Ancillary Scientific Instrument Attachment (ASIA): A Distributed Hitchhiker Payload Carrier

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ACADEMIC ABSTRACT

As more spacecraft reach more locations in the solar system, and with increasing residual capability of those spacecraft, an opportunity exists to improve scientific return at low cost to the satellite operator and minimal effect on its primary mission, regardless of the nature of that mission. The practicality of permanently attaching a small, mass-produced, non-deployable hitchhiker payload to modern spacecraft buses is investigated, and a case study of one such payload is presented. The Ancillary Scientific Instrument Attachment (ASIA) is a modified CubeSat bus that can be mass produced, independently tested, and delivered to spacecraft manufacturers with the design, analysis, integration, test, and software development already complete. All it requires are single-string power and data connections, and a location to mount the bus structure. The unit includes power regulation; data collection and storage; command processing; thermal control; and structural support. As many as five small scientific instruments can be included, all of which increase scientific value of the host spacecraft's primary mission without significantly interfering with that mission. Generally, ASIA would operate independently, with a minimum of interaction from the host spacecraft operations team; only routine data dumps for scientific return need be executed. Scientific data processing, distribution, and bus subsystem troubleshooting are offloaded to an independent facility. One possible scientific instrument loadout is described, designed to collect data about the space environment at any location in the solar system. Recommended forward steps for designing, testing, demonstrating, and implementing such a space-based system and its ground elements are presented.

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GENERAL-AUDIENCE ABSTRACT

Modern spacecraft (“buses”) are designed to provide basic services for one or more primary payloads. These services include electrical power, orientation control and orbit maintenance, radio communication with control centers and end-users on the ground, and structure to support the payload during launch. Spacecraft buses are often Commercial-Off-The-Shelf, built to include flexibility to support a wide variety of different payloads without extensive modification. The proposed Ancillary Scientific Instrument Attachment (ASIA) is a small, self-contained module that includes a variety of small, low-cost sensors. The unit can be mass-produced, independently assembled, and delivered to a spacecraft vendor as a low-priority, simple way to increase the scientific benefit of nearly any spacecraft that launches. It is a “hitchhiker” payload, acting as a self-contained add-on unit that, unlike CubeSats, is not deployed or released once in orbit; instead, it remains connected to the host spacecraft and relies on that spacecraft for power, radio, and attitude control services. All the unit requires are power and data connections from the host spacecraft, both of which are generally abundant on modern bus designs, and a location to mount it. Because of its low cost, ASIA units can be launched on multiple satellites to distribute development and operational costs while allowing for many measurements to be taken at different parts of Earth orbit simultaneously. A ground computer system will receive, process, and distribute the scientific results of the distributed units to the scientific community. The basic organization and technical characteristics of this concept are presented, including functions of the space unit, the corresponding ground system, and an example instrument loadout for sensing characteristics of the space environment throughout the solar system.

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ABC	Aft Bulkhead Carrier (Atlas V auxiliary payload mount point)
ACS	Attitude Control System
AFRAM	Active Flight Releasable Attachment Mechanism
AGCF	ASIA General Coordinate Frame
AIAA	American Institute of Aeronautics and Astronautics
ANS	American National Standard
ANSI	American National Standards Institute
APID	Application Identifier (for CCSDS packets)
APRA	Astrophysics Research and Analysis (NASA program)
ASIA	Ancillary Scientific Instrument Attachment
CCSDS	Consultative Committee for Space Data Systems
CDH	Command and Data Handling system (onboard computers and data buses)
CDS	CubeSat Design Specification
CFDP	CCSDS File Delivery Protocol
CII	Common Instrument Interface (NASA project)
conops	Concept of Operations
COTS	Commercial Off-The-Shelf
CRS	Cosmic Ray Subsystem, an instrument suite on the Voyager probes
CSD	Canisterized Satellite Dispenser
CSLI	NASA's CubeSat Launch Initiative
CSV	Comma-Separated Value (tabular data format)
DOD	(United States) Department of Defense
DPS	Data Processing System
DSCOVR	Deep Space Climate Observatory (NOAA mission)
DSN	Deep Space Network
ECSS	European Cooperation for Space Standardization
ELaNa	Educational Launch of Nanosatellite
EM	Electromagnetic (radiation, spectrum, or field)
EMI	Electromagnetic Interference
EPS	Electrical Power System
ESA	European Space Agency
ESD	Electrostatic Discharge
FGST	Fermi Gamma-ray Space Telescope (NASA mission)
FSW	Flight Software
GAS	Get Away Special, a Space Shuttle hitchhiker payload program
GBM	Gamma-ray Burst Monitor (instrument aboard FGST)
GEO	Geosynchronous Earth Orbit (not necessarily geostationary)
GOES	Geosynchronous Operational Environmental Satellite (NOAA constellation)
GOLD	Global-scale Observations of the Limb and Disk (NASA mission)
GOTS	Government-Off-The-Shelf
GRB	Gamma-Ray Burst

GSFC	NASA’s Goddard Space Flight Center (Greenbelt, MD)
HEASARC	NASA’s High Energy Astrophysics Science Archive Research Center
HET	High Energy Telescope, a high-energy particle detector in the Voyager CRS
HPA	Hosted Payload Alliance, an industry alliance
HSC	Host Spacecraft
HTV	H-II Transfer Vehicle (Japanese resupply ship to the ISS)
IEEE	Institute of Electrical and Electronics Engineers
IF or I/F	Interface
ISS	International Space Station
IT	Information Technology
ITAR	International Traffic in Arms Regulations
ITOS	Integrated Test and Operations System
I&T	Integration and Test
JAXA	Japan Aerospace Exploration Agency
JEM	Japanese Experiment Module “Kibo” aboard the ISS
JPL	NASA’s Jet Propulsion Laboratory (Pasadena, CA)
LADEE	Lunar Atmosphere and Dust Experiment Explorer (NASA mission)
LASP	Laboratory for Atmospheric and Space Physics (University of Colorado)
LEO	Low-Earth Orbit
LET	Low Energy Telescope, a low-energy particle detector in the Voyager CRS
LRO	Lunar Reconnaissance Orbiter (NASA mission)
LSP	NASA’s Launch Services Program
LV	Launch Vehicle
mAh	milliampere hour
MEO	Medium-Earth Orbit
MeV	Mega-electron Volt
MIL-SPEC	Military (Defense) Specification
MIL-STD	Military (Defense) Standard
MMOC	Multi-Mission Operations Center
MMOD	Micrometeoroid and Orbital Debris
MMS	Magnetospheric Multiscale Mission
MOC	Mission Operations Center
MRO	Mars Reconnaissance Orbiter
NASA	National Aeronautics and Space Administration
NEN	Near-Earth Network
NICER	Neutron star Interior Composition Explorer (ISS Experiment)
NLAS	Nanosatellite Launch Adapter System
NPR	NASA Procedural Requirement
NSP	NASA Strategic Plan, last released in 2014
NSP	(United States) National Space Policy, last released in 2010 (spelled out in the text for clarity, to distinguish it from the NASA Strategic Plan)
OPAL	Orbiting Automated Picosat Deployer
opcode	Operation Code, computer bit sequences designed to execute a function

OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer (NASA mission)
PFRAM	Passive Flight Releasable Attachment Mechanism
POST	Power-On Self-Test
P-POD	Poly Picosatellite Orbital Deployer
RF	Radio Frequency
RFI	Radio Frequency Interference
RMS	Remote Manipulator System (robotic arms and related equipment)
ROSES	Research Opportunities in Space and Earth Sciences
SAE	SAE International (formerly the Society of Automotive Engineers)
SC or S/C	Spacecraft
SCCF	SUPERNOVA Chassis Coordinate Frame
SMA	Safety and Mission Assurance
SMD	NASA’s Science Mission Directorate
SRAM	Static Random Access Memory
SSPP	Shuttle Small Payloads Programs
SSR	Solid-State Recorder
STEM	Science, Technology, Engineering, and Math
STP	Space Test Program (DOD)
STP-H	Space Test Program – Houston (DOD)
STS	Space Transportation System (naming convention for Space Shuttle flights)
SWaP	Size, Weight, and Power
TBD	To Be Determined (not enough information to definitively evaluate)
TBR	To Be Reviewed (information subject to change after further analysis)
TDRSS	Tracking and Data Relay Satellite System (NASA comm network)
TLE	Two-Line Element (spacecraft ephemeris format)
TOD	Time-Of-Day (computer message specifying current time to subsystems)
TRL	Technology Readiness Level
TRMM	Tropical Rainfall Measuring Mission
TVAC	Thermal Vacuum (space system testing process)
ULA	United Launch Alliance
USGS	United States Geological Survey (Department of the Interior)
USOS	United States Orbital Segment (NASA/JAXA/ESA/CSA part of the ISS)
UT1	Universal Time
UTC	Coordinated Universal Time
VBSDC	Venetia Burney Student Dust Counter, a payload on New Horizons
VDC	Volts, Direct Current
Wh	Watt-hour

1. Introduction

1.1. Project Overview

As the number and reach of deep space probes increases, the opportunity to carry sensors other than the prime mission sensors likewise increases. Many scientific probes include multiple sensors to maximize the effectiveness of a single flyby (e.g., Voyager, New Horizons); others contain multiple instruments for persistent observations (e.g., MRO, LRO); still others are dedicated missions with a single instrument travelling to a single location (e.g., the Magellan Venus mapping mission). Commercial satellites, including communications relay and mapping services, are becoming more common and can consist of dozens of coordinated units in constellations at various altitudes and orbit geometries. The common aspect amongst these missions is that a physical spacecraft bus with various subsystems designed to support one or more prime payload is at a scientifically-interesting location within the solar system.

This project proposal is to design a modular system – the Ancillary Scientific Instrument Attachment (ASIA), a non-deployable hitchhiker payload carrier that is cheap, lightweight, mechanically and electrically simple, and capable of hosting a small number of student or research payloads. The ASIA unit could be mass produced and attached to as many spacecraft as desired, providing low-cost opportunistic science data collection throughout the solar system. Wherever the host spacecraft (HSC) goes, scientists on the ground will receive science data not normally collected by the primary instruments (which in all likelihood will be switched off during cruise phases and perhaps some of the time during long-term operations).

This design concept provides the following benefits:

- Standardized design:
    - Production costs can be lowered when compared to a single instance of a sensor (reuse of the development resources, bulk orders of science instruments, etc.).
    - Integration and test can be standardized and broadly implemented with little or no effect on other development in a normal mission's prelaunch timeline.
    - No significant modifications to the HSC need be made except to provide the power, data, and mechanical connections; many spacecraft already have unused

connections available in power distribution units, data bus connectors, and several square centimeters of surface area on unused structural bracing or instrument deck plates, so no new capabilities need be added to an existing bus. Power and data margins required for ASIA could be capped at perhaps five percent of the HSC's total capacity.

- Since it is not a primary objective for the mission, ASIA can operate without fault tolerance for power and data; any data collected are more than would have been collected otherwise, and if the ASIA unit fails, the primary mission has lost nothing. That having been said, a number of missions have operated for extended periods with little or no redundancy by design.
- Low data rates and standardized formats permits low resource requirements for data transmission (both from the HSC and within the ground system), processing, storage, and distribution (either a standalone disc array with a web interface front-end or merging the data into an existing storage and distribution system).
- In situations where a single spacecraft is present (e.g., OSIRIS-REx), scientists could gain insight into various new aspects of a space environment, or continue studies using instruments similar to those used before, without the additional expense of a second launch vehicle and probe.
- In an environment where multiple spacecraft are present (Low Earth Orbit (LEO), Mars orbit), multiple ASIA units could provide simultaneous measurements of identical parameters, allowing for spatially-diverse interpretation and/or higher revisit frequencies (similar to the Magnetospheric Multiscale Mission operating in Earth's radiation belts).
- The hitchhiker concept eliminates the need for an independent attitude control system (ACS) and propulsion module (saving power, volume, weight, and complexity over free-flyer CubeSat missions, in addition to saving development time and money for those subsystems) and has the additional benefit of not scattering multiple hard-to-detect objects into crowded orbits where collisions may be more likely and carry greater consequences to other missions.
- Mission and payload longevity improve, as money and volume can be spent on

instrument quality and the HSC provides orbit maintenance. Additionally, resources need not be spent on space segment deactivation and disposal.

This system would also benefit from work in disaggregated systems: instead of plotting ideal trajectories for multiple spacecraft to maximize coverage, a model could instead be developed to predict sensor coverage based on given trajectories of the HSC and identifying areas of interest for different scientific parties. For example, areas of close temporal or spatial measurements of multiple ASIA units could be isolated and provided quickly to researchers.

The result is a low-cost, modular system that can be deployed *en masse* into a variety of environments. Development costs are spread across multiple flight units, and the overall body of scientific return (including return for non-scientific missions if the attachment is fitted to a commercial spacecraft) can be improved with minimal operating and maintenance costs. Data distribution can be accomplished through either existing U.S. Government scientific data systems or an independent, low-cost server hosted at an academic institution.

This document provides an historical perspective of secondary scientific experiments, small payloads, payload hosting (including requirements and evolution from both the HSC and the hosted payload), and the current state of NASA and commercial payload hosting. It goes on to describe a conceptual design of the basic ASIA bus (including the subsystems that would support the scientific system as well as its interfaces to the HSC); a sample scientific payload cluster which can detect and characterize the local space environment; the ground elements and interfaces to collect, process, store, and distribute the collected data and maintain the space segments; and discusses feasibility of the system and a road to program implementation.

1.2. Document Objectives and Layout

This project attempts to achieve the following objectives:

1. Describe the historical context, precedent, and state-of-the-art for small scientific payload hosting, where a larger space vehicle provides excess capability to secondary mission objectives.
2. Describe the proposed space and ground segments of a CubeSat-derived hitchhiker payload attachment which could facilitate hosting several small scientific instruments. A case study

for one possible instrument loadout is provided.

3. Discuss the feasibility of and next steps toward developing and implementing a system similar to the one discussed.

The research presented in Section 2 targets the history and development of hosted and small payloads throughout America's civil space program history, from the Space Shuttle to the International Space Station (ISS) to research and development projects. Recent developments in small satellite (SmallSat) design (including CubeSats) and commercial hosting of scientific instruments are also discussed. Interviews of scientists and engineers at NASA's Goddard Space Flight Center (GSFC) provide more information about these recent developments, and the application for the ASIA system. ASIA is a logical evolution of previous programs, updated to incorporate new technologies and design philosophies and the changing face of the U.S. civil space program, and fills a niche for small payloads that current programs do not fully address.

Section 3 presents a conceptual design of the ASIA program. The first subsection provides overview information regarding the system and its philosophy of minimal effect on the host spacecraft and its primary mission. Section 3.2 gives preliminary design considerations and high-level requirements of the space hardware (the "space segment" or "space element"), including the bus subsystems, the sample space environment instrument loadout, and interfaces between the ASIA bus and the Host Spacecraft (HSC). The preliminary design of the corresponding ground system for receiving, processing, storing, and distributing the collected science data is presented in Section 3.3. Administrative considerations for the sample project (program management, funding, infrastructure, staffing, and interaction with the science community) are discussed in Section 3.4. Assumptions about the HSC and the services it can provide to the ASIA program (both spacecraft services like power and communications systems, and ground-based systems such as ephemeris generation and necessary commanding), along with rationale for assuming those services will be available, are listed in Section 3.5.

The potential returns from this hypothetical program and its feasibility are presented in Section 4. This section also includes the forward path for implementing such a program, and its ability to expand and grow to different mission profiles (including one ultimate evolution, where the ASIA bus can host a number of unrelated academic or scientific experiments in a general fashion). A case study involving the adaptation of a free-flying 6U CubeSat to a common LEO host spacecraft bus is analyzed for cost savings, power and data margins, and effects on launch costs, ground systems, and scientific return.

Section 5 includes summarizes the project. Briefly, the concept of a CubeSat-based, non-deployable payload carrier appears to be viable with modern technology, system architecture, and engineering and administrative practices. The versatility of the proposed system provides a new method of allowing small, cheap payloads access to space, with significant scientific return and cost savings to the developer.

Section 6 lists citations, references, and key standards relevant to the systems described in Sections 2 and 3. Appendix A presents a concise set of high-level requirements of the proposed system.

1.3. Notes

The research and implementation of the ASIA concept described in this document are targeted toward a civilian-scientific application for space systems, in the hope that it will be adopted as an extension of NASA’s ongoing efforts in opening space access to a greater number and wider variety of missions. Military or commercial applications may exist, but they are not explored here. A similar platform could also be applied to airborne or suborbital launch systems, but one of the fundamental goals for ASIA is to increase small program longevity, best served by missions in well-maintained orbits.

Companies, system components, experiments, sensors, and other elements are named only to give examples of industry involvement in the ongoing SmallSat revolution, and not to endorse their use specifically or exclusively. Indeed, this paper attempts to describe capabilities and characteristics that a potential ASIA system could, or should, exhibit, and not to define the method or specific products by which it would achieve these characteristics.

2. Literature Review and Industry Research

Hosted scientific payloads aboard spacecraft are not new, and small deployable or retained systems have heritage back through the beginning of the Space Shuttle program. Continuing miniaturization, ruggedization, and radiation-hardening of electronics, along with increasing capability of both launch vehicles and satellite systems, have led to capabilities for even modest academic programs to design and build small satellite systems. Increased NASA interest and industry involvement have followed, producing a number of technological advances and the supporting administrative infrastructure, further opening access to space.

This section describes the background and modern state of concepts and systems critical to understanding ASIA, as well as the environment into which the program would fit. It also describes current hosted payload programs, as well as the miniaturization, increasing complexity, and cost reductions in smaller, secondary missions.

2.1. Hosted Payloads

The traditional assumption among the non-scientific community is to equate one launch with one satellite, a single vehicle that delivers a single probe to a single destination for a single purpose. In some cases, this is correct (the Magellan probe carried only one instrument to one location, a synthetic-aperture radar to Venus). However, as launch vehicles and flight systems (both on the component and on the spacecraft level) allow for multi-role spacecraft and multi-probe launches (up to ten Iridium communication satellites can be launched on a single launch vehicle, and the Juno probe to Jupiter contains seven scientific payloads).

Excess capability on spacecraft buses also gives the opportunity for lower-priority, externally-developed payloads. These are often built by research organizations such as universities and non-profit organizations, but can also include corporate, U.S. Department of Defense (DOD), or civilian government payloads. Such “hitchhiker” payloads can improve and diversify a mission while sharing costs between many projects and ultimately imposing little negative effect on the primary mission and equipment.

2.1.1. New NASA Mission Classifications

Traditional NASA missions fall into one of four categories based on their payload criticality (usually measured against NASA's Strategic Plan, (NSP)), cost, and required level of reliability [1] [2]. Briefly, these categories are:

- Class-A missions and payloads are critical to the national interest or NSP. They require the highest quality and tightest constraints on parts, plans, and operations concepts, in order to perform a unique mission for five years or longer with no chance of re-flying the payload. Examples include the Hubble Space Telescope and Cassini-Huygens.
- Class-B missions and payloads are critical to the NSP but can accept slightly less stringent constraints and redundancy for the sake of lowered costs and a somewhat reduced operational life, or the chance for a similar capability to be flown on a later mission (or operational redundancy). Examples include high-profile national programs like the United States Geological Survey (USGS)' Landsat series, NOAA's Geostationary Operational Environment Satellites (GOES), NASA's Tracking and Data Relay Satellite System (TDRSS) individual satellites, and one-of-a-kind, long-term scientific probes like MAVEN and OSIRIS-REx.
- Class-C missions are less complex and can accept a larger number of launch opportunities due to fewer constraints and a (usually) smaller package. The Lunar Reconnaissance Orbiter (LRO) and Magnetospheric Multiscale Mission (MMS) fall into this category.
- Class-D missions have the lowest complexity and cost (ranging from thousands to a few million dollars), significant opportunities for reflight on other missions or launches, and lower effect on the nation's and agency's science objectives; cost plays more into their design than reliability, longevity, or capability. This category includes ISS internal payloads and Space Shuttle Get-Away-Special (GAS) canisters. Some limited-scope, relatively low-cost scientific missions such as the Lunar Atmosphere and Dust Experiment Explorer (LADEE), Deep Space Climate Observatory (DSCOVR), and Neutron star Interior Composition Explorer (NICER) ISS experiment are also included.

With the increasing popularity of smaller payloads and smaller, more capable subsystems came the ability for universities and other small organizations to build their own miniature spacecraft. As NASA began working with such organizations in providing access to spaceflight opportunities to those projects, it developed an unofficial category of "sub-Class-D" missions, those not only with minimal effect on major science objectives, but also so small in scope and resources that traditional procedures, policies, requirements, and other elements of mission design (ranging from Safety and Mission Assurance (SMA) to component selection) cannot be effectively or logically applied. These missions are characterized by a budget in the low tens to low hundreds of millions of dollars, mission lifespans of a few months to a few years, heavy reliance on Commercial-Off-The-Shelf (COTS) parts, changes in the methods used for component and subsystem quality assurance, and putting an emphasis on a “make it work” philosophy [3] [4].

By 2013, new categories of payload, component, and risk definitions were being put into use at GSFC and other NASA centers. The broad category of Research and Technology projects (officially referred to by its NASA Procedural Requirement number, NPR 7120.8) is hallmarked by low priority of resources, high technical risk, and a number of short-life missions that make a general success rate more useful than an operational design life (e.g., 85 percent of projects successful over the calendar year, instead of an average life of four months for each subsystem in a project).

Later, another unofficial category of “Do No Harm” projects arose, where a program could execute an objective outside the NPR 7120.5 and 7120.8, usually attached to a larger spacecraft (i.e., not as a free-flying mission but rather a hitchhiker payload). The key characteristic of this class is that the payload must not harm the host spacecraft, with an additional stipulation that no mishap or mission failure would be declared if the hitchhiker payload fails (this condition occasionally applies to small Class-D programs as well).

2.1.2. Hosted Payloads and National Space Transportation Policy

As part of the effort to guarantee reliable and routine access to space, the National Space Policy since at least 2010 [5] has mandated the ability for (and encouraged the use of) hosted payload arrangements for government payloads on commercial satellites. Various benefits were described, including (among others) [6]:

- Fostering responsiveness and cost efficiency while maintaining manufacturing and national security abilities in the country
- Reducing the number of missions requiring slots in geosynchronous orbit, which are in limited quantity and high demand

- Reducing costs to perform on-orbit demonstrations to increase the Technology Readiness Level (TRL) of new systems and components, without the full cost of building and launching a dedicated satellite

The National Space Policy also describes intent to maintain space weather and prediction capabilities for use domestically and for the international scientific community.

The Hosted Payload Alliance (HPA), a "satellite industry alliance formed to increase awareness of the benefits of hosted government payloads on commercial satellites," was formed in 2011 [7]. It consists of seven executive members (a range of large vendors and operators like Boeing and Iridium) and nine other industry partners representing the DOD, communications equipment vendors, and international partners. The organization has assisted dozens of scientific and technical demonstrator payloads in reaching and maintaining orbit [8], including X-ray imagers on solar array yokes for the GOES program, radiation dosimeters and thermal coating tests on a commercial communications satellite, and receivers for the U.S. Coast Guard's Nationwide Automatic Identification System aboard seven different asset-tracking Orbcomm satellites.

Using a hosted payload agreement for a major or primary instrument has been suggested in a number of cases but has not always been accepted. The follow-on mission to Landsat 8 was under consideration to use "either a hosted payload or international partner concept," both of which were rejected by Congress on the grounds that the continuity of Landsat data was at risk due to delays and distractions inherent in such concepts [9]. Other missions with lower priority (as well as one-offs and technology demonstrators) have had greater success.

The New Horizons mission, which flew by Pluto on July 14, 2015, carries the Venetia Burney Student Dust Counter (VBSDC), produced by the University of Colorado Boulder. Designed to collect particles from more than twice as far from the sun as any previous instrument, this secondary payload represents a number of different roles academic institutions play in the modern space program [10]:

- As a secondary payload, it contributed to the overall scientific return of a larger mission without interfering in primary objectives.
- The New Horizons project provided funding and routed it through the Johns Hopkins

Applied Physics Laboratory, who manage and operate the mission. The Southwest Research Institute (an external organization) and the university's Laboratory for Atmospheric and Space Physics augmented this funding.

- Students garnered experience about space mission design and scientific return.

As a small add-on payload produced by the academic community, the VBSDC represents an example of the science data collection proposed in this document (see Section 3.2.2.1).

2.1.3. Space Shuttle Small Payloads

With the Space Shuttle's large cargo volume, upmass capability, and capability to return payloads from orbit came the opportunities for non-NASA parties to send more secondary and minor payloads at significantly reduced prices. Early in the program, administrative and technical initiatives began to make the most of these capabilities, resulting in several formally-defined processes for internal and external payload hosting. These processes were later adapted for the ISS.

