enterprise is expected to continue in future mission architectures. COTS components, such as database engines, are already standard parts of telemetry processing packages so they are well vetted for operational reliability. In the future, we expect that there will be less of the handcrafted, one-of-a-kind applications and more COTS products that are directly written for mission-support applications, or that can be adopted from other operational domains, such as industrial process control, to be adopted for the mission control domain.

FOSS software packages are not typically found in MCC's at this time except for one major exception – the Linux operating system. Another tool that falls in the category is Open Office. The use of reliable COTS and FOSS tools will help control the cost of mission software and permit cross-platform support and hardware/software upgrades in the mission systems.

One concern that mission architects will continue to need to address with COTS and FOSS software is security of the applications. We take it as a given that government-owned mission architectures will continue to require rigorous security verification of all COTS and FOSS products.

A second concern with COTS and FOSS is “orphan software.” Today, government mission centers and spacecraft will pay almost any price to keep operating software maintained, this will not always be true with COTS and FOSS packages. Once the market prefers a new approach, even market leading products can fade to oblivion rather quickly once they fall out of favor. In this case, how will these “orphan” products be maintained and supported if they are adopted for mission support. Mission designers will need to keep this concern as part of their mission risks to be mitigated.

2.3.3 Service-based Capabilities

Service-Oriented or Service-Enabled Architectures are those that depend on each entity having two lists: the services that the entity needs to accomplish its own functions and the services that it can provide to other entities. Generally, the service definitions are defined through a standard specification protocol. Entities advertise the services required when they are needed (caching is allowed for commonly-used services) and suppliers respond. This allows individual entities in the system to be upgraded/maintained and have new capabilities added without reconfiguring the entire system. This

also allows the system design to evolve over time from basic to advanced capabilities as operational experience is gained.

2.3.4 Open System Architecture

In Open System Architecture, entities within the system utilize common interfaces to exchange messages. Designers use interaction patterns that are defined to allow for a broad spectrum of functional products to be easily added to the system. The open architecture really should extend from the control center to the spacecraft level, including all intermediate nodes, to permit all entities to easily exchange data and functional requests. A major architecture emphasis is on the ability to add new components from multiple vendors during maintenance upgrades and to allow for the inclusion of new ideas at any time. The approach does not specifically call out the functionality required in specific modules as long as it can be encapsulated and configured in a specific system entity.

To be successful over the mission lifetime, open system architecture requires that the design be a standards-based approach to permit entities within the system to exchange data and services. By using well-recognized standards, the mission architecture could have full international interoperability and even software sharing, if properly planned as the mission architecture is designed.

2.3.5 Enterprise Architecture

The entirety of the mission enterprise architecture will change over the next decade due to changes in computing, communications, and user expectations. In particular, mission control centers are, in a sense, becoming commodity entities with the new business models from mission control center COTS vendors leading to new product lines and options. Mission software is available from several commercial vendors in a turnkey mode that only needs the user to customize the data base linkages to have a ready command and telemetry processor on any one of several platforms. Additionally, system simulation, modeling, big data, data mining, and data analytics can be seen as special discipline areas for mission health assessment enabling new operations approaches.

In software systems, a *framework* is an abstraction in which defines a set of generic functions and how they interrelate, and where code is added for specific applications. From this, a mission architecture specification can be considered to be a framework because it would specify the operations to be performed and the communications protocols between the entities. Earlier in Systems Engineering, we often spoke of “Systems of Systems.” With multiple-spacecraft architectures and multi-mission control centers, we can now speak of a “System of Frameworks” to describe the overall operations. NASA will need to keep abreast of this new way of abstracting the mission architecture description.

2.3.6 “Zero Footprint” Control Center Architecture

One of the complementary developments to Cloud-based software and data storage is the development of the concept for Cloud-based appliance software. In this environment, specific user software does not necessarily reside on the user’s computing device until it is needed. At that time, the applications software is loaded from the Cloud along with corresponding data files. As data files are modified or generated, they are stored back to the Cloud. In this environment, mission operations software becomes an “appliance” application for the user. Also in this environment, the user will expect to have

“anytime, anywhere” access to the appliance application and data across multiple computing platforms (desktop, laptop, tablet, smart phone, etc.)

With the development of multiple appliance mission support applications, there comes the ability to have a virtual control center with each user accessing their job-specific application on their preferred computing device wherever they are located. This permits the mission architects to construct a Zero-Footprint Control Center (ZFCC) with virtualized applications, data storage, and operating locations.

The ZFCC can be further enhanced by utilizing standard networking services in multiple modes. For example, existing software will allow a satellite to publish its telemetry data as a web server application residing on the satellite that can be queried from the ground station. Small satellite architectures have been proposed where critical telemetry and burst commands can be exchanged between the satellite and the ground station using Short Message Service or even Twitter packet formats.

In all of these concepts, the available networking infrastructure can be leveraged to support mission operations. Naturally, this type of open architecture will also come with security concerns that will need additional overhead to protect the assets.

2.3.7 Advances in System Development Tools and Processes

Earlier we discussed common technologies such as virtualization, Cloud technologies, and Software-Defined Networking. In this section, we will examine some advancing technologies that NASA should be monitoring for inclusion within the timeline of this study.

We have already indicated our assumption that users will expect that “anytime, anywhere” access to mission operations and resources will be the norm, driven by the explosion of remote computing advances in hardware (tablets, smart phones, etc.) and software (Cloud-based everything). The question that we need to begin preparing for now is “How will we interact with our personal mobile devices in 10 years?” Personal mobile devices will have the computational horsepower, the storage, and the user interface. We need to prepare the communications security, the access protocols, and the operational methods to be ready for this new environment for operations and data processing.

Traditionally, mission software development and maintenance, and data processing have been closed-shop activities performed by a well-defined team of participants. A relatively new model that has been successful on several projects is to use crowdsourcing as an innovation/discovery approach. Examples such as *SETI at Home* have allowed individuals to donate computer time from their machines to support a scientific endeavor. How might such a model be used to allow the public to participate in mission operations to fulfill their own wishes to participate in space exploration?

The “Internet of Things” is expected to be the coming Internet architecture for the near future, where basically, everything and everyone is connected to everything else. We have often discussed making satellites as smart nodes on the Internet. In this mode, not just the satellite but the sensors and science instruments are nodes on the Internet. The flight computer is mostly a router. Global interconnectivity enables the ZFCC mentioned above to be the normal mode of operating for future users. NASA needs to plan for the infrastructure and security to accommodate this communications intermix. This will

naturally include both public, private, and government networks, Cloud storage and processing, etc. The open environment will be a sea change from the current closed environment.

