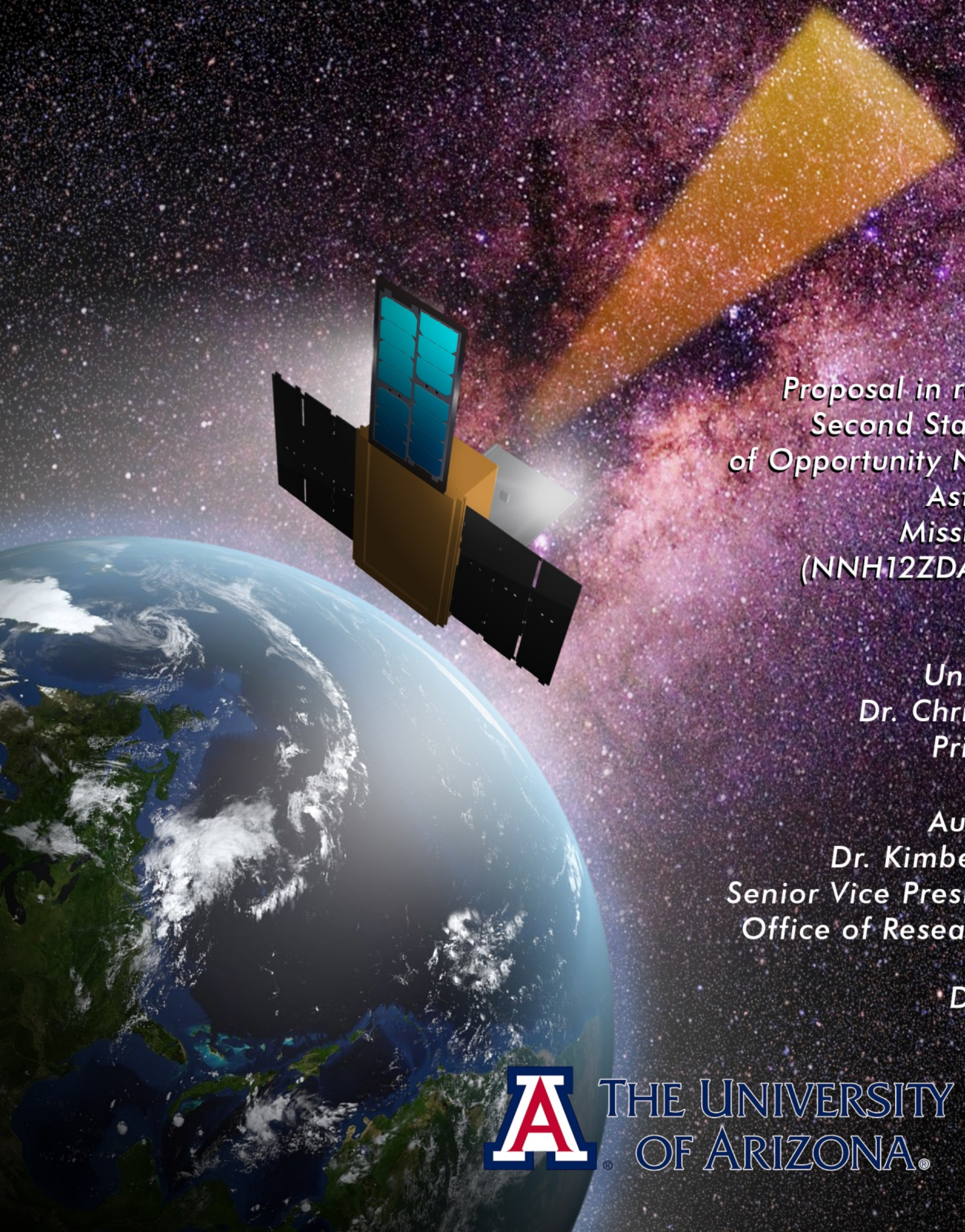
SLS

How Do Stars Form?

Spectral Line Surveyor:

Astrophysics CubeSat Mission of Opportunity



Proposal in response to NASA's Second Stand-Alone Missions of Opportunity Notice PEA R, 2016 Astrophysics Explorer Mission of Opportunity (NNH12ZDA006O-APEXMO3)

Submitted by the University of Arizona,
Dr. Christopher K. Walker,
Principal Investigator

Authorizing Official:
Dr. Kimberly Andrews Espy,
Senior Vice President for Research
Office of Research and Discovery

December 15, 2016

THE UNIVERSITY OF ARIZONA

SwRI

Spectral Line Surveyor

A Proposal for an Astrophysics Cubesat Mission of Opportunity

NNH12ZDA006O-APEXMO3
Program Element Appendix PEA-R
December 15, 2016

STATEMENT OF COMMITMENT:
The University of Arizona is fully committed to the cost, schedule, and scientific and technical performance reflected in this document.

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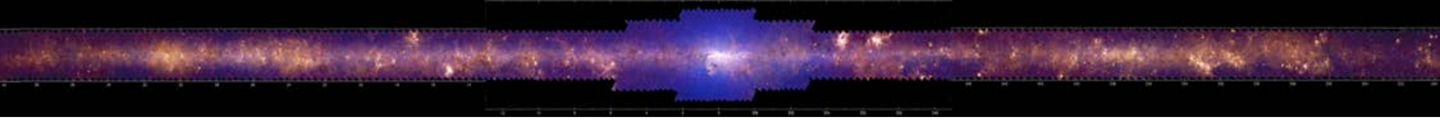


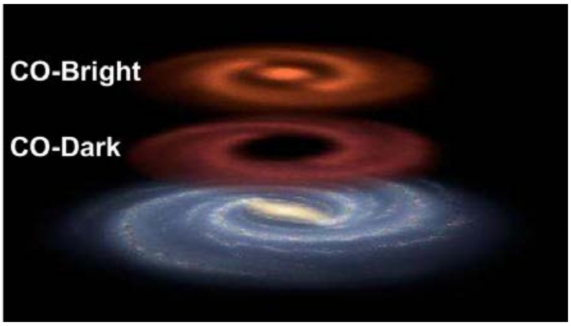
Spectral Line Surveyor:

An Astrophysics CubeSat Mission of Opportunity

How do stars form in the Universe?

This fundamental question permeates much of astrophysics and can only be answered through comprehensive observations of the Interstellar Medium (ISM) of the Milky Way and beyond. The Spectral Line Surveyor (SLS) will perform a ~1000 sq. degree survey of the Galactic Plane in the astrophysically important [CI] $^3P_1$-$^3P_0$ fine structure line of carbon and the mid-level ^{12}CO J=4→3 rotational line of carbon monoxide. This foundational data set will enable development of a template of the ISM that permeates the Milky Way. Such a template is essential to the understanding of our own galaxy and the evolution of galaxies through cosmic time. SLS's ~0.3 meter telescope, heterodyne receivers, and simple twin-spacecraft mission profile will provide the angular resolution, sensitivity, and spectral resolution needed to untangle the complexities of the molecular medium from which all stars are born.

SLS will expand our understanding of the star formation process in the nearby and distant Universe.



Star, planets, and people are formed from the dense "CO-Bright" molecular gas of the Milky Way. However, results from ~500 lines of sight (LOS) observed with Herschel suggest as much as ~30% of the molecular mass of the Milky Way is "CO-Dark". SLS will observe >160,000 LOS's to make a full inventory of both the CO-Bright and Dark molecular gas within the Milky Way (Image credit: ESA/NASA/JPL-Caltech)

Science Objectives

- Provide the first full census of "dark" molecular gas in the Milky Way
- Explore the life cycle of molecular clouds
- Construct a Milky Way template to help understand high-Z galaxies
- Establish quantitative synergy with theoretical models of galaxy/star formation
- Determine the origin of variations in the stellar Initial Mass Function

Data Products

- Galactic Plane Survey: $-180° < l < 180°$; $-1° < b < 1°$
- Targeted Deep Surveys: ~1 deg^2 maps of selected regions

Key Mission Characteristics

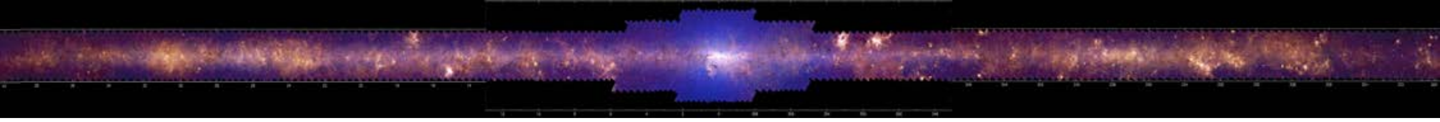
- "Identical Twin" 6U CubeSats
- 2-year baseline mission, Apr 2022 launch
- Sun synchronous ~650 km orbit
- Ultra-simple, nearly autonomous operations
- Highly flexible orbit and mission profile

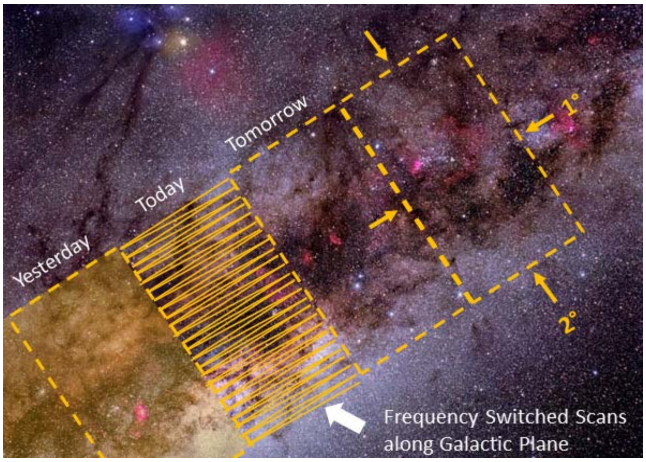
Key Instrument Characteristics

- Single identical instrument on each CubeSat
- 30x20 cm off-axis Cassegrain telescope
- ~8 arc min angular resolution
- Dual polarization Schottky receivers, 492 and 461 GHz, radiatively cooled to 100 K
- Two 1 GHz spectrometers, ~0.6 km/s res'ln
- Heritage: Odin, SWAS, Herschel, STO

Key Spacecraft Characteristics (each)

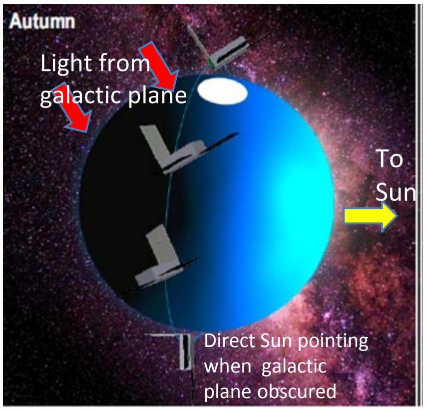
- 6U CubeSat, 9.1 kg and 24 W MEV
- Pointing knowledge 2 arcmin
- Downlink ~10 Mbps X-band
- Onboard propulsion allows orbit flexibility; not required for baseline mission
- Extensive use of COTS Cubesat components, heritage from SwRI CYGNSS, CuSP, and in-house SwRI LEO Explorer platform





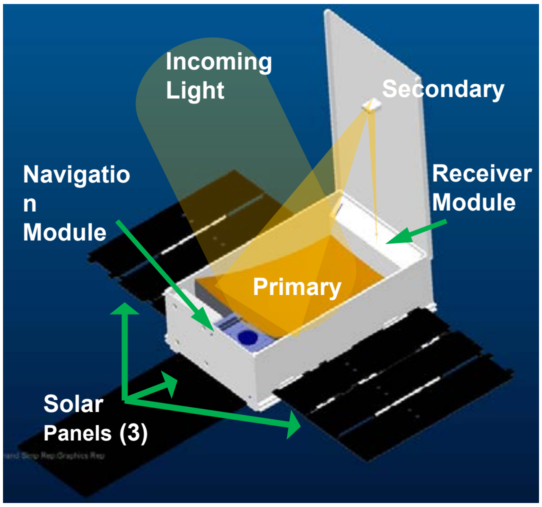
Mission Profile

Each day SLS will scan *a* 1°x 2° box centered on the Galactic Plane opposite the Sun. A dual polarization receiver observes the [CI] $^3P_1$-$^3P_0$ and ^{12}CO J=4→3 lines simultaneously. Frequency switching allows maximum observing efficiency. The scans are pre-programmed and require no commanding. Each spacecraft will complete two independent Galactic Plane surveys over the 2-year mission, resulting in a robust dataset comprising over 1000 sq deg. Targeted deep surveys of well-studied star formation regions push the sensitivity of the survey into the more diffuse ISM for comparison with complementary data.



Orbital Design and Flexibility

SLS launch and operations are highly adaptable and compatible with rideshare constraints. The baseline 650 km sun-synchronous dawn-dusk orbit is optimal for science, but virtually any high inclination orbit over 550 km is acceptable with modest adjustments to science objectives. Even a single SLS spacecraft operating for one year will meet the science threshold. The sketch shows the orbit and spacecraft configuration during one season. The Sun illuminates the solar panels at an oblique angle that yields sufficient power margin. The telescope primary mirror is oriented toward the galactic plane, the spacecraft rotating as needed to maintain pointing during the orbit.



High-Heritage 6U CubeSats

SLS will adhere to the CubeSat standard using flight-proven components. The design is based on the CuSP CubeSat under development now for launch on Space Launch System EM-1. Ejection is via the Canisterized Satellite Dispenser (CSD) system. The spacecraft is 3-axis stabilized using momentum wheels offloaded via magnetic torque rods. Deployable tri-fold solar panels provide ample power, and passive thermal control maintains receiver temperatures well below 160K. The science payload is integrated into the SLS interior allowing sufficient volume for all subsystems.

The SLS Team

University of Arizona
PI, project management, science payload, data products
University of Florida
Project Scientist
Southwest Research Institute
Spacecraft, I&T, mission operations

Cost and Schedule

SRR: 3/15/19 PDR: 9/1/19 CDR: 5/1/20
Launch: 4/1/22 (flexible)
EOM: 4/30/24

PI Managed Mission Cost: $23.5M (FY17)
Total Cost: $23.5M (FY17)

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D. SCIENCE INVESTIGATION

The Spectral Line Surveyor (SLS) will bring new clarity to our understanding of star formation through cosmic time. SLS will do so by performing the first complete survey of the Galactic Plane in [CI] $^3P_1$-$^3P_0$ and ^{12}CO J=4⟶3. This will provide an unbiased census of the dark molecular gas in the Galaxy, a more detailed view of the phase structure of the interstellar medium (ISM), a better understanding of the origin of the stellar initial mass function (IMF), and allow the creation of a Milky Way ISM template for comparison to galaxies in the distant Universe.

D.1 Science Goals, Background and Objectives

The goal of SLS is to bring new clarity to our understanding of the star formation process in the nearby and distant Universe by conducting the first complete census of molecular gas in the Milky Way and determining the conditions under which stars are created. SLS will do this by performing the first galaxy-wide survey of both "CO-bright" and "CO-dark" molecular gas (see D1.2 of Foldout D). This foundational data set will provide a critical, missing piece of the puzzle needed to construct a template of the Milky Way ISM. Such a template is essential to the understanding of our own galaxy and to the evolution of galaxies through cosmic time.

D.1.1 Science Background

How stars form in the Universe is a fundamental question that reaches across astrophysics. The answer to which requires a wide range of observations; including wide field maps of the Milky Way ISM, infrared observations of protostars, optical observations of young stellar clusters, and observations of the ISM in galaxies through the earliest epochs of galaxy formation. Over its mission lifetime, SLS will conduct surveys in the far-infrared lines of [CI] $^3P_1$-$^3P_0$ and ^{12}CO J=4→3 that will serve as an observational bridge between these seemingly disparate fields (Fig. D1.3, Foldout D):

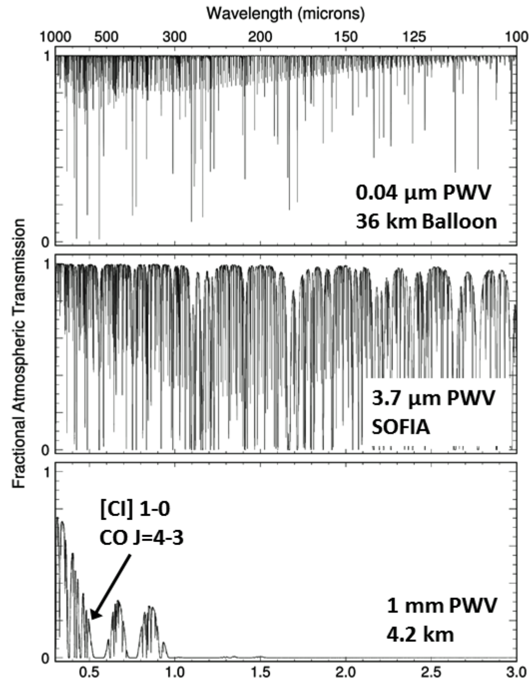


Figure D-1: *THz atmospheric transmission under typical conditions from a mountaintop site (4.2 km), airborne altitudes (14 km), and balloon-borne altitudes (32 km). Here the transmission in the [CI] 1-0 (i.e. $^3P_1$-$^3P_0$) and ^{12}CO J=4-3 lines from mountain top sites, e.g. Mauna Kea in winter, is ~20%. Greater transmission is possible from high altitude Antarctic or Atacama sites. However, even at these sites the atmospheric transmission is subject to seasonal variations, as well as limitations in sky coverage. Airborne and balloon-borne observatories have higher transmission, but fall short of being able to provide the flight hours and/or sky coverage required for the proposed survey. (Figure after Walker 2015; see also Melnick 1988)*

- ***GPS:*** *A Galactic Plane Survey ($-180° < l < 180°$; $-1° < b < 1°$)*
- ***TDS:*** *Targeted Deep Surveys (~1-deg^2 maps selected regions in the Galaxy)*

The breadth of the surveys together with requirements on data quality and calibration necessitate that they be performed from a space based platform (see Fig. D-1). This unique data set will provide the community with a transformational tool for providing the first complete census of dark molecular gas in the Galaxy, understanding how the stellar initial mass function is set in galaxies near and far, and will serve as a Rosetta Stone for interpreting observations of high-redshift galaxies.

D.1.1.1 Current Surveys

Molecular line surveys have been performed over large swaths of the sky in millimeter-wave lines of CO and used to synthesize our current understanding of the molecular content of the Galaxy (see Table 1 & Science Foldout D). Major surveys include the landmark ^{12}CO J=1→0 Galactic Plane survey of Dame et al. (2001; 1987), and the ^{13}CO J=1→0 Molecular Ring survey of Jackson et al. (2006). Large scale Southern CO surveys have recently been performed at sub-arcminute resolution (Barnes et al. 2015, Burton et al. 2014).

On smaller scales (10's of deg^2), submillimeter-wave spectral line maps in ^{12}CO and ^{13}CO J=3→2 have been published from JCMT (Dempsey et a. 2013, Rigby et al. 2016). The PI's Supercam instrument has also recently performed a complementary Northern and Southern survey in ^{12}CO J=3→2 from the 10m Submillimeter Telescope (SMT) on Mt. Graham, Arizona and the 12m Atacama Pathfinder EXperiment (APEX) on Chajnantor, Chile. Additionally, the proposing team has recently performed the largest-scale maps to date (20 deg^2) in the $^3P_2$-$^3P_1$ atomic carbon line, [CI], at 370 um with the HEAT telescope in Antarctica (e.g. Burton et al. 2015, Kulesa et al. 2017). A ~0.5°x1° of [CI] 2-1 galactic plane emission made with HEAT is shown in Figure D-2. The ~1000 square degree SLS survey will be made in the more pervasive [CI] 1-0 line to a sensitivity level comparable to or better than that of the Dame et al. (2001) ^{12}CO J=1→0 survey. Small-scale maps of a few deg^2 have been published in mid-J CO and [CI] from JCMT, APEX, SMT, and AST/RO (see D1.4, Foldout D).

Table 1: Ancillary Surveys*

Survey Name	Spectral Line	Area (deg^2)	Resolution (')
Columbia/CfA	^{12}CO 1-0	7700	10
Galactic Ring	^{13}CO 1-0	75	0.7
Mopra Thrumms	^{12}CO 1-0 ^{13}CO 1-0 C^{18}O 1-0	120	1.2
Mopra SGPS	^{12}CO 1-0 ^{13}CO 1-0 C^{18}O 1-0	18	0.6
FCRAO Taurus Survey	^{12}CO 1-0 ^{13}CO 1-0	100	0.4
JCMT COHRS	^{12}CO 3-2	45	0.25
JCMT CHIMPS	^{13}CO 1-0 C^{18}O 1-0	19	0.25
HEAT SGPS	[CI] $^3P_2$-$^3P_1$ ^{12}CO 7-6	20	2.5
Supercam GPS	^{12}CO 3-2	25	0.3
STO-2 GPS	[CII]	30	1.5
*** SLS ***	**[CI] $^3P_1$-$^3P_0$ ^{12}CO 4-3**	**~1000**	**8x12**

* Large-scale imaging spectroscopy surveys of molecular clouds. SLS will be the first all-Galaxy submillimeter wave survey **that will** probe the **warm, dense** star-forming **gas and** 'CO dark' molecular gas missing from contemporary surveys.

The PI's balloon-borne Stratospheric Terahertz Observatory will map up to 30 deg^2 in ionized carbon [CII] emission at 158 μm and [NII] at 205 μm in its upcoming science flight in January 2017. Herschel has observed ~500 individual lines of sight in ionized carbon emission through the GOTC+ Key Program, which very sparsely sampled the entire Galaxy (e.g. Pineda et al. 2013). ***These existing data are complementary to the SLS CO (J=4→3) and [CI] survey and will allow strong constraints to be placed on the gas densities and temperatures relevant to SLS's main science goals.*** SLS will sense, over the entire Galactic Plane, warm & dense molecular gas via J=4→3 and diffuse "CO-dark" molecular gas via [CI]. Both components are needed to complete an inventory of galactic molecular gas and synthesize a comprehensive understanding of the evolution of molecular clouds in the Milky Way.

D.1.1.2 Why do we need [CI] $^3P_1$-$^3P_0$ and CO J=4→3?

Despite the aforementioned wealth of data available for the Milky Way from the ground state rotational transition of carbon monoxide, CO J=1→0, our understanding of Galactic molecular clouds remains far from complete. As has long been recognized, CO J=1→0 is a reasonable tracer of the dominant constituent of molecular clouds, molecular hydrogen (H_2; Bolatto et al. 2014). However, CO J=1→0 appears to trace only a fraction of molecular clouds, thus rendering it an imperfect probe for painting a complete picture of star formation. CO exists only in gas sufficiently well-shielded to protect the molecule from FUV radiation and sufficiently dense such that recombination time scales dominate over cosmic ray ionization rates. As a result, diffuse molecular clouds or the surface layers of giant clouds may not be traced effectively by CO, but rather by neutral [CI] or ionized [CII]. Indeed, some models suggest that the ***majority of the mass in clouds*** can be dominated by [CI] and [CII] emission, rather than CO (e.g. Offner et al. 2014, Glover & Clark 2015, Narayanan & Krumholz 2016). This conclusion is supported by the brightness and extent of [CI] emission compared to that of CO observed by the FIRAS instrument on *COBE* (see Fig. D-2). ***The full cloud structure and life cycle of clouds, as probed by elemental carbon, can only be fully observed by combining CO data with [CI] and/or [CII].***

In addition, extracting cloud properties from the CO J=1→0 transition alone requires a number of assumptions. These include assuming local thermodynamic equilibrium (LTE), a constant CO/H_2 abundance, and a constant gas temperature. These assumptions are certain to be incorrect under a wide range of interstellar conditions. Only a multi-line approach spanning a range of excitation conditions can accurately probe interstellar clouds and yield a solid understanding of gas excitation and a reliable total column of CO and, thereby, molecular hydrogen. Furthermore, low-J CO emission is readily excited at low densities (<600 cm^{-3}). However, star formation is principally correlated with the *dense* (n > 10^{4-6} cm^{-3}) molecular gas in galaxies (see the review by Kennicutt & Evans 2012). Naturally, to trace this gas one needs to observe higher effective density tracers. While numerous tracers exist (e.g. mm-wave HCN, CS, HCO^+) that are easily observable from the ground, their chemistry makes them difficult to compare to the wealth of CO data. However, mid-J CO at sub-mm wavelengths provides a tracer of warm, dense gas that can be used to isolate the gas that participates in active star formation and in stellar-interstellar feedback mechanisms, such as UV radiation and shocks. Adding mid-J CO to existing CO J=1→0 data will also fully constrain the density and temperature of the CO-bright gas in molecular clouds. The ability to model the full CO Spectral Line Energy Distribution (SLED) in the Milky Way is needed to accu-

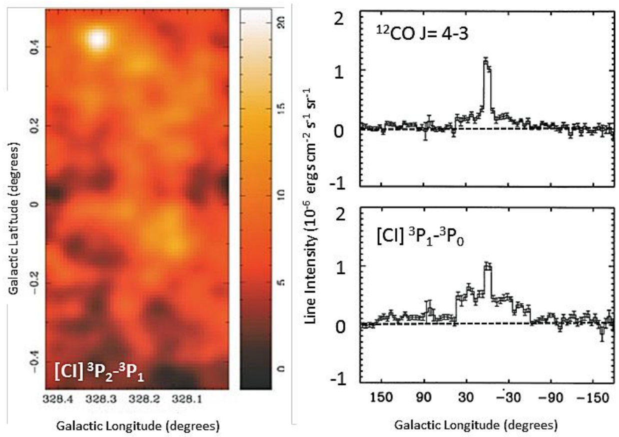


Figure D-2: *[CI] and ^{12}CO J=4→3 emission along the Galactic Plane. (left) Integrated intensity map of [CI] 2-1 line emission toward l=328° shows the presence of both clumps and large scale structure. (right) FIRAS longitudinal integrated intensity profiles of [CI] $^3P_1$-$^3P_0$ and ^{12}CO J=4→3 emission along the entire Galactic Plane smoothed over 5° in Galactic longitude and ± 5° in Galactic latitude (Bennett et al. 1994). [CI] emission is observed to be significantly brighter than CO over much of the Galaxy. The 0.16° SLS beam will spatially and spectrally resolve features in both intensity profiles with excellent sensitivity, permitting the sources of emission along each line of sight to be identified and characterized.*

rately model the evolution of molecular clouds under a variety of conditions.

These facts motivate the proposed survey of submillimeter-wave [CI] $^3P_1$-$^3P_0$ and CO J=4→3 in the Galactic Plane. Below, we outline the scientific objectives of SLS that will provide a more complete understanding of star formation through cosmic time.

into [CI] and C^+, rendering potentially significant amounts of H_2 molecular gas "CO-dark" (Narayanan & Krumholz 2016, Piñeda et al. 2013). By mapping [CI] along the entire Galactic Plane, SLS will complement Herschel surveys by providing the first census of dark molecular gas in the galaxy.