2.1.3.1. The Space Shuttle GAS Program

The Shuttle Small Payloads Project (SSPP) office began designing a process for routinely carrying small additional payloads into orbit when the Space Shuttle itself was still under design and initial testing in the mid-1970s [11]. Under the Get-Away Special (GAS) program, a cylindrical, thin-walled canister could be rented to an educational institution, U.S. Government entity, or private entity for a single flight for the purpose of executing some research or science experiment. Fees ranged from \$3,000 to \$10,000 for the mission, based on the volume and encapsulated mass of the experiment. Options included a motorized door to open the can to space, a window allowing the payload to conduct visual observations, and other "extra" functions. Interaction from the crew was limited to flipping a few switches a few times in the mission, minimizing the need for specialized crew training.

The first "GAS can" was flown on STS-3, the third validation spaceflight of the Shuttle program and one designed to expose the Shuttle to thermal extremes. The SSPP took the opportunity to characterize the internal environment of the canister, used the data to refine the GAS Experimenters Handbook, and published the data to the hundreds of organizations that had already submitted applications for the GAS payload opportunities. The first experimental GAS payload, GAS-001, was flown on STS-4 in June 1982 and contained ten experiments designed and fabricated by students at Utah State University.

As additional payloads were produced and the review/processing/integration flow matured, the number of flown GAS cans increased to three on STS-6, and then to seven on STS-7 (in June 1983, a year after the first flight). A specialized carrier structure that spanned the width of the Shuttle cargo bay, carrying up to 12 canisters at once, first flew on STS-61C in January 1986. By 1989, the program was working with between 60 and 90 payloads at various stages in the processing flow at any given time with an average of 13 months from initial proposal to completion of all major payload reviews from the NASA office.

Figure 1 shows a typical set of GAS canister payloads, installed on the STS-91 cargo bay sidewall during preflight processing; the left contains a small experiment payload, and the right contains commemorative flags being transported to the MIR space station [12].

Figure 1: Two GAS cans mounted on STS-91 cargo bay sidewall (Credit: NASA)

The SSPP later branched out to larger and more complicated auxiliary payloads. The Full Diameter Motor Drive Assembly door on GAS cans, allowing ejection of a small satellite up to 68 kg (a forerunner to the Poly-Picosatellite Orbital Deployer (P-POD) type of microsatellite deployment systems of three decades later [13]). The “GAS bridge” hitchhiker carrier system (shown in Figure 2 [14]) included support for a 2500 kg payload (12 canisters) in a cross-bay structure and allowed payload interaction via laptop computer (for the crew) or direct telemetry link (via Space Shuttle communication assets) to a control center at GSFC. The Shuttle Hitchhiker Experiment Launcher

System (SHELS), a system of intermediate complexity would allow for satellites up to 180 kg to be deployed from the cargo bay without anything as complicated as the payload deployment and retrieval system’s robotic arm, but with greater mass and volume capacity (and therefore payload complexity) than the GAS can adaptation [15].

Figure 2. GAS bridge prior to installation in STS-107 (Credit: NASA)

The GAS canister program foreshadowed later scientific payloads, research and development programs, and some small ISS payloads. For example, STS-41G launched with two GAS canisters flown to test in-flight refueling for satellites [16], a concept that is still under development and demonstration phase in the Robotic Refueling Mission payload on the ISS [17].

2.1.3.2. Middeck Payload Accommodations

The Space Shuttle middeck was located below the flight deck, and included the main hatch, airlock, sleeping restraints, and a number of lockers for supplies and payloads. Shuttle middeck payloads were carried in these lockers, installable racks, and more rarely in the underfloor or other less-accessible locations. These general-purpose storage compartments were approximately 25x51x44 cm and could accommodate about 27 kg each; around 40 of them provided the vast majority of internal storage for the Space Shuttle [18], both for crew equipment (clothes, food, etc.) and for pressurized experiments. A number of lockers (and some of their contents, mostly food packets) and a larger, cylindrical payload occupying the space of two lockers are shown aboard the middeck of STS-4 in Figure 3 [19].

Figure 3. Middeck lockers aboard STS-4 (Credit: NASA)

Much like the GAS cans described above, various special modifications to the locker payloads were possible, ranging from thicker adapter plates for heavier payloads to increased insulation or air cooling for temperature control [20]. The middeck lockers could also be split into two half-size drawers, anticipating the split-unit configuration of the EXPRESS ISS racks described in Section 2.1.5.1. Later in the program, additional standards were specified for transferring the contents (or the drawer itself) to be transferred internally to the ISS or returned to Earth from the station.

Even though middeck locker scientific payloads were not added until after the Space Shuttle program was underway, more than 40 such payloads had been flown by 1986 (of which more than a half-dozen had been re-flown multiple times; one particular experiment, a radiation monitoring system, had been flown ten times). The addition of a dedicated payload rack in place of the standard galley increased the rate to an average of about nine middeck locker payloads per flight [21].

2.1.4. DoD Space Test Program

The Space Test Program (STP) series of Department of Defense missions, administered by the United States Air Force, has also benefitted from routine access to space. These are small, self-contained payloads that do not qualify for their own launch program but can still provide worthwhile technology development or demonstration [22], including civilian payloads in the national interest (though not necessarily scientific in nature). Since 1965, hundreds of payloads have been launched either as "piggy-back" payloads on larger rockets, as Space Shuttle middeck or GAS experiments, or occasionally in clusters on dedicated satellites designed to be lightweight, rapidly produced, containing standardized interfaces for different payloads, and compatible with many launch vehicles.

As the program grew, the organization began developing a satellite bus that could quickly and economically accommodate multiple non-conflicting payloads on a single launch, reducing recurring costs [23]. This Standard Interface Vehicle (SIV) provides well-defined electrical, thermal, data, and mechanical connections for up to four payloads, with capabilities for various altitudes and inclinations. Certain payload elements, including electronic interface cards, are provided to the payload development teams to further guarantee interface compatibility. The expected mature timeline allows for multiple vehicles to be in production at once, with a 26-month turnaround for initial development, design, fabrication, and integration/test; however, with standard interfaces, payloads can be added to the SIV late in the development process. Enforcing volume constraints allows flight on a variety of launch vehicles, including both Evolved Expendable Launch Vehicle (Atlas V and Delta IV) and commercial (for example, SpaceX and Blue Origin) rockets, so that a delay in the SIV schedule would allow flight on the next available LV instead of the next LV of the same type as originally planned. As of 2017, three STP satellites have been flown.

Because of the scale of the program and the Shuttle's flexibility, the STP was also able to formulate and implement the Quick Response Shuttle Payloads process where simple middeck payloads could be flown after only a few months, assuming the Shuttle had both unused volume and available upmass. By the end of the program, more than 250 small DOD secondary payloads and experiments had flown aboard 95 Shuttle missions [24].

A subset of STP missions is the STP-H (Space Test Program-Houston) series, hosted on standard ISS external payload accommodations. These are launched aboard commercial resupply missions (previously aboard the Shuttle, until that system's retirement) and installed robotically on the space station truss or other mount points. Experimental payloads range from an aerogel-based thermal insulation demonstration (launched aboard Endeavour on STS-134 in 2012) to miniaturized high-power computing platforms [25] and lightning strike sensors [26], launched aboard the SpaceX CRS-10 resupply ship in February 2017. These payloads are operated for a number of months or years before disposal (including safe return).

STP-H4 is shown in Figure 4, showing its overall size and the variety of instruments which can be supported (in this case, radiation dosimeters, space weather sensors, and nanosatellite communications technology demonstrators) [27]. It was launched to the ISS in 2013 aboard a Japanese H-II Transfer Vehicle (HTV) resupply ship and was installed on the Express Logistic Carrier (ELC)-1 pallet on the ISS truss.

Figure 4. STP-H4 during preflight processing (Credit: DOD Space Test Program)

2.1.5. ISS Hosted and Small Payloads

The International Space Station is an orbiting laboratory that provides not only engineering demonstrations for future vehicles and missions (NASA's "Moon, Mars, and Beyond" vision) but also scientific research for various international government, academic, and corporate institutions. A number of scientific experiments, especially those requiring direct human interaction, are located in one of several internal laboratory modules; experiments and other payloads too large to store inside, containing hazardous materials, or requiring direct access to the space environment are stored externally on a number of attach points on modules, logistics carriers, or directly on the space station truss itself.

Because of its multi-decade design life, the space station was designed to be modular both in terms of the construction itself and in the logistical sense. The average duration of a Space Shuttle flight late in the program was around two weeks, so a "permanently" mounted GAS canister payload meant only that it would not be changed during that two-week flight. Such an approach for the ISS would be inappropriate for anything except essential and non-upgradable hardware, because the ISS' maintenance capabilities allow it to outlast the operational lives of most payloads. Instead, NASA and the international partners on the United Space Orbital Segment (USOS) of the ISS (which includes the ESA Columbus Module, the Japanese Experiment Module, and the US-provided modules) opted for modular designs of every major connection, attach point, holster, and stowage location to allow everything from food packages to entire pressurized modules to be relocated, removed, replaced, or upgraded as needed. While many of the larger systems will no longer be moved (truss segments, the USOS-to-Russian Segment interface), others will maintain that mobility (pressurized mating adapters for future crewed spacecraft, new experiment racks lifted on commercial cargo, and external logistical spares like ammonia coolant tanks).

One well-publicized example is the set of three Synchronized Position Hold, Engage, Reorient, Experimental Satellites (SPHERES) [28]. These plastic modules, about the size of volleyballs, can be released into the ISS cabin, performing maneuvers to orient and position themselves using carbon dioxide thrusters, and include cell phones as their onboard computing platform. They can be operated individually or in unison to perform simple goals, including formation flying tests, educational outreach, demonstrating methods for space debris capture and disposal, and testing rapid deployment of firmware updates to onboard (albeit non-critical) systems. As recently as the summer of 2017, NASA was still soliciting proposals for experiments using the SPHERES.

Two SPHERES modules are shown in Figure 5, performing an autonomous docking experiment in the ISS atmosphere [29].

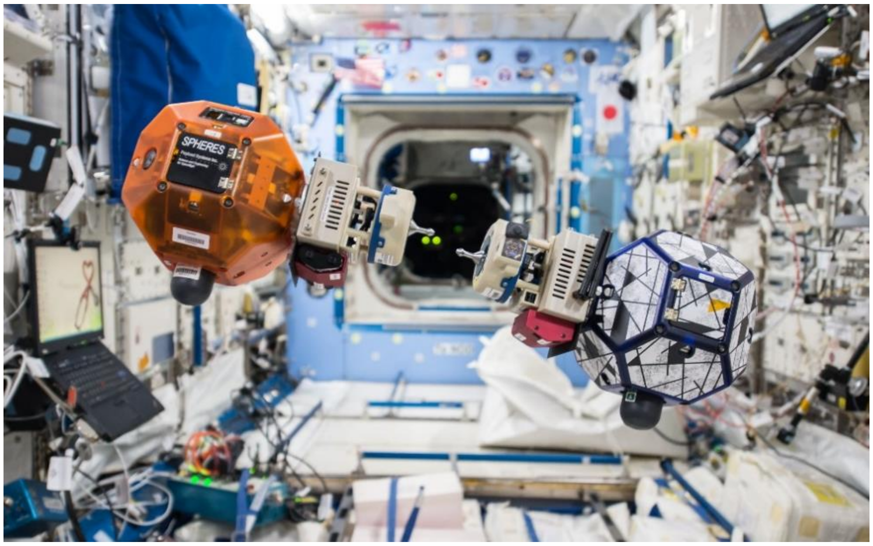

Figure 5. Two SPHERES modules attempt a docking maneuver (Credit: NASA)

2.1.5.1. Internal Accommodations

Most internal payloads in the USOS are stored using the International Standard Payload Rack (ISPR) system, a general-purpose container for experiments and other stowage. These racks measure approximately two meters tall by one meter wide by one meter deep at most (the rear is curved to conform to the space station's pressure shell) and mass between 800 and 1000 kg fully loaded [30]. Built for standardized mounting points, the ISPRs were designed to interface with and internally distribute various ISS-provided services, including DC power in primary and auxiliary feeds (up to 6kW in some of the 37 rack locations onboard); air and water cooling loops; data connections (1553 bus for command and control, 10Mbps Ethernet for data, and high-rate connections for direct interface with the Ku-band downlink system); vacuum, both for experiment and for waste gas removal; and nitrogen, carbon dioxide, argon, and helium connections in certain locations are also available [31]. ISPRs can be moved throughout the station as necessary, and can be launched on commercial cargo resupply ships, international cooperator vehicles like the Japanese HTV, and, previously, the Multipurpose Logistics Module (MPLM) carried in the Space

Shuttle cargo bay. The MPLM and SpaceX Dragon also allow for rack return instead of disposal during reentry.

For greater flexibility with smaller payloads, a variant of the ISPR called the "EXpedite the PRocessing of Experiments for Space Station" (EXPRESS) was made available in eight ISPR locations onboard starting in 2001. The EXPRESS racks allow modular integration of up to ten experiments into a single unit for launch. Eight slots are the same size as Space Shuttle middeck locker, with two-cubic-foot and 72-pound (0.057 cubic meters and 32.7 kg) capacity, and the remaining two are International Subrack Interface Standard drawers, which total 1.3 cubic feet and 44 pounds (0.037 cubic meters and 20 kg) combined. Payloads can be controlled directly with a connected onboard laptop, or via ground command [32].

Figure 6 [32] shows the EXPRESS rack size and configuration after its delivery and installation during STS-131 in April 2010. All eight middeck locker units are shown, along with a variety of jumpers and connections on the front panel.

Figure 6. JAXA astronaut Naoko Yamazaki with an EXPRESS rack (Credit: NASA)

2.1.5.2. External Accommodations

In addition to interior payload racks, three major types of interfaces are allocated for exterior "small" payloads (roughly 1 cubic meter and mass 200 to 300 kg) on the USOS [33], and one additional type on the Russian segment:

1. Four ELC pallets, attached to the outer elements of the truss, each of which can accommodate eight to twelve payloads combined between both sides of the pallet
2. A total of ten sites on the Japanese Experiment Module (JEM) Exposed Facility (JEF) platform, of which five are allocated for NASA's use
3. Four sites on the ESA's Columbus science module's External Payload Facility
4. Nine external workstations on the Russian Segment's "Zvezda" Service Module

These sites are shown in Figure 7 [34]. Three External Stowage Platforms (ESPs) provide additional locations for on-orbit spares [35].

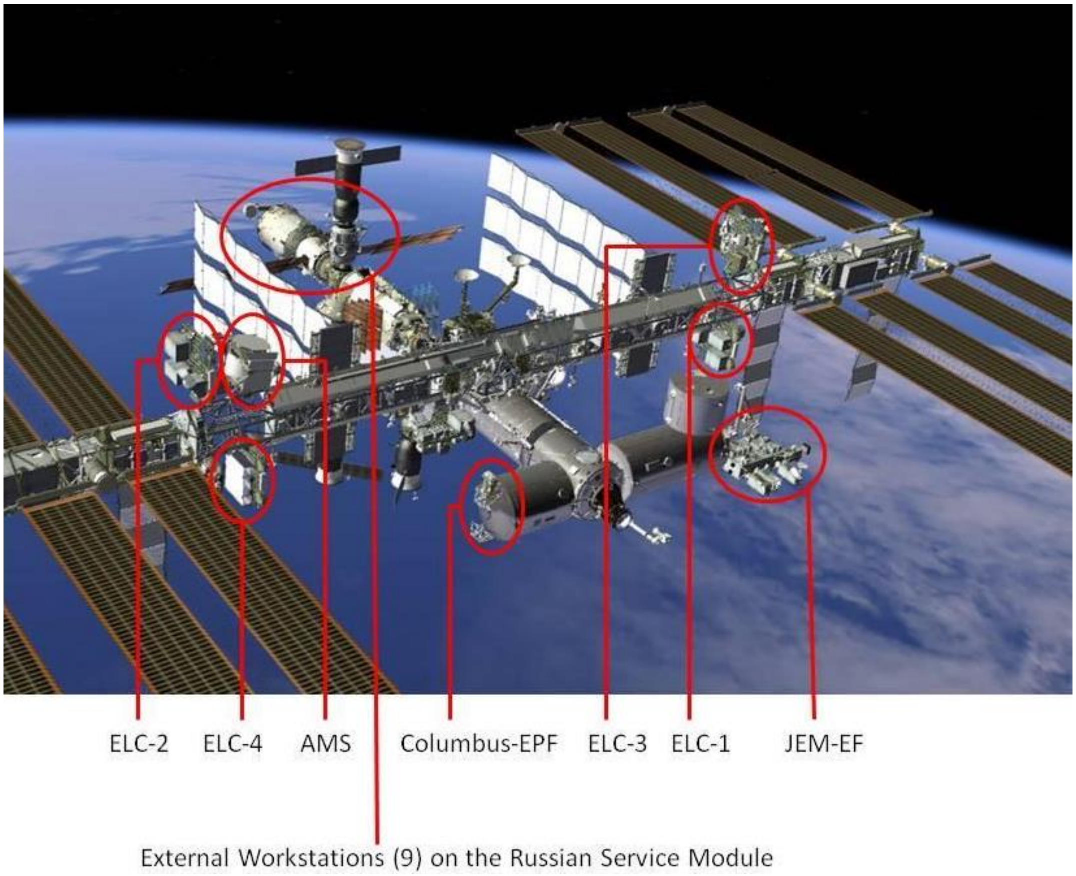

Figure 7. ISS external payload accommodations (Credit: NASA)

Between these accommodations, these different sites offer mechanical systems to retain a payload for weeks, months, or years at a time (plus the station's robotic manipulator system to install and remove them), power in the 500W to 2kW range for equipment operation and electronics survival heaters, and data connections to the ISS Command and Data Handling system (CDH), ranging from the 1Mbps of a 1553 bus connection to 10/100 Mbps Ethernet, plus access to the ISS Ku-band high rate downlink communications system. The ISS host provides wide-angle sky and earth observation coverage (with some blockage from station structure, depending on the particular mounting location), a low surface-contaminant rate, and a varying but well-known and predictable pointing and vibration environment. The STP-H payload series referenced in Section 2.1.4 above makes use of berthing slots on the ELC pallets.

The Active Flight Releasable Attachment Mechanism (AFRAM) is a standardized system used to attach these large payloads to the ELCs and Columbus exterior locations. The AFRAM drives mechanical latches and power and data connections to mount the payload onto the passive half of the mechanism (PFRAM). An ISS External Stowage Platform with a spare nitrogen tank and a number of PFRAM locations are shown in Figure 8, during STS-126 preflight processing [36].

Figure 8. ESP with PFRAMs and Spare Equipment (Credit: NASA)

A special case of a hosted external payload is the Alpha Magnetic Spectrometer 2 (AMS), installed aboard the ISS during the STS-134 mission in May 2011 [37]. The high-energy particle detector experiment is designed to detect cosmic rays and probe the balance of “normal,” dark, and antimatter in the universe. The AMS is permanently mounted directly to the station’s S3 zenith truss mount point, and other than its size (roughly four meters on a side and 8500 kg in mass) and the fact that it occupies one of only six such truss attach points, it represents a fairly typical ISS hosted payload. It has flight heritage with AMS-01, an instrument carried aboard a Shuttle flight in June 1998, uses ISS power and data services but maintains its own internal CDH and thermal control, and was delivered as a self-contained unit designed to use existing ISS infrastructure instead of custom interfaces [38].

The installed AMS-02 and a pair of ELC pallets are shown in Figure 9 [39]. AMS-02 is the silver cylindrical unit on the far right, with the ELC-2 pallet immediately behind and ELC-4 on the opposite side of the truss. Note the relative size compared to the two spacewalking astronauts, and the various spare parts attached to both sides of the ELCs.

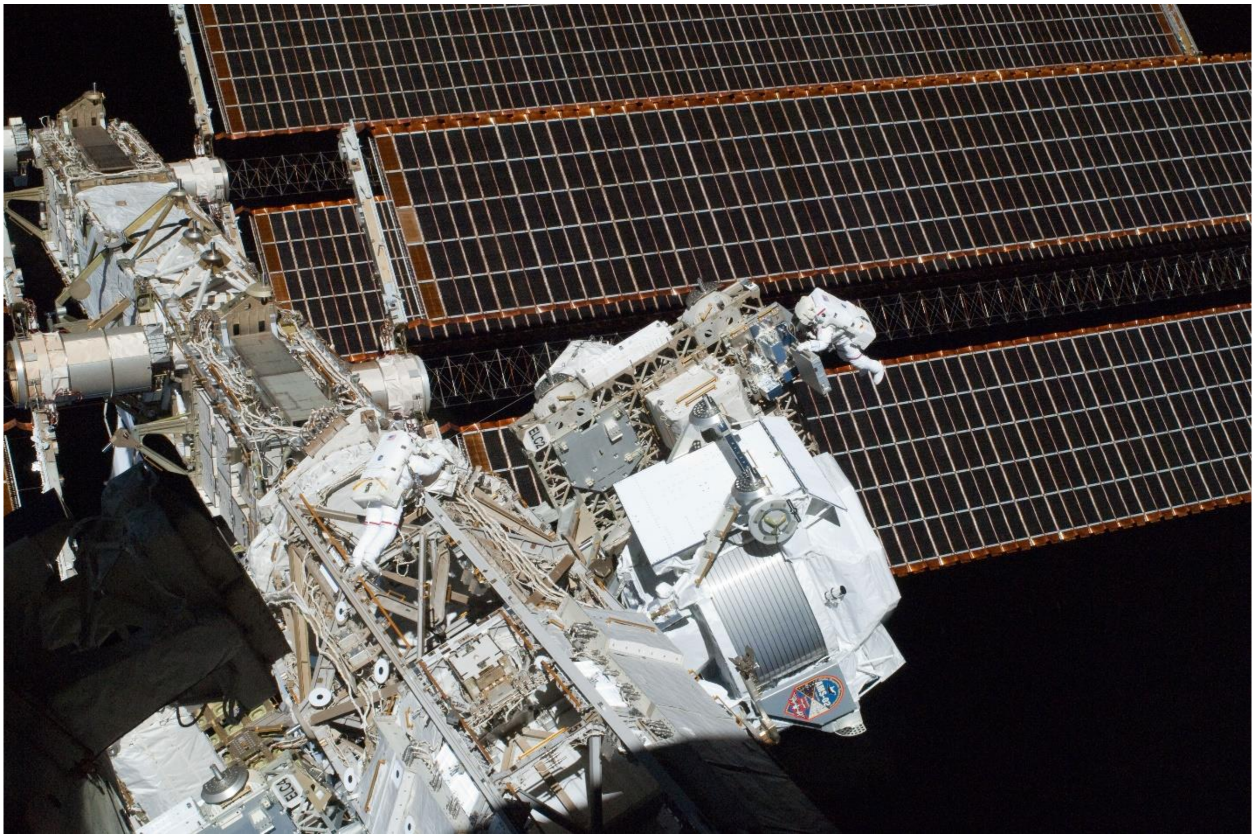

Figure 9. AMS, ELC-2, and ELC-4 mounted on ISS exterior (Credit: NASA)

In addition to these permanent and semi-permanent payload accommodations, the ISS also serves as a temporary storage and deployment platform for CubeSats on certain kinds of rideshare agreements; see Section 2.2.2 below.

2.1.6. NASA Solicitation for Projects

The NSPs of 2011 and 2014 [40] include objectives to "optimize Agency technology investments, foster open innovation, and facilitate technology infusion, ensuring the greatest national benefit." The Earth Science Division (part of NASA's Science Mission Directorate (SMD)) established the Earth System Science Pathfinder (ESSP) Program in 2011 to accomplish this objective with regards to climate and environmental change. ESSP projects are "operational and developmental, high-risk, high-return orbital and sub-orbital Earth Science missions and advanced remote sensing instruments for missions of opportunity," which "encompass the entire life cycle from definition, through design, development, integration and test, launch or deployment, operations, science data analysis and distribution [41]."

One category of ESSP projects is the Earth Venture program for small missions. Earth Venture projects are broken down by scale:

- Earth Venture Instruments, known as "missions of opportunity," which are deployed aboard other orbital vehicles (including free-flying satellites and the ISS)
- Earth Venture Sub-orbital projects, including missions with life spans shorter than a conventional free-flying satellite mission. Mission platforms range from sounding rockets to aircraft to CubeSats)
- Earth Venture Missions, which are "uncoupled, relatively low-to-moderate cost, small to medium-sized, competitively selected, orbital and sub-orbital projects that are built, tested and launched [in] short time intervals"

In order to increase the likelihood of program selection, and to ease the development and integration of these missions, ESSP has also funded a number of recommendations for standardizing interfaces between prospective payloads and generic host spacecraft and ISS platforms, implemented by NASA's Common Instrument Interface Project [42].

More broadly, NASA's SMD occasionally advertises opportunities for funding, development, and implementation of scientific missions, including the annual Research Opportunities in Space and Earth Sciences (ROSES) solicitations [43]. One recent solicitation of ROSES includes provisions for suborbital-class payloads for studying the sun, its interactions with Earth and other planets, and the space weather environment. (Note that “suborbital-class platforms” in this context is a term for the size and complexity of the payload; the definition extends beyond true suborbital equipment such as sounding rockets and into CubeSats and small ISS-hosted payloads.) Proposals can be awarded between \$100k and \$1M, providing one potential source of formal funding through a major government organization.