2.4 Operations Concepts

Many mission control centers were designed on an air traffic control model with a cadre of controllers sitting around consoles all arranged in a single room. At that time, satellites were designed as hand-crafted, one-of-a-kind systems. Modern satellite design is typically based on a common product line from a commercial vendor. Current budget and risk postures require spacecraft and instrument designers to utilize high-reliability components with significant flight heritage. This common product line permits the mission control community to have new approaches to managing not just single spacecraft but multiple spacecraft from a single control center. Additionally, small satellite mission designers are forcing vendors to create new products and paradigms. For example, in 2014, Kratos produced a mission operations support environment that runs on a single laptop computer. Their quantumCMD™ is the “industry's first commercial-off-the-shelf (COTS), self-contained, pre-integrated appliance designed from the bottom up to meet the specific technical, mission, schedule and budget needs of small satellite operations.” Appliance ground stations and the evolution of standardized spacecraft buses with high heritage subsystems and instrument components indicate that NASA should look for new approaches to the overall mission support needs, the duties of the control center personnel, and the overall support environment. We will examine these topics in the following subsections:

- Changing Support Needs
- Changing Personnel Roles
- Changing Environment

Table 2-4 shows why these operational concepts were chosen and how we see them as disruptive in the current MCC environment.

Table 2-4 Evaluation Parameter Space for Operations Concepts

Study Case	Reason for Choice	Disruptive Nature
Changing Support Needs	Satellite design changes, adoption of expert systems and automation, new financial constraints	Increased autonomy in all phases of operations, single operators managing a fleet of satellites, distributed data gathering satellite clusters, smarter spacecraft require different operations
Changing Personnel Roles	New models for organizing personnel for mission control staffing	Changing roles, responsibilities, and skill mixes, managing satellite fleets and hosted payloads
Changing Environment	Changes in the communications, computing, architecture, and staffing drive a changing environment	Movement towards untethered mission support, virtual control centers, standard support and operations services

2.4.1 Changing Support Needs

The satellite operations philosophies have greatly evolved over the past two generations of mission controllers. This is driven by a number of influences: longer operational experience, common/high-heritage components, more capable software, and financial constraints. This trend will only continue in the future, especially as operations and support migrate from the human-based ground system to on-orbit expert systems. We envision the following changes in support needs as coming in the future – and some very soon:

- More autonomous spacecraft capabilities imply that the spacecraft will have the necessary software and expertise programmed into the satellite infrastructure to permit routine scheduling of events, making changes to schedules and operations based on space situational awareness inputs, and performing diagnostics for anomaly resolution. Coordination with the ground will come after initial attempts at modification have been completed or if the spacecraft encounters a situation beyond its experience base. In the future, the mission controller will be sending more acknowledgements of operational state changes than actually “flying” the spacecraft.
- Traditional ground stations were organized around subject matter experts dedicated to one facet of mission operations for one spacecraft. Smarter ground systems will imply that the mission operations personnel no longer need to be detailed experts in a narrow subject area relevant to satellite and instrument operations. With highly capable software on the satellite and in the ground station, an operator can oversee more satellites at a higher level. The experts can move from on-console to the “back room” to provide their expertise if there is a problem that the console/smart system cannot handle in real time. In this mode, the “back room” need not be located at the ground station.
- Because the ground station is using more capable control systems and the operators are taking on a more supervisory role, it makes it economical for the single ground operations system to be employed in managing satellite fleet and constellation approaches. Commercial telecommunications companies are already operating fleets of similar satellites from a single ground station using minimal on-console staff. These operations do not manage diverse instruments but one can see how that is the next stage in the evolution.
- One of the drivers for small satellite fleets is that the cluster of satellites constitute the instrument and not a single sensor suite on a single bus. In the future, mission operations will be structured around gathering the science data set distributed across many platforms – not necessarily all owned by any one agency. The science acquisition process then becomes the management of the set of instruments, regardless of platform, and not managing one instrument on one platform.
- With high-heritage components having significant flight heritage, the operations controllers do not need to spend as much time overseeing equipment as in the past. With smarter spacecraft and instruments in the future, some degree of adaptability and self-healing will be built into the spacecraft and instruments. Improvements in space situational detection and information dissemination will also mean that future spacecraft and instruments can become more self-reliant. All of these trends imply that mission operations can move towards data-driven and event-driven operations and away from 24x7 screen watching mode in the mission control center. The future mission control stations will handle exceptions and not participate in constant monitoring.

- With all of the trends discussed above, the goal of having lights-out operations whenever possible in mission control centers is a reasonable design approach. This will be the payoff for the investments in spacecraft and instrument improvements.
- Ultimately, the production of scientific knowledge is the reason for the mission. Delays to generation of Level 0 and Level 1 data products only impede the mission goals. Utilizing smart communications systems and data production methods to reduce sensor-to-scientist time are worthy investments for the future. This is where a service oriented architecture can help by taking a standards-based data formatting for the data sets and then applying data communications and data product production as a competed, catalog service to produce the minimal time to user with highest quality delivery metrics.
- As we have noted throughout this document, the trends in all data communications services is to provide the user with access to their data at anytime, anywhere. As this has become part of modern culture, the mission control center designers now need to make their design paradigm match this expectation. In the future, there may not be a physical location for the ground station. Rather, it is with the controller at all times.

2.4.2 Changing Personnel Roles

In the future, the personnel running mission control stations will not be organized as they were in the “air traffic control mode” of traditional ground station design.

- Virtual ground station architectures, smart communications systems, and expert software systems operating from standards-based data systems will permit control centers to be service centers themselves. This will permit a control center design to switch contexts to service multiple satellites from a common infrastructure. With operating multiple satellites being the new normal, operators will also need to be better trained on multi-mission cross training because they will be the first line of operations. Only if the problem is an exception will they need to avail themselves of experts.
- With the mission operations concepts described above, there is a responsibility increase in the individual roles at the mission control center. Cross training in functions and missions will be required so that one person can be trained to do most functions. NASA should look to commercial operations and the military to see how this type of training can be successful for complex system operations.
- Because the mission operations of the future will be highly communications and computer dependent, the mission operators will need to design the systems to provide greater security, insure data provenance, and ensure that operational services are always available. In this mode, the System Administration and Security team functions become critically important positions because they ensure the integrity of the mission operation enterprise.
- One interesting approach to developing mission control operators is to have universities perform routine operations while NASA provides engineering, anomaly support, and critical operations support. This permits students to gain experience and grow into positions through co-op programs. This model has been used successfully at specific government and contractor locations (GSFC, LASP, General Dynamics) but making this a formal part of the mission operations culture and mission proposal process should be considered.
- Hosted payloads are teaching NASA that the NASA mission operations do not need to cover the entire system. Rather, the non-science parts can be contracted out to an expert service provider and the NASA-funded scientists can concentrate on their areas of expertise. This is a natural

partitioning of responsibilities that emphasizes the expertise of each player and relieves NASA from providing everything.

2.4.3 Changing Environment

With the changes coming in the communications, computing, architecture, and staffing modes for mission control centers, the overall approach to the control environment will change. Mission control center designers will need to adapt to trends such as:

- Sustaining operations that permit the controllers to move towards untethered mission support from home and with mobile access for anytime, anywhere, zero footprint control center operations.
- Configuring routine monitoring operations for office-environment operations and using the control center space for critical operations.
- Designing totally virtual control centers that support multiple missions across multiple platforms from any location.
- With interconnected communications, smarter spacecraft buses, smarter instruments, and software expert systems in both the ground segment and space segment, explicit point-to-point data transfers will not be efficient. Rather, a service-oriented satellite functionality where data products and operational support needed at a node will be provided as a published service from a provider. As we have noted earlier, this will permit mission functionality to evolve and upgrades to existing services to be executed without reprogramming the entire system. Data processing becomes a “catalog service” that the end user can request, perhaps from multiple, competing providers.