We know very little about the dark population of molecular clouds in any galaxy, even our own. How much of the Milky Way's molecular component is CO-dark? How important is this gas in the star formation process? What are its typical densities, temperatures, pressures, and cooling rates? How does the fraction of dark gas vary with the ambient environment (*i.e.* the incident ultraviolet radiation field)? How important is the gas phase metallicity? These questions become more pertinent as we try to correlate observations of gas in high-redshift systems with luminosity func-

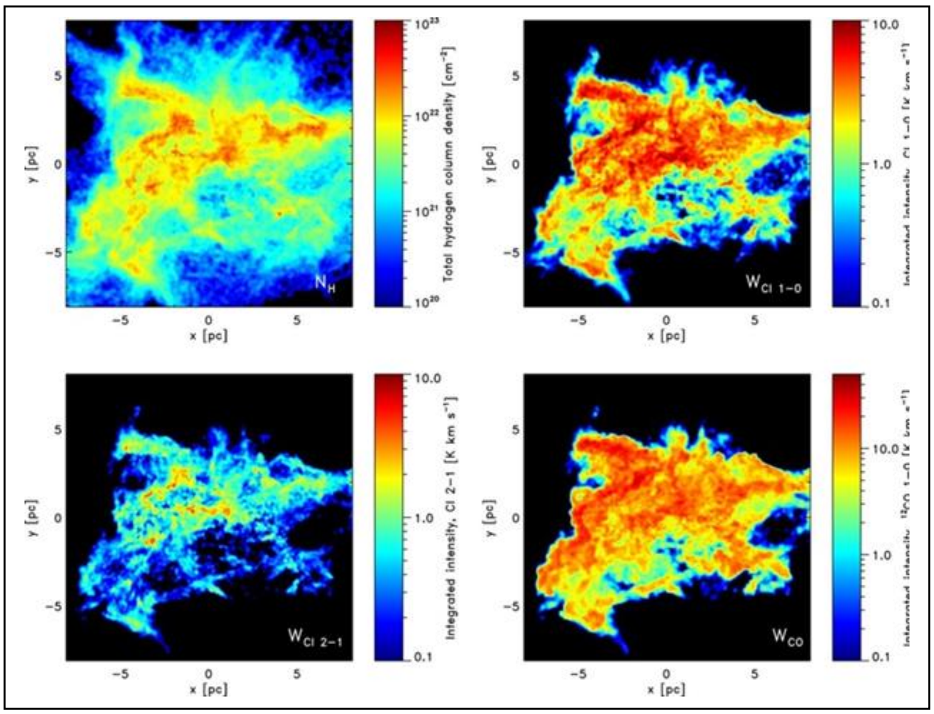


Figure D-3: *Simulated CO and [CI] images from simulated giant molecular cloud from Glover & Clark (2015). Top left shows the total hydrogen column density, top right shows model [CI] 1-0 (also referred to in this proposal as "[CI]") emission and bottom right model CO emission. Bottom left shows [CI] 2-1 emission. While [CI] 2-1 is not excited enough to trace substantial fractions of the gas, [CI] 1-0 can emit from deep in the molecular cloud due to deep penetration into the cloud by UV radiation. [CI] can trace significant fractions of gas missed by traditional CO surveys.*

D.1.2 Science Objectives

D. 1.2.1 Objective 1: Providing a Census of Dark Molecular Gas in the Milky Way

> Large fractions of neutral gas in the galaxy are missed in HI and CO surveys. SLS will provide the first full census of cold molecular gas in the Milky Way.

Chemical equilibrium models, as well as Herschel maps of [CII] fine structure emission, show that CO is easily dissociated and ionized tions, cosmic star formation rate densities, and ionizing radiation fluxes during the epoch of reionization.

The Galactic Observations of Terahertz C^+ ($GOTC^+$) survey (Piñeda et al. 2014) provided observational evidence that a substantial amount of CO-dark molecular gas may permeate the Milky Way. Due to extreme undersampling, it is possible that substantial fractions of dark molecular gas were missed by this coarse Herschel C^+ survey. CO is first photodissociated into neutral [CI] and then further ionized into C^+. *Only by performing a fully sampled survey of neutral atomic carbon as traced by [CI] across a significant fraction of the Milky Way can we fully leverage existing (and future) CO and [CII] observations to provide a full census of the dark molecular gas in our galaxy*.

In fact, there is strong theoretical support that substantial fractions of giant clouds are CO-dark. As an example, Glover and Clark (2015) performed coupled hydrodynamic molecular cloud simulations with chemical equilibrium and radiative transfer calculations to examine the theoretical [CI] and CO abundances. Their model results are shown in Figure D-3. The key point from this figure is that [CI] 1-0 can trace layers deep in a cloud traditionally thought to only be occupied by CO, owing to UV radiation penetrating deep into the cloud through density inhomogeneities driven by supersonic turbulence. This result is consistent with the early work of Stutzki *et*. *al*. (1988) toward M17 SW, where the authors concluded the extensive [CII] emission they observed required a clumpy structure which allowed UV radiation to penetrate deep into the cloud. The UV field can then photodissociate CO and lead to wide spread [CI] and [CII] emission. This conclusion was soon supported by other observations (*e*.*g*. Walker *et*. *al*. 1993).

The models of Glover and Clark (2015) further indicate significant fractions of dense, star-forming gas can be traced preferentially in [CI], and be ***completely missed*** by traditional CO or C^+ surveys. Similar results have been reported by Offner et al. 2014, who utilized completely different modeling techniques from the aforementioned Glover & Clark study, thus adding to the robustness of this conclusion. ***The SLS survey will provide a critical test of these models under a wide variety of conditions; from the Galactic Center to the outer rim of the Galaxy.***

D. 1.2.2 Objective 2: Understanding the Life Cycle of Molecular Clouds

SLS will explore the life cycle of Giant Molecular Clouds (GMCs) along the entire Galactic Plane.

Theories of the life cycle of giant clouds in the Galaxy are guided and constrained by observations of the cold atomic and molecular gas components. Fundamental questions in this field remain open: How long do clouds live? What destroys them, and what is the time scale for their re-formation? Theories for these processes vary widely. Essential to our understanding of the life cycle of giant clouds in the Galaxy is relating internal processes (*e*.*g*. supersonic turbulent velocity dispersions; star formation rates; radiation fields) to the phase structure of giant clouds. Only then can we begin to converge on a picture for the driving forces behind cloud destruction and the self-regulation of star formation.

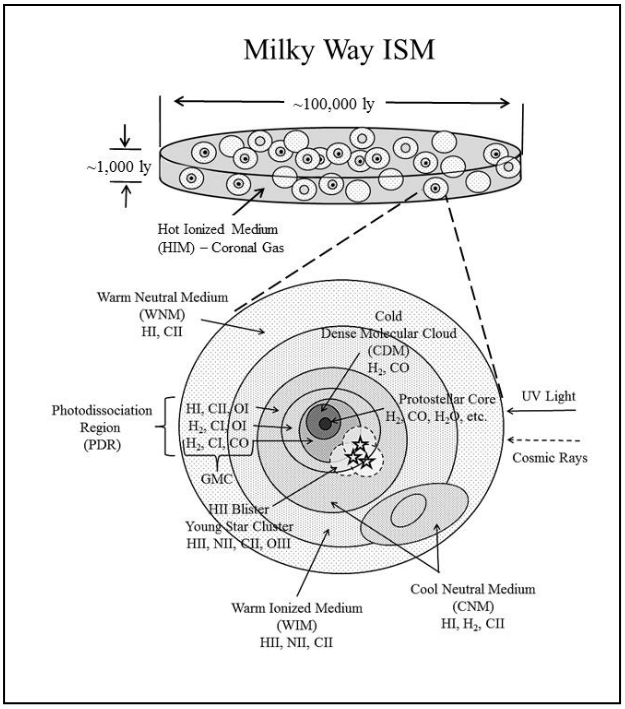


Figure D-4. *Schematic representation of the Milky Way ISM. Different phases in clouds are traced by different carbon species. SLS will detect [CI] $^3P_1$-$^3P_0$ line emission from low density gas, while the CO J=4-3 line emission will trace hot, dense cores. Together with available [CII] and CO (J=1-0) data, SLS observations will provide maps of the phase structure of giant clouds in the Galactic Plane. (from Walker 2015)*

Figure D-4 is a simple schematic representation of the chemical and phase structure of star-forming clouds. Our combined CO (J=4→3) and [CI] observations will be critical in mapping and distinguishing these structures in giant clouds throughout the Galaxy. Ionized [CII] dominates the cooling of the cold neutral medium (CNM) clouds and dominates in molecular cloud surfaces where the density is less than the critical density for collisions with atomic hydrogen ($n \leq 3000\ \mathrm{cm}^{-3}$). At higher column densities, where the carbon can be protected from ionizing photons, the [CII] atoms transform to neutral [CI]. It is only in the most well shielded gas (typically $A_v \geq 1$) that CO molecules form. The internal structure of clouds is believed to be clumpy and/or fractal in nature, in which the chemical structure of Fig. D-4 occurs on multiple clump boundaries. While the GOT C+ project studied the distribution of [CII] in the Galactic Plane, we have no constraints on the thermal and density structure of clouds as the gas transitions through different ISM phases.

With our proposed Galactic Plane SLS [CI] and ^{12}CO (J=4→3) survey, SuperCam ^{12}CO (J=3→2) data, and existing [CII] and ^{12}CO (J=1→0) observations, we will be equipped to derive the masses of gas in clouds in dense molecular cores, diffuse molecular gas, the transition [CI] atomic layer, and the ionized C^+ layer exposed to an intense interstellar radiation field. By correlating this with the observed star formation rate (as inferred from IRAS and Spitzer maps), star formation efficiencies, turbulent velocity dispersions, and background radiation fields, we will be able to place important constraints on whether and how the phase structure of giant clouds change in response to internal star formation.

D. 1.2.3 Objective 3: Developing Templates for the Early Universe

The SLS survey will serve as a Rosetta Stone from which ISM properties of distant galaxies can be derived.

The advent of the Atacama Large Millimeter Array (ALMA) has opened a new window for studying molecular gas and star formation in early galaxies, with an exponential growth in CO, [CI] and [CII] detections from z~1 to 6. This critical period in the Universe's history covers the end of the epoch of reionization through cosmic noon (*i.e.* the period of peak cosmic star formation activity). The next frontier with ALMA in high-z studies will be to determine the cosmic evolution of the star-forming molecular gas content in galaxies (*i.e.* Ω_{H2}). Indeed, large programs such as the revolutionary ASPECS survey (Walter et al. 2016) have begun to place initial constraints on the cosmic evolution of Ω_{H2} (Fig D-5). This said, there are fundamental uncertainties in deriving the gas masses from observations of high-z galaxies that can best be addressed through the proposed SLS [12]CO (J=4→3) and [CI] data set, alongside our ongoing SuperCam [12]CO (J=3→2) campaign.

While the canonical method for determining H_2 gas masses is via a conversion from the ground state [12]CO (J=1→0) emission line, this line is generally difficult to measure at $z>2$ due to the wavelength coverage of typical sub-mm wave facilities. Instead, high-J CO lines are typically detected, owing to the placement of receivers in sub/mm atmospheric windows. Converting these detections to an estimate of CO (J=1→0), and thus an H_2 gas mass, require an assumption of the excitation of CO in the observed system (the CO rotational ladder, otherwise known as the Spectral Line Energy Distribution [SLED]). Moreover, the few available multi-J CO observations of galaxies show an incredible diversity of rotational ladders, making any assumed line ratios highly uncertain.

In Fig. D-6 we show, for example, the SLEDs (normalized to the J=1-0 line) from two local galaxies (M82, and the Milky Way on large scales), as well as high-*z* dust submillimeter galaxies (SMGs, black points), and high-*z* quasars. As is clear, in these active systems more than an order of magnitude uncertainty can exist in down-converting high-J lines to the ground state. Variations in temperatures, densities, and ISM filling factors drive this large observed dispersion in the observed CO SLEDs. Unfortunately, this observed dispersion in rotational ladders translates to a fundamental uncertainty in deriving gas masses at high-redshift.

Our SLS survey will provide a key to help unlock these observations. With SLS [12]CO J=4→3, Dame *et. al.* [12]CO J=1→0, and SuperCam J=3→2 data soon in hand, we will be able to construct SLEDs for much of the Galactic Plane. It is unlikely that there will be significant emission from much higher rotational CO lines. Martin et al. (2004) found relatively little [12]CO J=7→6 emission arising from molecular clouds in a survey of the Galactic Center, aside from a few individual pointings.

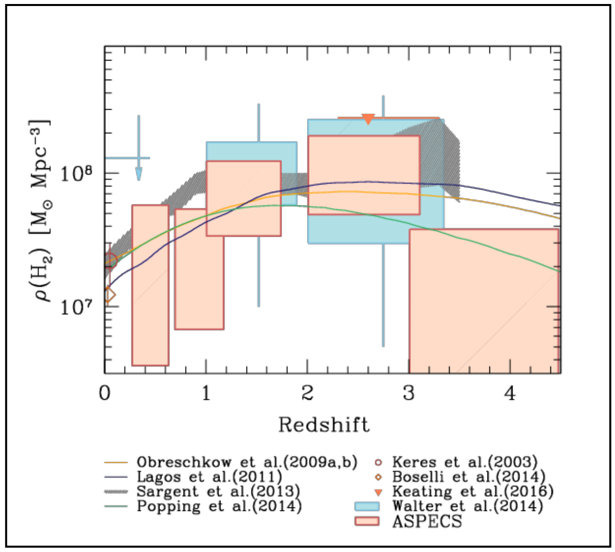


Figure D-5*. Initial constraints on the cosmic evolution of the H_2 density from ALMA observations (DeCarli et al. 2016). These measurements are critically dependent on uncertainties related to CO excitation, and completely miss any contribution from CO-dark molecular gas. Our SLS survey will enable us to build templates for high-z galaxies that will make a significant impact on our understanding of unresolved star formation, and the cosmic evolution of the gas content of galaxies.*

Our constructed SLEDs will derive from a broad range of physical conditions. We expect to be able to correlate the SLEDs from each of our pointings with luminosity surface densities, dust temperatures, Spitzer and Herschel color ratios, and other observable quantities that will provide a template for understanding the excitation of CO at high-*z* (see D1.5, Foldout D). At the same time, our investigations from Science Goal 1 will increase our understanding of how the dark fraction of molecular gas varies with observable properties, and allow us to constrain the fraction of molecular gas that may be missed in typical CO deep fields. These SLS derived results will serve as a Rosetta Stone for high-z observations as ALMA enters full operations in decoding observations of high-*z* galaxies.

D. 1.2.4 Objective 4: Quantitative Synergy with Theoretical Models

A unique aspect of the proposed program is to develop a quantitative synergy with theoretical star and galaxy formation models. Beyond our immediate team, we will actively engage a wide audience of theorists and observers to aid in providing theoretical interpretation for the data products returned from our SLS survey.

One modelling approach our team will employ is the "zoom-in" technique (similar to that used in cosmological hydrodynamic galaxy formation simulations) to develop realistic models of Milky Way-like galaxies. Here we will isolate galaxies that reside in environments similar to the Milky Way in a cosmological simulation and re-run a subset of that region at an exquisitely high resolution of ~500 $M_\odot$; that is, these models will *super-resolve* giant clouds by at least 64 elements. The hydrodynamic galaxy formation models that we will construct in support of the SLS survey will be run with the state-of-the-art and well-tested `GIZMO` hydrodynamics code. These models will be coupled with `Despotic` (Krumholz, 2014), a non-equilibrium chemistry, thermal balance, and radiative transfer solver that will derive both chemical abundances, as well as mock spectral line fluxes from CO (J=1→0), (J=2→1), (J=4→3), [CI], and [CII] to compare with what is observed in the SLS survey. In short, we will be able to create full mock Galactic Plane surveys from the model Milky Ways in all of the lines covered by the SLS and SuperCam surveys. This synergy with observation will allow us to:

- Understand the origin of [CI] and [CII] emission in molecular clouds (and the role of metallicity and radiation fields in setting the spatial distribution of those lines).
- Utilize the mock CO, [CI] and [CII] maps from simulations to develop methods for deprojecting the observed 2D maps into realistic 3D structures.
- Constrain the validity of these models by comparing the mock observations with our own Galactic Plane survey.

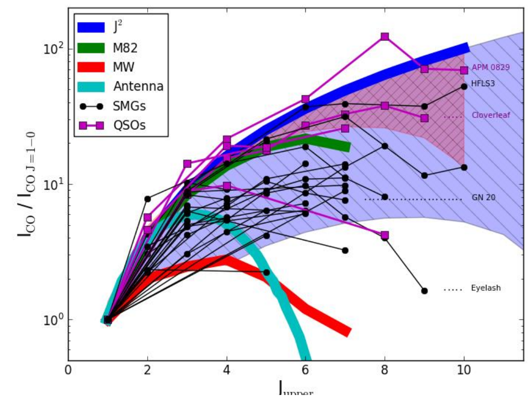


Figure D-6. *Observed CO rotational ladders for all high-z submillimeter galaxies (SMGs) and quasars with a CO (J=1-0) detection. The ladders show extraordinary diversity in their line ratios, resulting in ~an order of magnitude uncertainty when down-converting to the ground state transition. This can have severe impact on the derivation of molecular gas masses at high-z. SLS will provide the first ever templates for CO rotational ladders for high-z observations. Figure from Casey et al. 2014.*

The phase structure of the Milky Way's ISM as derived by SLS will serve as a critical test of galaxy formation models; in the same way that luminosity functions, stellar mass functions, and star formation rate distributions have done in the past.

D. 1.2.5 Objective 5: The Origins of Variations in the Stellar Initial Mass Function

SLS will be the first mission to systematically explore the physical conditions of star forming gas across the Milky Way in velocity resolved submillimeter-wave emission lines. The maps will be used to help understand the origin of variations in the stellar initial mass function.

The initial distribution of masses that characterize a stellar cluster impacts nearly every aspect of astrophysics: from determining chemical enrichment in the pre-solar nebula to dictating the amount of thermal and radiative feedback in galaxies both near and far, to anchoring optical and infrared tracers of the star formation rate, stellar mass, and stellar ages of galaxies. Characterizing the stellar IMF is one of the most pressing questions across astrophysics.

While direct measurements are notoriously difficult, a substantial amount of evidence suggests that the stellar IMF may vary in extreme environments. This evidence includes variations in gravity-sensitive stellar absorption lines that show more bottom-heavy IMFs in early type galaxies of increasing mass, dynamical modeling of massive galaxies, and direct measurements in the Taurus, Orion and Arches regions (Conroy & van Dokkum 2012, Treu et al. 2010, Luhman et al. 2003,2004, Da Rio et al. 2012). Whether the IMF varies in the bulk of Milky Way clouds as dramatically as is inferred in some of the aforementioned extreme environments is uncertain. However, in the next decade this picture will change dramatically as we enter the era of big data astrophysics.

Nearly every theory that aims to explain the origin of the IMF depends on the shape of the IMF derived from the physical conditions in the star-forming gas that formed the stellar cluster (see the review by Offner et al. 2014b). For example, some models suggest that the location of the peak of the IMF depends on the sonic length in the star-forming gas (Hennebelle & Chabrier 2008, Hopkins 2012), others on the Jeans length (e.g. Larson 2005, Narayanan & Dave 2012, 2013), and yet others on either radiative feedback or dynamic interactions and competitive accretion (Krumholz 2011, Bonnell et al. 2001). *Critically, what is missing is a direct mapping of the initial conditions to variations in the stellar IMF: The SLS mission offers a unique opportunity to provide this missing link.*

We propose a two-pronged attack to solve this problem. First, as part of the TDS observations we will observe ^{12}CO J=4→3 and [CI] of out-of-plane clouds with well-characterized IMF measurements, such as ρ-Ophiuchus, the Orion Nebular Cluster, Taurus, and the Chameleon. With SLS observations of ^{12}CO J=4→3, the ongoing SuperCam ^{12}CO J=3→2 survey, and archival data of CO J=1→0 in hand, we will be able to model the gas densities, temperatures, velocity dispersions and Mach numbers that give rise to the observed rotational ladder using standard escape probability codes (e.g. `RADEX` and `Despotic` ; van der Tak et al 2007; Krumholz 2014). This alone would be a transformational step forward, as it would provide the first map between gas physical conditions and observed IMF variations. Our team has both the radiative transfer and computational expertise to take full advantage of these data products.

Our second approach to relate the physical conditions in molecular gas to the IMF will be to take advantage of the coming of "Big Data" astronomy. The proposed SLS survey will be an important contribution to Big Data astronomy, providing unique insights into the nature of the ISM. SLS observations combined with those of *Gaia* and the Large Synoptic Survey Telescope (LSST) will revolutionize our characterization of the IMF in the Galaxy (Covey et al., 2011). The SLS survey of the Galactic Plane is built for the modern era, leveraging these massive datasets to provide large scale mapping between ISM physical conditions and the shape of the stellar IMF.

We note that even a seeming null result would be transformative. That is, even if *Gaia* and the LSST measure minimal variations in the stellar IMF across the Galaxy, our measurements of the physical state of the molecular gas in the Galactic Plane will serve as a strong constraint on the variations in the physical conditions in the initial conditions of the stellar IMF that are allowable, even for relatively muted variations.

D.2 Science Requirements and Baseline Investigation

The SLS Level 1 science requirements are provided in the Science Traceability Matrix (see Table 1.1 of Foldout D). The baseline science requirements are met with two identical Spectral Line Surveyor (SLS) CubeSats launched into a sun-synchronous, ~650 km orbit. The nominal mission lifetime is 2 years. Each SLS CubeSat will complete a 1°×2° survey of the Galactic Plane in [CI] and ^{12}CO J=4→3 each day. Over the course of a year two independent Galactic Plane Surveys are performed (see E1.1, 1.2). In achieving its science goals, SLS will survey ~1000 deg^2 of the Milky Way. In its Galactic Plane Survey (GPS), SLS will achieve a 1σ antenna temperature detection limit of ~0.1 K km/s in [CI] and ^{12}CO J=4→3. SLS will detect (≥ 3σ) [CI] and ^{12}CO J=4→3 emission from GMCs with column density of $N_H > 10^{21}$ cm^{-2}, or $A_V \geq 1$ mag. These are conservative estimates. Thermal modelling and laboratory tests indicate a factor ~2 improvement in sensitivity can be achieved by radiatively cooling the Schottky diode mixers. In which case clouds of $A_V \sim 0.5$ should be detectable. GMCs with sizes ≥ 50 pc will fill the ~8' beam of SLS from across the Galaxy. SLS is capable of detecting all GMCs undergoing massive star formation.

SLS will perform four targeted deep surveys in the Milky Way, each ~10 deg^2. The Milky Way targets will be well-studied star-forming regions (e.g. Chameleon, Orion, ρ Ophiuchi, and Taurus). TDS surveys will be performed to ~3x the sensitivity level of the Galactic Plane Survey, pushing the sensitivity of the survey into the more diffuse ISM (~0.2 A_{v}). The SLS survey will be made publicly available in a large-scale, velocity-resolved database of [CI] $^3P_1$-$^3P_0$ and ^{12}CO J=4→3 line emission. The database will also contain existing complementary line and continuum survey. The SLS survey will be of two types:

- *Galactic Plane Survey (–180° < l <180°; –1° < b < 1°*
- *Targeted Deep Surveys: ~1-deg^2 maps of selected regions in the Galaxy.*

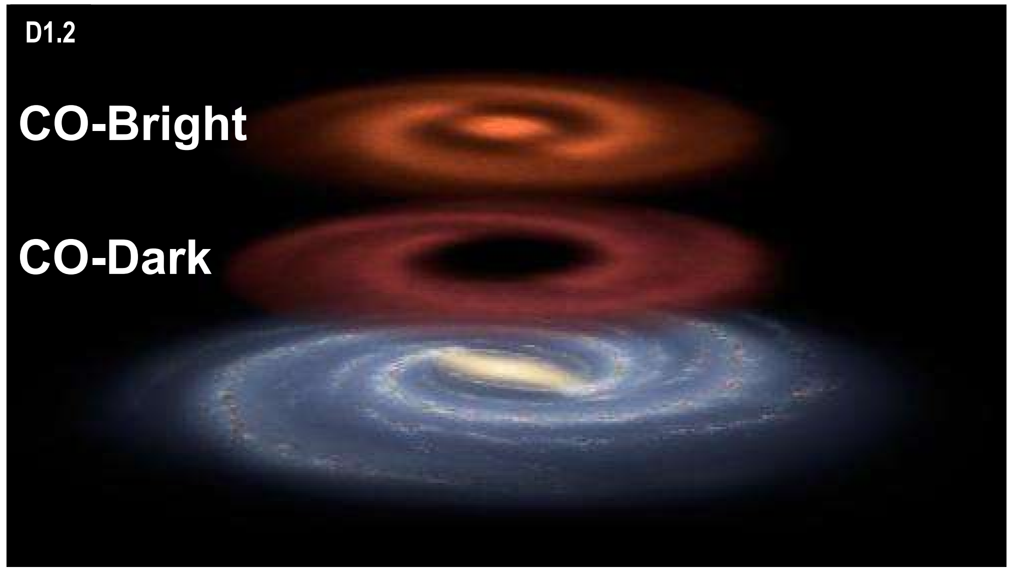
The data products from SLS will be cubes of calibrated, baseline-subtracted spectral line maps (a standard radio astronomy product). The expected size of the data set is ~237 GB/spacecraft over a 2 year mission.

D. 3 Threshold Science Mission

The SLS threshold science mission addresses four of the five baseline science goals with one SLS spacecraft in ~1 year.

SLS's threshold science mission will be to conduct a fully sampled Galactic Plane survey in [CI] 1→0 and ^{12}CO J=4→3 (–180° < l < 180°; –1 < b < 1°). The total time required to complete the threshold mission is ~400 days. The threshold science mission would have sufficient coverage and sensitivity (0.06 K km/s) to address four of the five major science objectives. It lowers cost by (1) reducing the required number of spacecraft to one and (2) reducing the required mission lifetime by a factor of 2. What is sacrificed is (1) overall map sensitivity (reduced by $\sim\sqrt{2}$) , (2) the ability to fill-in drops in survey coverage by any one spacecraft, and (3) the ability to map regions outside the Galactic Plane Survey region, necessary for Science Objective 5.