ROSES also caters to other areas of research programs in a manner similar to Earth Venture. The Space Science Division of NASA’s SMD provides funding for low-TRL technologies and demonstrations through the Astrophysics Research and Analysis (APRA) [44], with the Strategic Astrophysics Technology (SAT) program providing funding for mid-range TRL missions that align with agency strategic and decadal survey objectives.

2.2. CubeSats and Small Payload Rideshare

Modern technology has matured to where electronic components are available to a wide clientele. General-purpose open-source hardware, such as Arduino and Raspberry Pi, can sell a basic unit that includes a microprocessor, onboard storage, multiple digital and analog I/O connections, and power/data connections for less than \$30 and 30 grams of mass budget. Other companies and organizations offer modular, plug-and-play structures, solar arrays, gyroscopes, and similar spacecraft components designed to the CubeSat standard. The technological burden of small-satellite builders then falls into a narrower set of tasks, such as coding and instrument or payload construction, testing, and integration. There are also organizational hurdles, especially acquisition of launch contracts; competition is tight for the number of available launch slots.

While terminology varies slightly in industry, NASA classifies small satellites (“SmallSats”) as those with mass less than 180 kg, which can be categorized further by their launch mass (with an expectation of greater mission duration, systems complexity, and cost for larger systems) [45] [46]:

- Minisatellites (>100 kg, <180 kg)
- Microsatellites (>10 kg, <100 kg)

- Nanosatellites (>1 kg, <10 kg)
- Picosatellites (>0.01 kg, <1 kg)
- Femtosatellites (>0.001 kg, <0.01 kg)

Each of these requires different amounts and types of resources to be provided by the launch vehicle and may fall under different mission categories per NASA's risk and priority structure. However, despite their small size, they can operate independently of major missions and organizations (after launch), allowing academic institutions and other small organizations the option to directly implement an independent mission through dedicated communications networks and internally-developed command and control systems. Others choose to rely in part or whole on existing communications networks and COTS software.

2.2.1. The CubeSat Standard

The CubeSat Design Specification (CDS), developed as a partnership between the California Polytechnic State University and Stanford University's Space Systems Development Laboratory in 1999, provides general specifications for design, development, testing, and implementation of picosatellites [47]. Cal Poly continues to maintain the standard, currently at Revision 13. Cal Poly's standards document is comprehensive, incorporating everything from mechanical drawings to deviation acceptance waivers (though all programs will encounter variations and deviations from any "baseline").

Fundamentally, the standard includes mechanical, electrical, logic, and deployment specifications for a 10x10x10 cm deployable satellite with mass at most 1.33 kg. This size and weight limit is considered to be one "unit" of CubeSat, so that a single cubical nanosatellite measuring 10cm on a side and massing no more than 1.33 kg is a "1U CubeSat." Multiple units can be combined to produce larger satellites. Common larger configurations include 3U (30x10x10 cm, 4 kg) and 6U (either in 60x10x10 cm or 30x20x10 cm format, both at 8 kg; for examples, see Figure 11 and Figure 13, respectively). When larger CubeSats are assembled, the chassis is generally a single piece (a 6U CubeSat bus is bought or built as a single piece, rather than bolting or welding six 1U CubeSat shells together). Six common CubeSat configurations are shown in Figure 10 [46].

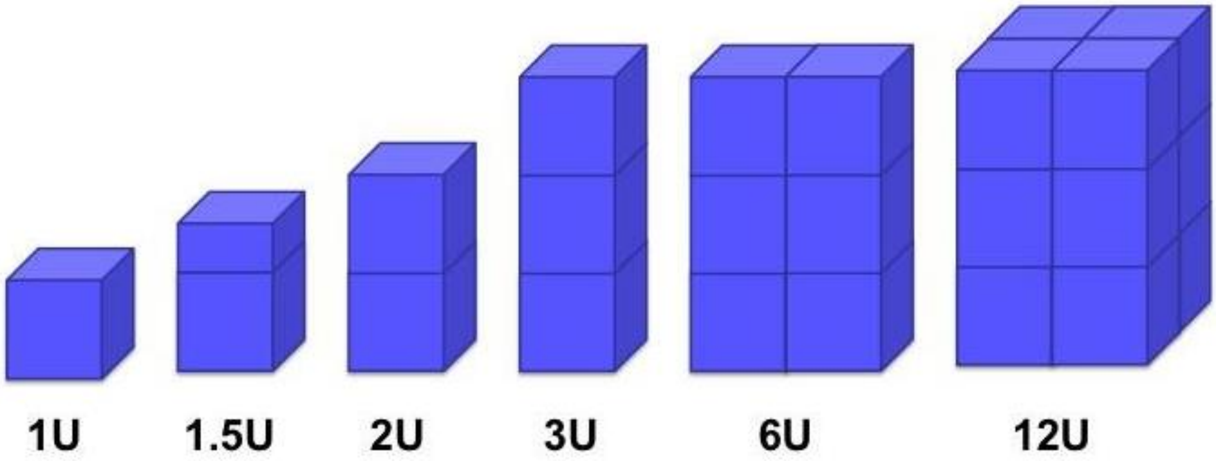

Figure 10. Common CubeSat form factors (Credit: NASA)

From 2013 to 2017, between a half and two-thirds of all U.S. built satellites launched in a calendar year were CubeSats, up from a negligible proportion in 2002 [48]. The 3U configuration continues to be the most popular form factor, but larger buses (6U, 12U, and above) and deployment systems are beginning to mature and be more broadly deployed. Thirty-seven percent of U.S. spacecraft launched in 2016 were CubeSats, but this proportion accounted for only about one percent of satellite manufacturing costs. The number of overall launches (and proportion of CubeSat launches) both diminished in the last few years due to bottlenecks in the launch services industry (especially due to commercial LV failures for ISS resupply, limiting the number of deployments possible from that platform).

2.2.2. The NASA CubeSat Launch Initiative

NASA has embraced the CDS, going so far as to form a program dedicated to providing rideshare services for the picosatellites. The NASA CubeSat Launch Initiative (CSLI) is the logistical and administrative pathway for NASA centers, educational institutions, and non-profit organizations to procure launch services for their CubeSat.

Potential CSLI projects must provide initial information about their desired orbit, mission restrictions, and summaries of their benefit to NASA and the goals laid out in the NSP. Additionally, they are subjected to a merit review for their overall goals and objectives, and a feasibility review to investigate technical implementation, risk, and probability of success. Unless a waiver is granted, the project must also comply with the Launch Services Program (LSP) requirements and must not interfere with the timeline or baseline risk of the primary mission. Technical considerations of the applicants are balanced with “softer” considerations, such as increasing geographic diversity of organizations participating in the program [49]. The program has matured to where the procedure is well defined and easily navigable; the most difficult part is competing against other qualified applicants [50].

One subset of CSLI missions is the Educational Launch of Nanosatellites (ELaNa) [51]. Mission objectives range from technology demonstrations to Earth science to space weather to near-earth object observations. Between the program’s start of operations in 2010 through the end of 2017, nine program cycles have seen 58 projects launched aboard 16 flights, with about 50 more in the processing flow.

Since adopting the CDS into its mission, NASA has provided recommendations, standards, and other documents to facilitate their development and implementation. NASA’s LSP has provided a high-level requirements document [52] which provides guidance about the philosophy, goals, and implementation of CubeSats being carried aboard NASA launches. In addition to technical requirements levied on the CubeSat itself (such as total mass, outer dimensions, restrictions on hazardous materials and radiation, and operational restrictions on its power-up timeline), it also provides specifications on the environmental test program for the flight units, interface control, and the role of the program office.

The ISS provides the capability to deploy individual CubeSats from the station itself [53]. Rideshare agreements can lift a number of (up to 6.5U) CubeSats, pre-installed in NanoRack launch cases, to the ISS via pressurized supply craft for later deployment. The cases contain stabilizing rails and a plunger that, when triggered, will gently push the CubeSats out of the case at a predictable velocity. Once aboard, the cases are moved to the station exterior via the JAXA Airlock Slide Table in the Japanese Experiment Module (JEM) and repositioned using the JEM’s Robotic Manipulator System (RMS), either for immediate deployment or temporary storage. During deployment, the JEM RMS will orient the case and trigger the CubeSat’s ejection at a predetermined time.

Because of the number of rideshare agreements on vehicles travelling to the ISS, the CSLI application explicitly asks whether a 400 km deployment altitude at 51.6-degree inclination is acceptable [49]. The number of launch slots, combined with the ability to release a CubeSat at a specific time with a specified orientation and relative velocity, can make ISS deployment an attractive alternative to "standard" deployment from a P-POD aboard a launch vehicle upper stage (which cannot afford the spatial and timing flexibility) [54]. The tradeoff, however, is a limited orbital regime into which it can be deployed, and potential resource conflicts with ISS astronaut time and other JEM RMS activities. Many organizations have determined that this tradeoff is worthwhile, with 33 of the 55 CubeSats launched in 2016 being deployed from the ISS [48].

The Spacecraft for High Accuracy Radar Calibration (SHARC) Mission, a 6U CubeSat (in its 6x1x1 configuration) providing radar calibration for the US military, is shown during its deployment during ISS Expedition 51 in Figure 11. The JEM RMS is visible in the lower left corner, the NanoRacks deployer (with several open doors) is in the center of the frame, and SHARC is the long rectangular object with green-and-black panels.

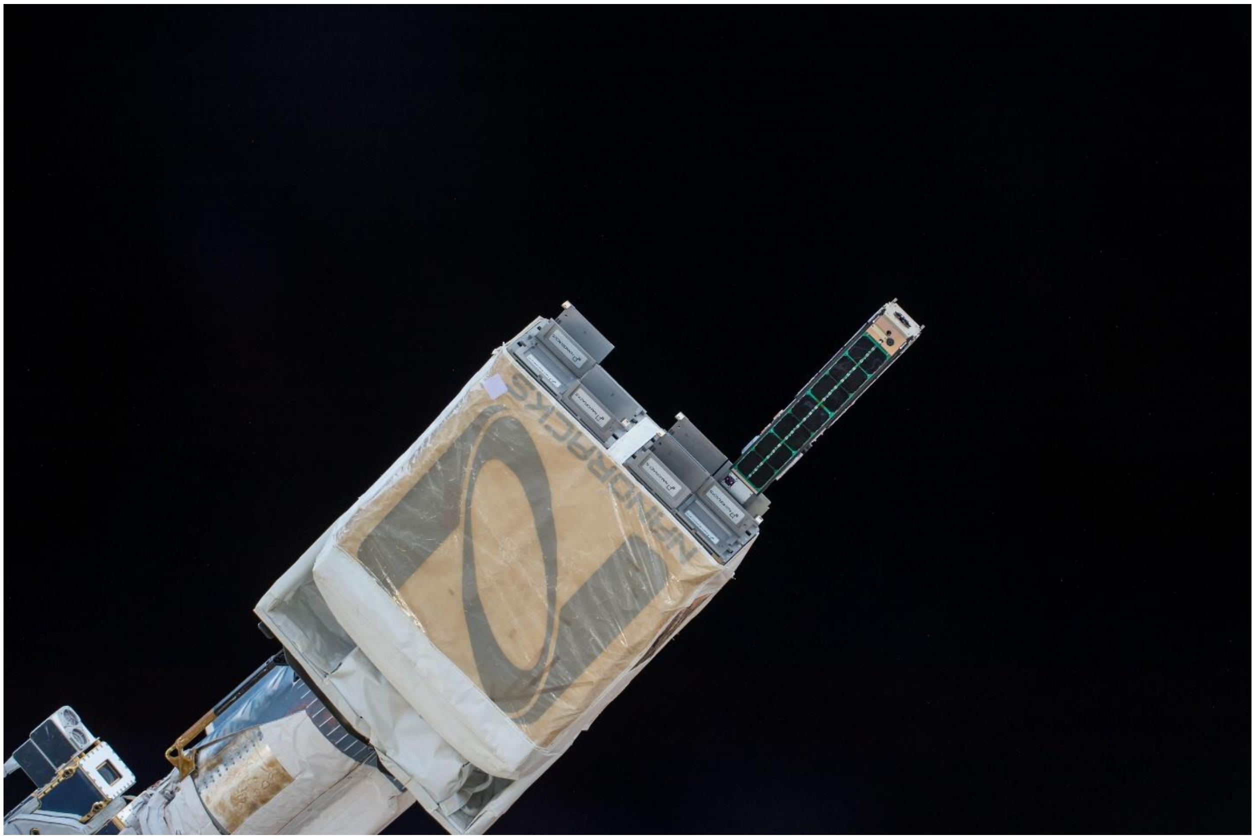

Figure 11. SHARC CubeSat deployment (Credit: NASA)

2.2.3. Launch Vehicle Rideshare and Deployment

Various companies offer built-in capabilities for launching free-flying hitchhiker payloads. One dedicated system available on the United Launch Alliance (ULA)’s Atlas V launch vehicle (LV) is the Aft Bulkhead Carrier (ABC), an auxiliary payload mount that can carry approximately 70 kg into whatever orbit the primary payload requires, including GEO transfer or LEO sun-synchronous, and provides a range of services for loads analysis, contamination prevention, and telemetry/command interfaces [55]. The carrier itself is mounted on the aft bulkhead of the (single engine) Centaur upper stage and is expected to be compatible with the Centaur version to be used on the Vulcan LV currently in development.

More recently, the United Launch Alliance has developed a variety of intermediate systems into a conceptual CubeSat Express launch system, which can accommodate up to 24U of CubeSat payload (up to four 6U buses, or eventually two 12U buses) on the ABC interface [56]. The current design is for 21U of the total to be revenue-generating payloads, with the remaining 3U for Science, Technology, Engineering, and Math (STEM) educational programs. In addition to the technical work, they are preparing concepts of operations (conops) for selecting which missions can accommodate which CubeSats (for example, whether the added payload and deployer weight can be supported without the addition of solid rocket boosters), their deployment characteristics, methods of prolonging the CubeSats’ operational life, and determining the number of electrical and pyrotechnic door mechanisms available to deploy them. As of spring 2017, ULA has launched 55 CubeSats, and CubeSat Express is designed to continue increasing the capacity per launch and decrease costs.

Additionally, there are standardized and customized systems for deploying one or more CubeSats from LV upper stages or carrier spacecraft. The Space Systems Development Laboratory at Stanford University’s Department of Aeronautics and Astronautics developed one of the first: the Orbiting Automated Picosat Deployer (OPAL), a small picosat carrier which could deploy six small “daughter” satellites in addition to carrying its own technology demonstration payloads. OPAL was launched aboard a Minotaur rocket on January 22, 2000 and deployed all six of its picosat payloads within about a week.

The most common modern CubeSat deployment system is the P-POD, a metal structure that protects the CubeSat during preflight processing and launch, and then ejects them into space after the LV primary payload has been deployed [45]. The standard P-POD structure is designed to carry up to three 1U CubeSats each massing 1.5 kg, sustaining up to 15g acceleration during launch, and then deploy them on command. The launch tube provides minimal rotational motion, a fixed and predictable ejection velocity of approximately 0.3m/s, and mechanical standoffs to toggle the CubeSat's kill switch to an operational state. Additionally, optional data ports, power connections, and access hatches can be used to verify CubeSat health and complete final configuration prior to launch. P-PODs can be modified to accommodate larger CubeSat configurations, and can also be stacked or otherwise multiplied to carry more CubeSats on a single launch opportunity. The P-POD was developed in parallel with the CDS, ensuring interoperability.

NASA also developed a Nanosatellite Launch Adapter System (NLAS) [57] to dispense several CubeSats on a single launch. Between two and four CubeSat deployers are mounted inside a metal structure, which can be mounted between the LV upper stage and the primary payload of the launch. The deployers can carry a total of up to 24U of CubeSat secondary payloads in 1U, 1.5U, 2U, 3U, and 6U configurations, each massing up to 14 kg (significantly heavier than the baseline CDS) and deployed via on onboard programmable sequencer; multiple NLAS units can be stacked to accommodate even more CubeSats on a single launch. An NLAS unit with the launch sequencer is shown in Figure 12; the deployers themselves are the blue tubes visible on the lower left and through the top of the structure, and the large gold box is the deployment sequencer.

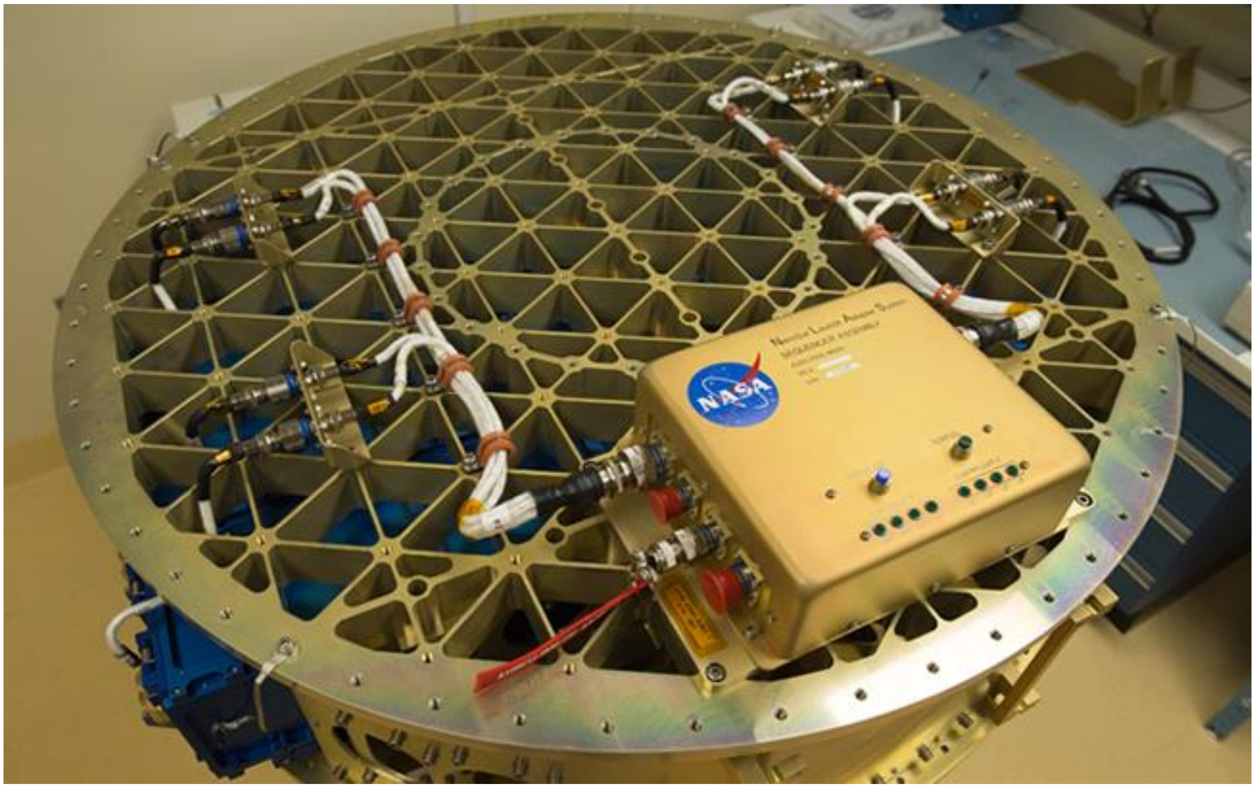

Figure 12. NASA's Nanosatellite Launch Adapter System (Credit: NASA)

There are a number of other systems in development or in active use throughout the international launch community. Many of these conform to the CDS (launching various numbers or form factors of CubeSats), while others are designed for custom payloads or equipment too large or heavy for standardized dispensers.

2.2.4. Simplification and Standardization in the Manufacturing Process

The commercial SmallSat industry is moving toward a “parts-bin” model for providing components, services, and systems [50]. Some companies provide fully-developed and flight-tested equipment for individual subsystems, such as Honeybee Robotics solar array systems. Other companies (like Harris and NearSpace Launch Inc.) provide payload hosting, where a full satellite bus is provided by the vendor and the operator only need provide and integrate the payload.

Several companies are also offering spaceflight services alongside physical deliverables. These range from Honeybee Robotics’ systems engineering development, verification/validation, and cleanroom services to NearSpace Launch Inc.’s communications and data delivery systems. These

COTS services can help SmallSat developers by further offloading the breadth of knowledge required to produce and fly a satellite on tight budgets and timelines, though some academic organizations choose to develop the systems and processes themselves for educational benefit [50].

In 2016, NASA’s Small Spacecraft Technology Program published a report regarding the State of the Art of Small Spacecraft Technology. The report highlights not only specific companies and their subsystems, buses, and services, but also continuing research into new and evolving technologies and their application to SmallSats [58], and demonstrates NASA’s continued involvement with technology development, transfer, and COTS solutions for new, small systems. Missions designed to increase the TRL of new technologies, such as laser communications, passive heat pipes, and smartphone-based CDH systems, are also presented.

NASA has also been developing its own capabilities for SmallSat development. In June 2014, NASA JPL commissioned a dedicated facility for the production of CubeSats. The 1250-square-foot (116 square meter) Integrated CubeSat Development Laboratory is designed to allow parallel development of up to four independent projects at once and provides capabilities such as clean-room air processing, electrostatic discharge (ESD)-sensitive equipment handling and storage, and regulated power systems [59]. The facility represents a shift toward parallel development of small projects via resource sharing and operating in limited infrastructure footprints, similar to academic laboratories, but with the benefits of NASA-sponsored quality assurance best practices (like contamination control and ESD-equipment handling provisions) and without the need for the size provided by more conventional satellite factories.

A number of Government-off-the-Shelf (GOTS) software packages are available free or at cost to many non-commercial missions, ranging from automation control to telemetry decommutation to dataset distribution. These systems have heritage with larger NASA missions and are widely used in Mission Operations Centers (MOCs); designing small satellites and data systems compatible with these software packages would ensure interoperability with existing networks and control systems, as well as providing proven capabilities for minimal cost.

2.3. Reflight, Multi-Generational, and Distributed Sensor Systems

While some instruments and missions are singular, others are parts of families or systems of sensors designed to distribute measurements and evolve as technology improves.

One method of improving science return for minimal cost is to re-use the same sensor multiple times. The Shuttle Pointed Autonomous Research Tool for Astronomy (SPARTAN), a reconfigurable, multipurpose space telescope, was deployed to orbit from the Space Shuttle cargo bay, maneuvered away from the Shuttle, controlled remotely, and recovered several days later before the Shuttle landed. Objectives included heliospheric and space weather sensing (including cross-calibration of the Solar and Heliospheric Observatory), and imaging of galactic structures and composition. One variant or another of SPARTAN was flown on eight separate Shuttle flights; one unit, SPARTAN 201, flew a total of five times with a variety of instrument packages which could be reconfigured between missions [60].

Scientific sensors can also fall into multigenerational families of similar or evolving design to accomplish similar purposes. Because the near-Earth environment contains many satellite constellations, it contains many examples:

- The Shuttle/ISS Shuttle Ionospheric Modification with Pulsed Localized Exhaust Experiments (SIMPLEX) experiment flew on missions starting with STS-7 in 1983 and ending with a three-year stay on the space station [61].
- The Multi-Spectral Scanner (MSS) was flown on Landsats 1 through 5, with progression for increased spectral and spatial resolution on later models (ground-based computer models were used to upscale resolution from Landsats 1, 2, and 3 to match that of newer models) [62]; Landsat 8 uses the Operational Land Imager (OLI), which will be duplicated for Landsat 9.
- The Visible Infrared Imaging Radiometer Sensor is flying aboard Suomi National Polar-orbiting Partnership and Joint Polar Satellite System (JPSS) 1 satellites, and will be carried aboard future JPSS missions; together, they provide coordinated, repeating coverage of weather and various environmental variables [63].
- The Magnetospheric Multiscale Mission is a four-satellite constellation designed to fly in a 10-kilometer-baseline tetrahedron; all four spacecraft were launched aboard the same LV and carry identical instrumentation, to provide three-dimensional measurements of the magnetosphere [64].

The InterPlanetary Network (IPN) is a series of gamma-ray burst (GRB) detectors mounted on dozens of spacecraft located throughout the solar system [65]. When an astrophysical event produces gamma rays, these distributed sensors will detect the burst at different times; the timing differences can provide information about the direction of the burst. Additionally, the variety of sensor locations and orientations give overlapping sky coverage far greater than what could be obtained by a single spacecraft in LEO. The first IPN began operating in 1977; the current, third-generation network has been operating since 1991.