As we can see, all of these trends are possible to envision within the time horizon of this report. NASA needs to become proactive in planning for these trends by the way current mission operations are upgraded and by how new missions are selected over the next decade.

2.5 Business Models

For future mission operations, NASA’s technical and business approaches impact each other. How missions are funded, how collaborations and sharing-arrangements are established, and how industry makes new options available all influence the business decisions for a mission and thereby influence the development of future ground systems. The goal is not to build the best ground system – it is to best meet the mission operations requirements of a mission and the Agency. Business approaches we may consider include:

- One-Off Solutions
- Common Facility
- Common Software
- Multi-Mission, Incremental Addition
- Multi-Mission Enterprise
- Multi Center Commonality Model
- The European Budget Reduction Business Model
- Outsource
- Hosted Payload

Table 2-5 shows why these operational concepts were chosen and how we see them as disruptive in the current MCC environment.

Table 2-5 Evaluation Parameter Space for Business Models

Study Case	Reason for Choice	Disruptive Nature
One-Off Solutions	Represents the traditional mission-specific paradigm for the MCC architecture	May be appropriate for specific mission classes with one-of-a-kind needs
Common Facility	Develop a landlord-tenant model for facility operations and maintenance	Need to be modular and reconfigurable to support multiple missions
Common Software	Develop a catalog of common software applications for MCC support	Tension between common software, new developments, and mission-specific
Multi-Mission, Incremental Addition	Use a common core infrastructure for multi-mission support and augment as necessary	Will force common approaches to be taken for MCC operations; may also need budget resilience for “down” times
Multi-mission Enterprise	Adoption of an enterprise approach over a mission-specific approach	Will force new operational, acquisition, and funding approaches
Multi-center Commonality	Use commonality in mission operations across multiple ESD mission control centers	Can force more widespread adoption of standards, open systems approaches, and common MCC elements
European Budget Reduction Business Model	Different funding paradigm for traditional US government approach	Fix ground system budgets at a lower amount than traditional to force improved operations approaches
Outsource	NASA no longer in total control of the mission control center	Mission operations are treated as a procured, commodity service
Hosted Payload	Major differences from the traditional mission operations approach	NASA no longer prime on launch, rapid I&T cadence, need to interact with commercial control and data centers

2.5.1 “One-Off” Solutions

Having a mission make its own system support decisions based solely on its own needs may, in some cases, be the lowest cost approach for that specific mission. But this approach may ignore the concepts of “the greater good” and the benefits of commonality across other mission sets within a NASA Center or across the Agency.

With this approach each mission has sufficient funding to build its own ground system and provide its own dedicated operations team. Although this may sound like a very costly and inefficient approach, there may be cases where it is beneficial:

- For very low-cost technology-demonstration missions, the development of new ground system and mission operations approaches themselves may be seen as part of the innovation goals of

the mission. The leeway to develop the ground system without other limitations is one approach to develop new innovations with long-term benefits to future missions. It is a valid research and development approach.

- A mission may find that very little investment is needed due to the completeness of commercial systems and the price point at which they are offered.
- For very large, observatory-class missions, missions may find that their requirements drive them to solutions different than those commonly used at their Center. One example would be the desire to maintain compatibility or commonality across many integration contractors or partner sites when it is not practical to bring all of the organizations in-line with an existing Center solution.

The one-off solution approach, however, should be selected only after careful consideration. Consider the following potential drawbacks to this approach:

- Testing and training costs may be higher for a system that is very different from past systems.
- Long-term maintenance costs could be higher since they cannot be shared with other missions.
- There is no contribution towards high goals of the Center or Agency, as this mission is acting on its own.
- Common tools used by other missions may have great potential benefit, but integration may be more difficult due to the special one-off system development approach.

2.5.2 Common Facility

The infrastructure supporting a mission operations system can be a significant cost element of the mission operations cost. Connections to networks, availability of clean power with backup capability, voice loop capability, and environmentally controlled server rooms can add significant cost to a mission ground system development. Regardless of how a mission data system is developed, the use of a common facility can significantly reduce mission costs – both for individual missions and for the greater set of missions a Center may be supporting.

Several NASA Centers are already following the common facility approach. At GSFC, missions residing in the Science and Payload Operations Control Center (SPOCC) sign a landlord-tenant agreement that spells out the costs and benefits of the facility. Modular wall systems can be reconfigured, consoles and computer equipment are typically left for the next missions, and even the security plan can be shared between all that share the facility. The GSFC facility managers are now encouraging the use of common servers and software as well.

A common facility may require some up-front investment that any single mission may not want to carry as its burden. At GSFC, the timing was right to have several missions in their early development phase all agree to share the initial common costs.

2.5.3 Common Software

With this model, an organization may be tasked with maintaining a suite of software components that can be used by any number of missions. The suite may be developed as a catalog of capabilities or as an integrated configuration tailorable to a mission's specific needs. Funding approaches vary across

Centers and range from direct mission “taxes” to more direct funding for the organization. Individual missions are generally asked to fund mission-specific changes and support.

A concern raised with this approach has to do with the expectation of a mission that software already developed and available within an organization is “free”. Missions want to select the common software to keep their costs as low as possible but if they are unwilling to provide funding beyond the absolute minimum to keep the product working, then the products may become out-of-date over time. Products for which missions may not have a current need may have to be abandoned.

For the reasons mentioned above, it is important to develop a sustainable business approach for how to best maintain existing common software and how to develop new products to add to the common software catalog.

2.5.4 Multi-Mission, Incremental Addition

Another long-term business model involves establishing a common facility with common multi-mission capable software. Ideally, the system would be established in such a way that new missions can be added as relatively simple additions to the system. For example, a common telemetry and command data base format such as XTCE could be used to help characterize the new mission and console positions could be configurable to specific missions upon user request. This common approach increases the opportunities for cross training of the operations team, decreases overall test efforts, and keeps the overall mission operations efforts on a consistent path.

A common multi-mission system would require initial startup funding and will then rely on a shared funding model from the missions using it. A difficult business approach has to do with the handling of the “ups and downs” of mission support. In any given year the number of missions supported may go up or down, and therefore either the budget goes up and down or the cost per mission changes.

On the technical side, one needs to deal with the case of a mission needing special capabilities which may impact the other missions.

2.5.5 Multi-Mission Enterprise

The multi-mission enterprise business model is an expansion of the multi-mission incremental-addition concepts. With an enterprise approach, a separate team manages the facility, computing infrastructure, networks, etc. and the mission teams become user groups of the system. The physical assets of the enterprise may encompass multiple facilities at different locations. Enterprise technical capabilities may include the sharing of status or detailed information across missions, the use of common tools, location-independent support, and common security measures.