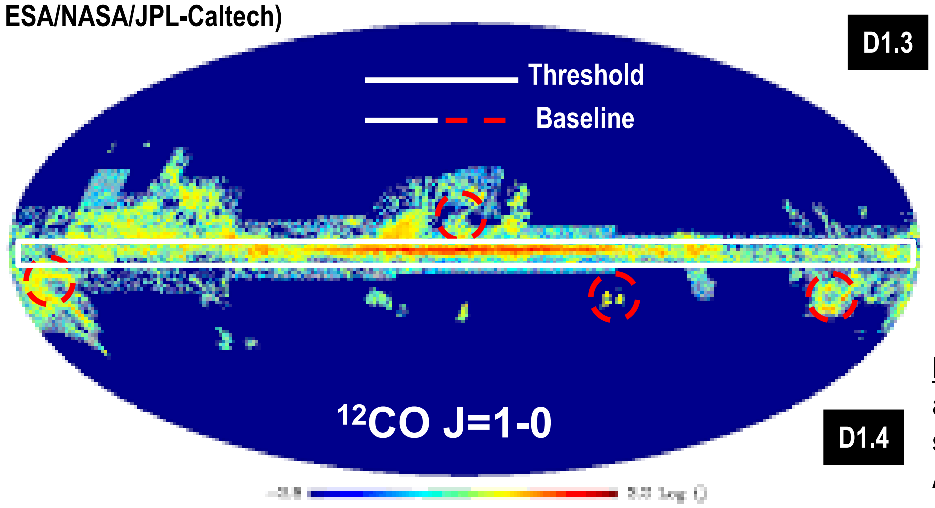
Foldout D. SLS Science Requirements Flow: __Goal – To heighten our understanding of how stars form through cosmic time__; including the life cycle of interstellar clouds, how bursts of star formation affect global Galactic structure and evolution, and the intricate dynamics of gas and stars in the Galactic Center. It will also provide a template for interpreting these processes in distant galaxies (above: MIPSGAL image with SLS survey region in white box).



Above: Star, planets, and people are formed from the dense "CO-Bright" molecular gas of the Milky Way. However, results from ~500 lines of sight (LOS) observed with Herschel suggest as much as ~30% of the molecular mass of the Milky Way is "CO-Dark" (Pineda et al. 2013). SLS will observe >160,000 LOS's to make a full inventory of both the CO-Bright and Dark gas within the Milky Way (Image credit: ESA/NASA/JPL-Caltech)

SLS relates strongly to NASA's research objectives of Evolution of Galaxies and Star Formation.

D1.3



Left: The SLS [CI] $^3P_1$-$^3P_0$ & ^{12}CO J=4—3 surveys will have comparable angular resolution, spectral resolution, and sensitivity as the Dame et al (2001) ^{12}CO J=1-0 survey; a direct comparison to which gas physical conditions can be derived throughout the Milky Way.

D1.4

Below: ^{12}CO J=4 -3 map of NGC 6334 and associated CO 7-6 and [CI] 2-1 spectra observed by our team with the AST/RO telescope. SLS will map the entire Galactic Plane in the more pervasive CO 4-3 and [CI] 1-0 lines, providing insight into both the distribution and dynamics of the dense and diffuse ISM.

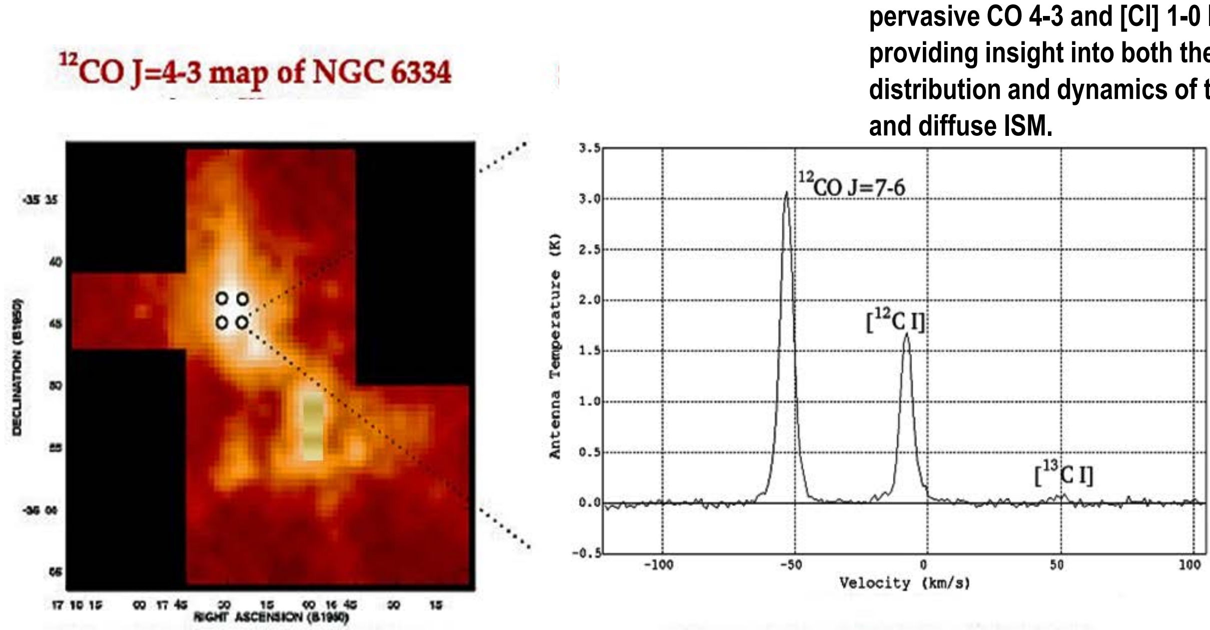


Table D1.1. SLS Science Traceability Matrix

Science Objectives	Level 1 Science Requirements	Scientific Measurement Requirements: Observables	Scientific Measurement Requirements: Physical Parameters	Instrument Functional Requirements	Projected Performance	Mission Functional Requirements
1) Provide first full census of "Dark" molecular gas in the Milky Way	Measure mass & 3D position of all molecular gas in Galactic Plane	Map [CI] 1-0 line over all 360° of Galactic Plane	Column/volume density and temperature of atomic carbon	Dual Polarization Heterodyne Receivers with Frequency Switching	Maxiumum possible observing efficiency	~2 year Baseline Mission with 2 CubeSats (~1 yr with 1 CubeSat at threshold)
2) Understanding the Life Cycle of molecular clouds.	Differentiate between 'CO bright' and 'CO-dark' gas	Map ^{12}CO J=4-3 lines over all 360° of Galactic Plane	Column/volume density and temperature of CO	Receiver covering 461 & 492 GHz	Observe 2 target spectral lines simultaneously in each polarization	Spacecraft tracks Galactic Plane to ± 1° in galactic latitude throughout orbit
3) Developing galaxy templates for the Early Universe	Spatially resolve GMCs	Observe GMCs with angular resolution of existing CO J=1-0 survey	Line intensity ratios	~0.3 m primary antenna	8 arcminute diffraction-limited beam	Pointing Accuracy: 2' RMS Knowledge: 2' RMS Jitter: < 1' RMS
4) Quantitative Synergy with Theoretical Models.	Velocity resolve interstellar clouds	Detect Spectral Lines from GMCs	Width of spectral features	1 GHz Spectrometer with 1 MHz resolution	1 MHz spectral resolution	~650 km, Sun-synchronous orbit
5) Understand variations in the stellar Initial Mass Function (IMF).	Cover range of Galactic radial velocities	Able to observe all GMCs	~300 km/s velocity range	Doppler Tracking of LO's	Spectrometer Bandwidth: 2x 1 GHz	28 kbps data rate raw
	Sensitive to $A_V \geq 1$ clouds in Galactic Plane Survey	Observe atomic/molecular interface	Ability to detect $T_{cloud} \geq 0.4$ K km/s	T_{rx}(DSB) ~3,120K Schottky receivers	~2500 K (DSB)	Receiver front-end can be cooled for greater sensitivity

Table D1.2. SLS Science Team: Roles & Responsibilities

Science Team Member	Role and Responsibility	Relevant Capabilities and Experience
Chris Walker (UA)	Principal Investigator	Instrumentation, Star Formation, PI- STO, DPI-HEAT
Craig Kulesa (UA)	DPI: Galactic Plane Survey Lead	Instrumentation, ISM Physics, D-PI STO, PI-HEAT
Chris Groppi (ASU)	Mission Scientist	Instrumentation and Techniques , Star Formation
Daniel Marrone (UA)	Milky Way Template	Instrumentation, ISM Physics, Extragalactic
Desika Narayanan (UFla)	PS: Milky Way Template Lead	ISM Physics/Theory, Star Formation
Gopal Narayanan (UMass)	Data Products	Star Formation, Instrumentation, Data Analysis
Yancy Shirley (UA)	Star Formation Lead	ISM Physics, Star Formation
Tony Stark (SAO)	Galactic Center Lead	Star Formation, AST/RO PI, Galactic Plane Surveys

E. SCIENCE IMPLEMENTATION

SLS features a proven measurement approach, a high-heritage payload, and a simple, repeatable observing strategy that will readily meet all science objectives with margins within the planned 2 year mission. SLS is a spectroscopic mapping machine: automated, repeatable drift scanning observations yield high-fidelity maps whose raw data is downlinked each day over a Ka or X-Band link. Flying two low-cost CubeSats provides built-in redundancy and robustness for achieving science goals.

E.1 Science Mission Profile

The baseline science requirements are met with two identical Spectral Line Surveyor (SLS) CubeSats launched into a largely sun-synchronous, ~650 km orbit. The nominal mission lifetime is 2 years. The SLS orbit characteristics and mission key resource estimates and margins are listed in Table F-1. Both SLS spacecraft will be launch-ready by the summer of 2022.

In a sun-synchronous orbit the solar panels on the back of the SLS spacecraft are bathed in sunlight and the telescope points in the opposing direction. Our Sun is located near the middle of the Galactic Plane about half-way out (~27,000 ly) from the Galactic Center. Therefore, the Galactic Plane surrounds us and each day the Earth's orbit brings a new, one degree slice of the Galactic Plane into SLS's view. Each SLS CubeSat will complete a 1°×2° survey of the Galactic Plane in [CI] $^3P_1$-$^3P_0$ and ^{12}CO J=4→3 each day. Over the course of a year each satellite will complete a full Galactic Plane Survey in both of these astrophysically important transitions. The ~2.5 Gbits/day of raw data collected per satellite will be transmitted to one or more ground stations during a daily pass using a Ka or X-band telemetry link (to be assessed during Phase A). Foldout F summarizes the mission scenario including downlink budget. Conservatively, we calculate a telemetry bandwidth margin of ~38%. The science observing profile does not have any time-critical events.

E.1.1 Science Observation Strategy

SLS is primarily a survey instrument, with the goal of spectroscopically mapping the entire Galactic Plane (0≤ l ≤ 360°; ± 1° b). In addition, it will perform deep, ~1 deg^2 surveys toward selected star forming regions.

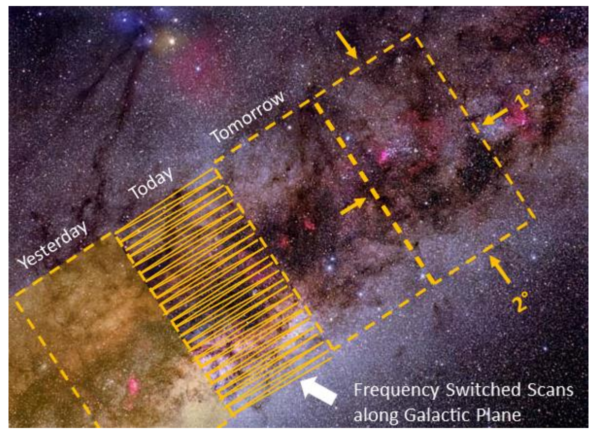


Figure E-1. *SLS Frequency Switched scan along the Galactic Plane. Each day SLS will scan a 1°× 2° box centered on the Galactic Plane opposite the Sun. Dual polarization receivers observe the [CI] $^3P_1$-$^3P_0$ and ^{12}CO J=4→3 lines simultaneously. Frequency switching (FS) is used to achieve maximum observing efficiency.*

E.1.2 Mapping Strategy

An efficient observing technique for performing spectroscopic surveys of the Galactic Plane is Frequency Switched, On-The-Fly (FSOTF) mapping (see Fig. E-1). In this mode, each SLS CubeSat continuously scans across a 1° wide field at constant velocity for ~96 min (~1 orbital period) while the local oscillator (LO) frequency is shifted by ± 20 MHz from the nominal line frequency at a ~1 Hz rate. Here the OFF spectrum is obtained not by moving the telescope, but by offsetting the center frequency of the receiver to an emission free region of the receiver's bandpass (see Figure E-2; Walker 2015; Ewen and Purcell 1951). At the end of each scan row the telescope reverses direction and performs an adjacent scan offset by 1/2 beam (Nyquist) spacing. During turnaround, the telescope slew

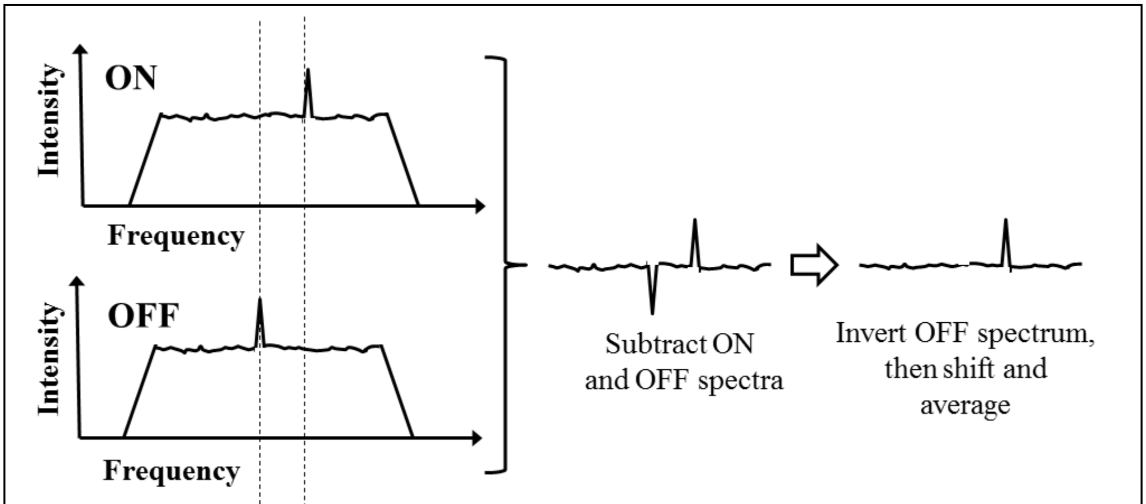


Figure E-2. *Frequency Switched (FS) Observation (after Walker 2015). Looking ON source the receiver bandpass includes the spectral line from the source, as well as noise from the receiver. In FS mode the telescope does not move to an OFF position as it does with standard absolute position switching. Instead, the telescope stays pointed ON source and switches the receiver frequency by an amount,* $\Delta\nu_{off}$ *, so that the target line appears in a neighboring part of the spectrometer. The switched OFF spectrum contains very similar receiver noise contributions as the unshifted spectrum. The OFF spectrum is subsequently subtracted from the "ON" frequency spectrum. The OFF spectrum is then inverted, shifted back by* $\Delta\nu_{off}$ *, and averaged with the ON spectrum. The frequency switch typically occurs one or more times per second and is often done on either side of the emission line frequency, e.g.* $\nu_{shift} = \nu_{line} \pm \Delta\nu_{off}$ *. Frequency switching is ideally suited for Galactic Plane survey observations where finding an emission free OFF position is challenging. It was employed by Ewen and Purcell (1951) during their pioneering observations of HI in the Milky Way.*

overhead is productively used to observe a calibration load. This 96-min FSOTF scan sequence represents the fundamental unit of observation for SLS; it is simply repeated over and over along the Galactic Plane. This observational approach yields a highly regular, automated observing profile that minimizes operational oversight and risk. The frequency switched observing mode was recently validated at 809 GHz by D-PI Kulesa using similar instrumentation at the HEAT observatory on Dome A, Antarctica. A full Galactic Plane Survey can be completed by each SLS CubeSat within a baseline mission of ~400 days; this includes a month of on-orbit commissioning before the commencement of science operations. During the commissioning phase calibration scans will be performed on the Moon, planets, and bright sources (e.g. Orion and IRC+10216). Each SLS is designed to operate autonomously by using an automated scheduler program running on the Command & Control (C&C) computer. Having two satellites increases the survey sensitivity and helps ensure uniform sky coverage over the survey region. Having a second satellite also helps to ensure the threshold mission can be accomplished, even if one satellite loses functionality.

E.2 Instrumentation

SLS benefits directly from Schottky mixer development performed by VDI for the ICECUBE mission and the 6U bus developed by SwRI for its CuSP mission. Much of the instrument control software and data pipeline were developed by the UA in support of its Stratospheric TeraHertz Observatory (STO) and HEAT projects.

The observational goal of SLS is to make high spectral (~1 km/s) resolution maps in the [CI] 492 GHz and ^{12}CO 461 GHz emission lines at an angular/spectral resolution and sensitivity comparable to or better than that of the Dame et. al (2001) ^{12}CO J=1→0 survey (~8 arcmin; ~0.65 km/s; ~0.1 K km/s). To achieve this angular resolution requirement, the SLS telescope is designed to have an aperture of 0.3 x 0.2 m. To achieve the required spectral resolution and sensitivity, SLS will utilize high performance receivers. The science payload portion of each SLS consists of (1) a telescope; (2) a dual polarization Schottky diode receiver capable of observing both target lines simultaneously; (3) two, 1 GHz bandwidth autocorrelator spectrometers; and (4) instrument control electronics. The SLS CubeSat bus is derived from successful SwRI designs and is described in section F.3 (see also heritage in J.9.7–J.9.28). ***Much of the SLS instrument architecture and hardware is based on the experience gained in developing and flying previous CubeSats*** (see heritage discussion in J.9.4). The SLS instrument and telescope will be fully integrated and thermal-vacuum tested at SwRI.

A block diagram of the SLS instrument is shown in Foldout E1.1. A CAD model of the science payload is provided in Foldout E1.3. Key instrument parameters are provided in Foldout E, Table E1.1. The overall design of SLS resembles that of the successful *SWAS* spacecraft (see J.9.4.4 and Melnick *et*. *al*. 2000).

E.2.1 System Description

The SLS optical system (Fold-Out E1.1; E1.2) consists of an off-axis, ~30 x 20 cm Cassegrain telescope, anti-reflection coated lens, a calibration load, and solenoid actuated calibration mirror. As on SWAS, both the primary and secondary are diamond turned aluminum, here with a surface accuracy of ~4µm rms. SLS's mixers, local oscillators (LOs), intermediate frequency (IF) system, and spectrometers are located in a receiver module directly below the secondary (Fold-Out E1.3).

A block diagram of the dual polarization receiver system is shown in Fold-Out E1.1. The converging beam from the telescope's secondary encounters a lens which brings the light to a focus just inside the receiver's feedhorn. From the feedhorn the unpolarized light is split into horizontal and vertical components by a waveguide orthomode transducer (OMT, Fold-Out E1.4) and then downcoverted to an IF of ~16 GHz by two independent, second harmonic Schottky diode mixers. The mixers are thermally tied to a dedicated radiator, dumping heat to deep space. Using this approach spacecraft thermal modelling indicates mixer operational temperatures of ~100K can be achieved. The IF signal from each mixer then passes through a low noise amplifier (LNA, see Fold-Out E1.4) and is further downconverted and amplified by an IF Processor to match the input frequency and power requirements of the 1 GHz wide autocorrelator spectrometers (Fold-Out E1.7). The front-end mixers are pumped by a solid-state local oscillator (LO) tuned to ~476 GHz, such that the [CI] and ^{12}CO J=4→3 lines both appear in the bandpass of each spectrometer separated by ~500 MHz.

E.2.2 Performance Margins

Recent lab measurements by SLS team members on a 492 GHz Schottky diode mixer of the type to be flown on SLS yielded double side band (DSB) receiver noise temperatures of ~2,500K at room temperature and ~1,100 K at operational temperatures close to those expected in flight (see Foldout E1.6). These measurements include losses due to vacuum windows and atmospheric absorption that will not occur in a space-based SLS system. Adopting the more conservative room temperature noise temperature, for a 1 km/s line width (δv), each SLS receiver system will achieve an *rms* single sideband (SSB) noise temperature of 0.15 K in 384 sec of integration. This is the amount of observation time available each day toward a Nyquist sampled pixel in the 1°x 2° box being surveyed. Since there are two SLS spacecraft, this *rms* noise level is further reduced by a $\sqrt{2}$ in the survey, yielding ~0.1 K km/s. With passive cooling of the receiver module, these noise limits are expected to drop by as much as a factor of two, yielding survey sensitivities of ~0.05 K km/s. These limits vary as $\delta v^{-0.5}$. The SLS instrument characteristics are summarized in Foldout E, Table E1.1. The backend spectrometers provide ~67% margin on spectral resolution. Including the effects of a ± 20 MHz frequency switch, the system IF bandwidth for each line is ~300 km/s, sufficient to support all velocities expected in the Galactic Plane when Doppler tracking is employed (see Figure E-3).

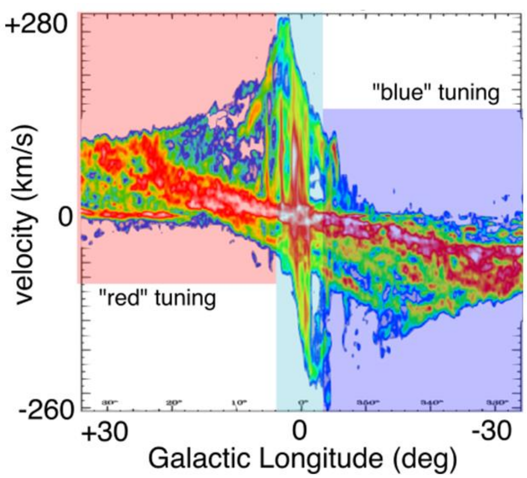


Figure E-3. *P-V diagram of ^{12}CO J=1→0 emission in the Galaxy (Dame at al. 2001). SLS will employ Doppler tracking to center the lines within the spectrometers, whether on the 'red' or 'blue' side of the Galaxy.*

E.2.3 Telescope

The implementation of the optical system within the SLS 6U CubeSat is shown in Foldout E1.2. Both the f#1.1 primary and f#18 secondary mirrors are made from diamond-turned, light-weighted aluminum. The primary is attached to the 6U frame and serves as a thermal radiator for the spacecraft. The secondary is mounted to a spring loaded, hinged boom that is folded flat against the primary and held in place by a space-qualified Dynema cord and released once in orbit by firing a Clyde-Space Thermal Knife Driver (TKD) circuit. A limit switch is activated to confirm proper deployment. A small (~1 cm) solenoid driven mirror is located in the receiver module above the feedhorn. When activated the mirror optically couples the feedhorn to an ambient temperature, calibration load.

To ensure the telescope and support structure will maintain better than 30 arcsec optical alignment relative to the star camera, a preliminary Finite Element Analysis (FEA) and thermal analysis were performed. The analyses indicate telescope flexure contributes minimally to the pointing error. A more detailed FEA will be prepared during Phase A.

E.2.4 Mixers

The Schottky diode mixer and LO technology to be used on SLS are robust, proven, and meets all SLS instrument requirements. Both the SLS dual polarization mixers and LOs will be provided by Virginia Diodes, Inc., who has delivered two similar systems for other CubeSat missions (Fold-Out E1.4).

Schottky diode mixers have been in use for ~100 years. The first Schottky mixers were "cat whisker" diodes formed by bringing the tip of a thin wire into contact with a naturally occurring semiconductor, *e.g.* galena. Except for the size of the contacting wire and the type of semiconductor, this was the same mixer architecture used on *SWAS* (Melnick et. al 2000). Since then the fragile cat whisker diode has been replaced with a photolithographically produced beam lead equivalent which is more robust, has lower noise, better cooling performance, and can be readily integrated and pumped with subharmonically produced LO's. Unlike their superconducting counterparts, Schottky mixers do not require cryogenic cooling, but do improve in performance to a limiting value as their physical temperature is lowered (Fold-Out E1.6). For this reason the mixers and the low-noise amplifiers (LNAs, Fold-Out E1.4) that follow them are located in a thermally isolated `cold-box' within the receiver module. The cold-box is thermally sunk to a radiator that can potentially cool the

~15mW heat load from the mixers/LNAs to ~100K, increasing receiver sensitivity by a factor of ~2.

Schottky mixers also have the advantage of permitting ultra-wide operation and being extremely stable. It is these two qualities that allow SLS to simultaneously observe both the [CI] and ^{12}CO J=4→3 line and support frequency switching.

E.2.5 LO

The SLS LO system consists of a compact, programmable microwave synthesizer, power amplifiers, and a 2x2x3 multiplier chain. For minimum size and maximum efficiency the multiplier chain is integrated into the same block as the two Schottky mixers it pumps. The synthesizer is housed in the "Front-End Electronics Box" (Fold-Out E1.3). The final power amplifier is located just under the "cold-box". The programmable synthesizer allows the instrument computer to both Doppler track and shift the observation frequency by $\pm$ 20 MHz for frequency switched observations.

E.2.6 Spectrometers

To meet SLS's instrument requirements, each of the 2 IF outputs from the Schottky mixers and LNAs must be processed efficiently into spectra with per-channel resolving powers ($\lambda/\Delta\lambda$) of 5×10^5 by a spectrometer. The corresponding SLS spectrometer specifications are provided in Foldout E, Table E1.1. Two types of digital backend spectrometers are in common use: digital autocorrelators and FPGA-based, direct-FFT spectrometers. Although direct FFT spectrometer capabilities are developing rapidly, the well-characterized Highly Integrated Full-custom Autocorrelation Spectrometer (HIFAS) autocorrelator ASICs from Omnisys (see Foldout E1.7) have far better power characteristics and meet the TRL for a space environment. The HIFAS correlator is the fourth generation of autocorrelators from Omnisys. The first generation was developed for the Odin satellite, which was launched in 2001 and is still in operation. These characteristics render it superior to FFT spectrometers for the SLS mission. A prototype HIFAS spectrometer will be flown by our team on STO-2 in 2016. The Omnisys spectrometer and associated IF system are housed in the "Spectrometer/IF Processor Box" located in the Receiver Module (Fold-Out E1.3)

Figure E-4. Example OTF Image. *Top:* SuperCam ^{12}CO J=3→2 image of the Horse Head Nebula (after Walker 2015). *Bottom*: Comparable optical image. Much of the SLS data pipeline will be derived from the SuperCam pipeline used to generate the top image. SLS will map a comparably sized region in both [CI] and ^{12}CO J=4→3 to a higher signal-to-noise level during each day of operation.