2.4. Modern Systems Engineering for Small Space Projects

NASA has developed its system engineering, project development, and management techniques through six decades of experience, industry outreach and integration, technology research and development, and a culture of incorporating lessons learned into the next generation of projects. As the private sector and educational institutions increase their presence in the space industry, NASA has shared its experience and provided documentation and standards for others to follow, providing guidance (internally and with other organizations) for how to best adapt these practices for smaller teams running smaller, cheaper programs with a minimal increase of system and mission risk.

2.4.1. Operational, Concept, and System Documents

Formal documentation extends beyond requirements, databases, budget projections, and organization charts. Complex technical systems may maintain complex interfaces to other components, systems, and entities; management decisions and compromises based on balancing objectives from multiple stakeholders perhaps restrict the environment and capabilities even if the system's design can support more; operational constraints and human factors can often change plans continuously through a system's lifecycle. A program's overall success relies on this body of knowledge, but such documents are not best from a human perspective on the system's overall characteristics and use.

Conops documents are a method of formally documenting the way in which a system was designed and how it is intended to be operated, with rationale and references to other documents. These documents allow for a conceptual plan of the system to be described in words, figures, and other human-friendly ways, compared to the technically-necessary but cumbersome and dense system requirements. They are designed to inform and guide the end-user about the background and intent of the choices made about the system's design and operation, with more depth and less specific direction than a standard operating procedure or checklist. Operational guidance documents like conops are becoming a standard component of modern projects, to the point where professional organizations like the AIAA and ANSI have produced recommendations (not strict requirements, but applications of best practices and lessons learned) on how to generate them [66].

Technical guidance for operators comes in the form of Standard Operating Procedures and Contingency Procedures; user's manuals; functional block diagrams for electrical, data, and software subsystems; and testing records showing the as-built characteristics of the integrated system. Often, these are generated from more detailed vendor data and experience gained during the integration and testing campaign before launch; knowledge is compressed and filtered to provide the front-line engineering team key information for day-to-day operations, with the expectation that an offline support team can provide more in-depth troubleshooting in the event it is needed.

For scientific missions, the project science community can provide information about the resulting data products and their characteristics in the form of product user's guides or help pages, usually accessible through the distribution data portal (see Section 2.5) and sometimes in conjunction with calibration data for immediate application to raw data products.

2.4.2. Technology Development and Transfer

Small projects or limited missions are often selected to prove or improve conceptual designs as a larger program is developed. Examples can include engineering test articles for analysis in vacuum chambers to miniaturized systems deployed as CubeSats, to full-scale (but limited-duration) missions flying prototype sensors for conops development. The TRL of a component, element, system, or technology is a way of describing its maturity and confidence level, and therefore its suitability (or at least its associated risk) for use in operational applications. NASA's Earth Science Technology Office defines a nine-category scale [67] ranging from TRL-1, where basic principles of the underlying science have been characterized and applied research is beginning, to TRL-4, where basic components are integrated (even on a breadboard) to test a prototype, to TRL-7, for prototype operation in a space or other operational environment, and finally to TRL-9, which is given to systems that have been proven in their operational environment and are being transitioned into sustaining engineering. Between these extremes are the various levels of research, development, analysis, simulation, testing, demonstration, and implementation.

NASA makes a point of transferring information and technology developed in the course of its projects to the broader scientific and engineering community. Its 2014 NSP specifies that it "will continue to promote the availability of NASA technologies for use by the U.S. public and private sectors and accelerate the technology-to-market cycle" for its active programs (Objective 2.3 [40]). Several NASA (or NASA-funded) research and development projects are underway at any given time, including projects designed to advance the TRL of a particular element in order to prepare it for operational use aboard a future vehicle.

One example is the "Dellingr" 6U deployable CubeSat, which NASA designed, built, tested, integrated, and launched in less than a year (a self-imposed deadline) [68]. The satellite was developed as a flexible alternative to conventional 3U CubeSat buses that may have a higher risk of early-life failure; it promotes the user of the 6U (3x2x1) form factor, to provide more volume for the payload, and is intended to be developed into a cheaper (through the use of COTS components) and more reliable alternative for future 3U CubeSat missions for all U.S. users. Future applications could include low-cost science constellations and other LEO missions; the BurstCube 6U CubeSat currently under development intends to use the Dellingr bus as a platform for GRB detectors [69].

An exterior view of the first Dellingr unit (deployed from the ISS on November 20, 2017) is shown in Figure 13 [70]. In addition to its proof-of-concept role, this Dellingr unit also carried a number of small technology demonstrations specifically to improve their TRLs for later development into full-scale equipment on larger missions, including scientific instruments (ion spectrometers and magnetometers), CubeSat-specific technologies (deployable boom mechanisms and sun sensors for attitude determination), and satellite technologies that could be applied to larger systems (a no-electronics thermal control system) [71].

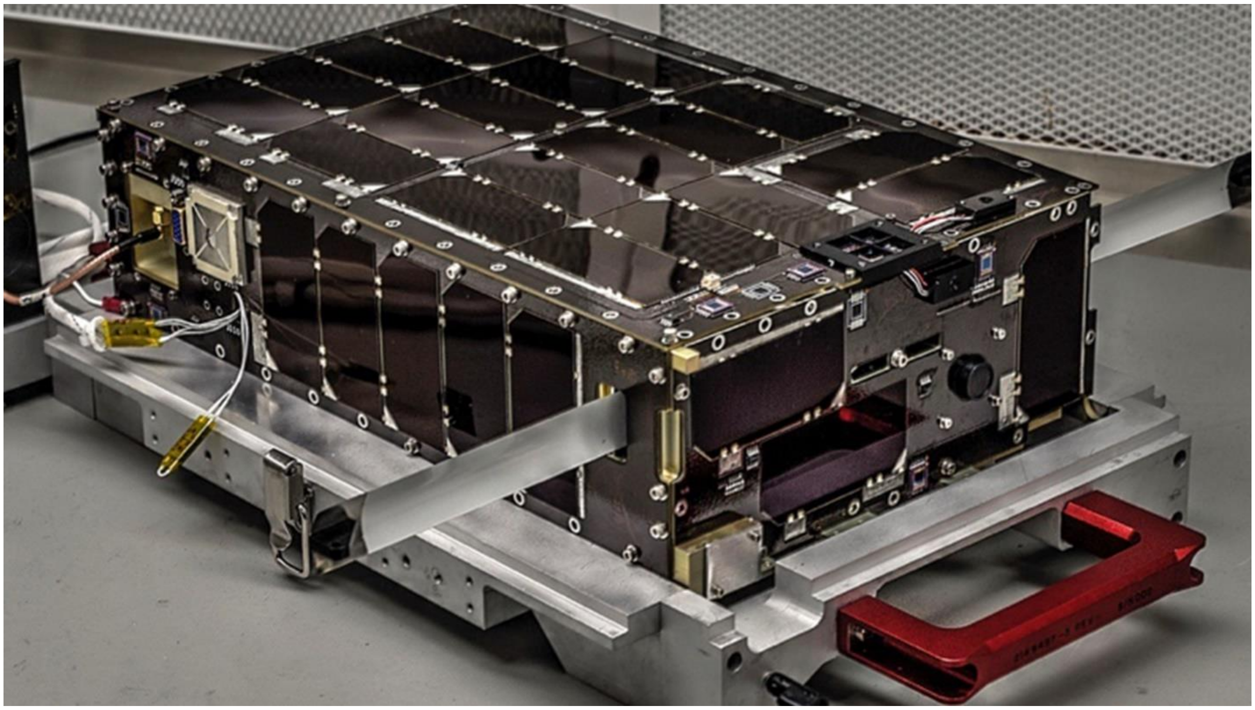

Figure 13. Dellingr CubeSat during ground processing (Credit: NASA)

2.4.3. The Systems Engineering Lifecycle

NASA breaks down new project development and implementation into seven major phases, each of which has its own goals, considerations, and timeline, budget, and risk decisions. These include (wording from the NASA Systems Engineering Handbook, Revision 2 [72]):

- Pre-Phase A is a primarily administrative period, to identify project justification, programmatic goals, and a basic operations concept; to generate basic schedule, cost, and risk budgets; and assign roles to stakeholders. The Mission Concept Review (if approved) ends this phase.
- Phase A develops the mission and system architecture, with the primary product being baselines for cost, risk, operations concepts, mission architecture, and requirements. Technology development may take place in this timeframe if existing capabilities do not yet exist. This culminates in the System Requirements Review.
- Phase B is preliminary design of the system. Ending in a Preliminary Design Review, Phase B settles on the best results of Phase A for system performance and updated requirements, and prototyping may occur to finalize technologies.

- Phase C consists of final design work and initial system fabrication, including coding and documentation. Additional engineering test units are built to validate designs, and the Critical Design Review allows for moving through to operational fabrication of flight components.
- Phase D involves system assembly, integration, test, and launch of the space hardware. A Mission Readiness Review allows all stakeholders to give final go-ahead to launch the equipment, and after on-orbit testing and final requirements verification are completed, the system is considered "operational."
- Phase E is the stable phase of the mission. The team size diminishes as the primary mission is carried out, and focus changes from developing and proving the system into using it day-to-day and maintaining it for maximum return and longevity. This phase can last from days to decades, depending on intended mission length, system performance, and budgetary constraints.
- Phase F, referred to as "closeout" or "disposal" in different literature, involves the deliberate end of operations. This phase involves a Disposal Review or Disposal Readiness Review, after which space hardware may be abandoned in orbit, intentionally deorbited to reduce the debris environment, or removed from a returned vehicle. The program administrator finalizes documentation and, if applicable, provides final scientific data to the customer, and "closeout" or "disposal" ends the operations.

Phases A and B are considered part of the "project formulation," while Phases C through F are part of "project implementation."

Smaller programs and projects are sometimes encouraged to adapt or alter these phases to assist in developing their products. Secondary payloads and sub-Class-D missions are often tightly constrained in their budget and workforce, so full-up reviews and strict adherence to the same systems engineering framework used for multi-billion-dollar missions would present an undue drain on their resources. For example, "agile" approaches to coding, with heavier emphasis on rapid feedback from component testing, can reduce labor, cost, and schedule delays [73].

Additionally, mature systems or continuations of existing programs may abbreviate certain development phases when requirements and conops have already been developed and mature technology already exists. When existing space hardware systems (either for design or hardware) are mostly carried over or reused, development can focus only on the changes to the baselines developed in the first system's Phase A, significantly reducing the time required for the project formulation cycle by months or years. Fabrication of components from the first-generation equipment may also proceed quickly or may even use flight test or qualification units from Phase B; the Challenger Space Shuttle orbiter was originally a structural test article but was pressed into flight after refurbishment [24] in about half the time of Columbia's development schedule.

Academic institutions may follow these guidelines or generate their own internal development workflow, depending on the scope of the project, development timeline, and available personnel.

2.5. Ground Data Systems and Products

Science data collection and distribution relies not only on the instruments, ground antennae, and data lines to the intended audience, but also on calibration teams, reliable and high-uptime storage systems, and secondary products used to determine the quality of the end products.

2.5.1. Collection, Storage, and Distribution

Delivered data sets from space-based instruments are usually radioed to the ground in a standardized data format, like the Consultative Committee for Space Data Systems (CCSDS) File Delivery Protocol (CFDP). These standards provide uniform methods for sorting the incoming data stream by collection interval or time; wide compatibility with communications systems around the world (allowing for the use of international ground sites, not just those operated by the spacecraft's home nation); information on data integrity, such as checksums; and the option for automated retransmission if a data segment was corrupted or cut off during the transmission process. The CFDP file can be stripped of fill data, compressed, and distributed from the receiving station to the storage facility for processing and further distribution.

Partially- or fully-processed data product may be distributed in different formats, depending on the sensor type and data application. These files range from high-resolution TIFF images to comma-separated text files to binary files of a unique and specific format which cannot be easily interpreted without custom software.

NASA maintains a number of data archives and servers for various scientific data. These include (among others):

- The Earth Observing System Data and Information System (EOSDIS), for all types of Earth Science data (atmospheric, terrestrial, cryospheric, oceanic, solar radiance, and calibration data). This data set includes not only satellite observations but also aircraft and field measurements and data from other sources.
- The High Energy Astrophysics Science Archive Research Center (HEASARC), for energetic EM (ultraviolet through gamma-ray) phenomena ranging from black holes to the Big Bang to colliding stars
- OMNIWeb, for heliophysics-relayed magnetic field, plasma, and energetic particle science

These archives are organized in various ways, each with different interfaces. They can be combined into “virtual observatories” for coordinated searches across the electromagnetic (EM) spectrum, or sorted by mission or individual instrument. Over time, many original data centers have been consolidated into fewer, more broadly cast repositories for ease of searching and cross-referencing; in the future, this trend may continue with cross-referenced databases. With high-volume data networks, improvements in automated processing, and larger international participation, there is a potential for daily full-sky coverage with automated correlation between transient events across the EM spectrum [44].

Other organizations also maintain their own data processing and distribution centers. The USGS operates the EarthExplorer interface, which can provide Landsat and other data products ranging from fully processed and calibrated (or even instrument-raw) data sets for wide areas over decades to “individual use” processed pictures of a single location. NOAA has merged its three primary data centers (the National Climatic Data Center, the National Geophysical Data Center, and the National Oceanographic Data Center, which also provided coastal data sets) into a single National Centers for Environmental Information. Space telescope images, including those from Hubble, are stored in the Space Telescope Science Institute’s Mikulski Archive for Space Telescopes.

Still other data sets used for scientific data processing and collection environment information are also widely available. The U.S. Naval Observatory distributes Earth orientation parameters, GPS ephemerides, and timing signals, and NOAA’s Space Weather Prediction Center provides predictive and definitive reports of solar radiation, geomagnetic storms, and atmospheric expansion, all of which can affect satellite navigation (and therefore data collection, especially for precise measurements).

These data sets are scalable and flexible with new inputs. Modern space science data repositories can usually accept input from new missions and sensors [44], changes to instrument behavior and calibration, and updates to web interface standards. Many also provide quality information about the returned or processed sensor data; these can include bulletins of failed sensor pixels, degraded support equipment onboard, gaps from anomaly recovery, or cloud cover affecting surface reflectance.

Data user's guides and other written documentation for calibration methods and accuracy, processed data product types, and other information about the source sensors often are provided through these data web portals. They can also serve as a coordination point between project scientists, administration, and end users.

2.5.2. Support Products and their Distribution

Generally, raw instrument data must be processed so that irregularities from the collection system and method can be removed. Calibration and ancillary data are generated alongside the science data collection, and are applied to the science data, usually through ground-based computing, to produce uniform "true" representations of the actual measurement.

Calibration data describe the difference between the data collected by the instrument and the actual conditions present in a remote location. In some cases, the "true value" is known; one example is comparing remote-sensing data of temperatures in a given location with a local thermometer in that location, so that the difference between the sensed and actual value is known. In other circumstances, like X-ray observations of distant galaxies, the actual value is not known, so one or more objects with stable and measurable values provide a common image for all sensors of that type, allowing cross-calibration between instruments so missions will all agree on overall brightness (even if the true brightness is not totally understood). Still other types of calibration are designed to measure the internal performance of the sensor itself, such as the response across its CCD array to ensure uniform response of all pixels to a known-intensity calibration lamp.

Ancillary data are additional measurements and reports about the state of science data collection which could potentially affect the resulting science data. These can range from the condition of the instrument itself, such as internal temperatures affecting sensitivity of the sensor, to the actual position and orientation of the sensor (as compared to the predicted and desired values). These data sets are used to correct the science data product, or at least provide the end user with an understanding of the circumstances under which the data were collected (and therefore the magnitude and type of variation experienced during the collection period).

The needs of scientists and operators vary from user to user, so the variety of generated products will vary as well, and inherent flexibility of the data delivery is important to produce quality products without excessive workload from any of the stakeholders [74]. “Power users” of particular instruments (for example, a university that designed, built, and operates an instrument for their own scientists) may desire raw instrument output, including not only the collected science data but also internal or automated calibration and ancillary data. For those with only occasional need for the data, specific purposes, or limited computing resources, the fully-processed data sets without any ancillary data may be sufficient or ideal. Still other users may want some of the ancillary data attached, either merged in with the science data stream or separately in a correlated file, or perhaps only during certain collection circumstances.

Many of the data repositories listed above include calibration and ancillary data products and provide the flexibility for delivery of those data in various formats, but some provide only products that have been at least partially processed (even if the calibration or ancillary data are provided separately). Keeping this initial processing limited to one location ensures that all first-level processed data were all generated using the same calibration database and using identical methods, which can be important for certain types of measurements, or if a single location is to be the canonical repository for a particular data set.

Delivery methods also must change to accommodate the end user’s requirements. Some missions or scientists may desire automated delivery upon acquisition of new images, often by a web interface. Others may prefer their data to be on-demand either through an application programming interface or by manual selection of data sets through the web portal itself. Most data portals currently in use by NASA provide these functions.

2.6. Research Summary

The development of secondary payloads has followed the progress of primary mission systems and technologies, and these small programs are now a common method of testing and developing new equipment and systems, providing faster and cheaper scientific data collection, and providing educational outreach. Academic institutions are embracing the latest small payload practices as cost-effective methods of collecting science for and imparting experience to their students. NASA and the satellite industry are likewise embracing these new small systems through rideshare agreements, technology transfer, and providing guidance for best practices. As the demand for small payload launches continues to increase, and with the increasing capability of miniaturized electronics, new opportunities exist to extend secondary scientific payloads into new flight regimes for longer periods of time, improving scientific return. NASA's existing (and evolving) scientific and administrative infrastructure, as well as the civilian aerospace industry's increasing product and service sector for small satellite systems, now enable such missions.

3. ASIA Mission and System Description

This section provides technical, administrative, and general information about the ASIA program, and its components, goals, operation, and interfaces with HSC.

3.1. Overall Design and Mission Goals

At its most fundamental level, ASIA is intended to increase scientific data collection at minimal cost. This implies the maximum use of reused (heritage), COTS, and open-source components, including bus subsystems, scientific instrumentation, ground hardware and software, and existing data formats, to minimize unit and development costs and to promote interconnectivity with existing systems.

The baseline concept is a 6U CubeSat-style bus that is permanently attached to the HSC bus exterior structure. There are only three interfaces between the ASIA unit and the host: a single-string 28 VDC unregulated power supply, a single-string MIL-STD-1553 communications bus (or other standardized interface; see Section 3.2.1.3) with a remote terminal connection, and the mechanical fittings providing structural support and vibration mitigation (and possibly passive thermal dissipation or isolation). The whole unit has a mass of 10 to 15 kg and presents a low-aspect addition to the overall dimensions of the host spacecraft.

A suite of instruments inside the CubeSat's volume begins taking scientific measurements on command, storing time-tagged information to a small solid-state recorder (SSR) acting as a circular buffer. When the communication and operation schedule allows, a ground or onboard command will begin a dump of the data from the SSR, with the data downlinked in the same manner as a spacecraft subsystem diagnostic data dump (and without need for modification to the communication path or equipment). When downlinked, these data will be processed into a usable format, collated against a spacecraft ephemeris and timestamp to provide a sensor position and orientation for a particular data point, and stored in a NASA or other public server, in the manner described in Section 2.5.

A key difference between the ASIA space segment and a conventional CubeSat is that ASIA is not a deployable payload. Additionally, because of the increased mass/density requirements, reliance on the HSC for basic services, and general non-deployable nature of the unit, it does not fully conform to the 6U CubeSat definition put forward by Cal Poly [75], and should not be held to the same requirements as missions developed and operating under those standards. However, with proper analysis, testing, and design, a large number of CubeSat-compatible components and instruments may be used for executing the ASIA mission.

The ASIA space segment and its scientific objectives would be considered a “Do No Harm,” sub-Class-D payload, in the spirit of an Earth Venture mission of opportunity. As a secondary payload, it is designed with low complexity, high reflight opportunity, and low-to-medium significance to national objectives. This “Do No Harm” classification may or may not be used by other organizations, but can be cited as a goal or set of characteristics that can provide interoperability.

One key assumption is that the use of ASIA on a particular spacecraft will be dictated by the customer, with the understanding that the customer will likely be either NASA or NOAA, or potentially the DOD (all of whom have a stake in correct determination of space weather; see Section 3.1.2). It will be considered an ancillary payload requested by the contracting organization, and therefore its inclusion on the HSC is contractually required. If a spacecraft vendor chooses to adopt the system and offer its inclusion as an option for all customers, including organizations other than NASA and NOAA, the return data can still be made available if the operating organization is willing to accept the ASIA unit’s inclusion and configures their ground systems appropriately.

ASIA will include commercial components with well-known capabilities, and is not designed with encryption functions or to be considered for national security missions. This constraint on component selection and mission architecture allows scientific data and the web portal being made available to the broader international community, without restriction imposed by the International Traffic in Arms Regulations (ITAR). This may render the ASIA unit incompatible with certain missions or project architectures, and may require additional coordination with the HSC program for other missions.

3.1.1. Design Life

The design life goal for each ASIA space unit is at least one year of high-uptime operation, providing scientific data over a variety of environmental conditions, regardless of its destination orbit. Many modern COTS components are capable of exceeding this goal in many locations within the solar system, given routine monitoring and appropriate preventive and corrective action (e.g., periodic reboots).

Additionally, a goal to accommodate five years of post-launch hibernation (during HSC cruise phase) would allow an ASIA to survive a transfer to Jupiter orbit, for example, before beginning its operational life. This on-orbit storage capability is less relevant to overall mission life and more to improving the “range” of the payload (allowing travel to more distant locations).

Differences in the space environment (including radiation and particle density, average and minimum/maximum temperatures, exposure to the upper atmosphere, etc.) between various flight regimes affect both storage and operational life expectancies. This is the cost of using a single design in a variety of locations, further increased by the desire to keep material costs and masses low. However, large-scale distribution of the units will reduce the effect on data collection from a single lost unit, and significant individual unit risk would be offset by increased reflight potential.

The ground system hardware and software can be upgraded or refurbished more easily than the space segment, so its focus is more on high-availability and database redundancy than longevity of individual components. However, the dataset should have life-of-program storage and accessibility to maximize the scientific value.

3.1.2. Scientific Instrument Selection

Using instruments that do not duplicate measurements already taken by or derived from HSC sensors optimizes a small internal volume with limited resources. For example, nearly all modern spacecraft in LEO use magnetometers in conjunction with their momentum dissipation system; since magnetic field measurements can be re-derived from these sensors, including magnetometers separately in ASIA would not enhance the overall science collected by the mission. Instead, sensors that are not commonly included on primary missions will be selected when possible. Additionally, the use of COTS and bulk-purchase instruments minimizes development costs and encourages the use of instruments and technologies with high TRL based on flight heritage or incremental development from terrestrial equipment.

Critically, the baseline instrument suite described below would not require modification based on the ultimate HSC destination, nor would it add any requirements or restrictions on HSC orientation or attitude maneuvers. A camera or other imaging sensor is useful only in relative proximity to another object and requires precision pointing and maintenance of relative angular motion to produce meaningful results, neither of which are guaranteed in the most general concept of a space mission. Realistically, the only guarantees on such a general mission are a microgravity/vacuum environment within the sphere of influence of the sun (from gravitational and energy perspectives), and with a mission lifetime of longer than the few minutes or hours that a suborbital mission would last.

Therefore, to provide worthwhile scientific return without the need for modification to the ASIA unit for each HSC, the instrument loadout would require the following characteristics:

- Direct-sensing instruments (those which interact directly with their immediate environment in order to determine local conditions) must be designed for:
    - Lack of orientation-dependent sensing, in that the instrument should operate the same in ram or wake direction, either of the spacecraft or of some external reference, like solar wind
    - If the instrument is sensitive to orientation, additional information from the HSC will be required (an attitude quaternion history and coordinate transformation between magnetometers and the ASIA bus frame) to correlate the sensor readings with its true condition
    - Detecting quantities that are relevant in all parts of the solar system, regardless of local magnetic fields, eclipse from a planetary body, or other environmental “interfering” conditions
- Remote-sensing instruments, including any imaging systems, receive light or particles that have already been emitted or reflected by another object. Since active sensors would cause too much interference and draw too many resources, all such instruments would be passive and must be designed for:
    - Wide fields of view, to provide reasonable sky coverage both through individual units or in conjunction with units from the rest of the constellation
    - Imaging a spectrum that would be of general use (the gamma-ray, X-ray, or microwave sky), compared to a visible light camera that requires shading or

pointing to provide valuable return

- All instruments (and the support bus) must be designed for:
    - Ruggedness against damage from radiation, temperature swings from an orbital environment (or constant high temperatures if permanently exposed to sunlight), direct sunlight into the instrument boresight, and contamination from chemical thruster activity
    - Stringent weight and size limits to fit into the ASIA bus structure without more interference into the HSC operating environment than originally advertised
    - Standard power and data connectors at well-defined positions for proper integration into the ASIA bus
    - Minimal on-orbit activation requirements (avoiding launch locks and other mechanical systems that require additional commanding, present contamination risks, or increase mass)
    - Self-calibration without the need for external targets, or a model for instrument science changes or degradation over the life of the system

These design goals and requirements suggest (local to the HSC) space environment and space weather direct sensing as the primary scientific goal of the ASIA unit, with a robust GRB monitor as a supplemental remote sensor. The space weather environment can be detected throughout the solar system; cosmic particles and other high-energy phenomena occur with sufficient frequency that no single orientation relative to the ecliptic is necessary for at least some scientific return; and three-dimensional observation of the space weather environment would benefit many future missions to LEO and elsewhere in the solar system. Micrometeoroid and Orbital Debris (MMOD) measurements are of use scientifically and to prepare future missions for impact protection in the space environment. GRB detection need not be localized by such a small instrument. Instead, the burst's direction could be determined through overlapping fields of view from several ASIA units, or by timing differences between widely separated units, or purely provided by other missions, so that the ASIA GRB detector would provide a supporting or confirming dataset (more on this in Section 3.2.2.3).