On a large scale, the enterprise approach represents a significant change from the individual mission model or even the local multi-mission model. One government agency moving in this direction is planning a whole new operational structure, new acquisition boundaries and processes, and revised operations concepts to handle many different satellites as fleets. Their funding model will include new base-level funding for the infrastructure aspects and ground equipment operations, and separate mission funding for the space-asset monitor and control operations.

2.5.6 Multi-Center Commonality Model

At NASA, decisions on how to best support a specific mission have been made by the missions in the context of available capabilities at the responsible NASA Center. In some cases the mission operations are performed at Universities or partner sites and not at a NASA Center.

NASA Centers today often use common solutions (software reuse, multi-mission, local enterprise) for different mission classes. Some Centers are much more consistent in their use of common products across many missions than others. The AMMOS system used at JPL is a great example of common mission software. But as NASA looks to the future, maybe the commonality should extend to larger segments of the NASA mission set. Should there be commonality across all Earth Science missions? Should multiple Centers or even all NASA Centers use common software or operate using a NASA mission operations enterprise?

If the goal does become Agency-wide common solutions, the range of options include:

- A common NASA catalog of software available to each Center
- An open system approach that allows each Center to address their own unique needs while sharing common architectures or specific tools
- A common ground system solution that can meet the superset of requirements of all missions

The approaches are easy to request and difficult to realize. Governance issues, cost sharing issues, heritage software and operations approaches, the need or desire for local control, and equitable work-share split across the Centers must all be addressed.

2.5.7 The European Budget Reduction Business Model

Any of the models described throughout this section can be successfully implemented, but there are no real forcing functions today other than the generic “let’s try and do better and save costs” direction. The European Space Agency found that missions will spend what is available in their budget to build their mission control center, and the amount had not changed dramatically in years. Their solution was to build a suite of common tools and then set the mission ground system budgets for new missions to less than half of what they had been. Missions found that without budget to build things themselves, the only way to meet their cost and schedule constraints was to utilize the new common software that was being offered to them. It took a while, but the benefits began to grow and as commonality grew, training costs came down, cross training increased, and the mission teams realized they could be successful with a significantly reduced budget.

2.5.8 Outsource

It is now possible for missions to purchase operations support from an outside group using a fee-for-service model. This is currently offered by NRL/Blossom Point and was tried in the past by General Dynamics and others.

In the future, mission operations could be offered as a service, with data streams becoming the deliverable product from the operations sites. Mission personnel would focus on planning and scheduling activities and leave routine operations to the contracted support provider.

2.5.9 Hosted Payload

The hosted payload model has several major differences from the traditional mission approach. Firstly, the hosted payload is launched as a secondary consideration to the primary mission, usually a telecommunications satellite. Because it is a secondary payload, it does not drive launch accommodations or schedules as it would as the primary mission. This means that NASA must be ready for payload integration and testing at the time dictated by the primary's schedule. Long-term mission simulations are not performed prior to launch; perhaps a small number of end-to-end data connectivity checks is all that's provided. With the hosted payload model, mission infrastructure is greatly reduced. There is no NASA mission control center but the mission may have a smaller science operations effort or interact directly with science community. Science operations develop schedules and execute command uploads through the primary's mission control center. This implies an external interface between the host's control center and the mission science control center. Data can be distributed to the science control center either by direct broadcast from the host satellite to the science center or by utilizing one of the host's data ports and ground-based communications.

With the hosted payload model, NASA achieves a cost savings by not building a mission operations capability but instead contracting payload monitoring and routine operations with the host control center. NASA also achieves a cost savings by not paying the full cost of the launch but a pro-rated share of the launch cost as a secondary payload. There are additional communications costs in providing a link with the host control center; however, this can typically be implemented via an Internet connection and not a hard-wired land-line. There may be additional costs for data security services and data distribution protocols. NASA will need to conduct trade studies for the mission to determine the most effective approach to data distribution into and out of the host's enterprise environment.

3 Scenarios and Use Cases

Imagine the near future when . . .

- Tested ground systems are assembled in months, not years. Days or even hours may even be possible.
- PIs and spacecraft/instrument component vendors can view status information and help diagnose problems remotely.
- Different missions collaborate with each other through the Cloud to determine best science opportunities.
- Mission operations staffing is kept low or on-call; the software will call you if there are problems.
- A user can monitor dozens of small spacecraft and coordinate their activities. Individual satellites can easily be added or deleted from the mix.
- In addition to the spacecraft and on-orbit/in-situ instruments, we monitor the ground equipment and the data/product distribution progress; and we are aware of related activities on other missions.

These scenarios are discussed below to illustrate the potential impact of emerging technology on anticipated trends for new Earth science mission concepts. The scenarios are

1. Hosted Payload Scenario
2. Small Satellites Scenario
3. Airborne Science Locally and Remotely Piloted Vehicle Scenario

For each scenario, assumptions about the future mission operations environment is described along with specific examples of how the scenario might unfold, given the trends discussed in Section 2. The study team then identified both management and technology gaps between current capabilities and the future mission operations capabilities enabled by new technology.

3.1 Hosted Payload Scenario

Assumed Environment

For this scenario, we assume that typical Hosted Payload (HPL) applications will operate in Geostationary Earth Orbit (GEO) on a commercial telecommunications satellite; although LEO hosted payload opportunities, especially on the International Space Station, are expected to be common. In this environment, NASA will operate a “fleet” of different science payloads on multiple hosts.

In the ISS environment, the HPL is operating on the ISS, but with a simple direct interface from the payload control center to the hosted payload as described below for commercial satellites. This interface is designed so that ISS safety issues are resolved during the development stage and do not require “human-in-the loop” interactions during payload operations.

Mission operations for HPLs on a commercial host have the host satellite treating the science payload as a device on its operating bus supplying power and data services to the HPL. The host satellite’s control center monitors critical telemetry for health and can shut down the science payload if it is endangering

the host but otherwise has minimal interaction. If the science payload is a danger to the host, the host will shut it down based upon an agreed protocol and procedure. The science payload contracts with the host operator for delivery of any required host satellite processed data necessary to support science data processing.

The science payload control concentrates on processing the science data, payload housekeeping data, and payload commanding. The science payload control center has visibility into the host's mission operations to know when activities that affect the science payload occur, e.g. momentum dumps, but the science payload operations do not control any operations of the host spacecraft.

The science payload uses a secure, Cloud-based data storage paradigm that is available as a commodity service with guaranteed backup for all data. The host spacecraft operator provides data links between the HPL and the host mission control center as direct links to the science payload control center. For low-rate HPL commanding, the mission control center uses a means of direct transmission to the science payload without going through the host's control center and uplink process. For high-volume HPL commanding, e.g. major reconfigurations or software uploads, the science payload control center utilizes the host's command uplink to send the appropriate files through the host's mission control center to the spacecraft C&DH, and to the HPL on the host spacecraft bus.