E.3 Data Sufficiency

The SLS telecom data rate meets mission requirements with ample margin (see Sec. F.4.2). The detailed flow of science investigation goals to measurement objectives to data requirements is shown in Foldout D, Table D1.1. The data rate required to deliver SLS's raw data is ~28 kbps per spacecraft over the mission lifetime. Applying a lossless compression algorithm, the mean data rate becomes as low as ~14 kbps. Even with an additional 2 kbps of housekeeping data, this rate is readily handled by standard CubeSat K or X-band telemetry links to one or more ground stations.

E.4 Data/Calibration Plan

The Science Operation Center (SOC) at UA will be able to generate first-look maps from the raw data arriving from the designated SLS ground station(s). Initial calibration of the payload (e.g., telescope pointing/efficiency and receiver performance) will occur in the first 3 days after orbital insertion using available astronomical objects. A calibration sequence (pointing on and observing a calibration source) will be repeated at least once every 24 hours of mission operations. With each calibration, the SOC, via the Mission Operations Center (MOC) at SwRI, will adjust the observing parameters on each SLS. Over the course of the SLS mission, extensive 3D FITS spectral line data cubes of the Galactic Plane survey will be acquired. The Science Team will reduce, analyze, and distribute the survey data to the broader astronomical community, along with associated calibration data, via a permanent data archive within 6 months of flight termination. The SLS data products will be provided to the community from the University of Arizona, the Harvard Libraries Dataverse, and registered to the National Virtual Observatory (NVO). The data pipeline for generating the FITS cubes has already been developed for the SuperCam instrument and STO-2 by the UA members of the SLS team. A SuperCam ^{12}CO J=3→2 image of the Horse Head Nebula generated using the data pipleline is shown in Figure E-4. The SLS data reduction effort will be led by D-PI Craig Kulesa (PI of HEAT), in association with Co-Is Gopal Narayanan and Tony Stark (AST/RO PI), all of whom have extensive experience processing high-resolution spectroscopic data sets.

E.5 Instrument Technology Development Plan

As discussed in previous sections, the same or similar components which make up the SLS instrument have been tested in flight-like environments with heritage from SWAS (telescope), receivers (SWAS, ODIN), and spectrometers (ODIN). What remains is the test of the specific mixer architecture and synthesizers to be used in the receiver and the calibration mirror actuator mechanism. Prototypes of these devices will fabricated and undergo vibration and thermal/vacuum tests before PDR.

E.6 Science Team

The SLS mission is supported by an outstanding team of scientists with extensive experience in observations, modeling, theory, and interpretation of the interstellar medium, star formation, and Galactic structure. The roles, responsibilities, and experience of each Science Team member are summarized in Foldout D, Table D1.2. Prof. Christopher Walker (PI), Dr. Craig Kulesa (DPI), Dr. Jeffrey Hesler (VDI), Prof. Dan Marrone (UA). Dr. Tony Stark (SAO), and Prof. Christopher Groppi (ASU) all have extensive experience designing, building, and deploying terahertz receiver systems. Similarly, Mr. Doug Stetson, Don George, and other SwRI Team members have experience in managing, designing, and fabricating leading-edge CubeSat systems.

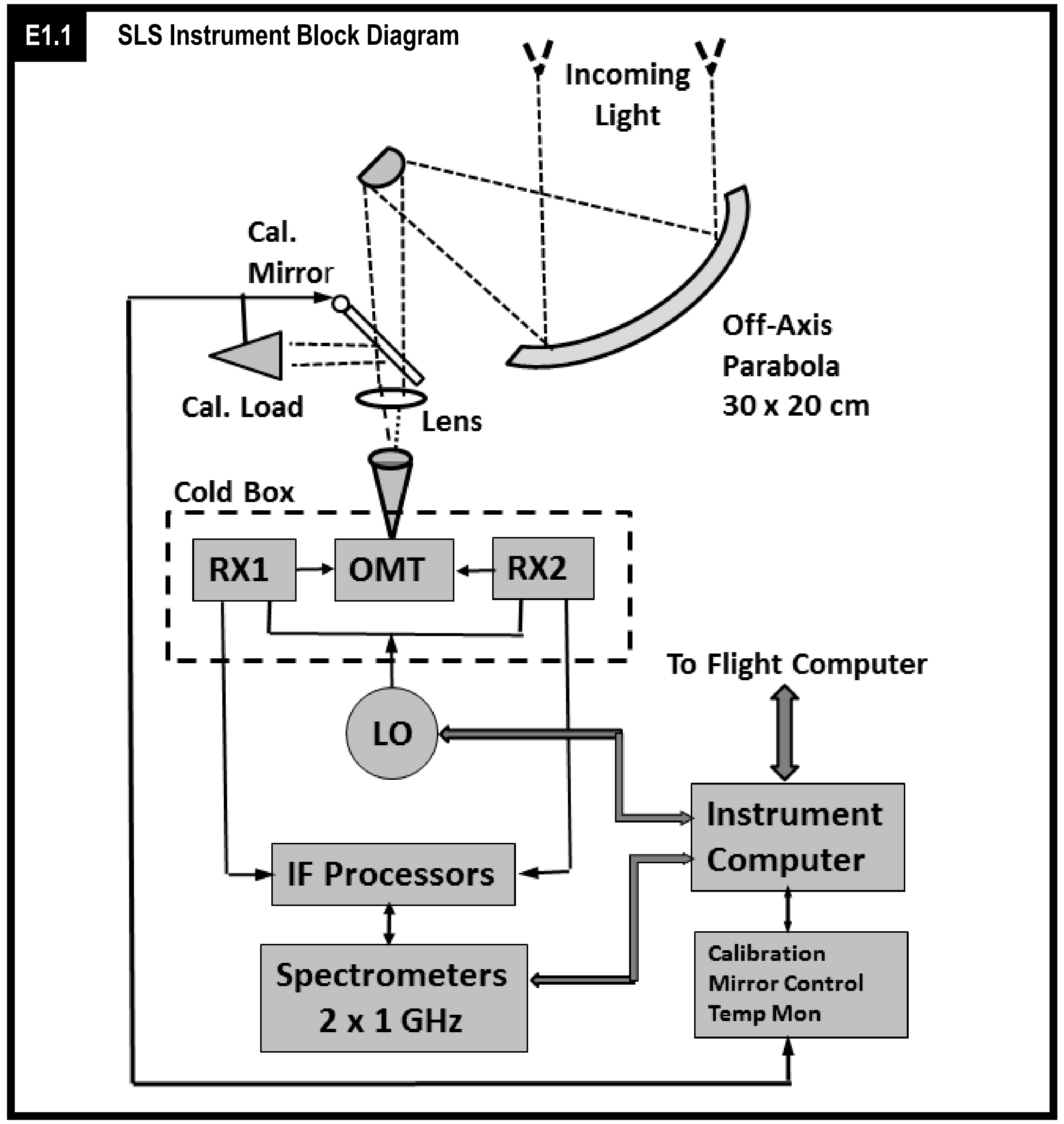
E.7 Science Enhancement Option

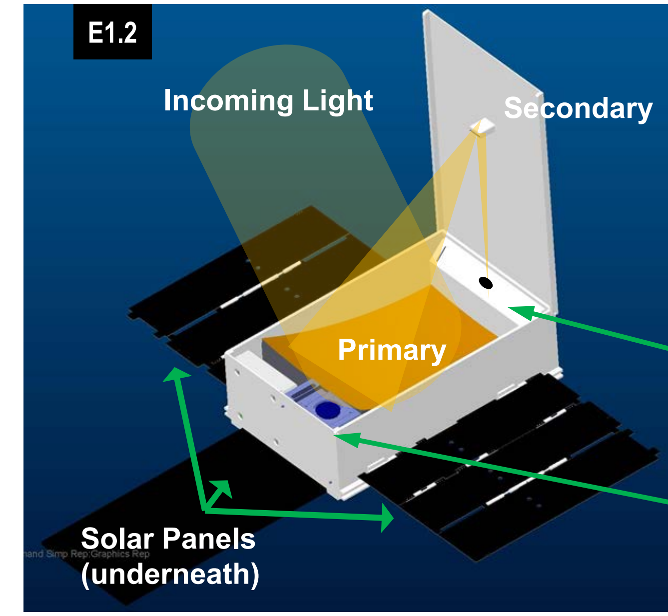
SLS's baseline mission of 2 years can be extended to 3 years at very low cost. This would enable expansion of the survey region by ≥30% and could allow additional targeted observations, significantly enhancing the mission's science return. The potential value of this SEO will be studied further during Phase A.

Foldout E. Instrument: *SLS's heterodyne instrument provides high sensitivity and high-spectral-resolution measurements of [CI] $^3P_1$-$^3P_0$ and ^{12}CO J=4→3 throughout the Milky Way. SLS's instrument components build upon NASA and ESA technology development.*

Table E1.1. Mission Parameters

Item	Description
Telescope	30x20 cm, off-axis, f # 1.1 Cassegrain
Target Frequencies	[CI] $^3P_1$-$^3P_0$: 492 GHz, ^{12}CO J=4→3: 461 GHz
Angular Resolution	~8 x12 arcmin
Receiver Type	Dual Polarization Schottky mixer
Receiver Noise Temp	~2500K (DSB)
Spectrometer	Digital Autocorrelator ASIC
Spectrometer Bandwidths	2x 1 GHz (~300 km/s with Frequency Switching)
Spectrometer Resolution	~1 MHz (~0.6 km/s)
Cooling System	Radiative
Instrument Mass	2.6 kg MEV
Operation Modes & Power	Frequency Switched Average Power ~16W
Data Demand	~28 kbps (raw data) + 2 kbps (housekeeping)
Data Storage	~4 Gbits
Mission Lifetime	2 year baseline
Pointing Acquisition	Star Camera
Pointing Knowledge	2 arcmin rms over ~96 min



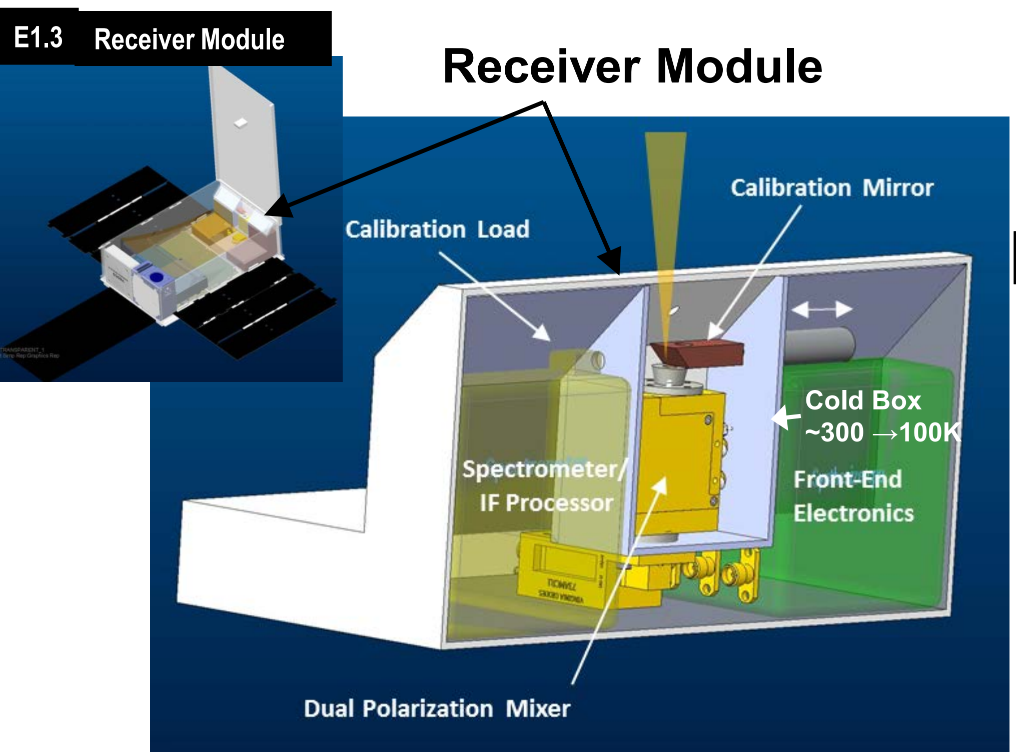


SLS Telescope

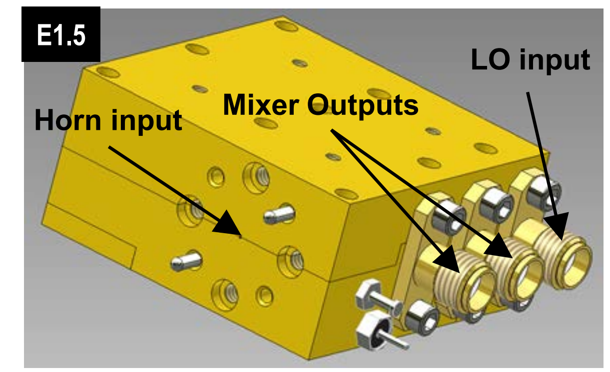
- 30 x20 cm, off-axis Cassegrain
- f # 1.1 primary (aluminum)
- f # 18 secondary (aluminum)
- ~8 arcmin angular resolution
- Simple, robust, low cost
- Cal Load & Flip Mirror (inside Receiver Module)

Receiver Module

Navigation Module

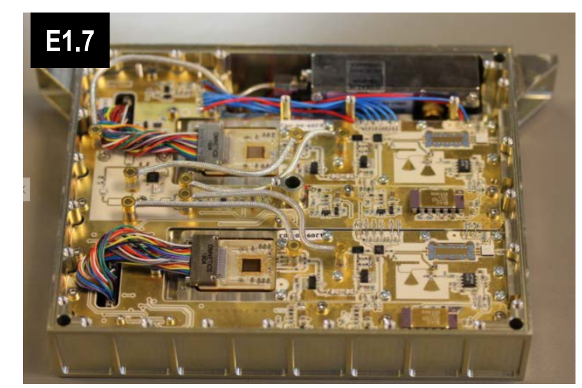


- Radiatively Cooled Schottky mixers with flight heritage
- Requires only <16 W , including frequency-switched LO's
- Compact 2.5 x 10 x 20 cm Package



Mixer Module

- Schottky diode mixers
- Dual Polarization
- Radiatively cooled
- Subharmonic LO
- Frequency-switched operation
- High heritage



SLS Autocorrelator Spectrometer from Omnisys

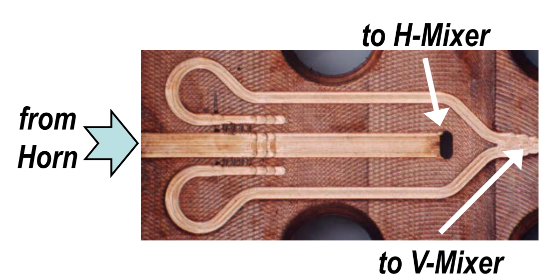
- Provides 2× 1 GHz bandwidth @ 0.6 km/s resolution
- Offers up to ~600 km/s of velocity coverage
- 90% efficient
- JUICE mission
- Prototype to fly on STO-2

E1.4 Heritage Components

Receiver Front-End

874 GHz Schottky Diode Mixer Assembly made by VDI for the IceCube Mission.

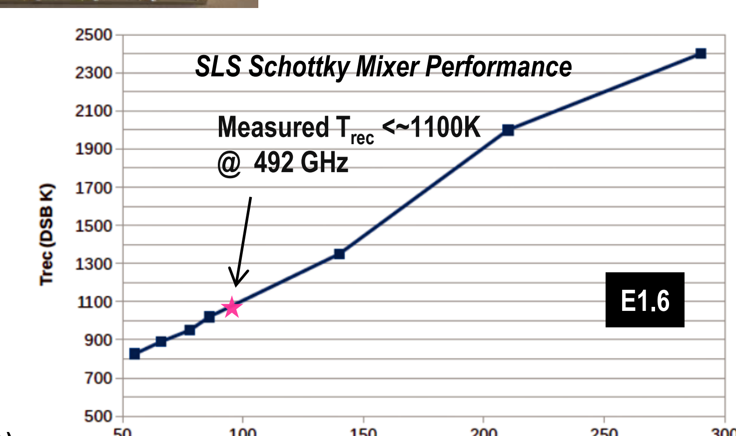
Orthomode Transducer (OMT)



384 –500 GHz OMT takes the unpolarized signal from horn and splits it to horizontal (H) & vertical (V) components for the mixers.

IF Amplifiers

SLS Low Noise Amplifier (LNA): Low Noise Factory -LNC6_20C



F. MISSION IMPLEMENTATION

F.1 Mission Requirements and Traceability

The SLS mission/system requirements in Table F.1 are derived from and traceable to the science requirements discussed in Section D. They are satisfied with minimal or no changes to the heritage flight system. The result is a robust mission architecture that achieves the science objectives with low risk and low cost.

F.2 Mission Concept Description

The SLS mission consists of two identical CubeSats, each with a ~30 x 20 cm radio telescope tuned to simultaneously observe the [CI] 1-0 and ^{12}CO J=4→3 transitions of atomic carbon and carbon monoxide. The two spacecraft perform independent surveys of the Galactic Plane and selected star forming regions, after which the survey results are co-added to reduce noise and increase sky coverage (see Sec. E.2).

F.2.1 Launch and Orbit Design

As a rideshare mission, a specific SLS launch opportunity and orbit can only be determined once the mission is manifested. The baseline mission, optimized for science acquisition, is designed for a circular sun-synchronous ~650 km orbit with dawn-dusk nodal orientation. This is a fairly common destination for a variety of satellites. This orbit accommodates: 1) near continuous science operation with an anti-solar FOV in summer and winter; 2) near-constant solar illumination to provide stable power and thermal profiles; 3) orientation facilitating ground communications simultaneous with observation; 4) consistent shading of radiators from both sunlight and Earth albedo; 5) a conservative EOL altitude ensuring passive de-orbit in less than 25 years (Appendix 7). The payload FOV will be oriented nominally anti-sunward with deflections both north and south to follow the galactic plane, enabling two full 360° Galactic Plane Surveys (GPS) as the orbit precesses during the 2-year mission. The orbit period is ~96 minutes and so there are ~14 orbits per day. Foldout F shows the details of the nominal SLS orbit. Each spacecraft operates independently so there is no requirement on relative position of the two spacecraft. Both spacecraft maintain pointing with their central field of regard normal to galactic north in the direction closest to anti-sunward. From this attitude and orbit, each spacecraft will be able to scan a 1° by 2° area of the galactic plane on a daily basis; thus as the sun vector varies over a one year period a 360° scan is achieved. The spacecraft roll about the field of regard to place the sun vector closest to the solar array normal, preserving the radiators in shadow.

Science Functional Requirements	Spacecraft System Requirements	Mission Design/ Ops Requirements
2-year mission lifetime Compatible with MO reqmts Passive deorbit in 25 yrs	Comply with 6U specs Prop system for altitude adjust RDM=2, TID=5 krad, SEU tolerant	Nominal 650 +35/-50 km orbit Max orbit flexibility
Map full galactic plane in 1 yr, 1 x 2 sq deg regions Map 4 targeted regions of 1 sq deg each over ~3 day period	Pointing acc/knldg 2 arcmin RMS Pointing jitter < 1 arcmin RMS FOV +/-70 º about ecliptic 5 deg/sec slew rate Payload FOV ~anti-Sun	Dawn/dusk Sun synch orbit Autonomous pointing profile Support eclipse up to 50% of 100 min orbit
Able to detect $T_{Cloud} \geq 0.4$ K km/s	Receiver front end uncooled Passive radiative surfaces/MLI	Maintain payload FOV nominally anti-Sun
Accommodate SLS payload	Support payload mass of 1.6 kg Provide payload power 16W	Data rate 30 kbps Downlink data 28 MB/day

Table F.1 SLS Mission Requirements Traceability Matrix

F.2.1.1 Orbit flexibility

The SLS observing plan accommodates a wide range of orbits and launch dates, providing maximum flexibility in SLS launch opportunity selection. While the baseline orbit is optimal, deviations are accommodated with minor modifications to the observing plan and/or slight reductions in data quantity, always remaining well above the science threshold.

Altitude. The baseline altitude of 650 (+35/−50) km is selected so that as the orbit decays over the 2-year baseline mission it will on average remain Sun-synchronous, allowing a consistent spacecraft attitude with no orbit maintenance required. The upper limit is set by the passive deorbit requirement. Although not required for the baseline mission, the heritage CuSP spacecraft design does include a small propulsion system capable of 20 m/s ΔV, which can be used to raise or lower altitude if necessary. This enables SLS to accept orbits down to about 550 km with no impact, using small maneuvers during the commissioning phase to raise altitude. Once the mission is manifested, if the planned initial orbit is high enough this propulsion system can easily be removed (or launched un-fueled).

Inclination. The baseline ~98° inclination is common for a variety of satellites and simplifies SLS operations. Small deviations can be accepted with no impact, while lower inclinations result in reduced observing time and may affect instrument sensitivity due to thermal input. The dual spacecraft approach substantially mitigates this effect allowing orbits as low as ~57° to be accommodated. This will be studied further during Phase A.

Orientation. The baseline dawn-dusk orbit allows uninterrupted science observation with constant solar power input during summer and winter (when the anti-sunward portion of the galactic plane is also near the ecliptic). Other orbits result in eclipses that increase reliance on battery power; the SLS batteries are sized to accommodate ~50 min (half orbit) eclipses so power margins remain satisfactory in all orbit orientations. The instrument pointing profile is adjusted to account for Earth entering the telescope FOV and observing time is reduced during spring/fall in the baseline missions and as appropriate for other orbits. Even in the “worst case” noon-midnight orbit, the two spacecraft still acquire data at least double that of the science threshold (one spacecraft/one year). Further study during Phase A will optimize the observing profile for alternate orbit orientations.

F.2.1.2 Science Operations

After deployment from the launch vehicle, SLS completes a standard autonomous sequence to deploy solar arrays, de-tumble, achieve a positive power state, and establish nadir pointing for telecom and health check. After commissioning, the spacecraft assumes science attitude. At any given point in the orbit the angle of the payload FOV is adjusted above or below the solar ecliptic by an angle up to +/-70°(see Foldout F). This angle is pre-calculated and depends entirely on the date, which determines the orientation of the Sun vector to the Galactic Plane. During a complete orbit SLS is always pointed in approximately the same direction towards the Galactic Plane while effecting a 1°x2° sweep. Each row of the 1°x2° GPS raster takes one orbit, requiring a 1 deg spacecraft slew in ~96 minutes. All attitude changes are pre-programmed.

The Targeted Deep Surveys (TDS) each cover a 1° square and take ~3.4 days. The observing mode is the same as the main GPS survey, but in a 1°x1° box repeated 3 times. Nominally SLS performs 2 TDS during the commissioning phase prior to starting the GPS. The remaining 2 TDS would be completed after the main survey is complete. This sequence will be reassessed once the final destination orbit is determined.

Each spacecraft nominally downlinks science data once per day to facilitate data product processing and maintain instrument calibration. This schedule can be adjusted if needed due to station availabiility or other issues. SLS has sufficient on-board storage for several days worth of data.

F.2.2 Flight System Description

The SLS spacecraft configuration is shown in Foldout F. The architecture of the two SLS spacecraft platforms is based on the 6U ***SwRI LEO eXplorer*** (SLX-6), part of an in-house development project for a standardized CubeSat. This design has been implemented in the CuSP mission currently in development and scheduled for launch in Sept. 2018 (Appendix. J.9). Both spacecraft are contained in separate canisterized (fully enclosed) dispensers and remain powered down during all ground operations and launch. Foldout F shows the block diagram of the major subsystems including functional interfaces.

F.2.2.1 Key Resource Estimates

Resource estimates and margins are shown on Foldout F. SLS has ample margin to fulfill its mission requirements. To verify resource requirements, a 3D mechanical model, a thermal model, a power model, an orbit-to-FOV model, a downlink telemetry model (link budget) and a payload optics model were created. SLS is compliant with the volume and mass requirements for a 6U CubeSat.

F.2.2.2 Payload Accommodation

The payload is discussed in detail in §E.2. Foldout F shows how the payload and its subsystems are mounted. The spacecraft provides a deployable panel serving both as a shield for Earth albedo and a mount for the secondary reflector that directs light into the spectrometer front end. This panel deploys in the same manner as the 2U x 3U solar array using the same heritage hinge assembly and deployment mechanism.

F.2.2.3 Command and Data Handling (C&DH)

The SLS C&DH is the SwRI ***SATYR*** single-board computer (SBC) which is also used on the CuSP Mission. ***SATYR*** is an I/O reduced version of the SwRI CENTAUR SBC that is flying on the 8-spacecraft CYGNSS mission launched in November 2016. The ***SATYR*** uses a space-qualified heritage SPARC8 processor (Aeroflex GR712RC) integrated with an A3PE3000 FPGA for CCSDS-compliant command and data handling. The FPGA also provides FSW-independent execution of a Level-0 command set intended for ground-based fault management. Commands are passed to the FSW command manager for execution or to the stored command sequence manager as onboard absolute and relative time sequences. The FSW telemetry manager provides collection and high-level formatting of housekeeping data. There are 2 MB of MRAM, 4 MB of SRAM and 8 GB of FLASH. The SATYR occupies 0.4U of the spacecraft volume. SLS leverages the FSW developed for CYGNSS and CuSP which is directly compatible with the SLS C&DH.

F.2.2.4 Micro Propulsion System (MiPS)

The high heritage (MarCO and CuSP) COTS Micro-Propulsion System (MiPS) from VACCO provides ~20 m/s of ΔV enabling an adjustment in altitude of ~40 km. The VACCO X14029003-4 has a specific impulse of 40 sec and a total impulse in excess of 157 N-sec from inherently safe R236fa propellant. The MiPS occupies 0.5U of the spacecraft volume. It is a part of the heritage design and will be used to adjust orbit altitude only if the initial orbit differs significantly from the desired baseline.

F.2.2.5 Communications and Data System

At present there are no CubeSat-compatible Ka-Band radio and antenna systems available to fit within a 6U volume already limited by the payload primary reflector. During Phase A we will continue to evaluate new systems that may become available. Pending new developments, the SLS baseline is a Syrlinks COTS Transceiver. This unit provides an X-Band downlink and S-Band uplink and allows for a downlink rate of 10 Mbps. With a 7 minute nominal pass and an average of 1 pass/day, each spacecraft can downlink up to 4.2 Gb/day. SLS has an uncompressed data rate (science plus eningeering) of 30 kbps (2.6 Gb/day). With 2.4% overhead, SLS has a downlink margin of ~38%. 4GB of onboard storage accommodates at least 7 consecutive missed passes with no data loss. The planning baseline is the NASA Wallops facility, but SLS can also utilize the other two NASA, three KSAT, and four SSC Near-Earth-Network (NEN) S/X capable facilities.