3.1.3. Minimal Effect on Host Spacecraft Design and Integration

In the same manner that launch services are provided by a company with a fixed capability portfolio, the host spacecraft will be able to provide only certain fixed capabilities and resources to the ASIA space segment. ASIA is being designed to accommodate reasonable power, data, mechanical, and other operational requirements, which most modern spacecraft buses and mission profiles should be able to provide without extensive modification.

Additionally, ASIA is being delivered as a package. The space segment's physical unit will have been designed, assembled, and tested before delivery to the HSC factory for integration, and all attachment hardware (excluding some power and communication bus cables, depending on the HSC vendor's preference) will be provided; its command and telemetry database definitions will be defined in documentation to the HSC vendor early in the design process; and operation manuals, training, and conops documents will be furnished by the ASIA program.

The Hosted Payload Interface Document, produced by NASA's Common Instrument Interface (CII) Project, provides general guidance (not requirements) for hosted payloads to integrate successfully with the HSC. ASIA strives to be fully general-purpose, deployable on commercial or national scientific missions to any location in the solar system, while the CII project is targeted specifically toward missions in circular LEO (with no restriction on inclination) or GEO, because its goal is to facilitate scientific payloads on commercial satellites. However, a number of the recommendations in the CII can be directly applied to ASIA (such as the "Do No Harm" philosophy and implementation of power and data interfaces).

3.1.3.1. Initial Design and Planning

The vision for the ASIA program involves the ASIA space segment being selected for a mission somewhere in project formulation (preferably in systems engineering Phase A; see Section 2.4.3 above). Because the space segments are to be mass-produced with identical designs, a single analysis of volume, mass, moment of inertia, power, data, and other physical parameters can be applied to all the flight units. Once the design has been finalized and frozen, and the first ASIA unit has been produced, its resulting properties can be measured and used as a baseline estimate for all subsequent units of the same design. Providing these measurements to the HSC vendor will simplify their initial planning for mass, power, and communication budgets, and equipment fields-of-view. Likewise, early delivery of standard telemetry point and command opcode definitions allows for easier integration into databases and operational products.

The principal goal is to deliver good measurements and properties as quickly as possible in the HSC life cycle, and to provide few, or preferably no, updates after Phase C. This is accomplished by unit standardization and design freezes early in the ASIA unit life cycle, in consideration of the HSC's development and fabrication timeline.

3.1.3.2. Mechanical Integration

Equipment for mechanically connecting the ASIA unit to the HSC, such as bolts, clamps, vibration mitigation measures, will be provided in the ASIA space segment delivery. As different HSC vendors have different specifications for their bus structure design and materials, a variety of packages may be developed, so that packages of hardware known to work with a particular bus family can be preassembled and delivered with the ASIA bus.

3.1.3.3. Electrical Power

Accepting an unregulated, single-string power supply from the HSC minimizes cabling and reduces the number of HSC commands. Electrical grounding can be accomplished through either a return line in the cable harness or a separate grounding line to the HSC chassis; both can accommodate resistors or another form of discharge/surge protection.

3.1.3.4. Science and Housekeeping Data

By storing bus health and safety information (known as "housekeeping" telemetry) and science data in a CCSDS-approved format, ASIA turns the HSC data transmission into a pass-through ("bent-pipe") operation to either the antenna or the HSC onboard mass storage device (where the stream can be immediately directed to the antenna at a later time) with no additional processing or formatting to the data stream. This preformatting offloads the computer processing overhead to ASIA and simplifies the downlink process: a single command produces a single downlink file that includes all the scientific and housekeeping data, which the ground system can then automatically strip out of the HSC downlink by virtual channel (and later processed by application ID (APID) for individual instrument results).

3.1.3.5. RF Communication, Commanding, Telemetry, and Database Integration

The simplicity of the ASIA system allows for a modest set of commands to accomplish most functions. These commands can be either coded into the HSC command database or passed through as raw opcode on the data bus addressed to ASIA’s remote terminal. The ASIA unit will provide a command echo of the received opcode and an indication of the command’s final result (e.g., “Accepted,” “Rejected,” “Error”).

Likewise, the simple design of the unit reduces the number of housekeeping telemetry points that must be monitored, and the responsibility of monitoring these points falls to the ASIA project office. The limited set of telemetry reduces (or even eliminates) the number of telemetry points that need to be processed by the HSC and its operations team, so there should be no burden on their telemetry processing systems or day-to-day activity.

The Radio Frequency (RF) uplink is shared with the HSC, so no new spectrum management agreement is required. Instead, HSC flight software (FSW) simply identifies the command and passes it through across the data bus, to the remote terminal address programmed during unit integration.

3.1.4. Minimal Effect on Host Spacecraft Operations

Spaceflight operations for robotic spacecraft vary by parent organization, mission complexity and duration, program budget, scope, security, and history (single mission, constellation, series), and a number of other factors. The real-time console operators, planning, flight dynamics, and engineering support personnel are collectively referred to as the Flight Operations Team (FOT); ground IT system administrators, budgetary and administrative support personnel, offline sustaining engineering and development personnel constitute the extended team.

FOT composition and operational requirements change over time. Generally, the staffing level will be highest in the prelaunch and early operations phase, and then diminish over time as products and conops mature. As the space and ground segments age, increased maintenance needs lead to higher ground support staffing requirements, and the eventual failure of onboard equipment can result in the need for increased operations oversight and the development of new conops.

One principal goal for the ASIA project is to minimize the effect on the host spacecraft’s development, integration, test, and launch; another goal is to minimize the workload imposed on the HSC FOT and offline personnel. The required interaction must be at a level that even the smallest FOT can administer routine functions under normal circumstances.

3.1.4.1. System Performance Monitoring

ASIA bus and instrument telemetry is restricted to a few key parameters and basic status binary states. These telemetry points can be coded into a telemetry display page with minimal effort, but making the FOT responsible for monitoring the health and safety of the ASIA unit would require time and training for the FOT and increase their average workload. Offloading the ASIA unit health analysis to the data processing facility would allow for maximum automation and minimize required day-to-day interaction with the FOT. If the HSC team chooses to increase its oversight of ASIA systems, it can supplement the off-site analysis from the ASIA project team, but this will not be stipulated as a requirement from the ASIA project office.

3.1.4.2. Routine Science Operations

Holding with the design goal of minimal effect on and required interaction from the HSC FOT, only three commands should be necessary during routine operations. First, during initial unit startup after launch or during recovery from an off-nominal situation on the HSC, the FOT will issue a power-on command, and perform an initial data dump for power-on self-test results a few minutes later. This can be performed at the HSC operators’ discretion, but the ASIA project office can provide a recommendation based on the launch profile to minimize thermal risk to the space segment. The activity should take less than fifteen minutes, but specific timing with required and desired minimum warmup time will follow ASIA design analysis and testing.

Second, on some routine schedule, the FOT will command the unit to report recorded data collection. The ASIA unit will relay its recorded information (both scientific and housekeeping data) through the communication line. The data stream may be routed to the HSC onboard mass storage device for later transmission or may be directed to the HSC antenna for immediate relay to the receiving station; the ASIA unit makes no distinction, and will not throttle or reformat the data stream. The precise transmission schedule will depend on the HSC’s downlink speed, onboard storage capacity, communication schedule, and the (still to-be-determined) ASIA instrument recording rate and internal storage.

Third, on startup and periodically throughout the mission, a Time-of-Day (TOD) sync pulse will be sent to ensure the onboard clock remains synchronized with the HSC clock. The HSC TOD format varies from mission to mission, but the format can be incorporated early in ASIA unit development, or the unit can be made to identify and accept a variety of pulses.

Once the data stream has been received by ground processing equipment, the appropriate data packets will be stripped out and transmitted to the ASIA project's Data Processing System (DPS). This data transmission is the last required action by the FOT and the HSC control center.

3.1.4.3. Anomaly Support

Because the burden of analysis has been removed from the HSC FOT, and because of their minimal training on ASIA systems, failure detection and resolution may rest entirely on the ASIA project's engineers. Any corrective actions, including those to decommission part or all of the unit, would come from ASIA and be relayed to the HSC FOT with the specific steps to perform the requested action. This decision can be made entirely without the input of the HSC; however, if the HSC online and support engineers wish to be involved, their efforts will offload some work from the ASIA program engineers. This level of support must be negotiated early in the development timeline to provide effective training to the FOT for this role, and clearly defined through operational agreements to ensure no time is lost due to miscommunication during an anomaly situation.

3.2. Space Segment Overview

The space segment of ASIA includes the space hardware, command and telemetry databases, and operational documentation and training delivered to the HSC FOT. Characteristics of the space segment subsystems, interfaces, and operations are described below. Each individual physical enclosure and its payloads is referred to as a "space unit," whereas the overall conceptual design of the unit and its interfaces is referred to as the "space segment."

3.2.1. ASIA Bus

The ASIA space segment ("bus") is the physical enclosure for the scientific payload, plus all equipment required for it to perform its mission and interface with the HSC. This includes structural, electrical, data, and thermal control systems and the scientific payload.

3.2.1.1. Physical Structure

The baselined configuration for the ASIA space segment is a 6U CubeSat bus, in a 3x2x1 configuration (approximately 30cm long by 20cm wide by 10cm tall). The basic structure allows for easy separation into six “bays,” each 1U in size, with indents for mounting screws around each of the apertures. One of the large faces is attached to the HSC exterior, with the operational apertures of the instruments facing outward into space from the opposite side; insulation and radiators will be mounted as necessary on the smaller faces perpendicular to the side of the HSC.

A simplified graphic of the 6U layout is shown in Figure 14, looking toward the space unit as it would appear mounted on the HSC exterior. The bays are labeled counterclockwise starting at the lower left. The bay numbering convention is arbitrary, and the orientation of the space unit may change if required to minimize interference with the HSC.

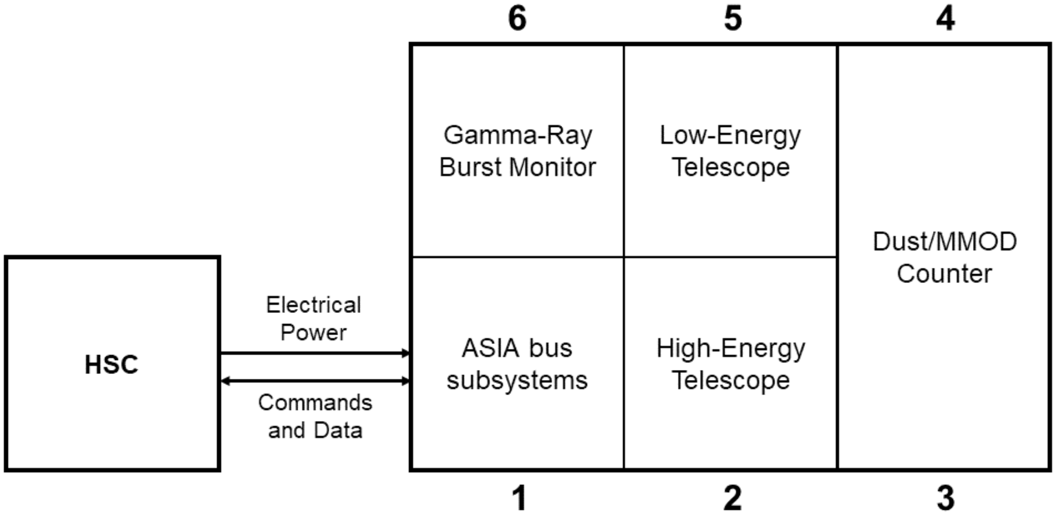

Figure 14. ASIA Space Segment Configuration

Bay 1 is allocated to ASIA subsystem equipment, including power conditioners, data collection and storage units, and HSC connectors, among other components. The remaining five bays are reserved for scientific instruments. One possible scientific loadout consisting of two particle telescopes, a dust and MMOD detector (occupying two adjacent bays for a total volume of 2U), and a GRB detector is shown as an example (see Section 3.2.2 for more details). Individual diagrams for internal power and data connections are provided below.

Gaps between the instruments will contain cabling for power and data distribution. The structure will be rated for launch acceleration and vibration loads, be made of materials to minimize thermal expansion and flexing in the variable environment of orbit, and provide paths for equipment to outgas in a controlled and directed fashion. The bus and its contents (including science instruments) will also comply with NASA end-of-life requirements, including those to mitigate orbital debris, minimize risk to people and material on the ground (in the case of deorbiting LEO spacecraft), and prevent contamination of other locations in the solar system per NASA's Office of Planetary Protection. These design restrictions are in the spirit of the ASIA mission not increasing the baseline risk of the HSC's primary mission, extending it from the ability to complete the primary mission into risk of affecting other systems.

3.2.1.2. EPS

ASIA requires a single power input from the HSC into its Bay 1. The ASIA unit will be able to accept unregulated or regulated 28 VDC power from the HSC Electrical Power System (EPS). The electrical power will be stepped down to operational voltages (probably several discrete power buses ranging between 2.5 and 15 volts) for scientific equipment, ASIA CDH, and operational heaters, and conditioned to provide stability as the source voltage varies (naturally between orbital day and night for solar-powered spacecraft, when other HSC loads change, and limiting inrush current when applying power). Wire gauges and power conditioning will be determined after selection of COTS components and design and construction of custom equipment, including the scientific payloads, but the total system dissipation must be low (tens of watts) to minimize load on the HSC EPS. Lower power draw also allows ASIA to fly aboard spacecraft powered by radioactive thermoelectric generators, which generally have a lower overall power capacity and no battery for surge support.

A small battery will provide emergency power for survival heaters only and will not allow science data collection or ASIA CPU operation. It will recharge automatically when main power is reapplied to the unit. The ASIA bus will not maintain any other power storage or generation capability.

Power distribution to individual loads downstream (instruments, heater, recorder, etc.) will be fused or use solid state power breakers. Breakers are preferable to allow system recovery in the event of a momentary fault but add cost and complexity. One possible configuration is shown in Figure 15. The diagram has been simplified for clarity, but the key points are that the overall power is controlled by the HSC, that instruments in Bays 2 through 6 are individually isolated, and that the ASIA CDH is an unswitched load. Signal ground for individual instruments and ASIA CDH are not represented, but may be made available with respect to spacecraft or ASIA chassis ground.

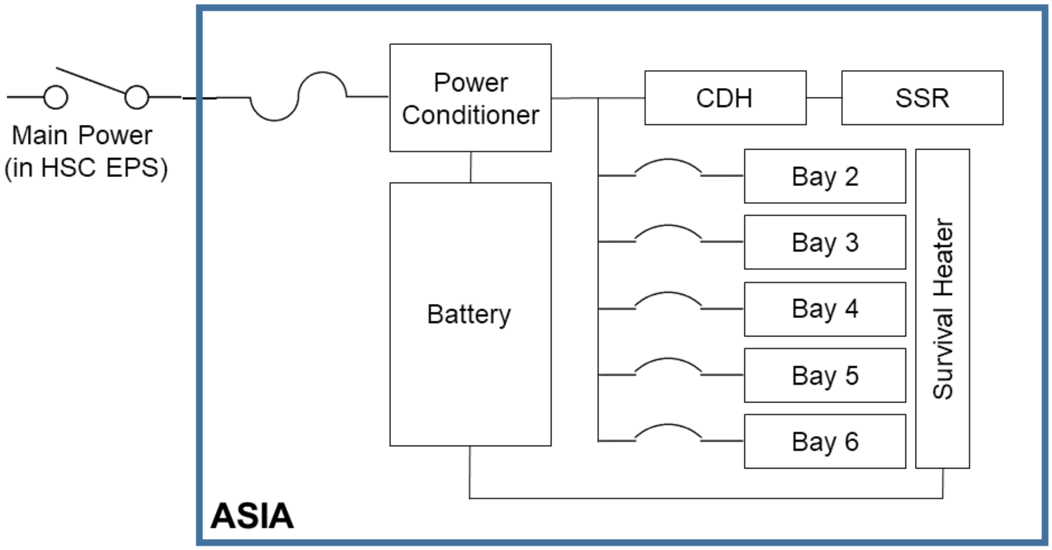

Figure 15. ASIA Electrical Power System

3.2.1.3. CDH and FSW

The onboard CDH will collect scientific data from the four instruments, as well as housekeeping telemetry from the bus flight software, multiplex them into a single stream (with data from different sources being separated by APID packet number), and store them in an onboard SSR. It will also handle clock management; after receiving a TOD pulse, the CDH sets its internal clock and propagates it forward for use in timestamping collected science and housekeeping data.

ASIA FSW is responsible for maintaining the communication schedule with the instruments and the HSC, collecting and recording housekeeping telemetry (data related to the health and function of the ASIA bus and the instruments themselves, such as voltages, temperatures, command counters, system uptime, and fault messages), and providing the command interface (receiving commands relayed through the HSC, executing ASIA FSW commands, and routing instrument commands). It boots automatically once the power-on self-test (POST) completes and begins collecting housekeeping data on the state of health and operating environment of the ASIA bus and instruments. The flight software will have to operate on limited hardware resources because of the small form factor of CPU and memory modules that the 1U bay can accommodate, as well as stringent electrical power limits; both the operating system and application software will likely be a mix of GOTS, COTS, custom, and scavenged code and software modules from similar missions.

ASIA's data connection to the HSC may be either MIL-STD-1553, IEEE-1394, or SpaceWire (see Section 3.2.3.3). Component selection may allow several of these connections to be accommodated. At this time, there is no specification for the internal communication between ASIA bus equipment and the payloads, but Universal Serial Bus, Controller Area Network, and other commercial low-power, lightweight, and well-defined interfaces are available.

Figure 16 shows conceptual paths for ASIA commanding and data collection. Data flows are shown separated for clarity; the actual unit will have only one physical line to the HSC, across which both command and science data will be sent; likewise, for weight and volume savings, there will likely be only one connection between each instrument and ASIA CDH for instrument commanding, housekeeping data collection, and science data collection.

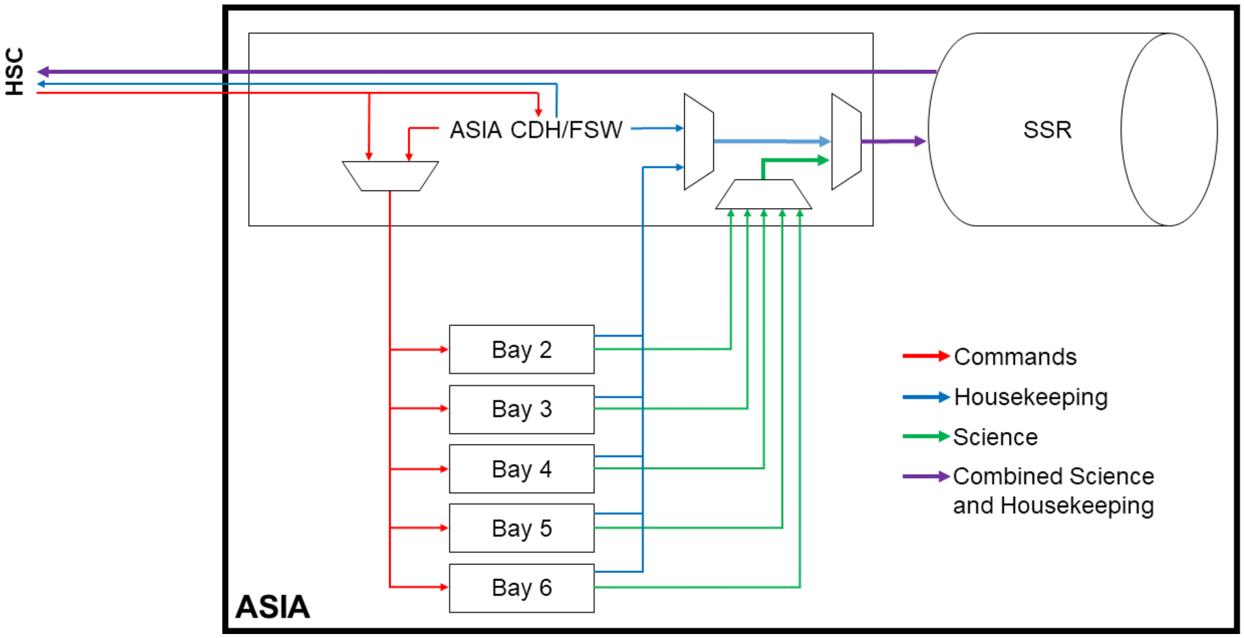

Figure 16. ASIA Command and Data Paths

Science and housekeeping data are interleaved on the recorder in a circular buffer configuration, so that a single playback command will produce a data stream which does not need to be sorted or processed by either the HSC itself or its ground system. Instead, each instrument and the CDH system itself will be allocated an APID so that the individual frames may be sorted and processed on the ground. Reducing the number of instruments that write to the SSR will decrease the overall data rate, allowing a longer time before the circular buffer is overwritten; disabling the instruments altogether, when the system is in Idle mode, will maximize the length of time housekeeping data are maintained on the recorder, facilitating system trending or troubleshooting. Recorded data are automatically timestamped and formatted to CCSDS data transmission standards as they are written to the SSR. At rest, the data are capable of being played back immediately without any additional formatting by ASIA CDH or the HSC, turning the data playback process into a bent-pipe operation.

ASIA will accept four types of commands:

- Commands stored in ASIA FSW, used during POST of the CDH and instruments
- ASIA bus commands, where ground or HSC stored commands are issued directly to the ASIA bus and its subsystems
- Pass-through commands, where ground or HSC stored commands are issued to ASIA FSW for distribution to the instruments or other downstream equipment
- Raw commands, where opcode is relayed directly to ASIA FSW or instruments in support of troubleshooting or software upgrades

The SSR will receive housekeeping data when the unit is powered, and science data while the unit is in “Science Collection” mode. On command, it will play back its stored data through the connection to the HSC. A design goal is the ability of the unit to record and play back simultaneously; if no mode transition is required to execute those activities, there will be no data collection gaps while the playback is in progress.

3.2.1.4. Thermal Control

Because the ASIA unit power-up complies with HSC timelines, and because it is considered a low-priority for power during HSC contingencies, there may be long periods of time when it does not receive power for active heating. A small battery will provide stopgap power for survival heaters, but ultimately multilayer insulation (MLI) blankets and paints/coatings will be key for maintaining internal temperatures during these times. The survival heater will operate on a thermostat control circuit to conserve battery power and prevent unnecessary heating (such as during prelaunch or when the bus is receiving enough external heat to keep the bus components safe without additional power draw). The battery should be sized for six to twelve hours of worst-case survival heater power, sufficient for launch activities and basic protection during electrical load-shedding events.

When the unit is first powered, operational heaters will automatically activate as required to bring the science instruments into their operational temperature range. After a length of time (determined through prelaunch analysis), the system can transition to science data collection without heightened risk of damaging onboard equipment due to rapid thermal changes.

Thermal dissipation will take place first through conduction from the instrument and bus electronics into the bus structure, and then either radiated out into space or, if the HSC vendor agrees, partially conducted to HSC structure. Specific balancing of those methods will be determined during the prototyping stage, using parameterized or finite element analysis.

3.2.1.5. Operational Modes

The ASIA space segment can operate in one of a number of different modes, broadly characterized by the state of its flight software:

- Unpowered: when no power is available to the unit, no processing can take place and only battery-powered survival heaters are active.
- Idle: when main power is applied, the CPU automatically boots, performs POST of the CDH, and begins waiting for a command to begin science data collection. Operational heaters are powered automatically, and housekeeping data is streamed to the onboard recorder.
- Science Collection: when the HSC issues or relays a command to begin science collection, the CPU will command all selected instruments to relay data through the CDH to the onboard recorder.
- Diagnostic: while this mode is active, the FSW can be reprogrammed, and guarded or raw commands can be issued to the unit through the HSC. Additional housekeeping data points not normally recorded can be made available for subsystem troubleshooting, if desired. This mode is intended for anomaly response troubleshooting but could allow software updates if necessary.

Mode transitions must be commanded from the ground, except when the system moves to “Idle” mode after power is applied. The mode transition hierarchy is shown in Figure 17.