Specific Scenario Example

- Commercially hosted payload with the vendor taking responsibility for the health and safety of the host.
- Payload data is provided to the NASA limited-function MCC along with some engineering data. The MCC will monitor the health of the NASA assets and serve as the coordination point between the instrument planners and the mission host.
- Little to no guidance, navigation, and control are necessary. Mission planning is primarily associated with managing the payload.
- MCC is merely a data collection and distribution center using Cloud-based data storage cobbled together with virtual equipment and/or software defined systems for a software defined MCC
- MCC collects data, scrubs it, and provides it to users in raw format.
- Users, in a crowdsourcing manner, perform data analysis, data analytics, and product generation.
- The MCC may collect the data analysis results and data products, including data provenance, into the data store for others. Raw data and subsequent data products are made available from the compendium through a store front.
- Standards must be set and followed.

Management Gaps

The LaRC hosted payload team tasked with developing a working relationship with the commercial satellite developer and operator community, has discovered management process deficiencies that are impacting the development cost and schedule. The team firmly believes that these impacts can be mitigated by better government processes in procuring services more like a fungible commodity. Specifically, the current experience has demonstrated that to have cost effective

management of the HPL fleet, NASA needs to develop a bulk services contract method that covers multiple years (up to 10 years) with a service provider so that multiple hosted science payloads can be brought under a common umbrella contract for services much like a Space Act Agreement. By treating the services as a fungible commodity, the government can take advantage of the working relationships in the industry to lock service provisions into place, even beyond the lifetime of a single HPL instance, so that multiple HPLs can be brought under this umbrella pricing structure.

Technology Gaps

The current technology suite is lacking in the following support areas:

- Telemetry data delivery formats that are compatible with the commercial transponders and teleport hardware/software configurations need to be standardized and accepted by the HPL fleet members.
- Vendors need to offer a Cloud-based ground station virtual application for command and telemetry processing that can be used on multiple platforms. Current analog: Microsoft's OneNote application that is available on PC, Mac, Kindle, and etc., platforms. OneNote loads user data from the Microsoft Cloud and the user can switch between any of the available platforms for utilizing the data "anytime, anywhere". In the hosted payload case, there needs to be developed an agreed upon standard allowing data to be stored on a secure Cloud site. In this standard, each hosted payload in NASA's "fleet" has a unique database in the Cloud storage. However, there is a firewall between databases for different science payloads.

Mission Operations

With these new capabilities in place, the hosted payload mission will operate in the following ways:

- Command and telemetry operations are accessed via the Cloud-based application with access to the secure data Cloud. New data arriving or generated are automatically stored to the Cloud database for the individual hosted payload.
- Individual command data packets are sent as encrypted short-message service packets over the commercial telecommunications link from the "anytime, anywhere" user platform to the hosted payload.
- Full satellite telemetry (housekeeping and science data) is sent as files over the commercial link, as required or contracted, to the mission teleport from which the data are delivered to the science payload control center.
- Bulk command and telemetry data are sent as files over the host spacecraft's forward link where they are delivered to the science payload via the host spacecraft bus.

3.2 Small Satellites Scenario

Assumed Environment

We assume that the demand for supporting small satellites in Low Earth Orbit will continue into the future with mission support being required for (a) individual satellites, (b) clusters of multiple satellites, and (c) cooperative configurations of small satellites with traditional major satellites or the International

Space Station. A typical cluster of small satellites is expected to range from three to ten members that will need support from a common mission infrastructure.

In this environment, we also assume that NASA's ground receiving station infrastructure will not have sufficient capacity to support the traditional Earth missions plus fleets of small satellites. In this environment, the mission designers will look to commercial providers for supplemental communications access to the small satellites. This will require that interface and licensing issues have been resolved and that the space-based or ground-based networks provided by companies such as USN, Iridium or Globalstar will provide this service as a routine option.

Mission operations for multi-satellite control will be conducted using minimalist infrastructure and not demanding 24x7x365 staffing. Mission operations will instead demand anytime/anywhere access to mission data, command capabilities, and critical status using a variety of computing platforms and data services. This presumes the availability of a secure, Cloud-based data storage provided as a commodity with guaranteed backup for all data.

Specific Scenario Example

- GSFC manages a fleet of 40 small satellites providing full Earth coverage at all times + 2 heritage satellites with 3 instruments each, using GSFC's common open architecture software.
- JPL manages 3 large Earth science satellites using their common software.
- Instrument operations are split between ARC and LaRC.
- Data from the large fleet is used in near real-time to task the larger satellites.
- Coordination across all 4 Centers is done using new CCSDS data exchange services to access Cloud-based storage (secure Cloud for government use).
- In-situ ground-based sensor data is used to calibrate space sensors.
- ARC coordinates activity planning using the planning & scheduling system that is standard across the Agency.
- GSFC's Flight Dynamics facility interacts with the missions for navigation functions.
- Cross-Center operations team shares a common access security system.
- Operations team staffing surges for launches – 8 satellites per launch.
- Routine operations for satellites are moved to another facility for launches (data lines reconfigured using software-defined networking).
- 4 hours of core support per day (all Centers available) are required for routine operations, most activities fully automated.

Technology Gaps

The current technology suite is lacking in the following support areas:

- Small satellite command and telemetry standards with minimal overhead and full IP compatibility need to be developed and adopted by vendors and users at all levels. In particular, command and critical telemetry are needed that are compatible with short message communications formats. Also, bulk telemetry file formats that are compatible with commercial delivery protocols are also needed.

- A command data encryption protocol with low computational overhead needs to be standardized for use in the small satellite environment. An initial assumption is that this will be a software-based design and not a hardware device.
- Vendors need to offer a Cloud-based ground station virtual application for command and telemetry processing that can be used on multiple platforms. Current analog: Microsoft's OneNote application that is available on PC, Mac, Kindle, and etc. platforms. OneNote loads user data from the Microsoft Cloud and the user can switch between any of the available platforms for utilizing the data "anytime, anywhere". In the satellite control case, there needs to be developed an agreed upon standard allowing data to be stored on a secure Cloud site. In this standard, each small satellite in the cluster has a unique database in the Cloud storage and the virtual application is capable of switching between databases on the fly.
- Cost points for mission control applications products for small satellites and multi-satellite configurations have come down compared to today's cost models with high cost for use on much more expensive missions.

Mission Operations

With these new capabilities in place, the multi-satellite mission will operate in the following ways:

- Mission operators utilize a "zero footprint" control center (ZFCC) application with Cloud-based storage to provide command and telemetry processing functions in an anytime/anywhere manner using the computing platform of their choice. The ZFCC application has full access to the secure data Cloud. New data arriving or generated are automatically stored to the Cloud database for the individual small satellite.
- Individual command data packets are sent as encrypted short-message service packets over the commercial telecommunications link from the zero footprint user platform to the target small satellite.
- Critical telemetry parameters can be sent on a periodic basis as short messages to the operations target application.
- Full satellite telemetry (housekeeping and science data) are sent as files over the commercial link a small number of times each day (one to three times, typically).
- Bulk command and telemetry data are sent as files over the commercial link.