X-BAND DownLink. The X-Band downlink is a 10 Mbps 2W RF transmitter operating between 8025 and 8450 MHz, software configurable at a resolution of 1 MHz. Its duty cycle will be approximately 8% per orbit during each downlink window. A 10cmx10cm Patch Array Antenna is mounted on the Nadir pointing surface of the spacecraft.

S-BAND UpLink. The S-Band uplink receiver operates at a frequency of 2025 to 2110 MHz and supports an uplink rate of 8 to 256 kbps . It operates continuously consuming ~1.5W, and can accept "fire code" transmissions to reset the spacecraft. A dedicated 10cmx10cm Patch Array Antenna will be mounted on the Nadir pointing surface of the spacecraft.

F.2.2.6 Attitude Determination and Control (ADCS)

SLS requires both knowledge and control of the spacecraft orientation in space. The SLS ADCS uses the Blue Canyon Technology XACT unit, which contains space-qualified sensors, effectors and electronics and is supporting over 13 funded AFRL and NASA missions to be launched before 2018. This past summer XACT was successfully launched on the MINXX CubeSat raising it to TRL 9.

The XACT provides better than +/-0.01°(36") pointing accuracy for all three axes and pointing knowledge is +/-0.001°(3.6") for all three axes, ~26 times the science requirement. Additionally it is capable of slewing ~5°/sec (for SLS mass) which is well above the requirements for SLS maneuvering. The XACT features a 3-reaction-wheel array, 3-axis magnetometer, 3 magnetorquers, star tracker, sun sensor, and an internal navigation computer. The BCT XACT greatly exceeds the SLS instrument pointing requirements. It was selected due to its highly integrated nature, small size, low power, design maturity, heritage, and superior capability; all functions are performed within 0.5U of the spacecraft in a single, flight heritage stand-alone unit.

F.2.2.7 Mechanical Structural Thermal (MST)

The SLS MST supports and protects the payload and spacecraft systems from environments including vibration, thermal and radiation, and is designed to meet GEVS launch loads within a commercial Canisterized Satellite Dispenser system. The structure is baselined with a minimum of 4mm of aluminum around electrical components as radiation shielding. Phase A analysis (See §F.3.2) will refine the structure.

F.2.2.8 Spacecraft Deck

SLS utilizes the same structural deck concept developed for CuSP. The backbone of each SLS spacecraft is an 11mm flat deck 364mm x 239mm. Two deployment rails integrated into the deck serve as the interface to the deployment canister (§F.2.3). It accommodates an embedded printed circuit board backplane that provides most of the spacecraft harnessing. Subsystem components are mounted directly to this spacecraft deck. Auxiliary mounts and structural components are used to ensure adequate structural Factors of Safety between components (e.g. deployable panels) and the deck. Foldout F shows a diagram of the spacecraft structure.

F.2.2.9 Spacecraft Thermal Control

Thermal control uses passive radiative surfaces thermally coupled to the spacecraft deck, and multi-layer insulation (MLI) shields the spacecraft body from solar illumination and re-radiated illumination from the solar arrays. All eight 3U deployed solar array panels are thermally isolated from the spacecraft body to prevent conduction. The deployed solar arrays help to block direct sunlight from the spacecraft and payload such that re-radiation must be accounted for with MLI on the sides of the body.

F.2.2.10 Payload Thermal Control

To meet the baseline and threshold measurement goals, the receiver front-end unit requires a temperature below 160°K which is easily achieved. SLS has targeted 100°K which would allow recovery of up to a factor of 4 in lost observing time due to unfavorable orbits; analysis shows that this is achievable with a passive radiator and will be further analyzed during Phase A. Cooled components are thermally isolated and generate ~25mW. Routine receiver total power calibrations will be conducted and applied to compensate for temperature variations.

F.2.2.11 Electrical Power System (EPS)

SLS uses a COTS EPS provided by Clyde-Space consisting of solar arrays, power conversion, batteries, and load switching. Additional subsystem switching is provided on the spacecraft backplane. The EPS occupies 2.8U of the spacecraft (including converter, batteries, and stowed solar arrays).

The solar arrays consist of eight 3U sub-panels, each with seven 28.3% efficient Spectrolab UJT solar cells arranged in a 7S1P configuration. This arrangement provides a total of 56 cells producing approximately 58W of power BOL at 20C. Thermal estimates of the deployed panels show they operate near 80C which derates them to 49W. There are two triple-deployed panels on either side of the spacecraft and 2 x 3U single deployed panels on the ~zenith pointing end (see Foldout F). The panels are held in the stowed configuration by space-qualified Dyneema cord and released by a Clyde-Space Thermal Knife Driver (TKD) circuit, whereupon the panels deploy to 90°. Clyde Space's deployable solar panels, including TKD circuitry and deployment hinges, have extensive heritage and are used on the CuSP Mission (CuSP deploys to 135°) .

Power conversion takes place on a COTS 3G FlexU EPS produced by Clyde Space. The EPS employs Maximum Power Point Tracking in nine independent Battery Charge Regulators to optimally charge the batteries and drive the output regulators. This system handles up to 99W input power from the solar arrays and has three power conditioning modules to drive a 22.5W 5V Bus, 15W 3.3V Bus, and an 18W 12V Bus as well as a 34W unregulated battery bus. It has an overall efficiency of 90% at full capacity. Load switching for spacecraft subsystems is accomplished by an EPS daughterboard with ten switched distribution lines. The EPS is controlled by the C&DH over an I2C interface. Additional loads are switched by 53111 solid state opto-isolators mounted on the spacecraft backplane and controlled directly by the C&DH.

Clyde-Space provides two COTS 40WHr battery packs. Each contains 8 Varta Li-Ion Polymer flex pouch batteries with extensive space flight heritage. The batteries meet three key requirements: (1) Ground operations during which no battery charging can take place; the Li-Ion Polymer Flex pouches ensure a 90% charge in case of a 9 month delay between the last charge and deployment. (2) Adequate charge for autonomous operations between deployment and establishment of sun point attitude. (3) Adequate depth of discharge to operate for at least a 30-minute eclipse period during a 96 minute orbit. Proper battery temperatures will be maintained using a combination of thermal stand offs and heaters, the details of which will be studied in phase A.

F.2.3 Canisterized Satellite Dispenser (CSD)

SLS will interface with the launch vehicle using a 6U CSD from Planetary Systems Corporation. The dispenser mounts on the launch vehicle on a 3Ux2U face with its 2Ux1U face normal pointing along the separation vector. The dispenser interfaces electrically to the launch vehicle or primary spacecraft via a DE-9 ("DB-9" per PSC data sheet) connector and requires a 28+/-6VDC signal at 5.5+/-5A for a minimum of 0.12

seconds to actuate deployment. Two internal switches, closed when an SLS spacecraft is stowed and open when deployed provide deployment feedback. SLS will deploy at a maximum tumble rate of 10°/s per axis.

F.2.4 Mission Operations

SLS will utilize the SwRI Mission Operations Center (MOC) facilities in Boulder. The MOC is a fully functional operations facility in use on CYGNSS and to be used on CuSP (see heritage appendix).

F.2.4.1 Ground System and Facilities

The MOC interfaces with the UA Science Operations Center to plan and uplink commands, distribute data to the science and engineering teams, coordinate generation of higher level data products, and provide all raw and end-product datasets. The SLS Level 0 data flows from the MOC to the SOC for conversion to Level 1 data via automated algorithms and stored to disk. The data are distributed within the science team, where detailed L-2 and L-3 data analysis are performed. The SOC acts as the active Resident Archive for the lifetime of the mission and beyond. The data with appropriate header files are delivered to a Permanent Archive (NSSDC or other specified archive).

F.2.4.2 Telecom, Tracking, and Navigation

All telecommunications, tracking and navigation functions will take place at SwRI Boulder via interface with the NASA Wallops ground station. Orbit determination and maneuver design (if any) will utilize software and processes from CYGNSS. X-Band downlink occurs at a maximum rate of 12.5Mbps with nominal contact duration of 420s. Preliminary link analysis indicates a downlink margin of 8.1dB at 650 km altitude.

SLS will coordinate frequency allocation of the S/X-Band radios with NTIA and NASA in order to gain the required frequency allocation prior to the flight. SwRI has experience with this process via CYGNSS and other missions.

F.3 Development Approach

SwRI will develop the spacecraft and is responsible for system integration, test, and operations. SwRI coordinates with UA to ensure compliance with SLS science requirements and schedules. UA develops the payload and manages all aspects of its assembly and test, and participates with SwRI in payload integration and final system test.

F.3.1 Systems Engineering (SE) Approach

SwRI employs a comprehensive SE process to guide flight system development, integration, and test. An SE team (SET) is led by the Mission Systems Engineer (MSE) working closely with the Spacecraft Systems Engineer, individual spacecraft subsystem leads, and the Payload System Engineer. The SET works to identify and resolve issues, maintain the system baseline, and coordinate the production efforts of all organizations. The team is responsible for ensuring definition and documentation of interfaces, managing and closing trade studies, and managing technical resources. The SET defines system-level requirements and assures flow-down to and management of the subsystem requirements. An SE Management Plan (SEMP) documents the SE process. It leverages the experience gained from CuSP and CYGNSS to tailor 7120.5E class D requirements for CubeSats.

Although each SLS spacecraft is single string, the pair represent a fully redundant approach since either alone can accomplish the threshold mission. System failure mitigation is achieved through extensive testing and significant reuse of high-heritage COTS designs.

F.3.2 Phase A Studies

During Phase A, planned trade studies will be conducted on: continuous nadir pointing vs. slewing for downlink to optimize science viewing; availability of a suitable Ka-band radio for downlink; on-board compression of data to further reduce ground contact requirements; and detailed thermal analysis to determine whether receiver sensitivity can be increased which would lead to enhanced science return, enhance orbit flexibility, and/or decrease the required mission lifetime.

F.3.3 Requirements Management

Mission requirements will be identified, tracked and verified by the SET. Requirements are either flowed down from the LV and NASA, imposed by COTS equipment choices, or derived based on design decisions. Requirements are tracked using Excel.

F.3.4 Interface Management

Interface requirements, electrical, mechanical, operational, data handling, and communications are either flowed down from LV requirements or determined during top-level system design of the spacecraft and MOC. Adherence to the CubeSat standard simplifies interface planning, and all subsystem leads have experience with prior CubeSat missions. Most subsystems are COTS and thus have known interfaces into the system design. These inputs are maintained in the SwRI Project Information Management System (PIMS) and controlled by the SET.

F.3.5 Radiation Design Strategy

Three requirements based on standard LEO environments and CYGNSS experience drive the SLS radiation design: a TID of <5kRad with an RDM of 2; a mission length of 2 years; and the ability to handle Single Event Upsets (SEU). Based on the predicted radiation environment and the cost constraints for this mission class, SLS does not require radiation hardened EEE parts. Radiation mitigation consists of a three-fold targeted approach. (1) For TID mitigation, SLS uses COTS components that are inherently radiation tolerant, such as sub-micron process FPGAs and MRAM whenever possible. (2) Based on the flight parts selection, radiation analysis determines if full coverage or spot shielding is required. Shielding is implemented as aluminum plate of 4mm thickness commensurate with the TID limit. Shielding mass has been accounted for in the resource estimates. (3) for SEE/SEU mitigation, SLS uses a reboot/refresh strategy including power cycling of susceptible components and subsystems through a watchdog timer that automatically initiates a reset. This is applied to the payload, radio, EPS and ADCS. In the event of a spacecraft lockup event that blocks a reset, indicated by a failure to communicate, the SATYR FPGA is capable of receiving a level-0 reset from uplinked commands initiating a fire code that resets the entire spacecraft entirely independent of FSW.

F.3.6 Mission Assurance

The Safety and Mission Assurance (SMA) Manager manages the SMA efforts following Mission Assurance Guidelines and Requirements, NPR 7120.5E tailored for this Category 3 and, as per NPR 8705.4, risk Class D CubeSat. The SwRI SMA process leverages practices developed and experience gained on the CuSP CubeSat Mission. These remain consistent with NASA standards and SwRI's AS9100-certified processes.

F.4 Technology Development

All spacecraft subsystems have heritage and are TRL 6 or greater. The SBC is identical to the heritage CYGNSS SBC in design and function, the only required change being removal of some I/O capability and a re-layout of the PCB to meet the CubeSat Form Factor.

F.5 Assembly, Integration, Testing, and Verification

System level I&T is managed and performed at SwRI based on processes developed for the CuSP CubeSat mission. Figure F-1 shows the entire I&T cycle, which is typical for a Small Sat (e.g. CYGNSS) or a CubeSat (e.g. CuSP) mission. The payload is tested independently at UA including functional and optical calibration testing prior to delivery to SwRI for spacecraft integration.

F.5.1 Assembly and Integration Testing

I&T will be conducted at the same facility used for CuSP. After subsystems are tested at

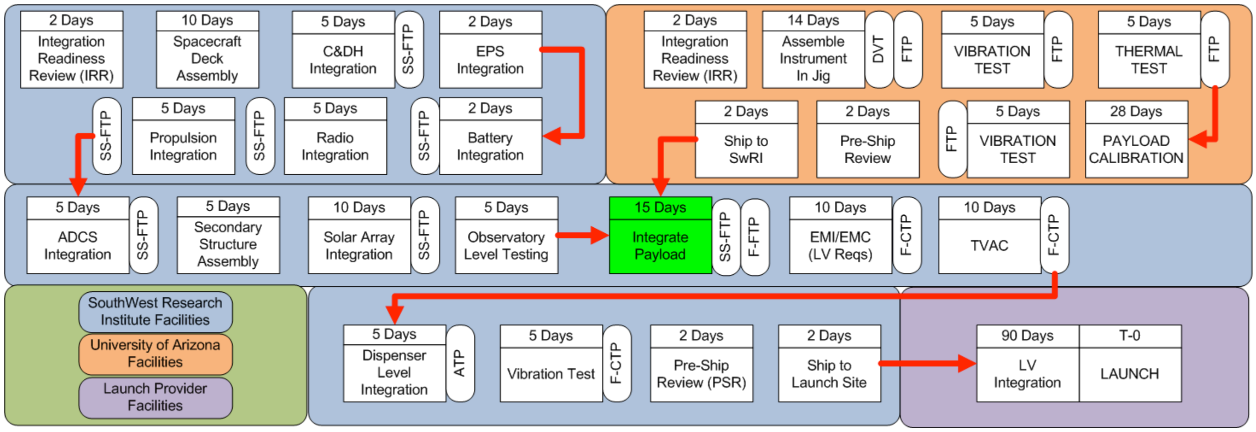


Figure F-1 *AI&T follows a typical sequence for CubeSat or SmallSat..*

the component level they are mounted on the spacecraft deck and integrated with the flight backplane embedded in the deck.

F.5.2 Environmental Testing

SLS environmental testing will take place at SwRI facilities in San Antonio. EMI/EMC will be performed to verify both self-compatibility and that SLS will not power up during launch due to LV emissions or conduction. TVAC will be performed under three hot-cold cycles whose values are determined by a detailed thermal analysis in Phase A. vibration test will be conducted according to the launch environment after selection of a LV. Until the selection of the LV all analysis and design activities will assume GEVS.

F.6 SLS Schedule

The SLS master schedule covering all phases of the investigation is shown in the schedule foldout. The scheduling processes at both UA and SwRI are flight proven and have demonstrated the ability to integrate diverse multiple program participants into a cohesive team that performs on time and within budget. An initial Work Breakdown Structure (WBS), WBS dictionary, and top-level schedule were developed by the project with the mandated schedule margin and target dates for mission milestones. The WBS and top-level schedule were then iterated with the team. The subsystem leads developed bottoms-up detailed schedules aligned to the WBS for their respective subsystems. During Phases B-D the schedule will be updated monthly to show work accomplished. Schedule performance metrics determine team performance and corrective actions are employed where necessary.

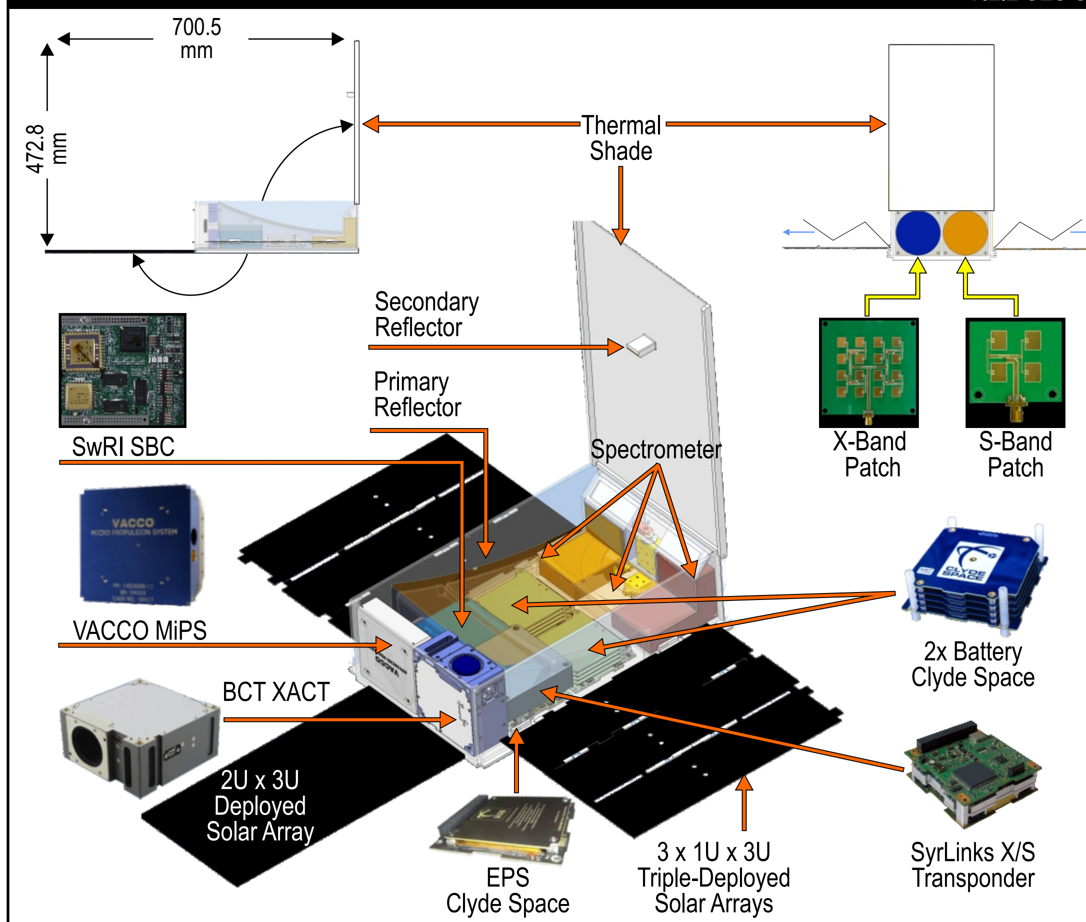
During the scheduling process, key receivables and deliverables (rec/del) were identified at the element level and integrated into a master mission rec/del list. This list is maintained throughout the life cycle to coordinate element development and the dates were vetted through the full mission scheduling process.

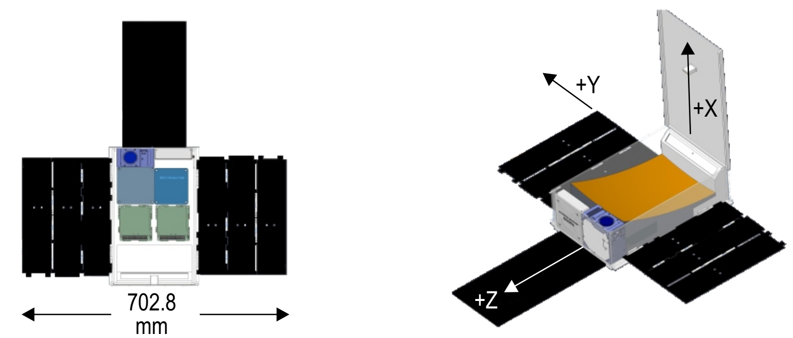
The design, fabrication, integration, and test of the instrument to the first spacecraft represent the schedule critical path. The secondary critical path is the spacecraft deck and structure through spacecraft integration. The full SLS development schedule (Phases B-D) includes 150 workdays of funded schedule margin. The Instrument fabrication and test schedule holds 40 workdays of funded schedule margin, Spacecraft AI&T holds 75 workdays of margin and Observatory AI&T holds 35 workdays of schedule margin. All schedule margin is fully funded within the respective WBS elements at the same ongoing spending rate. This schedule assumes shipping for launch on 9/27/21, over 6 months before the baseline launch date. The shipping date could easily be pushed out several months once the mission is manifested, resulting in even greater schedule margin.

SLS

Foldout F: Spacecraft and Mission

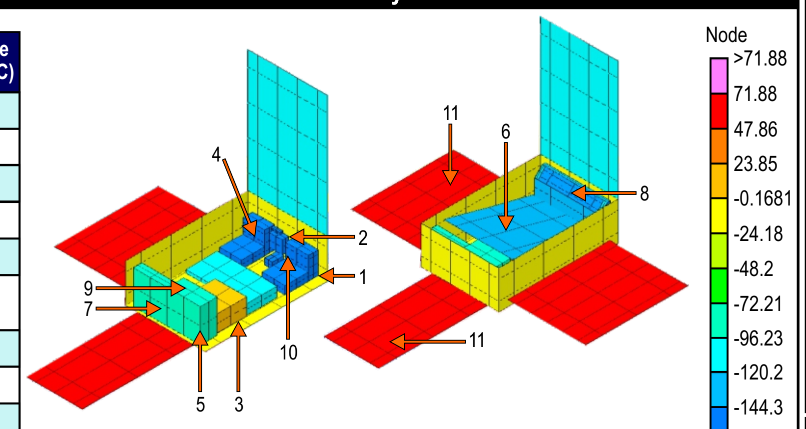
F.2.2 SLS Spacecraft





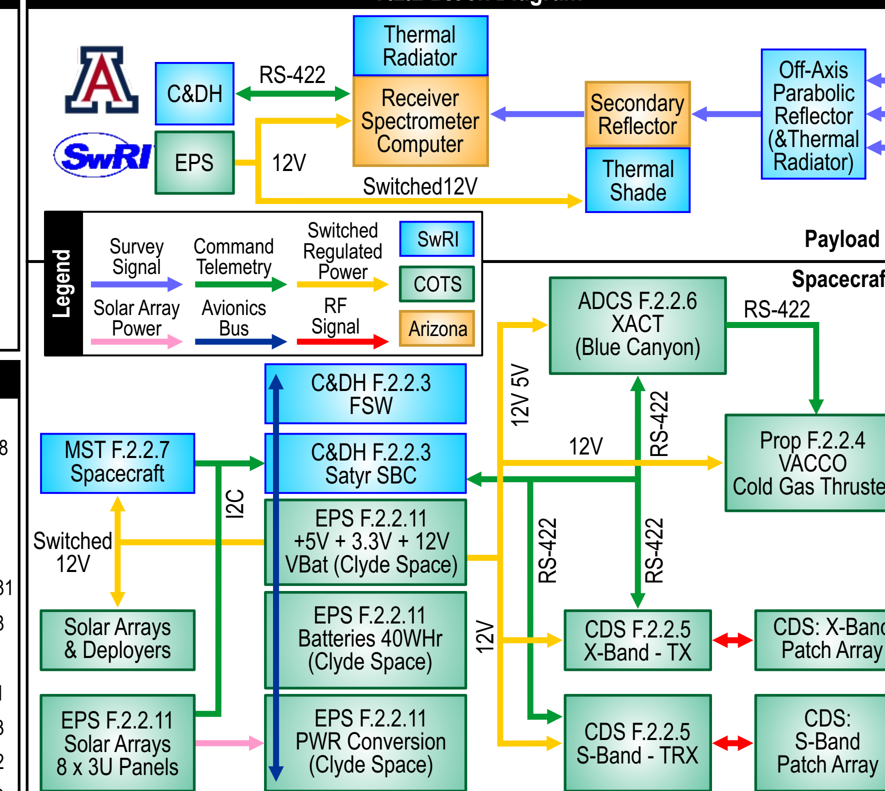
F.2.2.1 Thermal Model Analysis

Item #	Component	Average Temp. (C)
1	Spectrometer	-167
2	Feed Horn	-168
3	SwRI SBC	1
4	LO Box	-166
5	BCT XACT	-90
6	Primary Reflector Dish	-127
7	VACCO MiPS	-92
8	Radiator	-169
9	X/S Xponder	-7
10	Signal Mixer	-169
11	Solar Panels	69



Thermal analysis verifies the ability to cool the receiver feedhorn to at least ~100K (-173.15C). Battery thermal control will be studied further in Phase A to optimize thermal surface treatments and interface design.

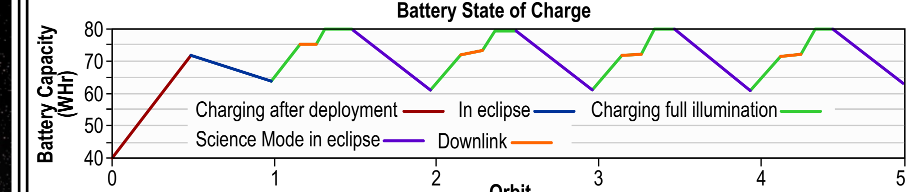
F.2.2 Block Diagram



F.2.2.1 Resources and Margins

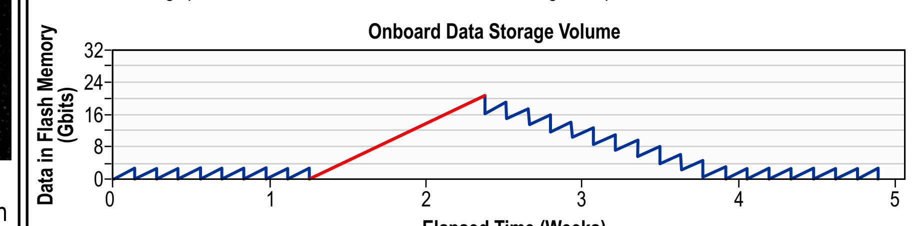
Resource	CBE	% Cont	MEV	MPV	% Margin
OAP (W) nominal case	28.2	17%	32.9	44.2	34%
OAP (W) worst case	20.7	15%	23.9	26.6	24%
Mass (kg)	8.2	11%	9.1	12.0	32%
Downlink (Gb/day)	2.59	24%	3.22	4.20	30%

Battery State of Charge



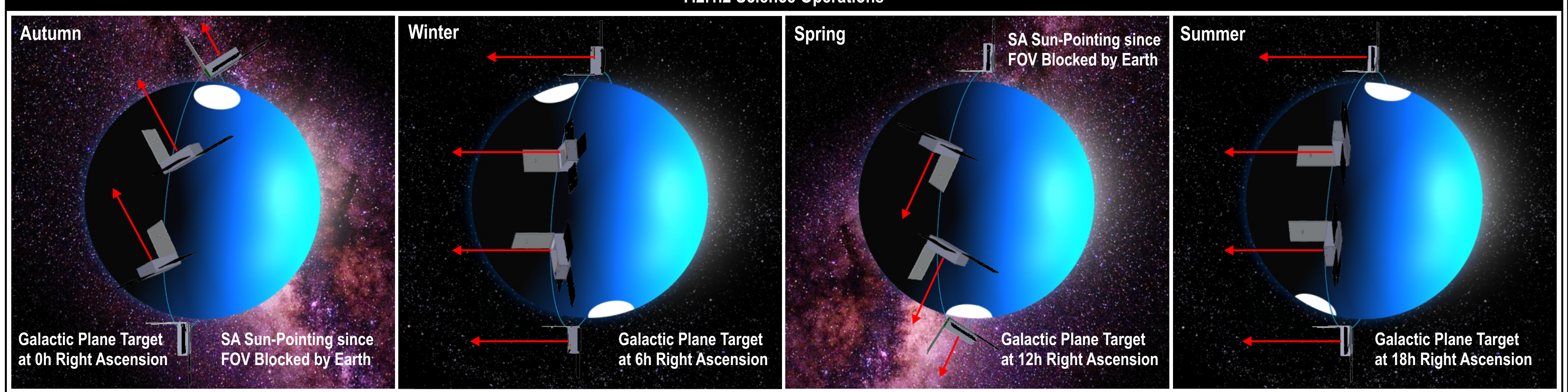
Power profile for initial deployment and transition into science mode (assuming no altitude adjustment) for the worst case orbit of 50% eclipse (nominal orbit eclipse is between 0% and 24% over a year). A conservative value of 50% DOD is assumed for the battery charge state after de-tumble and any self-discharge prior to launch. SLS maintains a 25% DOD throughout operations once it has assumed orbit.