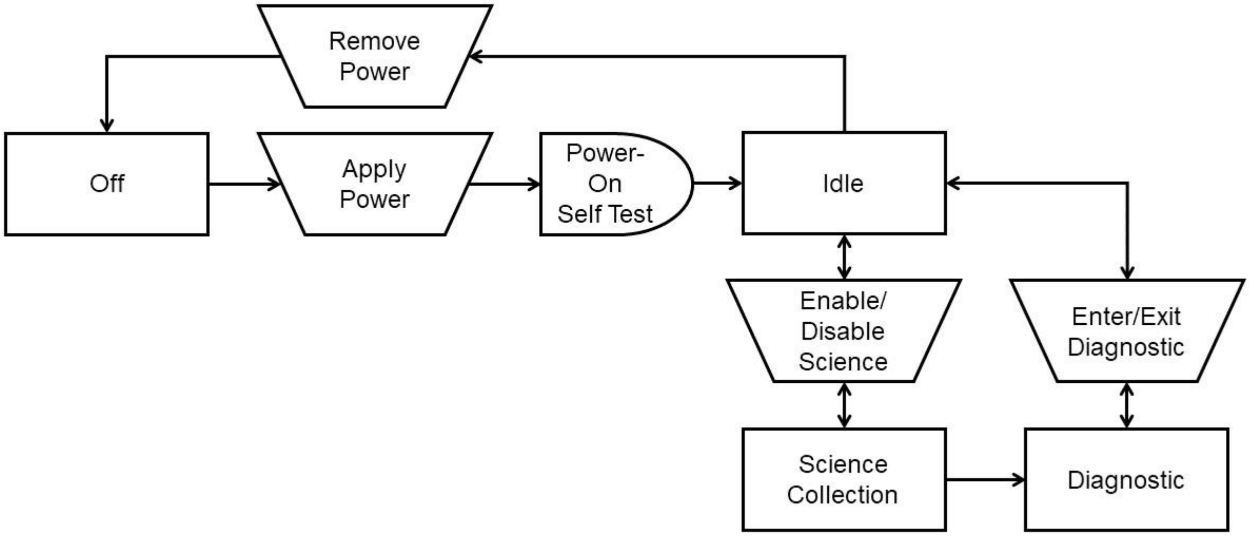

Figure 17. ASIA Operational Mode Transitions

3.2.1.6. Anomaly Recovery

Simplicity in the system’s design requires simplicity in its operations, including recovering from failures or other unexpected situations. Because the space segment is designed for minimal commanding, a power-on reset command will halt science collection, bring the unit back to “Idle” mode, and remain there for further troubleshooting or until commanded back to science data collection. Thus, a single command (which can be issued from the ground, via stored command load on the HSC, or internally due to fault detection) will bring the ASIA unit back into a stable, safe configuration which allows for troubleshooting data collection while minimizing power requirements and reducing data volume for maximum length of housekeeping data storage.

In the event of a single instrument failure, ASIA FSW can be configured to ignore input from one or more of the scientific payloads. Removing power from the individual components may not be possible based on the final design of the EPS (if a switchable power distribution system is available, those could be toggled via command; if the system is fused, the failed sensor will continue to draw power while the system is in Science Collection mode), but removing the instrument from the data collection set will increase data longevity on the local data recorder and reduce downlink time required on the HSC communications system.

3.2.2. Scientific Instrument Modules

The instrument package for the ASIA space segment proposed in this document includes two space weather particle detectors, a gamma-ray burst monitor, and a dust/MMOD counter. All proposed instrument designs have some heritage with prior space systems but will have to be modified for inclusion in the smaller package and to ensure they conform to tight power and data rate requirements. This sample loadout is not the only possible application of the ASIA bus (see Section 4.4.2).

The Dust Counter and GRB detector instruments described below may be configured to provide science data to the ASIA SSR only when triggered; for example, only when a GRB is detected will a data packet be written to the recorder. This is useful in keeping data volume low during periods of low activity; however, a drawback is that the science data rates for those two instruments are variable and unpredictable, so the length of time before the SSR circular buffer overwrites itself cannot be predicted with certainty.

3.2.2.1. Dust Counter

This is a 2U instrument that will occupy Bays 3 and 4 of the ASIA structure. The instrument is patterned after the Venetia Burney Student Dust Counter (VBSDC) on New Horizons, which itself followed the Cosmic Dust Detectors on the Pioneer 8 and Pioneer 9 probes. The purpose of the VBSDC is to characterize the dust and micrometeoroid environment during New Horizon's cruise and encounter phases [76]; the ASIA unit could likewise provide data both in orbit around a planet or during the HSC travel to that destination.

The New Horizons VBSDC is shown during assembly in Figure 18 [77]; both the brown-purple collection area and the electronics module are shown. The full-size VBSDC is 47x32 cm, so the unit in the ASIA bus will be scaled to fit in the 10x20 cm two-bay configuration, with instrument electronics mounted below the outer face.

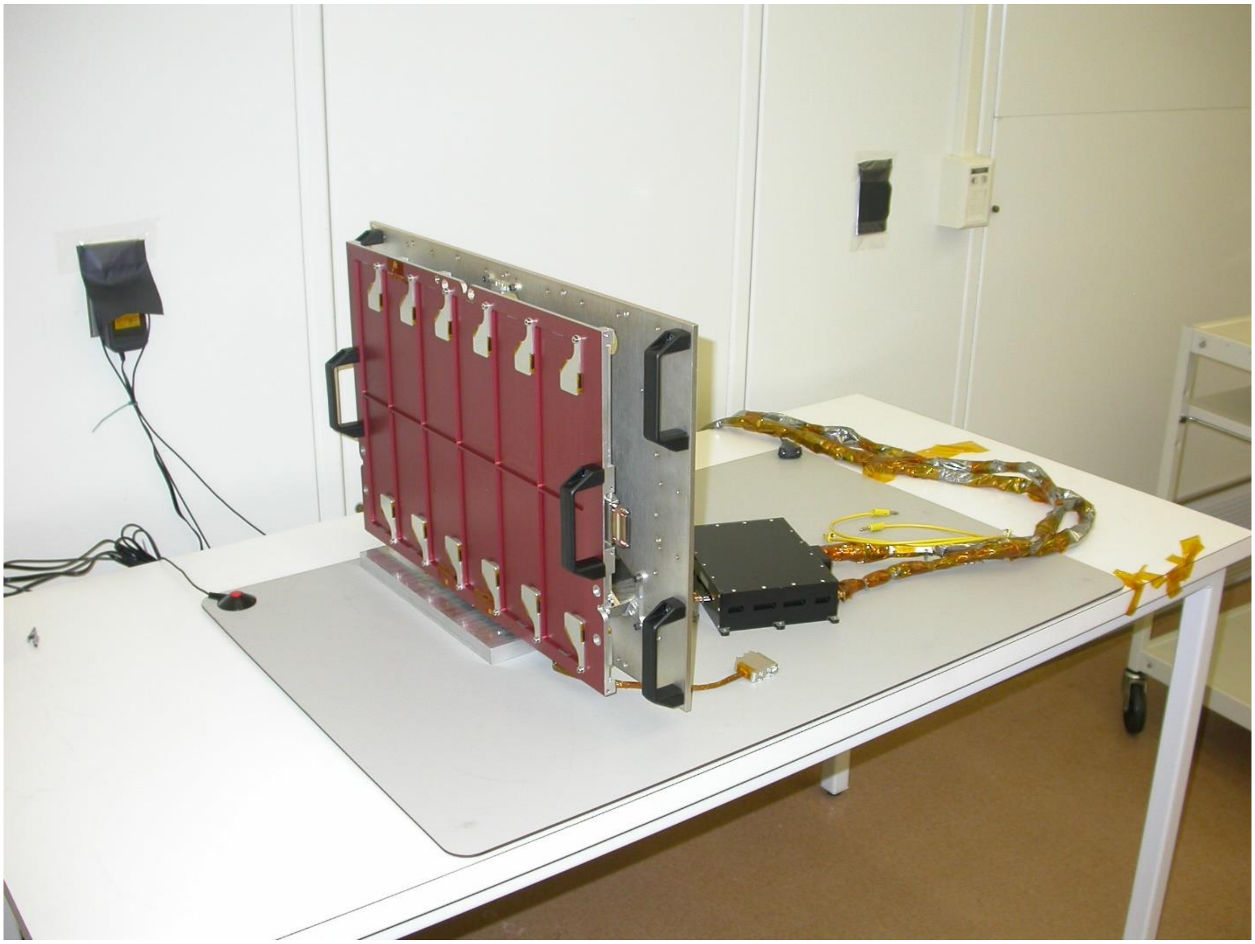

Figure 18. VBSDC under construction (Credit: NASA/LASP)

3.2.2.2. Low- and High-Energy Telescopes

The Low-Energy Telescope (LET) and High-Energy Telescope (HET) are two components of the Voyager program’s Cosmic Ray Subsystem (CRS) experiment [78]. Using solid-state electronics, these sensors could “measure the energy spectra and elemental composition of nuclei from hydrogen through nickel over an energy range from 3-500 MeV/nucleon,” and contribute to the exploration of solar wind and particle interactions with the magnetic fields of the gas giants and in the outer solar system. A photograph of the CRS is shown in Figure 19; the four units labeled A, B, C, and D are LET units, and the HETs are mounted immediately outboard of those telescopes [79].

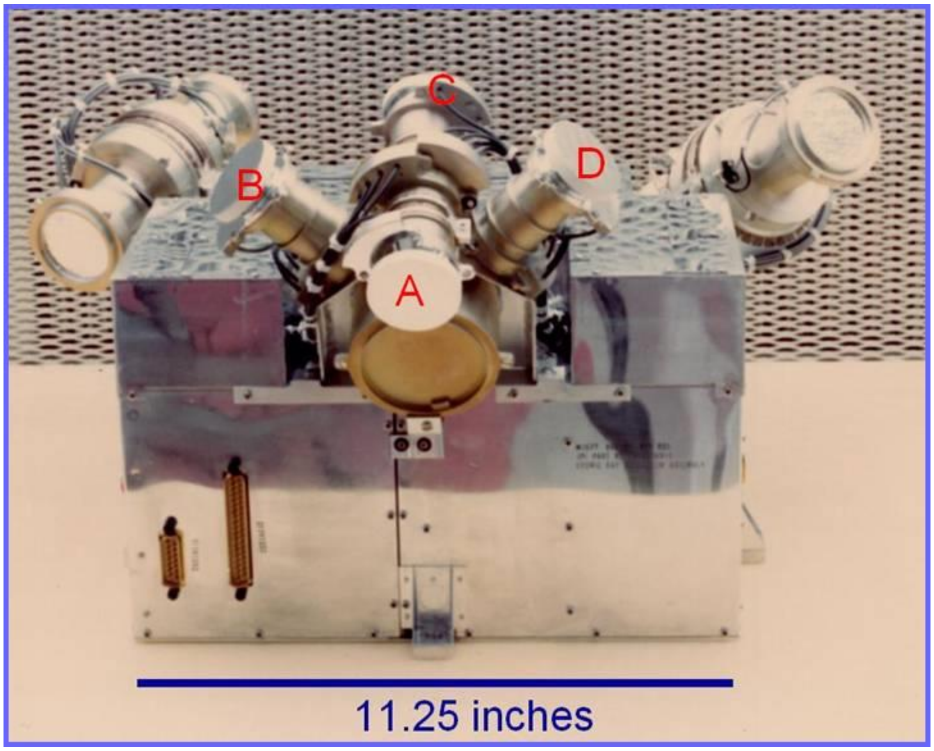

Figure 19. Voyager Cosmic Ray Subsystem (Credit: NASA)

One HET and one LET unit will occupy ASIA Bay 2 and Bay 5, respectively. This will provide the full range of energy detection with partial sky coverage.

3.2.2.3. Gamma-ray Burst Monitor

Gamma Ray Bursts (GRBs) are high-energy discharges of (sometimes indeterminate and usually extragalactic) origin. A 1U instrument, modeled after the Gamma-ray Burst Monitor (GBM) on NASA's Fermi Gamma-ray Space Telescope (FGST), will occupy Bay 6 of the ASIA structure. The FGST GBM sodium iodide (NaI) scintillators, one of which is shown in Figure 20 [80], are only 12.7 cm wide [81]. This is only slightly larger than a standard 1U CubeSat and could probably be modified to fit into an ASIA bay with modest effort. Alternatively, silicon photomultipliers are under consideration for future CubeSat-based GRB detection missions; these photomultipliers are smaller and have signal response benefits over existing photomultiplier tubes and could be adapted into ASIA [44].

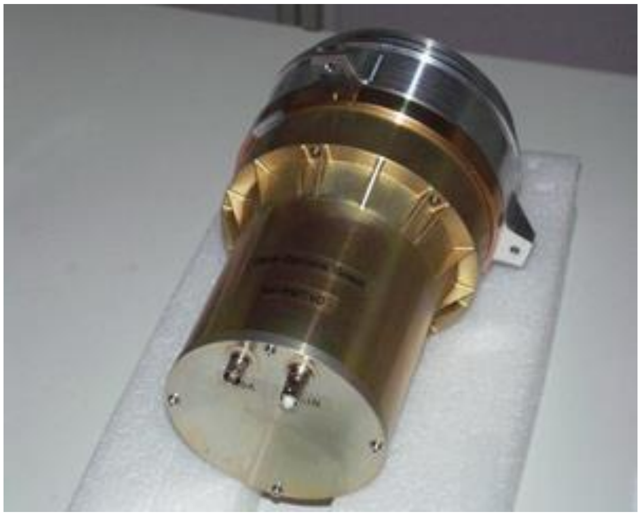

Figure 20. GBM instrument used aboard Fermi (Credit: NASA)

Burst monitor data gives a somewhat special case of remote instruments: while the content of the returned event information message is critical for understanding the source and characteristics of the burst, rapid reporting of the event allows other satellites and ground-based equipment to observe the quickly-fading afterglow through the rest of the EM spectrum [44]. This represents one of the difficulties in operating the IPN, where data transmission on the order of days can diminish the scientific value of the return [65].

A number of satellites currently in operation are configured to reorient and image the location of a detected gamma ray burst quickly and autonomously; while ASIA will not autonomously request HSC repointing (to minimize effect on the primary science mission), accurate and rapid reporting of detection time from widely-separated sensors can provide better triangulation of the source. Even the detection announcement process would require two modifications to the baseline ASIA concept: the HSC would have to poll the ASIA unit for GRB detection on a routine and frequent basis, and when a burst is detected the HSC would autonomously initiate a communication broadcast to relay the detection to the ground. Communication buses for onboard equipment usually have unused slots in the timing schedule, and if the HSC is operating in LEO then it could initiate a communication broadcast to any listening TDRS or ground station using standard transmission formats and frequencies. However, both modifications result in increased burden on HSC subsystems contrary to the non-interference nature of ASIA and would require additional coordination during development and operation, and this rapid-notification process is desired but not required from a scientific standpoint.

3.2.3. ASIA-to-HSC Interfaces

All components required to connect the ASIA space segment to the HSC are delivered as a package with the bus, all components having been assembled, tested, and prepared in the factory.

3.2.3.1. Mechanical

The ASIA bus will be bolted to the exterior of the HSC using fasteners at each of the four corners on the large face opposite the instrument boresights. The bolts will meet required launch load factors, provide vibration and thermal insulation between the HSC and ASIA, and could be used to electrically ground the space segment (with appropriate resistors to control transients). Its position on the HSC exterior will be determined by the HSC vendor; no assumptions are made, and no requirements will be levied for its location, thermal environment, or proximity to other equipment.

3.2.3.2. Electrical

A single electrical connector from a switched 28 VDC power supply aboard the HSC will connect to Bay 1. The cable will be appropriately insulated; provide return grounding; conform to standards for bend radius, surge protection, and thermal constraints; and include connections as appropriate for the HSC vendor. The HSC vendor may provide redundant or hot-backup power from the HSC EPS at their discretion, and the power feed may be regulated or unregulated; the ASIA unit will operate with whatever input is provided (given basic restrictions about minimum voltage without sharp transients) and perform its own conditioning.

3.2.3.3. Data

A single data connection for either MIL-STD-1553B, IEEE-1394, or SpaceWire, with associated cabling, termination, and balancing, will be provided with the ASIA unit. These three standards were selected over other industry standards because of their high availability in modern spacecraft buses, the high probability of extra connectors being available on the spacecraft bus (the 1553 standard allows up to 30 remote terminals; 1394 can connect up to 63 devices), long cord lengths, and the ease of obtaining and integrating a remote terminal junction in the ASIA unit. Other bus-to-HSC connections, like RS232, Ethernet, and USB, have their own advantages for robustness, data rate, or weight, but are not included standard with large spacecraft bus vendors as broadly as

1553 and 1394 (though they may be used for connections internal to the ASIA bus).

SpaceWire is a relatively new standard but is becoming more widespread throughout the space industry as the demand for large bandwidth increases. It has been implemented on a number of high-profile satellites over the last decade, including the Lunar Reconnaissance Orbiter and the GOES-R next-generation weather satellite, and has been adopted by ESA and JAXA in addition to U.S. organizations [82].

The 1553 bus standard was “high-speed” when developed in the 1970s, but the 1Mbps transfer rate is considered sluggish compared to newer standards, like FireWire’s multi-hundred-megabit rates. However, depending on the ultimate data rate developed by the science package, 1Mbps may be sufficient for frequent downlink intervals.

Remote Terminal address and available Virtual Channel information must be provided by the HSC vendor so that the ASIA space segment can be programmed in its factory, prior to delivery.

3.2.3.4. Thermal

No active cooling service is required from the HSC, and conductive heat transfer across the mounting bolts will be minimized to reduce effects on the HSC from any heat generated by the ASIA unit. This isolation also provides ASIA some protection if the underlying HSC structure is a heat source.

3.2.3.5. Passive and Inadvertent Effects

Thermal vacuum (TVAC) testing of the space segment and all connectors will be performed during the ASIA unit’s assembly and testing, before delivery to the HSC vendor; beyond the quality assurance and testing benefits of such an activity, vacuum chamber testing will reduce the unit’s outgassing on-orbit, which may pose a contamination risk to sensitive instruments.

In order to prevent detrimental interaction between ASIA and the host spacecraft’s bus and primary scientific instruments, radiation effects will be minimized, including electromagnetic (EM) and radio frequency interference. Radiative cooling may be required for some internal components, but no component onboard will release nuclear or RF radiation or generate EM fields beyond what is required for the normal electronic systems on-board. The ASIA unit will not contain active sensors.

Physically, the form factor of the unit has been chosen to present only a small profile compared to other components mounted to the exterior of the HSC bus; the low profile will increase the number of locations where mounting the unit will not interfere with HSC sensor fields-of-view or other equipment. Exterior coatings and exposed insulation will be chosen to reduce albedo and glint, to prevent ghost images or stray light from interfering with HSC sensors (like star trackers) or EM instruments.

All these effects will be simulated during program development and analyzed empirically after prototypes are developed. This information will be provided in the initial data package described in Section 3.1.3.1, so that the HSC vendor can determine the ASIA unit's mounting location where effects on primary mission objectives will be minimized, and the unit's activation sequence after launch to reduce interference with other activities and general risk to the primary payload and its mission.

3.3. Ground Segment Overview

The ground segment of the ASIA program includes all hardware and networks dedicated to ASIA data collection (including network interface control with the HSC MOC and other external ground systems), storage, processing, and distribution.

A conceptual model is presented here, with the understanding that existing GOTS or COTS services and software may already exist to perform one or more of these functions.

3.3.1. Science Data Processing and Storage

Raw returns from the spacecraft will not be immediately useful; the onboard clock may drift, requiring correction, and the science data must be collated with HSC position and orientation histories to give context to the measurements. Additionally, mass storage and a distribution mechanism for the returned science and housekeeping data must be available to both program engineers and end users in the scientific community. The ASIA ground segment will provide these services in its DPS.

A conceptual implementation showing the data flow from the space segment through delivery, processing, and distribution is shown in Figure 21. Details about storage and distribution will be driven by aspects of the program's implementation, such as the managing authority, sources of funding, and scientific instrument selection; these are discussed in Section 4.4.1.

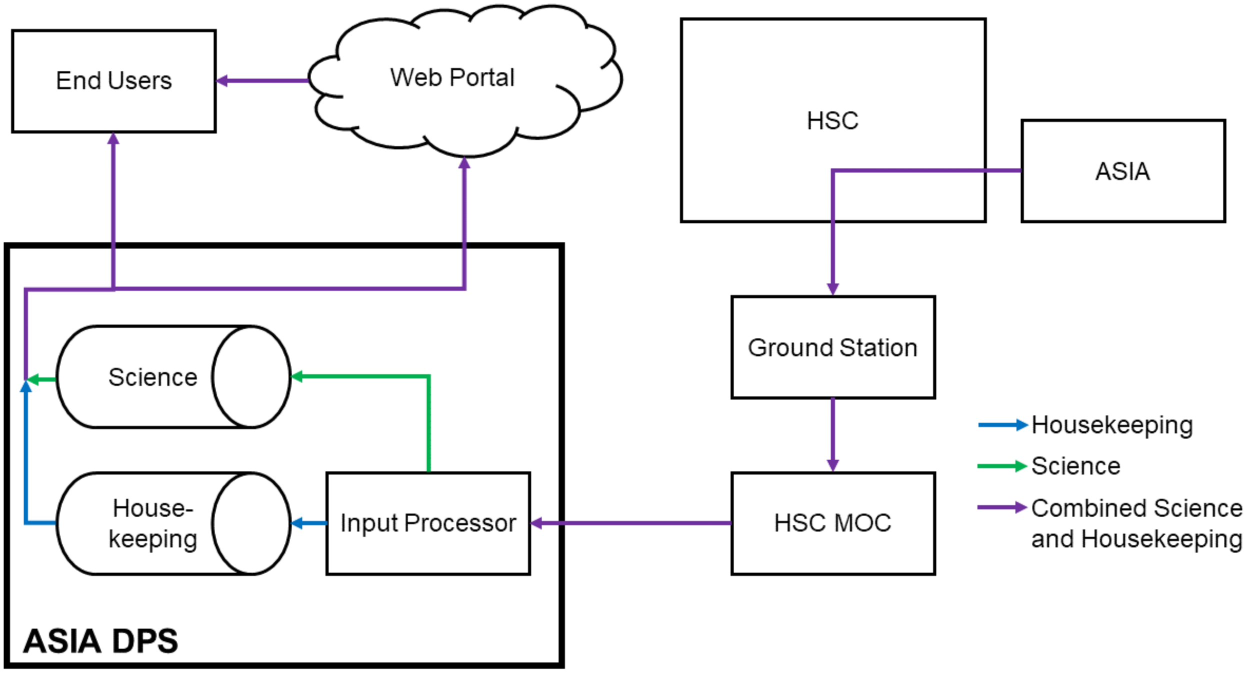

Figure 21. ASIA Ground System Data Flows

3.3.1.1. Input Processing

The data downlink from the space segment to the HSC MOC takes the form of a single file conforming to CCSDS protocol 727.0-B-4 (CFDP). Individual instrument data will be stripped out based on APID number and stored with the recorded-at timestamp and source ASIA unit or HSC (when multiple flight units are operating).

HSC timing offset information (if provided) and ephemeris/pointing histories are stored separately but likewise timestamped. Any data corrections (sensor calibration offset, timestamp drift updates, corrupt packet removal, etc.) should be performed during the write process, with the understanding that some of this corrected science data may not be available for hours or days after the original data are injected into the database. In this case, the science data may be labeled as "preliminary" and reprocessed when the final data corrections are available.

3.3.1.2. Mass Data Storage

Depending on the ultimate project owner for ASIA and the services available to that organization, the processing and storage may take place in a physical location, like a server rack in a NASA facility alongside existing infrastructure or with a dedicated room and equipment in a science or engineering building at a university. Mass data storage would be accomplished with a RAID array or some other high-uptime system that can feed the web portal. The overall size of the storage system will be determined after science instrument selection is complete and the overall data rate can be modeled; it will likely grow as more ASIA units are flown and cumulative time in space increases. Science and housekeeping data may be stored alongside each other. This reduces complexity and allows access to both data sets if desired (for example, to support science data calibration).

Alternatively, data storage could be implemented purely in the Cloud. For example, a number of NASA missions use a secured instance of Amazon Web Services to provide telemetry storage, distribution, and analysis tools in a broadly-accessible location [83], so a similar implementation (or using the existing process) may result in a relatively cheap, decentralized option for data storage without the need for local system maintenance or expansion.

A third option is to use existing NASA science data systems to store the ASIA datasets. The HEASARC, OMNIWeb, and EOSDIS web portals provide datasets for high-energy astrophysics, heliospheric and space physics, and Earth science missions, respectively, and can combine the storage and distribution functions into a single system.

3.3.2. Science Data Distribution

A web portal provides the main interface for data retrieval and download to the science community. End users can search for and request intervals of data by one or more of the following parameters:

- ASIA unit
- Date and time
- Regime (LEO, GEO, interplanetary, etc.)
- Instrument

After the request is received, the repository will read the appropriate data from the database, format it into a Comma-Separated Value (CSV) text file, append information (like timestamps, source ASIA unit ID, and HSC location) in-line with the science data, compress the file (using a standard format like .zip or .gz) for transfer, and deliver it as a download through the web browser. Larger requests may be split into multiple files sized for more reliable transmission, but file compression should be effective for text files with large segments of repeated information like timestamps.