3.3 Airborne Science Locally and Remotely Piloted Vehicle Scenario

Assumed Environment

We assume that the demand for real time observation of Science Phenomena not practical due to coverage, repeat time and instrument inadequacy of satellites in Earth orbit will continue into the future, with mission support being required for (a) citizen scientists, (b) regional phenomena analysis by domain experts, and (c) International collaborations which may, or may not, additionally involve small satellites, and/or traditional major satellites, and/or the International Space Station.

In this environment, we also assume that the level of semantic and procedural interoperability being currently achieved by groups like the Open Geospatial Consortium (OGC) and OASIS continues, and the

adoption and incorporation of these standards ubiquitous in both the consumer and commercial marketplaces.

Specific Scenario Examples

- A citizen scientist (e.g., non-civil-servant millionaire), a grape grower in California’s Napa Valley, is considering purchasing an adjoining piece of land, fallow for a few years. She wants to know the likelihood of Phyloxera being present in her, and the adjoining, fields. She fires up the browser in her phone, and types in her vineyard name, the adjoining property name, and the string “likelihood of Phyloxera”. She then makes a cup of coffee, chooses a vendor, from the 18 responses to her query, based on price and accuracy, dons her VR glasses, and walks out the door. She sees, overlain on her vista, a time series depicting the waxing, and waning, of Phyloxera for the past 10 years, and is offered a projection out 5 years at additional cost.
- The California Department of Emergency Services, in response to a wildfire that overnight changed direction and increased in intensity, and now threatens a small town that is home to a nuclear power plant, calls for the use of NASA’s Global Hawk UAS fleet, and is required to coordinate operations with US Forest Service small UASs already on site. The power plant needs at least four hours to be shut down, and, if shut down, will disable a major part of the Western US power grid.
- The International Disaster Charter has been invoked by a small but very populous island nation in the Pacific for a Category 5+ typhoon that has already broached a Chinese passenger ship and is hours from potential landfall. US Global Hawk UASs based on Guam have been requested for over-the-hurricane data collection and deployment of micro-drones into the storm, the Japanese HALE solar powered UAS has been requested to loiter and supply local area communications, and any available hi-resolution satellite imagery available is needed. The program manager will be in Taiwan.

Management Gaps

The current management suite is lacking in the following support areas:

- Distributed, federated, cross-realm Identity Management systems are required.
- International data/asset sharing agreements are not quickly or easily instantiated.
- Identification (and authentication) of regional asset managers is required.
- Trusted/provenanced information ingest is needed.

Technology Gaps

The current technology suite is lacking in the following support areas:

- Cross-platform planning and tasking services for both satellite and airborne assets
- Role based, distributed, federated, cross-realm Identity Management systems
- Real time communication between air, space and ground based assets
- Simple, in-flight re-configurability
- Mechanisms for traceable and verifiable machine-to-machine task costing

Mission Operations

With these new capabilities in place, the combined air and satellite missions will be able to operate in the following ways:

- A citizen scientist, in a MCC consisting of one human, can assemble a process chain containing space based observation assets, ground based archives and models, and value-added (for cost) brokers, quickly, efficiently and in real time.
- California's OES, utilizing a distributed, web-based Emergency Operation Center (WebEOC) can task NASA UAS assets, and coordinate them in one Common Operating Picture (COP) that works equally well on mobile phones and desktop computers. Additionally, tasks of a lower priority are pre-empted on a supercomputer based modeling system that predicts, with a high probability, that the fire will not endanger the power plant.

A room sized MCC can be assembled, in hours, in Taichung, utilizing commodity hardware. Using secure satellite communication links, a NASA Global Hawk UAS can be repurposed with micro-drones as one primary payload and its software defined communication systems re-configured, a Japanese solar powered UAS launched as a wide area communications platform, two remote sensing satellites re-aimed, and a third shifted in its orbital slot.

3.4 Use Case Gap Analysis

Looking across these uses cases, we compared their gaps as part of defining our conclusions and recommendations. Table 3-1 summarizes the use case gaps discovered.

Table 3-1 Use Case Scenario Gap Analysis

Dimension	Use Case Scenario		
	Hosted Payload	Small Satellites	Airborne Science
Assumed Environment	Science payload attached to a GEO telecommunications satellite	NASA center operating a cluster of 10s of small satellites for a science mission	Real-time science data delivery to customers and stakeholders
Example Mission Operations Leveraging Trends	Cloud-based command and telemetry operations, operators have “anytime, anywhere” access, data delivery using commercial links	Utilization of Zero Footprint Control Centers, secure Cloud-based data operations, use of commercial links for telemetry and commanding	Citizen scientist chaining information for air, space, and ground assets
Management Gaps	Procurement issues and processes affect overall mission cost and schedule	Cost points for mission control applications	Distributed identity management systems, international data/asset sharing, trusted information ingest
Technology Gaps	Data packaging compatibility with commercial transponders	Gaps in data standards, command encryption protocols, Cloud-based virtualization & data operations	Cross-platform planning & tasking services, real-time communications between air, space, and ground, in-flight reconfigurability

4 Summary of Findings

4.1 Study Findings

The following findings represent key principles gleaned from this study:

- **Approach the architecture as a system:** Simple suggestions like “just make one system for everyone to use” or “the latest technologies make the best system” or “now we need a new approach because of cubesats” miss the point that there are many, many factors that together should affect our final mission operations and system design decisions.
- **Use the best of the old and the new while reducing costs:** We are in a period of tremendous pressures to reduce long-term mission operations costs at the same time that the industry itself is going through a period of significant change. Many of our old practices and assumptions may no longer be ideal, but we cannot simply discard our current infrastructure and capabilities – we must plan to leverage our heritage and move deliberately towards our new goals.
- **The only constant is change:** The high rate of change in both space data systems requirements and operations concepts, as well as the rate of change in technology available to help address the new challenges requires us to carefully plan our future mission support architectures.
- **The architecture must be flexible across many domains:** Clearly, our future investments must help lead to new systems that are vetted from multiple perspectives, can themselves accommodate change easily, and can address the ever-widening range of mission support requirements. New systems will combine aspects of multiple existing approaches used in a more versatile open-system approach and leveraging appropriate new technologies that are now available or still to be identified.
- **Incentivize for new solutions:** We must find ways to incentivize our missions and organizations to encourage the creation of our new flexible systems which infuse extensibility and efficiently meet the growing breadth of common needs across our new missions.

The following represent the top themes that emerged from the study and should provide opportunities for continued ESTO investment to best benefit the future Earth science missions.

- **Lower cost and ubiquitous access.** Regardless of mission size, the need for lower and lower ground system and mission operations costs continues to be a primary objective and, in some cases, a potential mission-enabling criteria. A theme that can tie to lower cost is the desire for remote access and “lights-out” mission operations capabilities. Carried further, we see a move towards a goal of a “Zero Footprint Control Center” where all access is remote (even if it is at an office desktop or shared conference room). This would open up many new operations concepts. To accomplish this will require that NASA integrate the use of Cloud-based applications and storage, software defined networking, virtual machines, flexible and reconfigurable software, modern security protocols, etc.
- **Internet of Things.** Future mission operations systems will require knowledge from more sources than just the spacecraft’s telemetry stream. Data from other satellites, from ground-based sensors, from ground equipment and facilities and more will help inform the mission operations efforts when developing and executing mission operations plans. The concept of “the internet of things” is expected to become commonplace and ground systems will need to

be able to routinely and dynamically utilize data from many sources. The availability of many data sources introduces concerns over data security, multiple communications paths and networks, data provenance, and data reduction and comprehension.