Onboard Data Storage Volume



Onboard Data Storage Volume Profile over a 5 week period (Blue-Line). SLS is scheduled for one downlink per day for 7 minutes at 10Mbps. 4GB of onboard storage allows for at least 7 consecutive missed passes with no data loss (Red-Line)

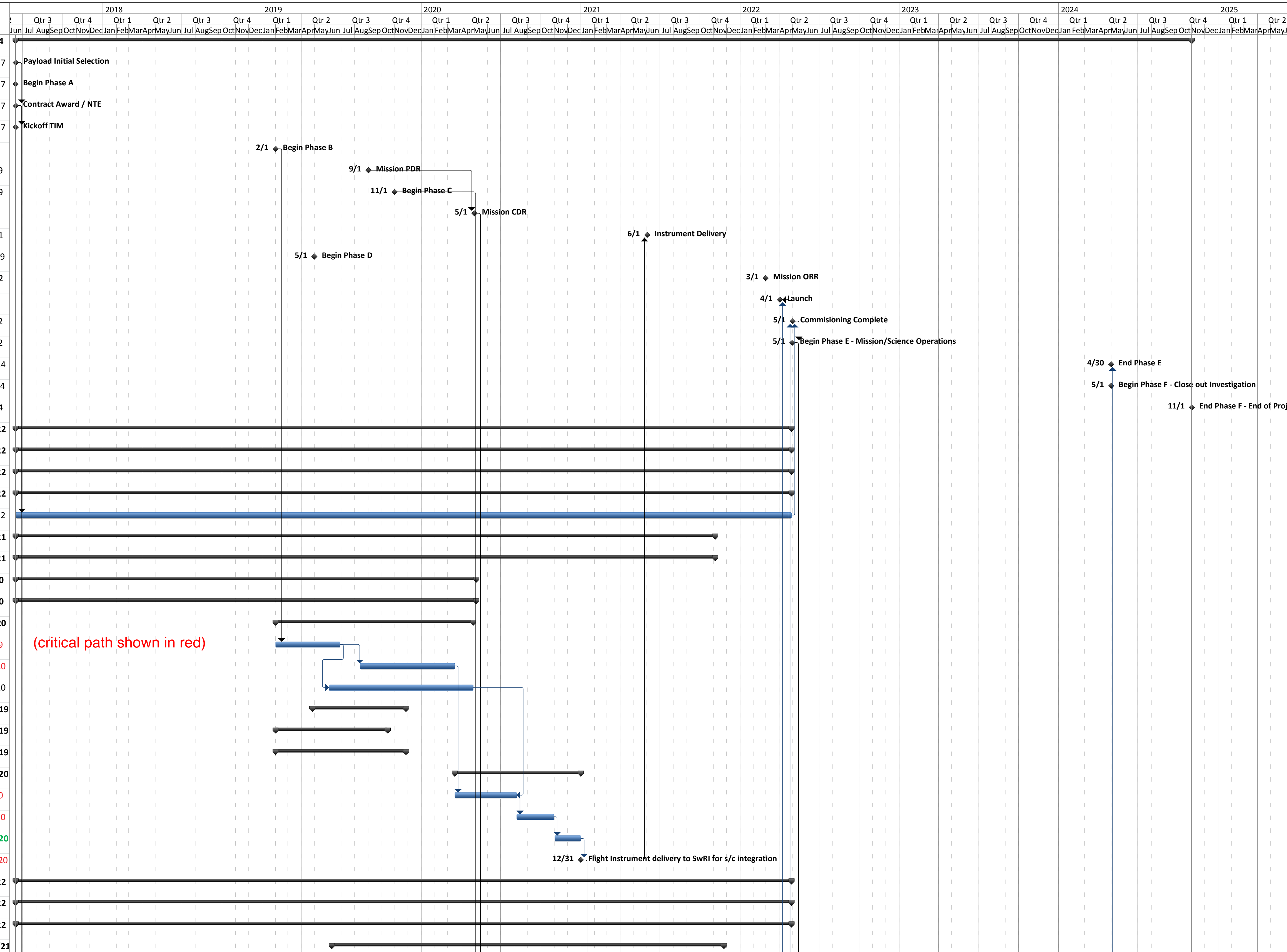
F.2.1.2 Science Operations



For Primary Pointing SLS orients instrument FOV anti-sunward, deflected ecliptic North or South to observe the Galactic Plane. (illustration POV is from ahead of Earth in its orbit.) Secondary pointing will optimize both instrument shading and solar array sun-pointing. Antennas point to nadir consistent with solar illumination only on back side of thermal shade. At equinoxes, Earth limb obscures observations part of the time, during which arrays point to sun and antennas to nadir. Worst-case 24% (equinox) power margin can be improved by extending array-to-sun duration.

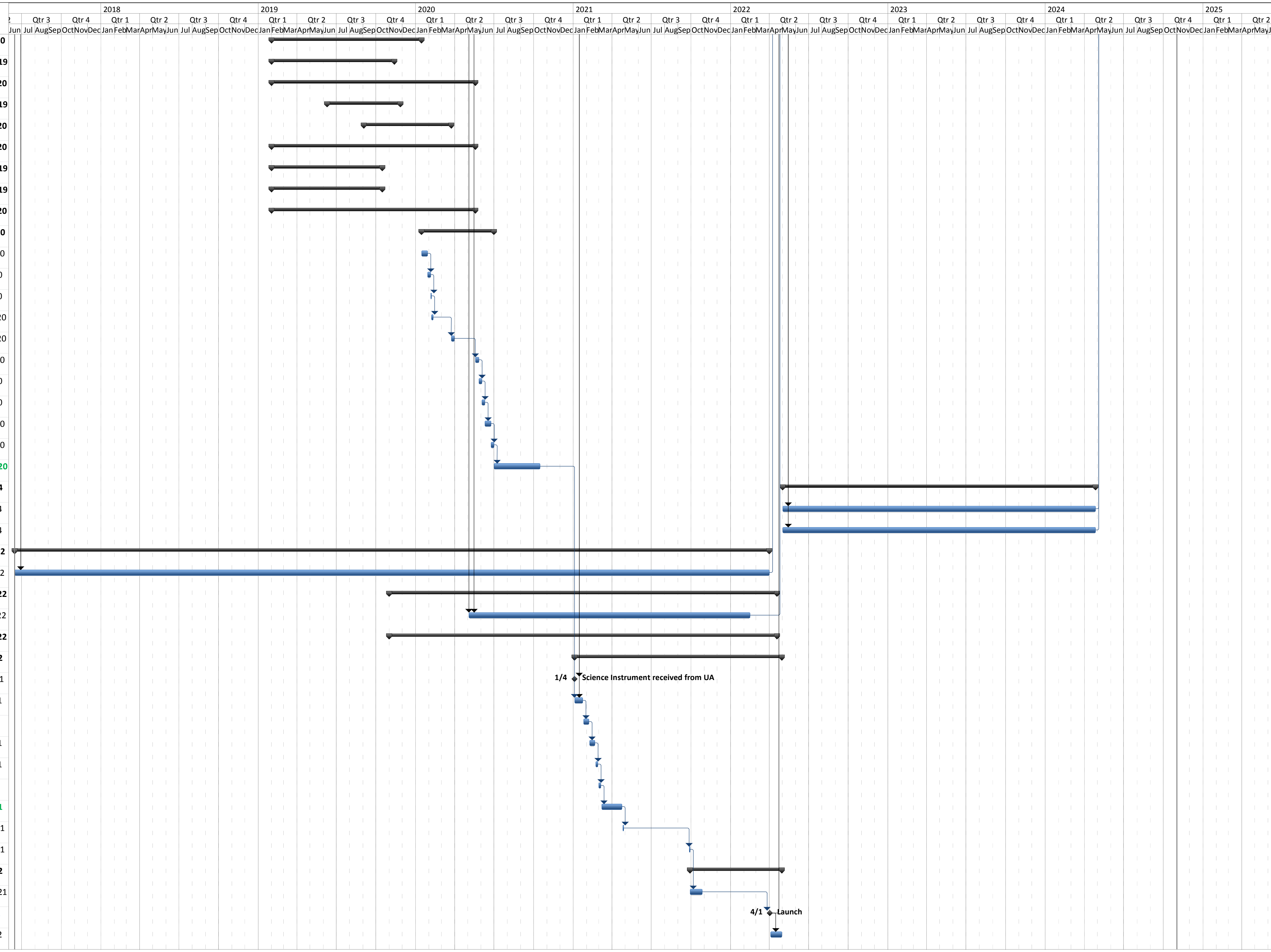
Spectral Line Surveyor Development Schedule - Proposal

ID	WBS	Task Name	DUR	Start	Finish
1	**0**	**Major Milestones**	**1885 d**	**Thu 6/15/17**	**Fri 11/1/24**
2	0.1	*Payload Initial Selection*	0 d	Thu 6/15/17	Thu 6/15/17
3	0.2	*Begin Phase A*	0 d	Thu 6/15/17	Thu 6/15/17
4	0.3	*Contract Award / NTE*	0 d	Thu 6/15/17	Thu 6/15/17
5	0.4	Kickoff TIM	0 d	Thu 6/15/17	Thu 6/15/17
6	0.5	*Begin Phase B*	0 d	Fri 2/1/19	Fri 2/1/19
7	0.6	Mission PDR	0 d	Sun 9/1/19	Sun 9/1/19
8	0.7	*Begin Phase C*	0 d	Fri 11/1/19	Fri 11/1/19
9	0.8	Mission CDR	0 d	Fri 5/1/20	Fri 5/1/20
10	0.9	Instrument Delivery	0 d	Tue 6/1/21	Tue 6/1/21
11	0.10	*Begin Phase D*	0 d	Wed 5/1/19	Wed 5/1/19
12	0.11	Mission ORR	0 d	Tue 3/1/22	Tue 3/1/22
13	0.12	*Launch*	0 d	Fri 4/1/22	Fri 4/1/22
14	0.13	*Commisioning Complete*	0 d	Sun 5/1/22	Sun 5/1/22
15	0.14	*Begin Phase E - Mission/Science Operations*	0 d	Sun 5/1/22	Sun 5/1/22
16	0.15	*End Phase E*	0 d	Tue 4/30/24	Tue 4/30/24
17	0.16	*Begin Phase F - Close out Investigation*	0 d	Wed 5/1/24	Wed 5/1/24
18	0.17	*End Phase F - End of Project*	0 d	Fri 11/1/24	Fri 11/1/24
19	**1.0**	**Project Management**	**1232 d**	**Thu 6/15/17**	**Thu 4/28/22**
22	**2.0**	**Systems Engineering**	**1232 d**	**Thu 6/15/17**	**Thu 4/28/22**
24	**3.0**	**Safety and Mission Assurance**	**1232 d**	**Thu 6/15/17**	**Thu 4/28/22**
34	**4.0**	**Investigation Science Team**	**1232 d**	**Thu 6/15/17**	**Thu 4/28/22**
35	4.1	Science Support	1232 d	Thu 6/15/17	Thu 4/28/22
36	**5.0**	**Instrument Design, Fabrication and Test**	**1112 d**	**Thu 6/15/17**	**Thu 11/4/21**
37	**5.1**	**Instrument Management**	**1112 d**	**Thu 6/15/17**	**Thu 11/4/21**
39	**5.2**	**Instrument SE**	**731 d**	**Thu 6/15/17**	**Tue 5/5/20**
41	**5.3**	**Instrument S&MA**	**731 d**	**Thu 6/15/17**	**Tue 5/5/20**
43	**5.4**	**Instrument Development**	**315 d**	**Fri 2/1/19**	**Tue 4/28/20**
44	5.4.1	Preliminary Design/fab/test	105 d	Fri 2/1/19	Fri 6/28/19
45	5.4.2	EM Model /interface validation	150 d	Tue 8/13/19	Tue 3/17/20
46	5.4.3	Flight Instrument Components delivered to UA	230 d	Mon 6/3/19	Tue 4/28/20
47	**5.5**	**Instrument Electronics and Harnessing**	**150 d**	**Fri 4/26/19**	**Tue 11/26/19**
50	**5.6**	**Thermal Subsystem**	**180 d**	**Fri 2/1/19**	**Tue 10/15/19**
53	**5.7**	**Instrument FSW**	**210 d**	**Fri 2/1/19**	**Tue 11/26/19**
57	**5.8**	**Instrument AI&T**	**200 d**	**Wed 3/18/20**	**Thu 12/31/20**
58	5.8.1	Flight Instrument Assembly	100 d	Wed 3/18/20	Thu 8/6/20
59	5.8.2	Flight Instrument Test and Calibration	60 d	Fri 8/7/20	Fri 10/30/20
60	5.8.3	Schedule Reserve	40 d	Mon 11/2/20	Thu 12/31/20
61	5.8.4	Flight Instrument delivery to SwRI for s/c integra	0 d	Thu 12/31/20	Thu 12/31/20
62	**6.0**	**Spacecraft**	**1232 d**	**Thu 6/15/17**	**Thu 4/28/22**
63	**6.1**	**Spacecraft Management**	**1232 d**	**Thu 6/15/17**	**Thu 4/28/22**
65	**6.2**	**Spacecraft Systems Engineering**	**1232 d**	**Thu 6/15/17**	**Thu 4/28/22**
67	**6.3**	**Spacecraft S&MA**	**625 d**	**Mon 6/10/19**	**Wed 11/24/21**



Spectral Line Surveyor Development Schedule - Proposal

ID	WBS	Task Name	DUR	Start	Finish
69	**6.4**	**Spacecraft Deck and Structure**	**240 d**	**Fri 2/1/19**	**Tue 1/14/20**
74	**6.5**	**C&DH**	**200 d**	**Fri 2/1/19**	**Tue 11/12/19**
79	**6.6**	**EPS/Batter/Solar Arrays**	**329 d**	**Fri 2/1/19**	**Mon 5/18/20**
88	**6.7**	**Harnessing**	**120 d**	**Mon 6/10/19**	**Tue 11/26/19**
91	**6.8**	**Communications**	**140 d**	**Tue 9/3/19**	**Mon 3/23/20**
93	**6.9**	**ADCS**	**329 d**	**Fri 2/1/19**	**Mon 5/18/20**
96	**6.10**	**Flight Software (FSW)**	**180 d**	**Fri 2/1/19**	**Tue 10/15/19**
103	**6.11**	**Thermal Subsystem**	**180 d**	**Fri 2/1/19**	**Tue 10/15/19**
107	**6.12**	**Propulsion**	**329 d**	**Fri 2/1/19**	**Mon 5/18/20**
110	**6.13**	**Spacecraft AI&T (Qty 2)**	**119 d**	**Wed 1/15/20**	**Tue 6/30/20**
111	6.13.1	Spacecraft Deck Assembly	10 d	Wed 1/15/20	Tue 1/28/20
112	6.13.2	C&DH Integration	5 d	Wed 1/29/20	Tue 2/4/20
113	6.13.3	EPS Integration	2 d	Wed 2/5/20	Thu 2/6/20
114	6.13.4	Battery Integration	2 d	Fri 2/7/20	Mon 2/10/20
115	6.13.5	Radio Integration	5 d	Tue 3/24/20	Mon 3/30/20
116	6.13.6	Propulsion Integration	5 d	Tue 5/19/20	Tue 5/26/20
117	6.13.7	ADCS integration	5 d	Wed 5/27/20	Tue 6/2/20
118	6.13.8	Secondary Structure Assembly	5 d	Wed 6/3/20	Tue 6/9/20
119	6.13.9	Solar array Integration	10 d	Wed 6/10/20	Tue 6/23/20
120	6.13.10	Observatory level testing	5 d	Wed 6/24/20	Tue 6/30/20
121	**6.14**	**Schedule Reserve**	**75 d**	**Wed 7/1/20**	**Thu 10/15/20**
122	**7.0**	**Mission Operations and Data Analysis**	**517 d**	**Mon 5/2/22**	**Fri 4/26/24**
123	7.1	Mission Operations Support (Ph E)	517 d	Mon 5/2/22	Fri 4/26/24
124	7.2	Science Operations / Investigation Data Analysis (Pl	517 d	Mon 5/2/22	Fri 4/26/24
125	**8.0**	**Launch Vehicle/Services**	**1212 d**	**Thu 6/15/17**	**Thu 3/31/22**
126	8.1	LV Support	1212 d	Thu 6/15/17	Thu 3/31/22
127	**9.0**	**Pre-Launch MOS/GDS Development**	**621 d**	**Fri 11/1/19**	**Mon 4/18/22**
128	9.1	MOC Development Support	450 d	Mon 5/4/20	Mon 2/14/22
129	**9.2**	**SOC Development**	**621 d**	**Fri 11/1/19**	**Mon 4/18/22**
132	**10.0**	**Observatory Level testing and Launch Ops**	**337 d**	**Mon 1/4/21**	**Fri 4/29/22**
133	10.1	Science Instrument received from UA	0 d	Mon 1/4/21	Mon 1/4/21
134	10.2	Integrate Payload	15 d	Mon 1/4/21	Fri 1/22/21
135	10.3	EMI/EMC	10 d	Mon 1/25/21	Fri 2/5/21
136	10.4	TVAC	10 d	Mon 2/8/21	Fri 2/19/21
137	10.5	Dispenser level integration	5 d	Mon 2/22/21	Fri 2/26/21
138	10.6	Vibe	5 d	Mon 3/1/21	Fri 3/5/21
139	**10.7**	**Schedule Reserve**	**35 d**	**Mon 3/8/21**	**Fri 4/23/21**
140	10.8	PSR	2 d	Mon 4/26/21	Tue 4/27/21
141	10.9	Ship to Launch Site	2 d	Mon 9/27/21	Tue 9/28/21
142	**10.10**	**Launch Site Operations**	**148 d**	**Wed 9/29/21**	**Fri 4/29/22**
143	10.10.1	Launch Site Operations	20 d	Wed 9/29/21	Tue 10/26/21
144	**10.10.2**	**Launch**	**0 d**	**Fri 4/1/22**	**Fri 4/1/22**
145	10.10.3	Commisioning Complete	20 d	Mon 4/4/22	Fri 4/29/22



G Management

Under the leadership of PI Dr. Christopher Walker, the University of Arizona is responsible for all aspects of SLS including scientific and technical performance, cost and schedule management, safety and mission assurance, and risk management. By maintaining management responsibility at the PI institution, SLS is able to realize efficiencies and control costs consistent with the Explorer MO constraints. UA has experienced program management personnel, a mature project control infrastructure, and a record of success on projects of this scope and larger for NASA and other customers. Southwest Research Institute will augment UA by managing spacecraft, I&T, and mission operations. The SLS team has proven its ability to successfully conduct Explorer-class missions and is well qualified to implement a Cubesat Mission of Opportunity.

G.1 Management Approach

The SLS organization is shown in Fig. G-1. The University of Arizona, under the leadership of PI Dr. Christopher Walker, has overall responsibility for the performance, cost, and schedule of the SLS mission. The Project Manager (PM) is Mr. S.H. (Hop) Bailey of UA, who manages all aspects of the mission development, schedule, and cost, and oversees all UA subcontracts. Mr. Bailey leads the SLS project office, which provides contract management, financial and schedule tracking, and other business management support.

SLS is implemented as a partnership between UA and Southwest Research Institute, building on years of successful collaboration as well as SwRI's extensive experience in spacecraft development, integration, and operations. As the flight system provider, SwRI will build, test, and integrate the spacecraft, utilizing its proven Safety and Mission Assurance processes and supporting the program-level SMA/QA led by UA.

G.1.1 Project Control

SLS project management leverages and integrates processes at the partner institutions and is consistent with NPR 7120.5E and Class D requirements. The PI is accountable to NASA for the success of SLS and has full responsibility for its scientific integrity and performance within cost and schedule. Final decision authority for all matters impacting Level 1 requirements and science, including descopes and reserves, rests with Dr. Walker. All decisions affecting technical aspects of SLS are based on a fully integrated assessment of the science requirements, risk, performance, budget,

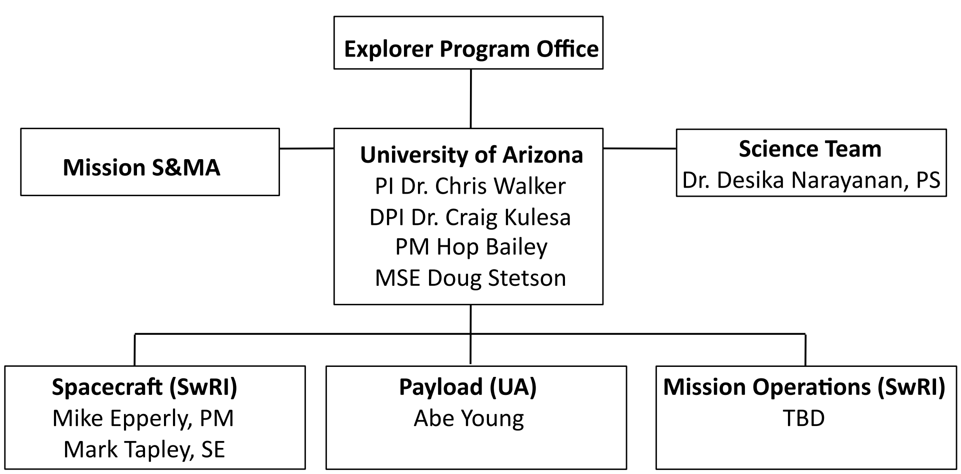


Fig G-1. SLS Org Chart

schedule, and available reserves and margin. Final decisions will be comprehensive in nature, drawing information, analysis, and recommendations from the Science Team, MSE, and engineering leads. Decisions impacting cost, schedule, or requirements are made by the PI after review by the management team and will be immediately reported to the Explorer program office.

G.1.2 Cost/Schedule Management

UA, working with SwRI and the payload component providers, will establish schedule, cost, and performance baselines in Phase A. The baseline will be updated prior to PDR to incorporate the preliminary technical data package including all drawings. An Integrated Baseline Review (IBR) will be conducted after PDR and serve as the basis for the Earned Value Management System (EVMS). Changes to the baseline require submission of a Baseline Change Request supported by fully developed cost, schedule, and performance impact statements. The PI, in consultation with NASA, is the decision authority for changes to the baseline.

In addition to the formal change control process, UA will conduct weekly telecons or meetings to monitor progress and promote thorough and open communication. Working groups will be established for systems engineering, management, and specific disciplines as required to facilitate complete face-to-face exchange of information. UA maintains the SLS Integrated Master Schedule (IMS) in Microsoft Project using inputs and updates from team members. The Phase A IMS represents the current baseline and is used to control changes in the schedule through Phase B. Prior to IBR and KDP C, a new IMS baseline will be established for the balance of the program.

UA implements EVM using Deltek Cobra EVMS which is compliant with the ANSI/EIA–748 Standard. Inputs to the program-level EVMS will be provided by the Payload (UA) and Spacecraft (SwRI). As the primary supplier of SLS flight hardware, SwRI’s institutional EVMS, used on many NASA and DOD programs, will constitute the majority of EV inputs, and UA will tailor its system accordingly. PM Bailey ran an earned value system for a large US Navy program and has established a working EVMS at UA that will be the foundation of the SLS EVMS.

G.1.3 Management and Reporting

The core management team will meet regularly to track resource and margin status, mission risk mitigations, planned versus actual costs, schedule status, staffing, subcontracting status, and workforce reporting. Weekly telecons will be established for Management and Systems Engineering, Instrument Systems Engineering, and Spacecraft. SLS will also conduct MMRs to provide a complete status of the project to the PI and PM. NASA personnel will be invited to every monthly review and will be provided a full report immediately following each review. The MMR will cover performance, cost, risk, and schedule and will be documented in a briefing package accessible in the SLS document library. Regular formal quarterly reviews, as well as all standard project reviews, will be held in coordination with NASA to provide insight into all aspects of project technical and financial performance.

G.1.4 Acquisition strategy

As the management institution, UA will be responsible for oversight of all elements of SLS. UA will be funded directly by the Explorer Program Office and will establish subcontracts to SwRI, the payload subcontractors, and science team organizations. SwRI will be funded through a Cost Plus Fixed Fee contract, and all other contracts will be fixed price. All contracts will include a cost cap consistent with the submitted budgets. UA will negotiate formal statements of work with each contractor including technical, schedule, and cost consistent with the project plan. For lower-level procurements, each organization will use their established processes to solicit and award purchase orders or contracts consistent with their statement of work. UA will retain and control the release of all reserves.

G.2 Roles and Responsibilities

Table G-1 summarizes the roles of the SLS team. The PI is responsible to NASA for the scientific integrity and success of the mission and is the final authority for all key decisions. With support from the DPI and science team, he leads science planning and coordination, data processing and analysis, and data archiving. The PI ensures that all science requirements are correct and works with the PM, PS, and MSE to flow those requirements to instrument subsystems, monitor compliance, and ensure adequate testing and calibration of the instrument. He is directly responsible for all decisions affecting the mission's science return. Authority for day-to-day technical and management decisions is delegated to the PM, who is co-located at UA and with whom the PI will work on a daily basis to maintain a clear understanding of the mission status.