Depending on the ultimate data rate for the ASIA units, large requests may be best fulfilled by way of physical delivery (disk, tape drive, etc.) at cost to the user. However, given the expected data rate of ASIA units and wide availability of high-speed internet services, this is an unlikely option.

Over time, the ASIA program's scientific return will increase in volume, and the end-users of those data may also increase. A scalable interface would allow for a consistent user experience regardless of changes in the number of users (overall or simultaneous), storage volume, downloaded dataset size and speeds, and changes to datasets themselves (through evolving sensor selection; see Sections 4.4.2 and 4.4.3). The commercial Cloud hosting services discussed above may fill those needs, in addition to maintaining the dataset's redundancy and the interface's uptime regardless of local conditions.

The architecture shown in Figure 21 includes a provision where datasets can be delivered directly to end users without the use of the web portal. The option of routine product delivery on a daily or weekly basis (for example), using premade configuration files or templates, may simplify processes for regular users or automated systems. The specific implementation of this feature would rely on the chosen distribution system.

3.3.3. Housekeeping Telemetry Processing and Analysis

Housekeeping telemetry is downlinked with the science data, with a separate APID for ease in separation. It is processed and correlated in a similar method to the science data, but is stored separately to expedite delivery of science data products on request. The science community may want access to the data on request, but not have it automatically delivered, so most or all of the data may be available through the science web portal.

After telemetry and command databases for the ASIA space segment have been built, any GOTS or COTS telemetry processing software can be used to decommutate and process the telemetry stream into a format suitable for storage in the database. Automated systems can perform routine monitoring of the returned housekeeping data. During decommutation and/or during injection into the housekeeping database, computer scripts can search through the values of key parameters and evaluate whether any values violate predetermined limits (such as low voltage or high temperatures). GOTS and COTS solutions exist for sending an email or text message notification to engineering personnel, alerting them to an off-nominal condition so that troubleshooting and corrective action can begin.

3.4. Project Administration

This section describes the non-technical consideration of implementing and operating the broader ASIA program. Three desirable qualities for the governing organization are the ability to fund the operation (both the initial investment and the long-term operation); the amount and type of infrastructure they already have in place for administration, facilities, and IT resources; and resident technical expertise and experience.

One obvious source of long-term administrative, technical, and budgetary support would be either NASA or NOAA, or potentially another federal government organization. These administrations already maintain large pools of technical resources, have management and organization structures in place, have a history of spaceflight operations and program development and sustainment, and possess budgets large enough to accommodate a small project like this for long-term implementation. Additionally, both agencies currently operate HSC-capable vehicles in LEO and GEO, so their existing and projected satellite programs include a built-in network to which ASIA could be added.

Additionally, NASA maintains a number of Multi-Mission Operations Centers (MMOCs), which operate several small missions simultaneously. A combined operations center condenses infrastructure and reduces human resource costs. One such facility, located at the Ames Research Center [84], oversees various ISS payloads and small space science missions. Another MMOC at GSFC flies the Advanced Composition Explorer (ACE) and the Wind solar wind laboratory, and has begun to integrate ground equipment and infrastructure for other space science satellites and SmallSats [83].

An alternative is a large academic institution or network of universities which could pool resources to operate and maintain the program. Such an institution may require funding support from NASA, NOAA, or another government organization for startup and ongoing material costs, but engineering labor could be offloaded to the student and research population; the resulting experience (technical and administrative) for students is a benefit sometimes as desirable as the scientific return [50].

A third option is for corporate funding, which may include development and sustaining operation costs. Given the large presence of telecommunications operators in low- to medium-earth orbit but relatively few missions from any one operator in geosynchronous orbits and beyond, this option by itself may not realize the fullest potential of widely-distributed sensor networks.

3.4.1. Project Office

The seat of the program will include offices, personnel, and services for ASIA operation. Depending on the ultimate scale of the program, this may require as few as five people part-time, performing engineering, documentation, budgeting, and procurement activities, and interfacing with parent organization management and the scientific community. Project office staffing will increase during project development and initial implementation, and may grow or shrink with the number of ASIA units in use and the age of the program. Depending on its implementation, source of funding, and location of stakeholders, it may or may not include a dedicated physical office or facility.

Example responsibilities include:

- Acquiring and maintaining remote sensing licenses in accordance with U.S. law
- Maintaining licenses for commercial software packages
- Maintaining any required labor charge codes and contracts
- Coordinating between stakeholders (the science community, sustaining engineering, HSC vendors)
- Developing corrective products (like software patches and bug fixes) for existing systems, and incorporating new technologies and lessons learned into future ASIA unit designs

3.4.2. Preliminary and Sustaining Funding

Major upfront costs include detailed design and prototype development, including a test flight if a suitable mission can be found. The data processing and storage requirements for a single unit would be modest, especially if there is no need to distribute the preliminary science data immediately. Data hosting could also piggy-back on an existing ground system that could accept input from another data source without heavy modification.

After program startup, costs will diminish to lower levels. Continuing budget items include space segment production, including testing, delivery, and HSC FOT support (like training); ongoing operations, including ground system maintenance, engineering analysis, costs for storing and distributing science data; and developing and implementing adjustments to ground and space segments.

Potential sources for funding are discussed in Section 4.4.1.

3.4.3. Resident Spacecraft Engineers

Offloading ASIA unit engineering analysis, subsystem trending, and troubleshooting from the HSC FOT will require a small staff of engineers to perform these functions. Automated trending systems and limit sensing software will check for degraded operation across individual ASIA units and their subsystems, with human interaction required only when a problem is detected. If appropriate, the resident engineers will develop a solution and communicate it to the HSC FOT for execution.

3.4.4. Ground System Administration and Maintenance

Information Technology (IT) infrastructure will require security patching, network updates, and storage upgrade and maintenance over the course of the mission. Once the primary servers are in place and network and web portal connections are configured for data reception and distribution, efforts will shift to repairing failed hard drives and other mechanical maintenance, coordinating network changes from external parties (like firewall changes or operating system upgrades), and setting up new connections for future HSC missions. If a data architecture using cloud services or existing NASA systems is chosen, those functions become the responsibility of the contractor.

3.4.5. Science Community Interaction

The ASIA project office will provide an interface between the science community and other stakeholders (though other communication channels may exist).

A spacecraft’s FOT provides first-line engineering expertise and skills for keeping the system healthy. They also provide a path for the wider engineering team (such as the development, manufacturing, and sustaining engineering groups) to interact with the system; if a software or conops change is required to improve scientific return or extend mission lifetime, the FOT collects the inputs, builds operational products and timelines, and implements the changes. Likewise, the science community will often designate a representative to oversee instrument operation and science data collection [74]. Because ASIA in its final form is a distributed system, with multiple units each providing a range of scientific data, one representative for each instrument, coordinating through the ASIA project office, may simplify interaction.

3.5. Assumptions about Host-Provided Services

The host spacecraft and its control center will necessarily include a number of functions required to perform its primary mission. These functions include attitude, position, and ephemeris determination systems; telemetry, command, and control equipment; and the ability to record (even temporarily) spacecraft diagnostic telemetry.

For many mission profiles suitable to ASIA's incorporation, there are a number of data points generally available to the public that can be used in conjunction with the ASIA data themselves. These kinds of publicly-available secondary data can add value to the ancillary science provided by the ASIA unit directly.

3.5.1. Attitude and Position Determination

Modern spacecraft have a variety of sensors available to them for position and orientation determination, and an ACS to effect changes to their orientation. The two most popular options for position determination are some kind of direct determination using an onboard receiver (the American GPS, Russian GLONASS, and Europe's Galileo constellations, and other satellite navigation systems), and measurement performed by other systems (especially tracking data from TDRSS or ground networks equipped for high-precision pointing and timing) followed by ephemeris uplink. In both cases, the orbit solution can be propagated between updates using onboard attitude control software, either in closed-loop (with inertial measurement units, IMUs) or open-loop with reasonable estimates of atmospheric drag, solar pressure, oblateness effects, and other perturbations. GPS receivers, IMUs, and high-precision timing devices are increasingly compact, affordable, and commercially available, so much so that even CubeSats can be equipped with them with minimal effects to cost, system mass, and schedule. Therefore, regardless of the

HSC configuration, it is reasonable to expect the FOT will be able to determine orbital parameters and package them for transmission to the ASIA ground system for data processing.

One example is Two-Line Element (TLE) ephemerides, which are commonly available for many remote observation and meteorological satellites in LEO on websites such as CelesTrak [85]; when combined with a timestamp contained within the data collected by ASIA, the samples taken by the ASIA unit can be positioned in space as well as time without the need for onboard GPS or inertial reference sensors. Common software suites for trajectory analysis, like FreeFlyer (from a.i. Solutions) and Systems Tool Kit (STK, from Analytical Graphics, Inc.), can interpret these files to provide information about where an ASIA unit was located when an instrument sensed a particular value.

HSCs elsewhere in the solar system (like Mars orbit) will not have access to GPS and so will rely on RF tracking data or inertial propagation. These methods will have lower overall accuracy of their position knowledge and onboard clock, and the resulting uncertainties will have to be relayed to the ASIA data processing system for incorporation into the processed data products.

Attitude control is critical for scientific data collection, directional antenna pointing, attitude maneuver planning and execution, onboard verification of system performance, solar power generation, and a number of other tasks, so all spacecraft must have some method of determining their attitude, if for no other reason than to properly enter a power-positive and thermally safe configuration after an anomaly. Depending on HSC pointing requirements, star trackers may be used for arc second accuracy; accuracy on the order of degrees may be available with coarse sun sensors and, in well-mapped magnetic fields, magnetometers; horizon and infrared sensors can provide two-axis determination on the order of tens of degrees. As the IMU propagates position between location-sensor updates, so can an Inertial Reference Unit or gyroscope (ring laser, mechanical, or other) propagate the orientation solution between attitude sensor updates.

STK and FreeFlyer both have proprietary formats for tabular display, storage, and analysis of attitude data, and can be configured to read text files with other formats, so long as those formats are well defined between the FOT and the ASIA data processing facility. Other general-math programs, like MathWorks MATLAB, can be programmed with commercial or custom code to perform orbit determination and attitude analysis.

Because the HSC can reasonably be expected to have attitude and orbit determination capabilities, the ASIA unit can offload those functions, thus eliminating the need for bus sensors, saving bus mass, and simplifying the overall system. In exchange for these savings, there is a heightened need for information transfer from the HSC mission operations team to the ASIA DPS. Still, this should prove to be a minimal increase in workload for the HSC team; for many missions, orbit ephemeris files are routinely provided to outside groups for communication scheduling and risk analysis for space debris collisions, so one additional transfer of an already-generated product could be added with ease. Attitude information may not be sent out as routinely, and the files can be larger than position records, but most automation systems could be configured to handle an additional outgoing file to an existing destination.

3.5.2. Environmental Condition Sensing

Host spacecraft sensors may detect conditions the spacecraft (and therefore ASIA) experiences in space. These can include magnetometer (especially in relation to electro-magnetic torque dissipation in LEO), temperature, and vibration and/or pointing stability measurements that could affect ASIA scientific data return. Calibration data for how these environmental conditions affect scientific instrument performance must be collected during the ASIA TVAC, HSC integration, and ground test campaigns, as space-based calibration may be difficult or impossible; pointed observations would require significant coordination with the HSC FOT and may affect the primary mission's objective. HSC measurements of these environmental conditions can then be provided to the ASIA DPS for correction of recorded science data.

3.5.3. Electrical Power

The ASIA unit will provide its own electrical power conditioning and distribution, but because it contains no onboard power generation it will require power provided by the host spacecraft bus. This input power should meet certain quality standards, many of which are generally desirable for the HSC's continued operation and so can be assumed in the ASIA design process. Examples include overall voltage ranging between 24 and 36 VDC (assuming normal solar array and battery power variation throughout orbital day/night cycles) and reasonable amperage on the upstream power switch in the HSC EPS. Inrush current limiting and surge protection will be provided by the ASIA EPS, but the more stability and current protection the HSC provides, the less stress on the non-redundant ASIA components.

These values are approximate and subject to change throughout the ASIA design and analysis process. The overall goal is simply to bound the conditions of input power which ASIA can expect for design, with the understanding that operational conditions will vary and may not be predictable in some anomaly situations.

3.5.4. Data and Commanding

The HSC will also provide communication capabilities to the ASIA space segment. This will include either a single MIL-STD-1553-B [86] compatible connection, a single IEEE-1394/AS5642B "FireWire" [87] connection, or a single ECSS-E-50-12A SpaceWire connection. These three standards have been flight-proven and are implemented in mission-critical applications in the aerospace and defense community, and as a result a broad range of COTS equipment manufacturers for spacecraft components will provide compatible connections. Additionally, even though spacecraft manufacturers themselves may use a proprietary bus protocol for their custom-built equipment, NASA expects that these interfaces will be implemented on many modern components and therefore requires its various internal workforces to be able to apply and maintain equipment using these standards [88].

Commands to be relayed to the ASIA unit must be accepted through the HSC flight software system and transmitted to the unit. If the HSC uses CCSDS command protocol, ASIA commands can be provided directly to the HSC vendor and the appropriate pass-through may be built into the HSC FSW database during preflight development. If it does not, the HSC will need to provide a mechanism to send opcode across the communications bus in a manner that will allow ASIA to identify that the code is meant for it, and that does not modify the data stream so that the command may be processed. This capability is standard on most modern space-rated data buses (to perform troubleshooting or write low-level commands to change equipment firmware).

3.5.5. Communications

The one key assumption regarding the HSC downlink capability is that the downlink path used for ASIA data relay is operated under CCSDS standards for data encapsulation and transmission. Requiring CCSDS allows the greatest interoperability with NASA-standard ground systems and HSC RF equipment, and gives the ASIA DPS the sorting capability it will need to effectively process the returned data.

The average data collection rate of the scientific instrument suite is highly dependent on sensor selection and design, and the transmission schedule is an operations decision to be made by the HSC FOT or program management. Because ASIA data dumps are performed when it will not interfere with the HSC's primary objectives, there are no assumptions that can be made about downlink bandwidth. Instead, the data volume and predicted HSC comm schedule produce a minimum downlink duty cycle that will produce no data loss when maintained, and can characterize the data loss that will occur if one or more updates are missed. The science and housekeeping data stored in the ASIA SSR will be overwritten oldest-first; therefore, this scheduling model can be analyzed and provided to the HSC FOT once the ASIA overall data rate is established after sensor selection.

3.5.6. HSC Mission Operations Center

The MOC overseeing routine operations of the HSC will include command and control equipment and the ability to receive spacecraft housekeeping (health and safety) telemetry. In many cases, the MOC will also provide at least routing, and occasionally storage, processing, or distribution of the science products. In either case, downlinked data can arrive at the MOC or a science distribution portal, and therefore the MOC can provide a science data dump from the ASIA space segment to the DPS.

To maintain ASIA data quality and maintain the space segment health and safety, certain routine interaction will be required between the MOC and the ASIA ground segment administrators and engineers. One example of this coordination is notification when the HSC timekeeping epoch is modified for UT1-UTC offset or leap second addition; the HSC FOT would inform the ASIA ground segment of what the modification was and when it took effect, in order for the ground segment to properly convert incoming timestamped science data into the proper UTC epoch. Such information transfers should be brief, regular, and well-defined; after the deployment of the first ASIA space segment, lessons learned for the specific number and type of interactions can be fed forward into future HSC coordination, but because different FOTs have different operational cultures, there will still be some variation between different host spacecraft.

3.6. ASIA Preliminary Design Summary

This section described key characteristics that a CubeSat-based hitchhiker payload carrier system would require, focusing on interaction between different elements:

- Criteria for selecting scientific instruments compatible with a mount-anywhere-fly-anywhere philosophy
- ASIA functions necessary to maintain itself and perform a scientific mission
- Services provided by ASIA to the instruments
- Interfaces between the ASIA unit and the host spacecraft, including assumptions about HSC-provided services and restrictions on the ASIA space segment to minimize interference with and risk to the primary mission
- Space-to-ground and ground-to-ground data flow, storage, and distribution of scientific, engineering, and ancillary data
- Coordination between project administration, scientific, engineering, and HSC vendor and operations teams, including distribution of duties and ASIA's easy and efficient integration with the host spacecraft

Heavy emphasis has been placed on a "Do No Harm" philosophy; ASIA will perform its mission while minimizing resource utilization and added risk to the HSC. Mission success will be achieved through the heavy use of equipment and scientific instrumentation with flight heritage, as well as engineering experience from NASA's previous small space systems and hosted payload programs.

4. Discussion

This section analyzes the feasibility of developing and implementing a system with the characteristics described in Section 3 and describes general actions required to do so. It also provides two courses which could potentially expand the program: broadening the sensor package options to generate a more targeted scientific return based on HSC destination, and opening the payload options to accommodate a wide variety of academic and technology demonstration objectives.

Recently, NASA implemented its first commercially-hosted, NASA-operated scientific payload. In addition to proving a concept for hosting civilian-scientific payloads on a commercial host, the program also illustrates how industry, academia, and government organizations can share the costs and benefits of small scientific projects; ASIA could follow this development and operational model.

4.1. Program Feasibility

Rather than specific advances in a technology or capability, the feasibility of the ASIA concept is driven primarily by historical precedent. Flight heritage of subsystem components, processes derived from the CDS and CSLI, experience from prior and current small and hosted payload projects, and reuse of existing ground data systems collectively produce a program in which risk of individual elements is minimized.

Because the ASIA space segment relies heavily on COTS equipment, the TRL for individual components generally will be high; prudent selection of parts with flight heritage improves the risk posture of the overall system. A number of small satellite components are already available through the CDS and increasing NASA/industry partnerships and manufacturing. These include power supplies and storage, data systems, and thermal control equipment. As the market for such equipment continues to grow and evolve with increasing use of CubeSats and small payloads, new technologies will mature and become accepted for use in “routine” functions (compared to a research and development role), and ASIA’s modular nature will allow system upgrades to improve performance without an increase in baseline risk.

Government programs (both through agencies directly and as part of educational outreach or research and development initiatives) provide an existing framework for both project administration and funding. NASA recognizes both the importance of space science research and the market for small payloads, especially with regards to technology development, infrastructure, and education; it routinely solicits proposals to fly space science projects, including payloads hosted aboard the ISS and deployable CubeSats, and while competition is intense, selection of high-profile missions over the last several years demonstrate an ongoing interest in space weather (DSCOVR) and the interaction between Earth and the sun (MMS), both of which can be served by the space environment instrument selection described above. While the Shuttle GAS program is no longer operating, small payload initiatives such as the CSLI continue promoting ease of space access to academic institutions.

4.2. Challenges to Implementation

Challenges remaining in the development of the ASIA system include:

- Defining and developing interfaces between the ASIA unit and the first HSC bus, confirming all interaction is properly considered, understood, and controlled to minimize risk and streamline the integration process for future units.
    - This is best accomplished by flying a demonstration unit as a hosted payload, which may not be readily accepted aboard a flagship mission or commercial HSC; intermediate steps such as sounding rockets or a free-flying demonstrator could provide some of this knowledge and are described in Section 4.4.1 below.
    - Restricting the first ASIA space unit to a less-general configuration (e.g., requiring MIL-STD-1553 bus architecture instead of allowing IEEE-1394 or SpaceWire) will restrict the number of available hosting platforms but reduces complexity in interface control; later units can increase flexibility once certain interfaces are defined and stable.
- Subsystem design, including COTS component selection and fabrication of custom equipment
- Developing test procedures and facilities
    - The NASA LSP requirements document provides guidelines for system testing prior to acceptance.

    - Test facilities such as TVAC chambers and vibration mounts may already be available to institutions that have flown equipment before, or could be contracted through commercial SmallSat component vendors.
- Project solicitation to find a programmatic home for ASIA (see Section 4.4.1)

As this report is principally directed to describing the engineering support systems and operational aspects of the ASIA concept, the science subsystem will require extensive additional work. Tasks related to the scientific mission include:

- Scientific instrument selection, design, fabrication, test, and integration
- Identifying a Principal Investigator (or other administrative point or points of contact) to lead interaction with the ASIA project office
- Coordinating data product format and delivery to the scientific community

Various other programs, from SmallSats to ISS hosted payloads, have experienced these hurdles before; therefore, none are insurmountable. Existing processes can be adapted and prior experience leveraged to complete this open work.

4.3. NASA's GOLD Payload – A Case Study

NASA's Global-scale Observations of the Limb and Disk (GOLD) Earth-observation mission launched on January 28, 2018. The 36 kg imaging spectrograph measures the upper atmosphere's temperature, density, and composition at 30-minute temporal resolution, and produces full-disk coverage similar to the narrower coverage from existing sensors taking similar measurements from LEO.

GOLD is the first NASA scientific payload to be hosted on an unrelated commercial satellite [89]; it is a hosted payload on the SES-14 telecommunications satellite, which provides Ku-band telecommunications relay for data and video services in Latin America [90]. The payload uses power and communications equipment aboard the host spacecraft, and relies on the HSC's attitude control system for both its pointing and the sensor's orientation determination.

This mission is an excellent model for implementation, administration, and operation of commercially-hosted scientific sensors, one that ASIA could follow. NASA retains managerial control of the GOLD payload itself, but the remainder of the program is distributed across a number of commercial, academic, government, and federally-funded organizations [91]:

- NASA sponsored the mission (and manages it from GSFC) and is a major user of the returned science data.
    - NOAA provides space weather modelling support.
- SES-Government Solutions provides the host spacecraft and its on-orbit resources, performs HSC operations, and downlinks the scientific data.
- Industry partners directly contribute to data analysis:
    - National Center for Atmospheric Research coordinates the science team, algorithm development, and scientific analysis.
    - Computational Physics, Inc. develops and implements the scientific algorithms.
- A variety of academic institutions share the cost and experience of scientific analysis and mission and payload operations:
    - The University of Colorado's Laboratory for Atmospheric and Space Physics is the scientific seat of the program, and includes the mission's principal investigator.
    - The University of Central Florida operates the science data center.
    - Virginia Tech conducts scientific analysis and space weather modelling.
    - The University of California, Berkeley, supplied the UV detectors and participates in scientific analysis.

Distributing the administrative and technical oversight of the mission allows for distributed costs, and raises the number of organizations that can share in the direct scientific return (and extra educational experience) from the program.

By 2013, GOLD was the only mission to have been accepted for development in the Earth Venture program, because of the stringent requirements and technical responsibilities levied on the applying programs [6]. However, a number of the complicating factors that lead to such a low acceptance rate are mitigated in the ASIA architecture:

- Carrier spacecraft selection: due to the flexible design of ASIA interfaces, no particular vendor or bus classification is required.
- Burden to HSC vendor: offloading the analysis of the instrument and its requirements from

the HSC reduces workload for the HSC team, and the small size and reduced complexity of the ASIA unit allows for a compressed timeline between project selection and delivery of the space hardware

- Destination environment: ASIA units can operate in a variety of thermal and radiation environments, so no particular orbital regime or destination is required
- Security and International Considerations: by using COTS components nearly-exclusively, ITAR and other technology-transfer concerns can be reduced or eliminated. This allows for a broader selection of LVs and HSC buses, increasing the opportunities for launch and hosting aboard international vehicles

4.4. Implementation, Expansion, and General-Purpose Hosting

This document is an outline of a project that is feasible and capable of providing significant, valuable scientific return for modest cost. However, at this time, it is theoretical. This section will describe the path toward realization, and possible avenues of evolution for the ASIA concept.

4.4.1. Prototypes, Programmatic Support, and the Road to Implementation

Assuming the feasibility of the concept and space environment sample loadout described above, there are three major steps to be taken on the road to program implementation. First, the technical system should continue to undergo conceptual and technical refinement (including engineering peer review; such semi-external verification is useful in completing CSLI milestones and increasing the probability of selection [50]) and eventually move into a Phase B preliminary design phase as described in NASA’s engineering life cycle (see Section 2.4.3). This could lead to constructing a prototype unit for ground analysis, refinement, and eventual flight, providing an evaluation of the concept in real-world circumstances. After preliminary design work, testing, and conops development comes proposing the mission (either a single demonstrator or the broader ASIA program) to NASA’s SMD for consideration as a program on the scale of an Earth Venture-class mission.

An intermediate step between ground testing and full implementation may involve a prototype or partial unit being flown on a balloon mission or suborbital sounding rocket, two common methods of demonstrating feasibility and gaining design and operation experience. A free-flying 6U CubeSat may also help refine the science subsystem and data processing flows and prove hardware configurations, though a number of the benefits of the non-deployable hitchhiker concept would be lost. These "crawl-walk-run" progressions for development of small payloads built and operated by academic institutions not only prove mission architecture and conops from a design standpoint but also demonstrate feasibility and value of the mission to NASA, which can in turn produce stronger applications for future rideshare slots for orbital deployment or operation [50].