- **Use of standards.** Standards are key to getting low cost consistency across system development and operations. NASA participates in space standards organizations, but reduced funding in recent years has eliminated much of the in-depth analysis and prototyping necessary to influence and take full advantage of new standards. In addition, new standards for cubesat and smallsat data interfaces and for NASA-wide approaches should be pursued. Investment by the organizations that will see the benefits of these efforts could supplement the NASA standards efforts and greatly increase the potential benefits.
- **Accounting for the rate of change.** Requirements, cost-points, technology, business models, and operations concepts are all changing rapidly. It is important that investments in new architectures be designed assuming that change will continue at a rapid pace. We need to look at ways to embrace it in our approaches and architectures. Concepts for study, evaluation, and implementation include service-enabled capabilities, open system architecture, system of frameworks, etc. Any new architectural approaches should be paper-tested against some of the potential changes that could occur over the next 10+ years.
- **Development of Use Cases.** It is suggested that sample Earth science future mission and ground system use-case scenarios be baselined and periodically updated. The scenarios could include small satellites, hosted payloads, suborbital vehicles, collaborative science mission, etc. New technology work and other investments could be vetted against the needs of these scenarios. The scenarios would have to be updated periodically and be openly available to those proposing new ground system investments.

4.2 Study Recommendations

The following recommendations are intended to help evolve the NASA Earth Science Mission Control Center systems to achieve the MCC Enterprise Architecture including 1) a common, robust baseline capability across mission operations, comprised of common services and tools to enable reuse and customization, and 2) an interoperable infrastructure enabling process virtualization, automation, and cyber security.

Going beyond the trends investigated during the study, three categories of actions were identified to help ensure that the MCC systems continue to evolve and enable efficient, affordable and secure operations of future missions:

- Actively participate in mission operations “Community of Interest” activities to represent Earth science interests
- Invest in new technologies to benefit Earth science missions through improved mission operations concepts
- Devise a capability for experimenting and validating advanced mission operations technologies and concepts

4.2.1 Mission Operations Community of Interest Participation

The study team recommends that HQ program management for mission operations ensure that Earth science interests are well represented in Agency and international initiatives to address on-going needs to improve space mission operations. This recommendation focuses on Earth science mission management activities that would enable mission operations planners to collaborate on identifying needed infrastructure changes, conducting studies and analyzing needs to address continuing MCC evolution. HQ program management overseeing the planning and development of Earth science missions needs to maintain awareness of external initiatives that will directly affect operation of NASA missions to ensure that resulting standards and business models will meet their needs. As was seen with the imposition of standards to protect MCCs from hackers, it was very costly to meet new requirements. Further, it will be more costly for Earth science missions if they cannot leverage new industry developed capabilities built on aerospace standards. It is essential that Earth science representatives participate to raise awareness of their needs and ensure that necessary options are included so that meeting NASA-wide requirements can be appropriately scoped to control costs.

Several ongoing candidate activities and forums were need further attention to support Earth science MCC evolution, including

- International standards bodies addressing satellite operations (e.g., CCSDS, OMG, OGC)
- USAF initiative to develop a common ground system
- NASA-NOAA joint operations initiative
- NASA Mission Operations TCAT (Technical Capabilities Assessment Team) follow on
Several common mission operations areas have been identified for deeper study, of which a couple deal with infrastructure architecture and common ground system software integration, issues that are significant to Earth science missions. The TCAT team recognizes differences between science mission and payload operations, balloons, rovers, and crewed and uncrewed missions. At the TCAT conclusion, a new Mission Operations Strategy Team (MOST) follow up.
- Mission Operations System Strategy Group
The current focus is to advise HQ on the NASA position regarding CCSDS decisions related to mission operations; however the team envisions this group could effectively expand to address common issues, emerging trends, and how to leverage technology, and in effect, support the Mission Operations Strategy Team (MOST)

Participation in a mission operations community of interest could be achieved with limited resources to collaborate and share insights. For example, the development of use cases has proven to be a useful method for explaining operations concepts. A Mission Operations Community of Interest could be responsible for baselining and periodically updating sample Earth science future mission and ground system use case scenarios. Initial scenarios could include smallsats, hosted payloads, suborbital vehicles, and collaborative science mission. Standards assessments as well as new technology and other investments could be vetted against the needs of these scenarios.

The following topics emerged as important candidates for further investigation via collaboration within a Mission Operations Community of Interest.

- **Use of emerging standards.** Standards groups are very active and their decisions will affect Earth science mission operations so it is critical that HQ stay involved. Science payload requirements differ significantly from NASA's manned spaceflight, and Earth observing missions differ from planetary missions. CCSDS has 26 active working groups. The OMG Space Domain Task Force has several standards they are working on. If there is no effort to recognize, prototype, and infuse the new standards, then the planned benefits will not be realized by Earth science missions. Earth science mission operations can benefit from emerging standards, including mission operations services, delay tolerant networking, cross support, and navigation by direct participation.
- **Development and Use of Smallsat Data Standards.** Smallsats are expected to become prevalent Earth science platforms because they enable cheap access to space but current emphasis is on standardizing cubesats form factors for flight. We will be in trouble if we don't have consistent ways to recognize and process the data streams to and from the various classes of small satellites. CCSDS? IP? TDM? Something new? Picking a couple of standards would be better than no standard. Could we even standardize, like Europe does, memory dump formats and interactions, stored command loads, etc.?
- **Fleet management for clusters of satellites.** Growth in use of smallsats and leveraging hosted payloads, both on ISS and geo platforms will enable more science missions with distributed payloads. The goal is to reduce the overhead and bring commonality to the NASA fleet through ground access scheduling, mixed public/private provider access, minimal scheduling overhead/real-time scheduling, leveraging public/private assets. Can we have a spot market for ground station access and data connectivity?
- **System of Frameworks Concepts.** What approaches can we use to allow the Agency-wide sharing of capabilities without interfering with successful heritage systems we may each have? How do we join the many independent data systems in common ways to simplify data exchange and coordination with minimal impact to each of the systems? More work is needed on the development of multi-protocol, multi-security gateways to help join independent mission control centers while allowing each center its own ability to manage its internal design and capabilities.

4.2.2 Technology Investments to Improve Earth Science Mission Operations

Given the rapid changes in technology and the pressing need to reduce costs through improved mission operations, the study team recommends a sustainable capability to develop, evaluate and evolve new technologies. This recommendation is focused on ESTO technology, including specific technology areas that would uniquely benefit ESD's ability to respond to the trends identified in the study.

Investigating satellite, operations, and information technology trends helped inform the identification of several timely candidate technologies.