The MSE reports to the PM and is responsible for the definition, implementation, and tracking of all mission and system requirements and interfaces. The MSE works with the PI and the spacecraft development team to ensure that all science requirements are properly reflected in the mission and system designs. When needed, he will engage support from SwRI engineers to provide insight into technical issues.

G.2.1 Project Team

The SLS project team has demonstrated experience in all technical and management areas necessary to make SLS a success. UA has managed and delivered many major spaceflight instruments, and the SLS PI and team members have implemented and flown balloon-borne astrophysics payloads equivalent to SLS in cost and complexity. SwRI has extensive experience in development, integration, and operations of scientific spacecraft. Key project team members are summarized below and their resumes are included in Appendix 3.

University of Arizona

Dr. Chris Walker, SLS PI, has over 25 years of experience designing, building, and using state-of-the-art instruments for TeraHertz astronomy. Under the direction of Dr. Walker, the Steward Observatory Radio Astronomy Laboratory (SORAL) has delivered a number of THz instruments, including single and multi-pixel receivers to the AST/RO telescope at the South Pole. Current projects include the 64-pixel SuperCam receiver for the Heinrich Hertz Telescope and the Stratospheric Terahertz Observatory (STO), a long-duration THz balloon payload flown in 2012 and 2016. SLS team members played a central role in these prior projects.

Organization	Role
University of Arizona	PI Dr. Chris Walker, Deputy PI Dr. Craig Kulesa SLS management, project-level SE/SMA. Coordination with Explorer Program Office. Payload management and systems engineering. Payload structures and component contracts. Instrument assembly and test. Science planning and Science Operations Center.
Southwest Research Institute (under contract to UA)	Spacecraft management, design, fabrication, SMA. Mission design, flight system/instrument integration and test, integration for launch. Mission Operations Center development and mission operations.
University of Florida (under contract to UA) ASU, UMass, SAO (under contract to UA)	SLS Project Scientist. Science co-Is.
Omnisys (Under contract to UA) Virginia Diodes (Under contract to UA)	IF processor/spectrometers. Schottkey receivers.

Table G-1. *SLS roles are based on prior teaming experience and successful missions/instruments.*

Dr. Craig Kulesa is the SLS Deputy PI, as he was for the STO project. He is also PI of the High Elevation Antarctic Terahertz (HEAT) telescope, a robotic 60 cm telescope that provides the SLS payload with its data pipeline, instrument and data computers, cryocooler heritage, and control electronics architecture. For SLS Dr. Kulesa will focus on payload development and observation planning.

Mr. S.H. (Hop) Bailey, SLS PM, has 20+ years of spaceflight and ground-based telescope management experience including Mars Observer Gamma-ray Spectrometer; Near Earth Asteroid Gamma and X-ray Spectrometer (jointly with SwRI); Mars Polar Lander TEGA; Mars Odyssey Gamma-ray Spectrometer; Large Optical Test and Integration System (LOTIS), a 6.5m Collimator built for Lockheed Martin; and the High-resolution Stereo Color Imager for the European ExoMars 2016 orbiter.

Mr. Doug Stetson (UA via contract), MSE, is responsible for completeness and correctness of the overall mission and system designs, requirements flowdown, design compliance, performance, and test compliance. Mr. Stetson is an experienced space systems engineer and manager, having played lead roles on a number of high-profile NASA planetary projects as a senior manager at JPL. He was Project Manager for the successful *LightSail* CubeSat mission.

University of Florida

Dr. Desika Narayanan is the Project Scientist. He will assist the PI with science and instrument requirements, instrument development and test, and science team management. Dr. Narayanan is a world leader in combining hydrodynamic and radiative transfer codes to model the ISM within the Milky Way and external galaxies.

Southwest Research Institute

Mr. Mike Epperly, Spacecraft Project Manager, will lead spacecraft development and test and be responsible for the spacecraft performance, budget, and schedule. He is currently the Program Manager of the CuSP Mission and has over 30 years of experience in the management, system engineering, design and production of satellite systems, avionics and instruments.

Mr. Mark Tapley, Spacecraft Systems Engineer, was MSE on the very successful IMAGE mission and also served as a systems engineer on IBEX and Gravity Probe B. He was Payload Systems Engineer for New Horizons during Phases A-E and most of cruise phase. He will oversee spacecraft development and implementation of all spacecraft requirements as well as spacecraft I&T, working closely with the MSE.

G.3 Risk Management and Mitigation

Table G-2 summarizes the top SLS risks with a concise statement of the risk and an assessment of likelihood and consequence before mitigation. Mitigations have been identified to retire the risk or lower it to an acceptable level.

G.3.1 Reserves and Margins

SLS currently holds 35% cost reserves in Phase B/C/D and 150 days of funded schedule reserves. Technical reserves (e.g. power, mass) as described in Section F are more than adequate to account for any credible development issue. The status of all reserves will be discussed at the MMR's and all major project reviews and will be reported to NASA on a regular basis. The PM maintains continuous visibility into the project's cost and schedule status including expenditures, obligations, and liens, and these will be assessed at each monthly review, quarterly reviews, and major project reviews.

Risk No	Risk Statement	L/C Rating	Likelihood Justification	Consequence Justification	Mitigation Strategy
1	IF orbital parameters (altitude, inclination, orientation) do not match baseline mission plan, THEN observing efficiency and science return may be reduced.	3, 3	As a rideshare mission, orbital parameters are dictated by primary payload and may not match SLS desires. However, SLS preferred orbit is a fairly common destination.	Reduced mapping speed results in decreased data collection, e.g. 30° misalignment doubles number of pointing maneuvers causing up to ~30% longer time to complete survey.	• Baseline mission is two spacecraft to increase mapping speed • Prioritize scientific data collection • Accept decreased coverage still above science threshold
2	IF the dual polarization mixer module and LNA's have higher noise temperature than expected, THEN science return may be reduced due to longer integration time required.	2, 3	While laboratory measurements of independent mixers indicate the target noise performance can be met with ~25% margin, a dual polarization unit has not yet been tested.	Mapping speed reduction results in decreased data collection. Longer time required to complete survey.	• Rely on radiative cooling to lower receiver noise temperature. • In flight: Prioritize scientific data collection • Increase mission duration.
3	IF one Cubesat fails on orbit, THEN mapping sensitivity or coverage may be reduced	2, 3	CubeSat bus and instrument have been developed and extensively tested for other missions. Will have flown well ahead of SLS.	Will be unable to co-add data from sister spacecraft.	• Increase mission duration • Revert to threshold science (single s/c for 1 year)
4	IF pointing knowledge does not meet requirement, THEN mapping accuracy will be reduced.	2,2	The pointing system has been demonstrated on a prior CubeSat mission and outperforms SLS spec by a factor of > 2.	Pointing knowledge is essential for mapping accuracy and post-flight scientific data analysis to diffraction limit.	• Carry sufficient onboard memory to store data from multiple orbits. • Smooth data product to pointing accuracy.
5	IF data downlink opportunities are missed for 3 consecutive days, THEN survey data will be lost.	2, 2	Ground station inaccessible; unlikely due to scheduling and ground backup systems.	Loss of areal coverage over 1x2 degree region to be mapped that day.	• Carry sufficient onboard memory to store data from multiple orbits. • Multiple ground stations available • Consider Ka-band in phase A to increase data rate

Table G-2. *SLS's top risks have been analyzed and mitigation plans are in place.*

The project will maintain a minimum of 25% unallocated future expenditures (reserves) on cost to go throughout the mission until completion of flight operations throughout the mission until completion of flight operations. If at any time the PM determines that the cost reserve level may drop below 25%, the SLS leadership will confer and recommend a plan of action. The response may include restructuring of tasks and procurements, adjusting workforce in coordination with the partner organizations, or the execution of mission descopes in consultation with NASA. The PM will also monitor the schedule status of all SLS partners and will adjust the IMS as needed. Special attention will be focused on the integrated payload (detectors plus telescope and support electronics) as the critical path. If and when a schedule impact is unavoidable, the PM will advise the PI and approve, with his concurrence, the release of reserves.

G.4 Project Descopes

The SLS PI and PM have established a prioritized set of descopes (Table G-3) that can be enacted if resource margins fall below acceptable levels. These represent a gradual transition from the baseline to the threshold. The table shows an estimate of the cost and mass savings for each descope and an estimate of the latest time at which it could be enacted to accrue the maximum benefit. Descope decisions will be made by the PI in consultation with all partners and with concurrence of NASA.

Descope	Savings	When Taken
Fly only one s/c	~$2M	PDR to CDR
Reduce mission duration to 1 yr	~$0.3M	Anytime

Table G-3. SLS mission descopes

H. Cost & Cost Estimation

The SLS PI-managed mission cost of $23.5M (FY17) includes all Phase A-F costs and unencumbered reserves of 29% (Phase A-D) and 14% (Phase E). Table B3 shows the estimates in FY17 dollars by WBS. This is a conservative estimate combining a bottoms-up approach with strong technical and management heritage. A number of cost-saving opportunities have been identified and will be explored in Phase A. UA as an institution, along with both the SLS PI and PM, have demonstrated success in managing complex space instruments and investigations with multiple partners on time and on budget. UA and SwRI together have many years of experience in space missions and instrument development and integration. The Cubesat spacecraft is based on well understood industry-standard designs with heritage from the current CuSP mission development, and instrument components are based on proven technologies and designs so that cost drivers are well understood. All of this leads to very high confidence that the proposed SLS cost is sufficient to successfully implement the mission.

H.1 Contracting Approach

All SLS activities are funded as shown in Table H.1. As the PI institution, UA is funded by contract to NASA and establishes subcontracts with vendors and science team members as required. All efforts will utilize cost-plus-fixed-fee (CPFF) contracts.

H.2 Cost Estimate Development

The SLS cost estimate was created using a bottoms-up approach based on the recent experience and heritage of UA and SwRI in instrument and Cubesat development and flight. The unique nature of Cubesat missions, utilizing an industry standard bus design and extensive use of COTS components, coupled with SwRI's experience with the ongoing CuSP spacecraft development, indicate that the bottoms-up approach is by far the simplest and most accurate costing technique for this type of mission. Currently available parametric modeling tools that are largely mass-based are less appropriate for Cubesat missions.

H.2.1 Estimating Process

The SLS spacecraft hardware estimate was provided by SwRI engineers using known costs for COTS components where

Organization	Scope of Work	Cost ($FY17)
University of Arizona (via contract from NASA)	PI, project management, systems engineering, instrument design and I&T, science operations	$11.71M (incl. reserves)
Various universities (via subcontract to UA)	Science team members	$1.35M
Southwest Research Institute (via subcontract to UA)	Spacecraft design and development, integration and test, mission operations	$9.14M
Virginia Diodes (via subcontract to UA)	Mixers and local oscillators	$0.33M
Omnisys (via subcontract to UA)	Spectrometers	$0.95M

Table H-1. SLS contracting plans and costs

available, with costs for other elements derived from the CuSP spacecraft development which is well into phase C/D. SwRI compiled total flight system costs including spacecraft management, systems engineering, I&T, and operations based on recent mission experience from CuSP and other small spacecraft. The UA PI provided an estimate of instrument development and I&T costs based on experience with highly similar instruments for balloon missions (STO-2 currently in flight and GUSTO currently in Phase A), ground-based instruments, and the SWAS mission. All instrument subcontract costs are based on formal signed proposals provided by the contractors. The UA PM provided estimates for the remaining mission elements based on prior mission experience and analogy to recent UA mission and instrument developments that equal or exceed SLS in complexity. The PM, PI, and MSE have reviewed and validated the cost estimates and they have been subjected to independent review to add confidence.

H.2.2 Work Breakdown Structure

The PM established a standard WBS to guide scheduling and costing. All team members used this common WBS, delivery schedule, and technical specifications in preparing their estimates. Table B3 provides rolled up cost by WBS element. Detailed descriptions each WBS element are shown in section H.3.

H.2.3 Minimization of Cost Risk

The BUE was generated using the most recent available cost data as well as relevant analogies and represents the most accurate possible estimate for a mission of this type at this stage of development. Since SLS requires no new technology and virtually all spacecraft and instrument components are directly derived from missions that have either flown or are under development, all major cost drivers are well understood. Any uncertainty is due primarily to the typical space mission cost risks related to integration and testing. Reserves have been strategically allocated to the areas where the greatest potential for cost growth exists, and the development reserves (Phase A-D) of 29% are more than adequate for a mission with such high hardware flight heritage and direct team experience. Furthermore, all estimators were instructed to be conservative in their inputs to ensure cost credibility, and it is expected that the SLS cost estimate will decrease when it is analyzed further in Phase A.

H.3 WBS Estimates

H.3.1 WBS 100 Program Management

The management cost is based on prior UA missions of similar scale and class, principally GUSTO which is in Phase A, and the BOPPS balloon flight with adjustments made for a Class D mission. The cost includes the Project Manager, financial manager, scheduler, and administrator, all of whom are part time. This encompasses all efforts necessary to perform day-to-day project management with insight into the activities at UA, SwRI, and lower-tier subcontractors; monitor and control project finances and schedules; conduct project level reviews including regular reporting to NASA; and work closely with the PI on all key project issues and decisions.

H.3.2 WBS 200 Systems Engineering

The systems engineering estimate was developed by the MSE and PM based on their experience, activities, and workload for prior missions, modified as appropriate for Class D and the unique SLS technical requirements. The staffing estimate covers systems engineering work performed by the MSE, including requirements development and management, V&V planning and activities, Systems Engineering Team leadership, trade study management, project-level review support, action item management, payload oversight, and I&T oversight. It includes all required administrative support and travel. It does not include the Payload Systems Engineer or Spacecraft Systems Engineer activities that are carried under the appropriate WBS elements.

H.3.3 WBS 300 Safety and Mission Assurance

The SMA cost estimate is based on prior UA experience (BOPPS GUSTO, STO), as well as CuSP and other SwRI missions and the MSE's experience with planetary and Cubesat missions. The estimate is responsive to the Class D requirements of 320-MAR-1001E and consistent with the SLS development schedule. Recent NASA communications have clarified SMA expectations (e.g. letter entitled "Guidance and Expectations for Small Category 3 Space Flight Projects") and these have been incorporated into the SMA plan and budget. This includes developing and implementing the Performance Assurance Implementation Plan (PAIP) as well as the Systems Engineering Management Plan (SEMP); performing inspections and assessments to ensure quality of hardware and software and conformance to technical requirements; providing safety data to support Range Safety; providing SMA oversight of spacecraft development and supporting system level I&T at SwRI; and supporting final delivery of the spacecraft for integration with the CSD Cubesat deployment module. Common SMA-related efforts covered in other WBS elements include purchasing, screening, and qualifying parts or materials (covered in WBS 500 and 600), performing reliability analyses (covered in WBS 200), and QA insight at subcontractor facilities to ensure compliance with requirements.

H.3.4 WBS 400 Science

Science costs were developed by identifying the time-phased science tasks associated with pre-launch planning, data processing, and post-launch data analysis. Each task is associated with specific products coupled to a need date and a statement of work developed by PI Walker in consultation with the SLS science team. All costs are based on inputs from the Co-I home institutions reflecting the statement of work and actual salaries and travel costs. These were compared with analogous tasks from past missions and validated by UA prior to review and institutional approval.

H.3.5 WBS 500 Instrument

All instrument costs were developed through a BUE validated by analogy to relevant flight instruments (SWAS, STO/STO-2, GUSTO) and consistent with SLS project-level requirements for cost and schedule management and reporting, systems engineering, and safety and mission assurance. Two full flight instruments are included in the cost estimate along with spares of selected components. The Deputy PI will oversee instrument development, working closely with the PI and payload systems engineer. Contract management support is provided under WBS 100. Instrument systems engineering costs include labor and travel for requirements development, validation, and flow down to subsystems and components, generation of instrument test plans and procedures, and oversight of vendor-supplied components. Safety and mission assurance costs include creation of an instrument MAIP compliant with the project-level PAIP, flow down and monitoring compliance to all subcontractors. UA runs a tailored parts program compatible with Class D (and above) missions.

Component and subsystem development, fabrication, and test costs are based on a specification and statement of work for suppliers and a quote from the subcontractor. Costs for instrument integration at UA are based on analogous instrument integration for STO/STO-2 and GUSTO combined with signed-off costs from suppliers who will support integration.

H.3.6 WBS 600 Spacecraft

SwRI estimated the spacecraft development cost based on their experience with the CuSP Cubesat, many prior small spacecraft developments, and known costs for COTS Cubesat subsystems and elements. Two SLS flight units are costed along with spares for selected sensitive or non-COTS elements to ensure no loss of schedule in case of issues that may arise during I&T. The budget includes labor for spacecraft management and systems engineering, subsystem procurement, development, and test, spacecraft assembly, quality assurance, and all related facility and administrative support.

H.3.7 WBS 700 Mission Operations

Mission operations costs assume two spacecraft operating independently for the two-year baseline mission. SLS operations are highly autonomous with all spacecraft scans, data management, and downlink opportunities pre-loaded prior to launch and updated as needed during flight. Instrument operations are governed by the Autonomous Scheduler software and generally require no commanding, except for parameter updates which may be provided based on quick-look science results after each daily calibration sequence. Mission operations during commissioning (first month of operations) will include more regular calibration scans of the Moon, planets, and other bright sources to verify instrument performance. Mission operations staffing assumptions are based the following profile:

- First week after launch: 2 engineers on-console 24/7
- Remainder of month #1: 2 engineers single shift
- Remainder of year #1: 1.5 engineers single shift
- Year #2: 1 engineer single shift

This is in addition to the ongoing support from the project manager, mission manager, MSE, and subsystem experts who will be engaged as needed to interpret telemetry and diagnose any issues.

SLS will utilize the Mission Operations Center at SwRI-Boulder that will be used for the CuSP mission and has been used for multiple prior missions. No significant modifications are planned for SLS. The SOC at UA will be based on that used for HiRISE and other planetary instruments and will require only minimal modification, to be scoped during Phase A.

This element includes tracking costs for Near-Earth Network stations based on the formula provided in the Explorer Program Library. One pass per day per spacecraft is assumed for the baseline mission. This is conservative since the spacecraft can store multiple days of data onboard. The tracking and downlink schedule may be further optimized during Phase A to save cost without risk of data loss.

H.3.8 WBS 800 Launch Vehicle

No costs are included for this element. The launch and all preparations are assumed to be GFE from NASA.

H.3.9 WBS 900 Ground Systems

SLS requires no mission-unique ground systems. A small cost is included for customization of the SwRI MOC, principally for purchase of several COTS computers.

H.3.10 WBS 1000 I&T

Flight system I&T cost is based CuSP and other small SwRI spacecraft. It includes two identical flight systems and instruments that are integrated in parallel resulting in efficiencies of staffing and equipment. SwRI facilities are ample for this dual spacecraft approach and no facility modifications are required. All test fixtures are heritage from prior programs with only minor upgrades for the unique SLS requirements. Flight spares of key spacecraft and instrument components will be procured in advance, ensuring that there is minimal interruption to the I&T flow due to test anomalies. There is substantial schedule reserve allocated to the I&T period, and as noted earlier the planned spacecraft delivery date is a full 6 months prior to the baseline launch. The UA instrument leads will support flight system I&T on-site at SwRI.

H.4 Project Planning & Control

After contract award, cost, schedule, and technical performance will be tracked using UA's management information systems and processes. Technical and administrative reports provide the program team with critical data on activity status, costs to complete remaining activities, and key schedule metrics so that all activities can be coordinated effectively to meet all SLS milestones and performance specifications.

As the implementing organization, UA is responsible for developing the integrated baseline plan (IBP), integrated master schedule (IMS), integrated EVMS if required, and reporting tools and processes. Each month the PM will generate a number of predictive tables and plots that will be summarized and submitted to NASA, including:

- Concise schedule update of major milestones, deliverables, and activities on the critical path, as well as their status
- Monthly and cumulative planned versus actual internal milestone completion
- Detailed funded schedule reserve blocks and their status
- Total project available funded schedule reserve vs. time
- Technical parameters, target values, and current margins
- Action items and their status

H.4.1 Schedule Management and Control

Detailed scheduling for SLS involves identifying discrete tasks and activities required to accomplish lower-level objectives and logically sequencing these activities. The development of a detailed activity-based, logic-driven, critical-path schedule ensures that the work can be reasonably performed within a specified period of time given a fixed number of assigned resources. SLS's IMS includes inputs from partner institutions and reflects the focus on high-priority activities and risk reduction required of any cost-constrained mission.

A baseline Microsoft Project schedule has been developed and is provided in section F. This schedule supports the mission milestones outlined in the AO and PIP. The PM is responsible for managing the IMS and has the support of a project scheduler at SwRI. The IMS is monitored weekly and updated and reviewed monthly so that problems can be identified and corrective action can be taken quickly when needed.

H.4.2 Cost Management & Control

SLS will implement a disciplined cost management approach by preparing and adhering to a detailed plan covering cost planning and risk identification, analysis, mitigation, and tracking. The EVMS process begins building a baseline for Phase C in late Phase B incorporating information from SwRI. Using monthly EVMS metrics, potential problems are flagged immediately, providing the PM with the opportunity to quickly implement corrective actions to mitigate schedule or cost variances. Monthly and cumulative performance and actual costs are tracked for each subsystem. Project estimate-at-completion (EAC) projections are prepared monthly. In addition to EVMS reporting, project financial reports are generated. Cost data are reported by element and submitted in NASA 533 format within days of the release of SLS fiscal data using financial/project data supplied by each subcontractor.

H.5 Cost Uncertainty and Estimated Reserve Requirements

The SLS cost estimate was generated by an experienced program team and has undergone rigorous review to minimize cost risk. Reserve levels were estimated as a function of complexity, uncertainty, and risk for each WBS element. To ensure a reliable reserve profile, the scope of each WBS element was reviewed by the PM and key project staff and institutional managers, and reserves have been matched against the areas with the highest potential cost risk. All cost reserves are held by the project and managed by the PM. They will be continually assessed in order to maintain the required minimum 25% reserves on cost to-go through the Key Decision Points in Phases B/C/D. If at any time the PM determines that the cost reserve is at risk of dropping below 25%, the SLS leadership will confer and recommend a plan of action. The response may include restructuring of tasks and procurements, adjusting workforce in coordination with the SLS partner organizations, or mission descopes in consultation with NASA. The SLS PI and PM will concur with the release of any project reserves. In order to maintain healthy cost reserves, SLS proposes that any unused portion of funds from both the cost and reserve pool of the previous phase be shifted to the succeeding phase.

Table H-2 shows the current reserve allocation by WBS. As the critical path schedule element and the most unique aspect of SLS, the Payload is allocated substantial reserves to account for possible anomalies encountered during test and calibration. Flight System I&T also carries larger reserves to account for the dual-spacecraft approach and to ensure that spares can be swapped in as needed without major impact to integration flow. Other WBS elements carry standard reserves based on heritage and prior project experience.