Second, programmatic support should be sought for the resources, infrastructure, and long-term commitment described in Section 3.4. NASA, NOAA, and the DOD all have stakes in space weather monitoring and research, and all have the capability to work with the academic sector to implement and maintain a venture of this size, scope, and complexity. Interagency partnerships and cooperative efforts between government agencies and academia would allow for sharing both the costs and benefits of the program. NASA's yearly ROSES solicitations provide potential avenues through which either the specific sensor package described above could be proposed for flight consideration as a demonstration unit or the broader concept could be proposed for full program implementation.

NASA also maintains a network of Space Grant consortia, based at 52 universities throughout the country (one in each state, plus the District of Columbia and Puerto Rico). In addition to providing funding for educational and research missions, the network encourages academic, industry, and government cooperative programs [92]. This cooperative approach aligns with the GOLD mission's model of sharing the costs, resources, experience, and scientific return of a mission. While this program may not provide funding for material or project development, it may fund student researchers operating the ASIA units or analyzing returned data.

Third, scientific administration of the program has not been addressed. Ownership of the scientific mission, either through a Principal Investigator or in the framework of another, broader effort, must precede final science instrument selection, preliminary design, and (usually) acquisition of funding. This report provides conceptual design guidance from an engineering standpoint and does not fully address the scientific payload; the scientific mission's goals, results, and implementation are left open and flexible, and may be addressed in Phase A project design.

4.4.2. Equipment Updates, Expanded Sensor Selection, and Larger ASIA Buses

The space environment sensor package described above represents one possible implementation of ASIA; it maximizes return for a general-purpose package and requires no modification regardless of destination in the solar system. If different scientific return is desired, the individual instruments could be replaced with different sensors for some or all future ASIA units being launched. The ground system database can be configured generically so that mixed-and-matched sensor returns would not pose a major performance hit to the data portal. Examples include:

- Terrestrial Imaging: multispectral sensors mass-deployed across a constellation in LEO or MEO, where sensor orientation could be generally guaranteed to be Earth-facing, could augment weather or resource mapping systems
- Cosmic Particle Detection: removing the dust collector and increasing the number and directionality of the gamma-ray and energetic particle telescopes would allow for increased sky coverage, up to perhaps 40 percent

Further increases in demand for ASIA scientific return, coupled with continuing miniaturization of space-rated components (and space-rating of new equipment, like mobile phones as data systems for CubeSats) may drive the desire to increase the space segment bus size on behalf of a wider variety of instruments (see below). COTS components exist for 12U CubeSat bus structures, and as long as power and mass requirements continue to be small compared to the total capacity of the HSC, larger units could be considered for later-generation ASIA packages.

ASIA’s low-cost and modular nature could also allow it to provide research and development opportunities in a variety of space environments. The modular payload system allows for new technologies to be tested in the space environment while known support equipment provides a standard and reliable testing framework; power and data systems are provided without additional burden on the HSC, since the ASIA interface will look the same regardless of its internal components. Alternatively, a new piece of equipment could be tested on ASIA as a parallel path for the existing subsystem; for example, an updated communication card could be added to a cable splitter so that scientific data return can be provided through the known-good, baseline equipment or the newer but untested equipment, allowing for in-space testing and an increase of its TRL.

4.4.3. Maximum Flexibility: General Purpose Small Payload Hosting

In the same way the CDS dictates maximum mass and size allowances before waivers are required, so could a set of maximum dimensions or quantities could be developed for the ASIA space segment in each of its bays. If a university or other organization developed a payload for education, research, or some other acceptable, approved purpose, and if it could fit into a standard CubeSat size with appropriate mass, moment, power, data rate, and safety margins, it could be integrated into an ASIA bus and mounted like any other payload module listed in Section 3.2.2. With these guaranteed mass characteristics and interface compatibility in the individual 1U units, the ASIA bus could be delivered early to the HSC vendor for integration, and individual payloads could be delivered much later in the launch processing flow, or changed late in the flow if an individual payload is behind schedule (or if a higher-priority payload is ready for flight earlier than expected).

What would follow, instead of a standardized payload package for immediate integration, is a program enabling NASA or another contracting organization to purchase space for an ASIA unit on any compatible satellite, with the same data collection methodology and support subsystems as described above, but with a variety of hosted payload slots which can be competed as with other CSLI rideshare slots. The need for a student organization to spend money and development time on a CubeSat’s power, RF communication, and attitude control systems is obviated; all the academic team’s resources and attention (and the whole mass and volume allocation) can be devoted to their scientific endeavor. Keeping the payload attached to the HSC also provides for potentially longer missions (given reboost capability of many Earth-orbiting satellites), a wider variety of destinations than “just” the near-Earth regime and reduces the number of non-maneuverable payloads in already-crowded orbits.

Such a concept for general purpose hosting would complement other modern initiatives for reducing cost and improving space access to a broader audience, including NASA’s CSLI and non-government programs like the Mach 30 open-source space hardware engineering program [93]. It would bridge the gap between nanosat/picosat technology and increasing capability of traditionally-sized spacecraft in a number of roles and orbits, allowing the use of low-cost, low-capability equipment without the heightened risk and increased resource requirements of a free-flying small payload. The Space Shuttle Get-Away Special program described in Section 2.1.3.1 piloted the administration and processing of these kinds of payloads, so there is historical precedent for hosting student, government, and commercial projects [11].

4.5. Dellingr/Landsat 8 Implementation Case Study

This section presents an analysis of the potential benefits of an attached payload carrier relative to a standard free-flying 6U CubeSat mission. The goal is to quantify the approximate cost savings achieved for each ASIA space unit, through the reduced need for power storage and the elimination of power generation, attitude determination and control, and communications systems, compared to a free-flyer CubeSat of similar capability. Ground system complexity and expenses, launch costs, and spacecraft bus margins for power and data links are also discussed. Scientific payload development and fabrication costs will be assumed to be similar between free-flying and ASIA implementations and are not discussed here.

As previously noted, specific components and companies are named as examples, and no sponsorship or requirement is implied for their use. Prices below are representative of a variety of components from different vendors, including (among others) Pumpkin Inc. and cubesatkit.com, Innovative Solutions In Space (ISISpace), Clyde Space, and CubeSatShop.com, from documents and websites available as of April 2018. In some cases, prices have been converted from euros to dollars using exchange rates in April 2018. All components listed below have flight heritage.

The Dellingr CubeSat demonstrator will be used as a baseline for system capability [94]. The 6U CubeSat bus provides fine attitude determination to an accuracy of 0.1 degrees, three-axis stabilization and pointing to an accuracy of 1 degree, science data downlink at 20Kbps, a thermal control system, and 10W worst-case average orbit power. It does not include a propulsion system.

4.5.1. Space Segment Components

A basic 6U CubeSat kit (referred to as SUPERNOVA) is available through Pumpkin Inc. The kit includes the structure, an EPS (with solar arrays, a battery, and distribution/regulation systems), a full CDH (including a processor, operating system, and bus/instrument interface cards), GPS, an attitude determination and control system, and development software [95]. The bus allows 3.5U for payload and masses approximately 8 kg. As of October 2017, the price for a SUPERNOVA kit is $334,500.

Services provided to ASIA by the HSC will eliminate the need for a number of components required for conventional, deployable CubeSats; removing the following components from the baseline CubeSat bus will provide a major source of cost savings for a non-deployable ASIA mission.

- **Solar Panels**

  Various solar array configurations are available to the SUPERNOVA chassis, and the kit comes with 65W of power production. No direct correlation between the parts list and power production is available through the website, but one 3x2U and two 3x1U panels approximate the solar array coverage for the Dellingr CubeSat shown in Figure 13. The combined cost for those components is $50,000 [95].
- **Survival Heater Battery**

  Power storage requirements will be different between the free-flying option and ASIA: ASIA will only need to operate the survival heater during periods when the HSC is not providing power, while the free-flying satellite must maintain all loads through eclipse periods. Pumpkin's baseline system includes up to 3500 milliamp-hour (mAh) batteries, cited as approximately 100 Watt-hours (Wh). Clyde Space offers an EPS with 20 Wh of storage for $6,700 [96], with battery storage capacity scaling through their products at about $800 for each 10 Wh battery pack, leading to around $6,400 saved by eliminating 80 Wh of capacity.
- **Attitude Determination and Control**

  Small satellites commonly use reaction wheels for attitude control, with magnetic torque rods to dissipate stored momentum. The magnetic sensor system also supports attitude determination relative to the Earth's magnetic field, which can be supplemented with coarse sun and horizon sensors. A fully integrated unit from CubeADCS provides attitude determination (via fine sun sensors, to an accuracy of about half a degree when in sunlight) and control (via magnetic torque rods and small reaction wheels) for $34,000 [97].
- **Navigation**

  The SUPERNOVA kit includes an L1 GPS module with antenna. In the ASIA concept, orbit knowledge is provided as a service from the HSC, so onboard position determination is not required. The baseline GPS unit, sold alone and without additional features like GLONASS compatibility or GPS L2, costs $7,980 from Pumpkin [95].

- **RF Communication**

  The minimum RF communication system useful for a free-flying mission is a command uplink receiver and a transmitter that provides sufficient bandwidth to downlink collected science and housekeeping data. ISISpace produces a full-duplex VHF/UHF system for $10,400 [98] and a variety of deployable monopole and dipole antennas for about $6,000. This transmitter provides 9600bps downlink, about half that of Dellingr.

- **Options for Subsystem Enhancement**

  Two additional options to enhance vehicle performance and improve scientific return are available: a star tracker is available to improve pointing knowledge by an order of magnitude (an add-on to the CubeADCS package for $13,000 [97]), and a high-rate S-band transmitter (available from IQ Wireless for about $8,000 [99]) which increases downlink rates to 1Mbps. These components improve their subsystems' performance to a level equivalent to or better than the Dellingr satellite's performance.

These baseline components total approximately $114,780, about 34 percent the cost of the baseline SUPERNOVA 6U kit offered through Pumpkin Inc. If the optional equipment were required to meet mission requirements for the free-flyer, eliminating them from the attached ASIA unit raises the total to $135,780. Note that these values do not include shipping costs and assume that the contents of the CubeSat and ASIA are approximately equivalent (including payload, wiring, thermal control systems, and so on). These savings will also be partially offset by the addition of mounting hardware and additional cables for power and data, but those components can be acquired for a few hundred dollars, a small proportion of the total possible savings.

4.5.2. Ground Segment

Dellingr and Landsat 8 both use the Integrated Test and Operations System (ITOS) language for telemetry processing and command/control functions, including during integration and test (I&T). The requirements for these functions will be the same for both free-flying and attached options, so the price will be unchanged. ITOS software is available for free for NASA missions, but a commercially-developed variant is also available [100]. Additionally, a single ITOS license can support multiple missions or spacecraft, so prices will not necessarily scale directly with constellation size and may not be significantly different between a mission operations center supporting a CubeSat and a payload operations center supporting (one or more) ASIA units.

Science data processing and storage options are available using existing NASA systems, which can scale with minimal additional cost (and which would need to scale for the scientific return of either option). Because modern ground networks include options to route data to a number of different locations, no new network cabling need be laid. Instead, software reconfigurations would allow data flows from the ground antenna to the ASIA DPS to be changed (in Figure 21, the HSC is removed so that ASIA downlinks directly to the ground station, the HSC MOC becomes the ASIA MOC, and all other data connections remain the same).

4.5.3. Host Spacecraft Power and Data Margins

Size, Weight, and Power (SWaP) margins exist on modern spacecraft buses due to their highly-configurable nature. The LEOStar-3 bus from Orbital ATK [101], a common bus that has been used for more than ten major missions in the last 15 years (including Landsat 8), supports payloads from 150 to 3000 kg and provides electrical power from 150 to 800 watts. Not all these options will be exercised on each bus, but missions are intentionally given excess power generation and storage capacity at launch with the understanding that the power system will deteriorate over time; power generation and storage at end-of-life must still be capable of supporting mission objectives. For example, the Tropical Rainfall Measuring Mission (TRMM) experienced an on-orbit power draw of approximately 700 W, less than the design requirement of 1100 W and far less than the solar array's measured capability of 3833 W; the battery depth of discharge was 16 percent in less-favorable beta angles, compared to the requirement of no more than 25 percent [102]. Dellingr was designed with a 10 W worst-case orbit average power, representing 2.5 percent of the 400 W excess capacity at beginning of TRMM's mission life.

While power draw usually remains stable through the course of the primary mission, any excess margin in science data storage and transmission tends to be used by increasing the quantity of data collected from the primary instrument. The data volume will increase until effectively the full data link is in use. Landsat 8 began capturing 550 images per day after launch in 2013; within a few years it was capturing up to 740 images per day [103], an increase of about 35 percent. For about two months a year, this 740-image threshold prevents all desired scenes from being imaged and returned, but margins of up to 140 images per day are available through the rest of the year.

4.5.4. Launch Costs, Mass Margin, and Mounting Surface Area

Launch and dispenser costs vary by manufacturer and launch provider, especially between commercial launches (where lifting a 6U CubeSat to LEO cost on the order of $500,000 [104] plus dispenser hardware) and subsidized rideshare (where most or all launch costs are assumed by the government organization). However, many LVs include excess mass capability to orbit, which can be utilized without requiring additional rocket boosters or changes to the primary vehicle's configuration. For example, Landsat 8 massed 3085 kg (including fuel and instruments) [105] when it launched aboard an Atlas V rocket in a 401 configuration, with no solid rocket boosters. That configuration of rocket can lift 8080 kg to a similar LEO polar orbit [106]. There will be losses in upmass from additional inclination and altitude, and some LV performance margin must be maintained, but the 160 percent excess in upmass capability is more than sufficient to cover these considerations. Therefore, launching an additional 10 to 15 kg in an attached ASIA package would not require significant modification to the LV configuration and represents less than one percent of the ascent performance margin.

The largest face of a 6U CubeSat is 30 cm by 20 cm, totaling 600 square centimeters of surface area. Landsat 8 is shown in Figure 22 during prelaunch processing [107]; it is based on the LEOStar-3 bus measuring 1.8 meters wide and 1.4 meters tall (not counting the tan launch adapter at the bottom and the instrument deck at the top). The large white rectangle on the center of the face toward the camera is the battery pack, measuring about a meter long; the 600 square centimeters required for mounting the ASIA unit is less than one percent of the same surface area. Additionally, the TRMM electrical power analysis specifically recommended against mounting batteries under the solar array on subsequent missions, in order to ease access to that equipment on the launch pad if necessary [102], so a large area of the spacecraft may already be reserved for non-critical equipment which does not need to be accessed on the pad.

4.5.5. Value of Collected Data

The Dellingr demonstration mission includes two heliophysics payloads, an ion and neutral mass spectrometer and a magnetometer [94]. These investigate the LEO space environment, including the dynamic ionosphere-thermosphere-mesosphere system and atmospheric interaction. While Landsat 8 operates at a higher inclination and slightly higher altitude than the ISS (from which

Dellingr was deployed), study of the magnetic and upper atmosphere environment would still provide meaningful scientific return, with the understanding that the spectrometer imagers must be oriented properly (leading to a constraint on ASIA's mounting location on the HSC bus).

Additionally, the GBM and MMOD instruments described in Section 3.2.2 may be used on a polar LEO vehicle to provide additional scientific or engineering data return over a baseline Earth-observation: additional GBM sky coverage would supplement gamma-ray detection aboard Fermi (in the same way that the proposed BurstCube mission would lift additional GRB sensors), and information about evolving MMOD conditions in the highly populated morning and afternoon constellations of Earth-observing satellites would help characterize risk to current and future missions in those orbits.

Figure 22. Landsat 8 during prelaunch processing (Credit: NASA/VAFB)

4.5.6. Results

Analysis of the components not needed in the attached payload option leads to the potential of saving $100,000 or more, about a third of the cost of the baseline 6U deployable CubeSat kit. Further cost savings can be achieved through reduction or elimination of launch costs and the deployer hardware, though the burden of these costs to the developer vary depending on launch sponsor and source of project funding. Additionally, the baseline SUPERNOVA 6U bus from Pumpkin allocates 3.5U for payload, where the ASIA concept could provide 5U of payload volume (following the 1U allocation for subsystems and interfaces described in Section 3.2.1). These benefits of decreased cost and improved internal volume come in addition to reduced overall system complexity, increased mission longevity due to orbit maintenance (provided by the HSC), and diversity in destination enabled by the more capable power generation and data storage/transmission systems aboard the host spacecraft, both of which include significant margin at the beginning of mission life.

Instruments from the Dellingr baseline mission and the instrument loadout described in Section 3.2.2 would provide data of scientific or engineering value similar to what is already being produced on other missions. SWaP margins available in a commonly-used spacecraft bus operating in polar LEO are sufficient to accommodate the ASIA unit, and additional scientific data collection and return can be achieved through the majority of the year without detriment to Landsat 8's primary mission.

5. Conclusion

NASA's scientific heritage for investigating the physical space near Earth and throughout the solar system has evolved through the last 40 years to include not only large, highly-capable, costly flagship missions but also smaller scientific systems. Besides cost savings, these smaller systems provide an opportunity for a broader range of organizations to build and fly space hardware. The original CDS is nearly 20 years old, but it continues to evolve with newer technologies, larger buses and deployment systems, and increased involvement from NASA and the launch industry to provide opportunities to deploy the hardware and support operations.

A scientific data package based on the CDS but implemented as a non-deployable hitchhiker payload would provide a number of benefits over existing CubeSat missions:

- Offloading power generation, attitude control, and RF communications to the host spacecraft minimizes costs, development resources, volume, mass, and complexity, allowing more resources to be spent on the scientific mission instead of bus overhead.
- Missions can be supported to a greater variety of destinations beyond Low Earth Orbit, including lunar, Mars, and heliocentric orbits, and the outer solar system.
- Minimal and well-characterized interaction with the HSC allows for deployment on a variety of spacecraft buses and missions.
- Orbital life is not limited to the limited consumables volume in a CubeSat form factor.

The proposed ASIA system represents the coupling of a number of existing technologies and processes for a new goal. The CDS provides well-understood standards for low-cost space equipment and their interfaces, testing procedures, and selection and processing flows. Modern launch vehicles and spacecraft buses for primary applications (including scientific missions and commercial operations) contain excess capacity; upmass, electrical power, and data communication systems are plentiful even in basic configurations, and increasing flexibility allows for added subsystems with little or no modification to the primary mission. NASA operates a number of data collection, processing, and distribution systems for a variety of space and Earth science missions and is beginning to branch out to Cloud computing and storage to accommodate increasing volumes of scientific return. NASA programmatic infrastructure for funding, development, deployment, and operation of small projects has been present formally since the late

1970s and continues to adapt as the types of small missions change.

ASIA represents the next evolution of heritage programs like GAS on the Space Shuttle, and existing programs like the CSLI and Earth Venture missions. Small, mass-produced equipment mounted to a number of host spacecraft can produce simultaneous science data collection from many locations in a variety of orbital regimes. Strict control of its interfaces with its host spacecraft minimize effects on the primary mission. Costs can be minimized through the heavy use of COTS equipment, mass production, distributing development costs across multiple flights, and merging the new system with existing operations and scientific infrastructure, such as control centers and data distribution systems.

Some existing and proposed programs offer small payload capabilities, but with key differences. The Dellingr CubeSat is designed for development and licensing as a standard unit, but it is a deployable system and is therefore subject to restrictions and requirements of a free-flying satellite; ISS-hosted payloads are given semi-permanent residence with power and data connections, but are restricted to a specific and generally static low-Earth orbit; and many small missions rely on custom equipment, networks, and interfaces to accomplish a one-time objective. ASIA provides a new framework that includes both flexibility in the choice of payload and destination but allows maximum use of COTS equipment and existing infrastructure, including data paths, system interfaces, and administrative support.

While one potential implementation (a space environment sensor package for detecting solar wind, particulates, and high-energy astrophysical events) is described in this report, the core system could be expanded to include different sensor packages. In its most general case, it could be made into a carrier for many kinds of science experiments or technology demonstrations that want or require long-duration missions or destinations considered exotic for current small programs. Modern spacecraft buses and systems contain sufficient margin to accommodate this type of payload without modification.

The result is a technologically feasible subsystem that can be easily implemented across a variety of existing launch vehicles and spacecraft buses without negative effect on a primary mission, giving the scientific and academic community long-term access to a larger volume of the solar system at reduced cost and minimal additional mission risk.

6. References

This section contains a list of all citations referenced within this this document. The majority of them are drawn from NASA or other government sources.

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The following list contains additional standards described in this document. Version numbers and dates specified are most recent as of summer 2017 and can be applied to a block 1 version of ASIA, but subsequent blocks or upgrades may require different versions (in order to comply with HSC systems that use older standards, to modernize when HSCs apply newer standards in the future, or to accommodate critical bug fixes).

- **LSP-REQ-317.01** “Launch Services Program”
- **SAE AS15531 (MIL-STD-1553-B)** “Digital Time Division Command/Response Multiplex Data Bus”
- **SAE AS15532A (MIL-STD-1553-B)** “Data Word and Message Formats”
- **SAE AS5643B (IEEE-1394-2008)** “Interface Requirements for Military and Aerospace Vehicle Applications”
- **CCSDS 121.0-B-2** “Lossless Data Compression”
- **CCSDS 133.0-B-1** “Space Packet Protocol”
- **CCSDS 133.1-B-2** “Encapsulation Service”
- **CCSDS 727.0-B-4** “CCSDS File Delivery Protocol (CFDP)”
- **ECSS-E-50-12A** “SpaceWire - Links, nodes, routers and networks”

Appendix A. High-Level Requirements

This section presents high-level requirements for the space segment bus, instrument suite, ground segment, and administrative elements of the ASIA program. Eventually, these may be flowed down into lower-level requirements for space and ground segment detailed design, but for this document they are provided as a quick reference for key characteristics and design considerations of the program and its elements.

Requirements are in normal text. *Rationale is provided in italics*.

Space Segment – Bus

- Under all situations, the ASIA unit shall minimize effects on the host spacecraft and its primary mission. *This is the definition of the ASIA unit providing extra scientific return for minimal extra cost, risk, mass, power, and data margins.*
- ASIA mission failure shall not add risk to the host spacecraft, its payloads, or its primary mission. *The "Do No Harm" philosophy of secondary payloads*.
- The ASIA bus shall provide regulated and conditioned power to all downstream loads. *Requiring ASIA to perform power conditioning offloads that function from the HSC.*
- The ASIA bus shall collect, format, store, and relay all collected science data and housekeeping information related to the system's operation. *Requiring ASIA to perform all data collection and onboard processing offloads that function from the HSC, turning the data relay process into a bent-pipe operation for the HSC.*
- The ASIA bus shall provide support and protection to its contents for structural, thermal, vibration, and electrical shock considerations. *Keeping the payloads safe preserves the ASIA science mission; this includes protection against launch loads.*

Space Segment – Instruments

- Instrument operation shall not interfere with active or passive sensors of the HSC. *Part of the "Do No Harm" philosophy of not interfering with the primary mission. This implies no active sensors and a minimum of internal RF or EMI noise.*

- Each individual instrument’s data collection shall be enabled or disabled in ASIA FSW. *In the event of a partial failure of a single instrument, deselecting it will increase storage capability for the remaining instruments and the continuation of the ASIA mission.*

- No instrument shall exceed the 6U CubeSat bus perimeter. *Keeping all instruments and other equipment within the 6U form-factor keeps the aspect consistent and helps prevent interference with optical sensors on the HSC.*

- Instruments shall comply with risk-control measures implemented with ASIA bus subsystems, including fault isolation (like electrical surge protection), anomaly recovery, and end-of-life disposal. *The ASIA unit as a whole must comply with the HSC primary mission risk profile, not just the support subsystems provided by the ASIA bus.*

Ground Segment

- The ASIA ground system shall maintain life-of-program data storage for all ASIA units and instruments. *This keeps in the tradition of the existing science archives mentioned above; long-term trends are critical to understand many physical processes.*

- The ASIA ground system shall provide methods for distributing collected science data to users on request. *Data distribution to the science community (at low cost and with low latency) supports the goal of providing low cost-benefit ratio science data returns from many missions. Data products should be made widely available for maximum scientific benefit. No requirement is levied on the method or mechanism, including government vs. commercial data storage and distribution.*

Project Office

- The ASIA project office shall maintain all necessary licenses for equipment, software, operations, data services, and other required functions. *This provides unified coordination and management of resources to prevent duplication of effort or redundant expenditures.*
- The ASIA project office shall coordinate with scientific users and instrument points of contact. *A single point of coordination between the ASIA project and outside organizations simplifies program administration.*
- The ASIA project office shall provide engineering expertise for maintaining safe and

effective operation of ASIA space hardware (and any dedicated ground hardware). *Maintaining engineering expertise allows for unified sustaining engineering to be provided from one location and with limited staffing, instead of offloading that function to the HSC FOT*