- **Advancing Near Real-Time Mission Planning and Sensor Tasking.** Dynamic tasking of missions to support science observations will continue to evolve as onboard processing resources mature. We anticipate an increased need for data analysis requiring near real-time data accessibility to enable spacecraft tasking, for example, to capture transient events (e.g., tornadoes), support severe storm warnings, report lightning strikes, etc. Goal-oriented onboard mission planning and re-planning, science data processing, and adaptive real-time mission responsiveness to events are capabilities requiring technology maturation.
- **Developing Expert Tools for Virtual Operations.** Mobile access to data and commanding interfaces through multiple platforms (from workstations to smart phones) will further enhance lights out

operations. Trends in smart devices are moving beyond speech recognition to machine learning techniques to examine data and predict outcomes or suggest solutions. Expert systems that know how to autonomously operate spacecraft are also needed to learn from operational experience (e.g., tools to analyze trends in the volumes of MCC data logs); model-based expert systems may be able to validate command sequences.

- **Leveraging the Internet of Things (IoT).** As many new device types evolve to be internet-aware, the variety of data sources will increase tremendously, a trend of special significance to Earth science. Subcomponents of instruments, small field sensors, or even personal devices could all become data sources that complement the traditional scientific sensor data we will continue to collect. Smart buildings are being configured with environmental sensors to detect weather and air quality (especially to manage electric use) enabling future missions to leverage these IoT sources for ground-based event detection. We envision a future need for data agents to know where to find specific data to support real time observations within the IoT, including monitoring of real-time targets of opportunity and tasking on orbit sensors in response. Technology is needed to handle and aggregate the variety of data types and associated data provenance, including communications and security challenges of the evolving IoT.

4.2.3 Capability to Experiment and Validate Advanced Mission Operations Concepts

The role of mission operations is essential to mission success and thus requires the ability to test and validate new operations concepts and supporting technology. Many emerging concepts are expected to be beneficial to all NASA missions as well as the common baselined capability envisioned for the future Earth science MCC. Hence, this recommendation would likely require collaboration between technology and mission management functions, both within ESD and across the Agency, including all of SMD as well as SCaN and STMD. The study team recommends that HQ consider a range of capabilities for testing and validating new mission concepts and technologies from ground-based prototypes to an on-orbit test environment, potentially based on space assets (e.g., ISS payload, end-of-life mission, or a dedicated cubesat). Such a suite of capabilities would enable designers to load new flight software or exercise new protocols without impacting basic spacecraft health (a strategy that the European Space Agency is employing.) Mission planning teams could propose new capabilities, allowing a user to interact with a live spacecraft to validate concepts and mature the technology. The study team identified the following concepts for further investigation:

- **Demonstrate Integrated Cloud Services:** Since the Cloud is key to virtualized operations, how do we manage it properly with multiple input ports (public and private), back up, data distribution, security measures, data provenance, data integration (multiple DTN delayed packets), etc.? Cloud technologies will continue to advance without specific Earth Science investment, but the potential use of the Cloud capabilities for secure mission-critical, time-sensitive mission operations will need additional evaluation and investigation.
- **Explore and Validate Cyber Security Strategies.** The use of Cloud-based technologies for data retrieval and storage, and for application software distribution brings up many security issues as has been noted earlier in this report. As we move to the Internet of Things, users will have similar security concerns not only with the data from the source but also with the value-added services that the source may provide. As data distribution increasingly involves public networks as well as government networks, there is a heightened concern for data security, especially with command data and spacecraft health data. Associated with these basic security issues is the accompanying issue of data provenance for insuring that the mission data comes from a valid source and has not

been compromised either in transit or in storage. All of these security concerns require missions to have the ability to test and validate proposed new protocols and algorithms for maintain data and applications security and provenance before adopting them into the mission control structure.

- **Rapidly Configure Modular MCC Components.** Software-Defined Networking, in addition to Cloud computing, can combine to enable mission operators to treat a physical control center room like a schedulable conference room – simply reconfigure the data access for different groups. SDN, logical abstraction to software-defined radios, could help manage external access to data streams and support “zero footprint” control centers. How do we integrate the networking layers with the Level 1 and Level 2 hardware and protocols of the radio? Also bring in the routing layers, etc. so we have the whole stack in the same box.
- **Prototype a Zero Footprint Control Center.** This concept can be used to tie together many of the independent technology capabilities listed above. An end-to-end system could be Cloud-based with network connections made dynamically. Such a virtual facility could support training of personnel in mission operations that would provide a foundation for understanding spacecraft design. With increased automation and remote access capabilities, an objective of going for extended periods of time without staffing a physical mission control center could be realized.
- **Infuse Mission Operations Improvements into Spacecraft and Sensor Design.** Onboard processors are catching up to the performance improvements available in commodity processors, and will continue to feed the migration of traditional ground operations functions to the spacecraft, so that self-controlling spacecraft and sensors enable “lights out” operations. Building on standards for common functions, spacecraft interfaces will feature “plug and play” capabilities both in the spacecraft electromechanical systems and the software and control systems.

In conclusion, we need to “Keep the conversation going”. Maintaining awareness of industry trends and advancement in a dynamic, ongoing process. This study identified a set of trends. These trends will change over time and, within a year, there will probably be changes in the directions of some trends, there will be new hot technologies to watch as new trends evolve, and there will be some areas where new ideas become commonly accepted as part of the baseline. For these reasons, it is important to maintain an awareness of industry advancements, new business practices, and new challenges, while supporting Earth science mission teams in accomplishing science goals. The effort put into participating in mission operations strategy groups, tracking technology and promoting the need for NASA-wide collaboration for mission operations advances will help achieve the common goals of providing more science for the science operations community.

Appendix A. Acronyms

ARC	Ames Research Center
C&DH	Command and Data Handling
CCSDS	Consultative Committee for Space Data Systems
COTS	Commercial off-the-Shelf
DTN	Delay- (or Disruption-) Tolerant Networking
DVB-RCS	Digital Video Broadcasting - Return Channel via Satellite
ESD	Earth Sciences Division
ESTO	Earth Science Technology Office
FDD	Flight Dynamics Facility
FOSS	Free and Open Source Software
GOTS	Government off-the-Shelf
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
HPL	Hosted Payload
IP	Internet Protocol
ISS	International Space Station
JPL	Jet Propulsion Laboratory
LaRC	Langley Research Center
LEO	Low Earth Orbiting
IoT	Internet of Things
MCC	Mission Control Center (also Mission Operations Center)
MPLS	Multiprotocol Label Switching
NASA	National Aeronautics and Space Administration
NASCOM	NASA Communications
OMG	Object Management Group
OGC	Open Geospatial Consortium
ORS	Operationally Responsive Space
PC	Personal Computer
SDN	Software Defined Networking
TCAT	Technology Capabilities Assessment Team
TCP/IP	Transmission Control Protocol/Internet Protocol
TDM	Tracking Data Message
TDRS	Tracking and Data Relay Satellite
VR	Virtual Reality
ZFCC	Zero-Footprint Control Center