WBS	A/B/C/D	E	AB/C/D/E	A/B/C/D/F
01 Project Management	15%	0%	14%	14%
02 Systems Engineering	12%	N/A	12%	12%
03 Safety & Mission Assurance	9%	N/A	9%	9%
04 Science / Technology	9%	N/A	9%	9%
05 Payload	54%	N/A	54%	54%
06 Spacecraft	15%	N/A	15%	15%
07 Mission Operations	8%	17%	16%	16%
08 Launch Vehicle / Services	N/A	N/A	5%	5%
09 Ground System(s)	12%	N/A	12%	12%
10 Systems Integration & Testing	42%	N/A	42%	42%
Overall	**29.3%**	**13.9%**	**25.8%**	**25.5%**

Table H-2 SLS reserve allocations

Total Mission Cost Profile Template
FY Costs and Totals in Fiscal Year 2017 Dollars (FY2017$)

WBS#	WBS Element	Phase A			Phase B			Phase C/D				Phase E				Phase F			FY2017$
		FY2017	FY2018	Total	FY2019	FY2020	Total	FY2020	FY2021	FY2022	Total	FY2022	FY2023	FY2024	Total	FY2024	FY2025	Total	Total
01	Project Management	$44K	$87K	$131K	$239K	$35K	$275K	$375K	$402K	$192K	$970K	$23K	$27K	$8K	$58K				$1,433K
02	Systems Engineering	$44K	$87K	$131K	$74K	$36K	$111K	$141K	$86K	$51K	$279K								$520K
03	Safety & Mission Assurance				$35K	$4K	$40K	$97K	$106K	$63K	$267K								$307K
04	Science / Technology				$228K	$15K	$243K	$274K	$282K	$115K	$670K	$280K	$496K	$204K	$980K	$134K	$116K	$250K	$2,143K
	PI Science Activities				$79K		$79K	$79K	$79K		$158K	$137K	$162K	$6K	$306K	$79K	$6K	$85K	$628K
	Pre-launch Science				$149K	$15K	$163K	$195K	$202K	$115K	$512K								$675K
	Post-launch Science											$143K	$334K	$197K	$674K	$55K	$110K	$165K	$840K
	Technology Development																		
05	Payload				$515K	$70K	$584K	$2,392K	$1,226K	$50K	$3,667K								$4,252K
	Program Management				$26K	$3K	$29K	$120K	$61K	$3K	$183K								$213K
	Systems Engineering				$51K	$7K	$58K	$239K	$123K	$5K	$367K								$425K
	Instrument Safety and Mission Assurance				$36K	$5K	$41K	$167K	$86K	$4K	$257K								$298K
	Instrument				$154K	$21K	$175K	$717K	$368K	$15K	$1,100K								$1,276K
	Electronics and Harnessing				$41K	$6K	$47K	$191K	$98K	$4K	$293K								$340K
	Thermal Subsystem				$51K	$7K	$58K	$239K	$123K	$5K	$367K								$425K
	FSW				$103K	$14K	$117K	$478K	$245K	$10K	$733K								$850K
	I&T				$51K	$7K	$58K	$239K	$123K	$5K	$367K								$425K
06	Spacecraft	$145K	$35K	$180K	$345K	$190K	$535K	$1,940K	$456K	$1,444K	$3,839K								$4,554K
	Program Management	$75K	$18K	$93K	$53K	$34K	$87K	$44K	$67K	$44K	$154K								$335K
	Systems Engineering	$69K	$17K	$86K	$62K	$31K	$93K	$31K	$54K	$31K	$116K								$295K
	Safety and Mission Assurance				$17K	$4K	$21K	$15K	$31K	$15K	$62K								$83K
	Spacecraft Structure				$29K	$13K	$43K	$26K	$39K	$26K	$90K								$133K
	IAU							$26K	$39K	$26K	$90K								$90K
	EPS, Battery, Solar Arrays				$19K	$13K	$32K	$257K	$11K	$7K	$276K								$308K
	harnessing				$19K	$13K	$32K	$26K	$39K	$26K	$90K								$122K
	Communications				$19K	$13K	$32K	$273K	$11K	$7K	$291K								$323K
	ACS				$27K	$13K	$40K	$289K	$11K	$7K	$307K								$347K
	FSW				$29K	$13K	$43K	$477K	$39K	$98K	$614K								$656K
	Thermal Subsystem				$27K	$13K	$40K	$95K	$39K	$26K	$160K								$200K
	Propulsion				$27K	$13K	$40K	$345K	$11K	$7K	$364K								$404K
	I&T				$19K	$13K	$32K	$35K	$66K	$354K	$455K								$488K
	Integration with Canister									$49K	$49K								$49K
	EGSE									$723K	$723K								$723K
07	Mission Operations	$35K	$18K	$53K	$132K	$28K	$160K	$52K	$93K	$104K	$249K	$1,098K	$1,346K	$720K	$3,164K	$7K		$7K	$3,633K
	Mission Operations Management	$18K	$9K	$27K	$3K	$7K	$10K	$5K	$10K	$5K	$21K	$36K	$67K	$26K	$129K				$186K
	Mission Operations Systems Engineering	$18K	$9K	$27K	$17K	$13K	$30K	$5K	$21K	$10K	$36K	$36K	$67K	$26K	$129K				$222K
	Mission Operations				$8K		$8K	$21K	$31K	$21K	$72K	$488K	$507K	$195K	$1,190K				$1,270K
	Mission Planning Team				$8K		$8K					$17K	$14K	$10K	$42K				$49K
	Spacecraft Team				$11K	$1K	$12K					$30K	$60K	$18K	$107K				$119K
	Flight Software Sustaining				$12K		$12K					$24K	$32K	$11K	$66K				$78K
	Ground Software Sustaining				$12K		$12K			$66K	$66K	$30K	$56K	$30K	$116K				$195K
	Science Operations				$12K	$1K	$14K					$141K	$248K	$114K	$504K	$7K		$7K	$525K
	Navigation Team Operations				$12K	$1K	$14K					$19K	$19K	$19K	$58K				$72K
	Mission Design				$12K	$1K	$14K	$21K	$31K	$2K	$54K								$67K
	Orbit Determination				$12K	$1K	$14K					$18K	$18K	$14K	$49K				$63K
	Near Earth Network (NEN)				$12K	$1K	$14K					$258K	$258K	$258K	$773K				$786K
	Other Direct Technical Costs																		
08	Launch Vehicle / Services							$9K	$23K	$9K	$40K								$40K
	Spacecraft to LV Interface Definition and Verification							$9K	$23K	$9K	$40K								$40K
	Launch site field support																		
09	Ground System(s)	$4K	$1K	$5K						$9K	$9K								$14K
	stations	$4K	$1K	$5K						$9K	$9K								$14K
10	Systems Integration & Testing								$501K	$1,312K	$1,813K								$1,813K
11	Student Collaboration in Excess of Incentive																		
	Reserves				$302K	$48K	$350K	$1,825K	$1,012K	$993K	$3,830K	$193K	$244K	$149K	$586K				$4,766K
	PI-Managed Mission Cost	$271K	$229K	$500K	$1,871K	$427K	$2,298K	$7,105K	$4,186K	$4,343K	$15,633K	$1,593K	$2,113K	$1,081K	$4,787K	$141K	$116K	$257K	$23,475K
	Student Collaboration Incentive (not applicable)																		
	Contributions (none)																		
	Total Mission Cost																		$23,475K

Organization	Role	Total Cost (RY)
Major Partners		
University of Arizona Tucson, AZ	PI institution, project management Instrument development Science operations	$11,710K
Southwest Research Institute San Antonio, TX	Spacecraft development Flight system I&T Mission operations	$9,140K
Science-only, non hardware partners		
Arizona State University Tempe, AZ	Science team	$315K
University of Florida College Park, MD	Science team	$393K
University of Massachusettes Boston, MA	Science team	$320K
SAO Cambridge, MA	Science team	$320K
Minor partners, vendors, and suppliers		
Virginia Diodes Charlottesville, VA	Local oscillators	$330K
OmniSys Sweden	Spectrometer	$950K

SOUTHWEST RESEARCH INSTITUTE®

6220 CULEBRA ROAD 78238-5166 • P.O. DRAWER 28510 78228-0510 • SAN ANTONIO, TEXAS, USA • (210) 684-5111 • WWW.SWRI.ORG
SPACE SCIENCE AND ENGINEERING DIVISION

December 9, 2016

University of Arizona
Attn: Dr. Christopher Walker
633 N. Cherry Ave
Tucson, AZ 85721

Subject: **Letter of Commitment for the Spectral Line Surveyor (SLS) Mission**
SwRI Proposal 15-79442

Reference: **NN12ZDA0060-APEXMO3**

Dear Dr. Walker:

The Southwest Research Institute® (SwRI) is firmly committed to participating in the SLS mission that you have proposed in response to the NASA Second Stand Alone Missions of Opportunity Notice (SALMON-2), NNH12ZDA0060-APEXM03.

SwRI, as described in the proposal, will: 1) design and develop the Spacecraft, 2) integrate the Science Payload with the Spacecraft, 3) conduct a full systems environmental test; 4) package and ship the spacecraft for launch, 5) provide a Mission Operations Center, 6) provide support to mission and sequence design, and 7) lead mission operations once in flight.

Sincerely,

J. L. Burch

James L. Burch
Vice President
Space Science and Engineering Division

:ms

cc: Mike McLelland
Bill Perry
Jeff Kirchoff
Kim Barclay

Christopher K. Walker
Steward Observatory, University of Arizona, Tucson, AZ 85721

Education

B.S.: Electrical Engineering, Clemson University, 1980
Graduated with Honors
M.S.: Electrical Engineering, Ohio State University, 1981
Advisor: John D. Kraus
Thesis: "Upgrading the Ohio State Radio Observatory"
Ph.D.: Astronomy, University of Arizona, 1988
Advisor: Charles J. Lada
Thesis: "Observational Studies of Star Forming Regions"

Experience

- Professor of Astronomy; Associate Professor of Optical Sciences and Electrical & Computer Engineering, University of Arizona, 2003-
- Associate Professor of Astronomy, Optical Sciences, and Electrical Engineering, University of Arizona, 2002-2003
- Associate Professor of Astronomy & Optical Sciences, University of Arizona, 2000-2002
- Associate Professor, Steward Observatory, University of Arizona, 1997-2000
- Assistant Professor, Steward Observatory, University of Arizona, 1991-1997
- Millikan Research Fellow in Physics, Caltech, 1988-1991
- Graduate Research Assistant, Steward Observatory, 1983-1988
- Research and Development Engineer, Jet Propulsion Laboratory, 1983
- Electrical Engineer, TRW Aerospace Division, 1981-1983

Synergistic Activities

1) Prof. Walker has written the first textbook on "TeraHertz Astronomy", released in 2015 by Francis Taylor Publishing Group.
2) Prof. Walker was recently selected to be a NASA Innovative Advanced Concept (NIAC) Fellow based upon his research into the concept for a suborbital, 10 meter Large Balloon Reflector (LBR). LBR can be used for astronomy, remote sensing, and a host of telecommunications activities.
3) Instruments developed by Prof. Walker's team have served as primary facility instruments at the Heinrich Hertz Telescope and the AST/RO telescope at the South Pole for over a decade.
4) Funded by the NSF, Prof. Walker has led the effort to design and build the world's largest (64 pixels) submillimeter-wave heterodyne array receiver (SuperCam).
5) Prof. Walker's lab the led efforts to construct the world's first 810 and 345 GHz heterodyne array receivers and helped developed one of the first 1.5 THz HEB receiver systems for radio astronomy.
6) He is PI of the NASA funded long duration balloon project ``The Stratospheric THz Observatory (STO)''.

7) Prof. Walker has served as dissertation director for eleven Ph.D. students (7-Astronomy, 2-Optical Sciences, 1-Electrical Engineering).

Sample Publications (130+ authored/co-authored papers in literature)

Walker, C. K., 2015, **TeraHertz Astronomy**, CRC Press, Taylor & Francis Group, Boca Raton, FL.

Kloosterman, J. L., Hayton, D. J., Ren, Y., Kao, T. Y., Hovenier, J. N., Gao, J. R., Klapwijk, T. M., Hu, Q., Walker, C. K., and Reno, J. L., 2013, "Hot Electron Bolometer Heterodyne Receiver with a 4.7 THz Quantum Cascade Laser as a Local Oscillator", Appl. Phys. Lett., 102, 011123.

Walker, C., 2012, *STO, GUSSTO (EXPLORER): Recent Activities and Results,* 39th COSPAR Scientific Assembly, 14-22 July 2012, in Mysore, India, p. 2114

Walker, C., Kulesa, C. & GUSSTO Team, 2012*, GUSSTO (EXPLORER): Phase A Study Report*, delivered to NASA, 23 September 2012.

C. Walker, C. Kulesa, J. Kloosterman, T. Cottam, C. Groppi, P. Bernasconi, H. Eaton, N. Rolander, B. Carkhuff, S. Hechtman, J. Gottlieb, D. Neufeld, C. Lisse, A. Stark, D. Hollenbach, J. Kawamura, P. Goldsmith, W. Langer, H. Yorke, J. Sterne, A. Skalare, I. Mehdi, S. Weinreb, J. Kooi, J. Stutzski, U. Graf, C. Honingh, P. Puetz, C. Martin, D. Lesser, and M. Wolfire, 2011, *The Stratospheric THz Observatory (STO): Preparations for Science Flight*, Proceedings of 22nd International Symposium on Space Terahertz Technology, Tucson, 26-28 April 2011.

Craig Kulesa, Christopher Walker, Abram Young, John Storey, Michael Ashley, 2011, *HEAT: The High Elevation Antarctic Terahertz Telescope*, Proceedings of 22nd International Symposium on Space Terahertz Technology, Tucson, 26-28 April 2011.

Bussmann, R. S., Wong, T. W., Hedden, A., Kulesa, C., and Walker, C. K., 2007, *A CO (J=3-2) Outflow Survey of the Elias 29 Region, Ap.J.,* 657, Issue 1, pp. L33-L36.

Hedden, A. S., Walker, C. K., Groppi, C. E., and Butner, H. A., 2006, *Star Formation in the Northern Cloud Complex of NGC 2264*, *Ap.J.*, **645**, p.345.

Kulesa, C., Hungerford, a., Walker, C., Zhang, X., and Lane, A., 2005, *Large-Scale CO and [CI] Emission in the Rho Ohiuchi Molecular Cloud, Ap. J.,* **625**, 194.

M.S.E.E. Graduate Advisor: John D. Kraus, OSU
Ph.D. Advisor: Charles J. Lada, SAO
Postdoctoral Advisor (Millikan Fellowship in Physics): Thomas G. Phillips, CIT

Past Ph.D. Advisees: Grace Wolf (Hansen Planetarium), Jason Glenn (UC Boulder), Gopal Narayanan (U. Mass), Craig Kulesa (UofA), Christian d'Aubigny (UofA), Christopher Groppi (ASU), Desika Narayanan (CfA), Abigail Hedden (ARL), Dathon Golish (UofA), Jenna Kloosterman (JPL)

S.H. (Hop) Bailey

Lunar and Planetary Lab, University of Arizona, Tucson, Arizona 85721
hbailey@email.arizona.edu

Program manager, Lunar and Planetary Lab, August 2010 - present

Program manager for the Large Binocular Telescope Interferometer (LBTI); the premier instrument on the Large Binocular Telescope searching for zodiacal scattered light from asteroid belts around exoworlds.

Program manager for the PolyCam imager for OSIRIS-REx, a 9" Ritchey-Christien reflector. This mission-critical system images the target asteroid at a distance of 25M KM for navigation purposes and is then responsible for high-resolution imaging of the surface regolith to assist in sampling site selection. OSIRIS-REx delivers flight hardware to integration in 2015.

Program manager for the Test Flat System, a $15M off-axis 2.7M clean room certified test reference system under a commercial contract.

Program manager for the 60cm Stressed Lap polishing tool for the Giant Magellan Telescope project.

Program manager for the High-resolution Stereo Color Imager (HiSCI) instrument, a $25M imager for Mars remote sensing planned to be part of the payload for the ESA Trace Gas Orbiter mission.

Program manager, Steward Observatory, May 2002 - August 2010

Program manager for the Large Optical Test and Integration System (LOTIS) Collimator, a $62M Lockheed Martin-funded 6.5m collimator deployed in a vacuum chamber. Delivery, reassembly, and optical performance tests are complete. Managed all aspects of the project from inception including systems engineering, procurements, assembly and test.

Program manager, Arete Associates, Airborne Laser Mine Detection System, September 2000 - April 2002.

Program manager and chief engineer for the sensor system of the Airborne Laser Mine Detection System, a U.S. Navy engineering model development program valued at $13.5M.

Program manager and principal data analyst for space flight projects, Lunar and Planetary Laboratory, University of Arizona, 1990 - September 2000.

Project manager, chief engineer, and principal data analyst for the Mars Odyssey Gamma-ray Spectrometer, 1996 - 2000. Responsible for the overall management of a $14.5M GRS instrument flying on the Mars Odyssey spacecraft.

Project manager, chief engineer, and data analyst of the Thermal and Evolved Gas Analyzer, a $4.4M key instrument on the Mars Polar Lander, 1995 - 1999. Successfully delivered fully-qualified, on-cost, on-schedule, space flight instrument.

Staff Scientist, Near-Earth Asteroid Rendezvous Gamma-ray and X-ray Spectrometer, 1992 - 2000.

Staff Scientist, instrument integrator, and mission operations specialist, and principal data analyst for the Mars Observer Gamma- ray Spectrometer, 1990 - 1992.

Project scientist, Naval Research Arctic Expedition, 1987 - 1989.

Responsible for the organization and execution of in-situ and laboratory ice experiments 500 miles from the North Pole including all procurements, sensor selection, data reduction, sensor employment and experiment conduct.

Project engineer, Applied Physics Laboratory, University of Washington, 1980 - 1987.

Responsible for technical management of a navy project for autonomous, underwater torpedo targets deployed from active U.S. Navy vessels including development of new technologies, manufacturing, sample testing, and fleet monitoring.

Graduate research assistant & associate, Physics Department, University of Washington, 1977-1980.

Member of Hans Dehmelt's research group working to trap single electrons, positrons, and protons in Penning Traps. Received a MS in Physics. Dehmelt won the Nobel Prize for Physics for this and other work.

Officer, U.S. Army, 1969 - 1974.

Education

M.S. Physics, University of Washington, Seattle, Washington, 1980.

B.S., Engineering, United States Military Academy, West Point, New York, 1969.

MICHAEL EPPERLY

Senior Program Manager
Space Systems Directorate
Space Science and Engineering Division

M.S., Technical Management/Systems Engineering, *with Honors*, Johns Hopkins University, 1995
M.S., Electrical Engineering, *with Honors*, Johns Hopkins University, 1991
M.S., Computer Science, Johns Hopkins University, 1989
B.S.E.E., Digital Systems and Biomedical Engineering concentrations, University of Texas at Austin, 1983

Mr. Epperly is an electrical systems engineer with over 30 years of experience in the specification, design, and production of satellite systems. He has a broad knowledge base, working with high proficiency on projects ranging from flight hardware and biomedical instrumentation to mass spectrometers and very high-speed optical data links. Mr. Epperly is currently the Program Manager of the CubeSat to measure Solar Particles (CuSP) mission and the Deputy Program Manager (DPM) for the Dream Chaser Flight Computer (DCFC). Some recent projects that Mr. Epperly has been responsible for are the Magnetospheric Mulitscale System's Central Instrument Data Processor (MMS-CIDP) and a 25Gbps DoD Satellite Image Rate Buffer. Mr. Epperly was the systems engineer for the Mars Science Laboratory's Radiation Assessment Detector (MSL-RAD).

As the program manager for the CuSP mission, Mr. Epperly is responsible for the overall mission design, performance, budget and schedule and coordinating a science team from JPL, GSFC and SwRI. CuSP is a 6U CubeSat with three instruments and miniaturized subsystems that perform all of the basic functions typical of a much larger satellite. CuSP is set to launch in April of 2018. As DPM of DCFC, Mr. Epperly supports the overall management, design and production teams to produce over forty flight computer assemblies for the Dream Chaser Crew Resupply Service 2 mission. For MMS CIDP, Mr. Epperly was responsible for all aspects of the unit's specification, development, test and delivery including budget and staffing. The CIDP is a cPCI-based avionics chassis that provides the interface between the spacecraft and 21 different sensor elements. Four redundant CIDP flight units were delivered and MMS successfully launched in 2014.

As the systems engineer for the MSL-RAD program, Mr. Epperly was responsible for the conceptual design, requirements tracking and also development of an Application Specific Mixed-Mode Integrate Circuit (ASMMIC) that handled all of the analog signal processing required by the 30 separate channels within the RAD instrument. RAD was given and subsequently met a challenging budget of only 4 Watts and 1 kg. RAD was successfully launched and was the only instrument to take scientific data during the cruise phase to Mars. The instrument is currently collecting data as the MSL traverses the Mars landscape.

Prior to arriving at SwRI, Mr. Epperly served as lead digital designer for the Operational Linescan System (OLS), the primary sensor in the Defense Meteorological Satellite Program (DMSP) at Westinghouse Electric Space Division, now Northrop Grumman Advanced Sensors Division.

PATENTS & PUBLICATIONS: Ten Patent Disclosure Awards. Over 20 published papers on spacecraft data systems.

HONORS & AWARDS: 1993-WEC/JHU MS Systems Engineering Scholarship; 1989 & 1991-George Westinghouse Signature Awards for Innovative Design; Ten Patent Disclosure Awards.

PROFESSIONAL CHRONOLOGY: Westinghouse Electric Corporation: lead digital designer, 1983-96; SwRI: senior research engineer, 1996-2000; program manager, 2000-2014; sr. program manager, 2014-present.

MEMBERSHIPS: IEEE; Board of Directors, Alamo Region Academy of Science and Engineering; Board of Directors, John Jay Science Academy; Associate, Consultative Committee for Space Data Systems (CCSDS), 2001-present.

December 2016

CURRICULUM VITAE

Christopher Emil Groppi

School of Earth and Space Exploration, Arizona State University
PO Box 871404, Tempe, AZ 85287-1404
Tel: 480-965-6436, Fax: 480-965-8102
Email: cgroppi@asu.edu http://thz.asu.edu/cgroppi/

Professional Preparation:

B.A. with Honor in Astronomy, Cornell University, 1997
Ph.D. in Astronomy with minor in Electrical and Computer Engineering, University of Arizona, 2003
Director's Postdoctoral Research Associate, National Radio Astronomy Observatory, 2003-2005
National Science Foundation Astronomy and Astrophysics Postdoctoral Fellow: 2006-2009

Appointments:

Associate Professor, Arizona State University School of Earth and Space Exploration: 2015-present
Assistant Professor, Arizona State University School of Earth and Space Exploration: 2009-2015
Assistant Staff Astronomer, Steward Observatory, 2004-2009

Selected Publications:

Groppi, C.E., Kawamura, J.H., Coherent Detector Arrays for Terahertz Astrophysics Applications, IEEE Trans. on Terahertz Science and Technology, v. 1, no. 1, pp. 85-96, 2011.

Groppi, C.E., Walker, C., Kulesa, C., Golish, D., Kloosterman, J., Weinreb, S., Jones, G., Barden, J., Mani, H., Kuiper, T., Kooi, J., Lichtenberger, A., Cecil, T., Puetz, P., Narayanan, G., Hedden, H., *Testing and Integration of Supercam, a 64-Pixel Array Receive for the 350 GHz Atmospheric Window*, Millimeter and Submillimeter Detectors and Instrumentation for Astronomy V, Edited by Duncan, William, Holland, Wayne, Withingtonm Stafford, Zmuidzinas, Jonas, Proc. SPIE 7741, 774110X, pp. 1-11, 2010.

Walker, C.,Kulesa, C., Bernasconi, P., Eaton, H., Rolander, N., **Groppi, C.**, Kloosterman, J., Cottam, T., Lesser, D., Martin, C., Stark, A., Neufeld, D., Lisse, C., Hollenbach, D., Kawamura, J., Goldsmith, P., Langer, W., Yorke, H., Stern, J., Skalare, A., Mehdi, I., Weinreb, S., Kooi, J., Stutzki, J., Graf, U., Brasse, M., Honingh, C., Simon, R., Akyilmaz, M., Puetz, P., Wolfire, M., *The Stratospheric Terahertz Observatory (STO),* Ground-based and Airborne Telescopes III, Edited by Larry M. Stepp; Roberto Gilmozzi; Helen J. Hall, Proc. SPIE 7733, 773330N, pp. 1-9, 2010.

Narayanan, D., Walker, C., **Groppi, C.** *Warm-Dense Molecular Gas in the ISM of Starbursts, LIRGs and ULIRGs* Ap.J., v. 630, pp. 269-279, 2005.

Groppi, C.E., Walker, C.K., Kulesa, C., Golish, D., Hedden, A., Narayanan, G., Lichtenberger, A.W., Kooi, J.W., Graf, U.U., Heyminck, S. *First results from DesertSTAR: a 7-pixel 345-GHz heterodyne array receiver for the Heinrich Hertz Telescope*, Proc. SPIE, v. 5498, pp. 290-299, 2004.

Synergistic Activities:

- Involvement in all facets of the design, construction, test and integration of five heterodyne array receivers (PoleSTAR, DesertSTAR, SuperCam, Stratospheric Terahertz Observatory, Kilopixel Array Pathfinder Project).
- Development of CNC micromachining techniques for THz circuit fabrication.
- Study of molecular gas content and star formation in nearby galaxies.
- Galactic star formation research using mm-wave and sub-mm wave telescopes, concentrating on the interaction of protostellar sources with the surrounding ISM, and the dynamics of protostellar accretion disks.

Craig A. Kulesa

Steward Observatory
University of Arizona
Tucson, AZ 85721

Telephone: (520) 621-6540
FAX: (520) 621-1532
Email: ckulesa@email.arizona.edu

Professional Preparation

Ph.D., Astronomy	December 2002	The University of Arizona
B.S., Physics	June 1993	Miami University (Ohio)

Appointments

2012-	Associate Astronomer (Univ. of Arizona)
2006-	Assistant Astronomer (Univ. of Arizona)
2003-2006	Assistant Staff Scientist (Univ. of Arizona)
1994-2002	Teaching/Research Assistant (Univ. of Arizona)

Selected Papers

1. "Large Scale CO and [CI] Emission in the Rho Ophiuchi Molecular Cloud", Kulesa, C.A., Hungerford, A.L., Walker, C.K., Zhang X., & Lane, A., 2005, ApJ, 625, 194.
2. "Warm, Dense Molecular Gas in the ISM of Starbursts, LIRGs, and ULIRGs", Narayanan, D., Groppi, C. E., Kulesa, C. A., & Walker, C. K. 2005, ApJ, 630, 269.
3. "The Mopra Southern Galactic Plane CO Survey - Data Release 1", Braiding, C., Burton, M. G., Blackwell, R., Kulesa, C., et al. 2015, PASA, 32, e020.
4. "Extended Carbon Line Emission in the Galaxy: Searching for Dark Molecular Gas along the G328 Sightline", Burton, M. G., Ashley, M. C. B., Braiding, C., Kulesa, C., et al. 2015, ApJ, 811, 13.
5. "The Carbon Inventory in a Quiescent, Filamentary Molecular Cloud in G328", M.G. Burton, M.C.B. Ashley, C. Braiding, J.W.V. Storey, C. Kulesa, D. Hollenbach, M. Wolfire, C. Glueck, G. Rowell, 2014, 782, 72.

Experience Relevant to this Proposal:

1. PI of *HEAT*, an automated 0.6-meter terahertz telescope with 0.5-2 THz heterodyne receivers deployed in January 2012 to Ridge A, Antarctica, the best ground-based site for far-IR astronomy.
2. Deputy-PI of the *Stratospheric Terahertz Observatory* (STO), a balloon borne experiment to explore the life cycle of the ISM, scheduled to fly in December 2016.
3. Deputy-PI of *Supercam*, a 64-beam, 345 GHz heterodyne receiver deployed at the 10-meter HHT telescope in Arizona and the 12-meter APEX telescope in Chile. Responsibilities focus on the I&T of IF processor and spectrometer, system level testing, telescope integration, data system.
4. With PI-Mccarthy, implemented *ARIES*, the Arizona Infrared Imager and Echelle Spectrometer, for the adaptive optics secondary at the 6.5-meter MMT. Aside from NIRSPEC at Keck, ARIES is the only cross-dispersed NIR echelle spectrometer in the northern hemisphere.

Daniel P. Marrone
Biographical Sketch

Contact Information:	Department of Astronomy University of Arizona 933 N. Cherry Avenue Tucson, AZ 85721	Phone: (520) 621-5175 dmarrone@email.arizona.edu

Chronology of Education:

B.A.,	Physics, *summa cum laude*	University of Minnesota	2001
B.A.,	Astrophysics, *summa cum laude*	University of Minnesota	2001
M.A.,	Astronomy	Harvard University	2003
Ph.D.,	Astronomy	Harvard University	2006

Chronology of Employment:

Assistant Professor	University of Arizona, *Dept. of Astronomy*	2011-Present
Hubble Fellow	University of Chicago, KICP	2009-2010
Jansky Postdoctoral Fellow	NRAO, University of Chicago, KICP	2006-2009

Professional Experience

Marrone uses astronomical observations at nearly all wavelengths, as well as instrumentation he constructs for radio/submillimeter wavelengths, to explore problems in extragalactic astronomy. Most relevant to this proposal is his work to measure the growth of molecular gas across cosmic history through the technique of intensity mapping in the COPSS survey. This work has provided the first constraints on the power spectrum of CO emission at z~3. He has built submillimeter instrumentation for several telescopes, most recently providing a complete 230 GHz VLBI receiver system to the South Pole Telescope. He has served as a panelist for two rounds of NASA APRA and SAT proposal review. He has mentored four PhD students and three postdoctoral researchers during his five years at the University of Arizona.

Bibliography of Recent, Relevant Publications *(135 total refereed publications, h-index 44)*

1. "A survey of the cold molecular gas in gravitationally lensed star-forming galaxies at $z > 2$," M. Aravena, J. S. Spilker, et. al., 2016, Monthly Notices of the Royal Astronomical Society, 457, 4016.
2. "COPSS II: The Molecular Gas Content of Ten Million Cubic Megaparsecs at Redshift z~3," G. K. Keating, D. P. Marrone, G. C. Bower, E. M. Leitch, J. E. Carlstrom, D. DeBoer, 2016, The Astrophysical Journal, 830, 34
3. "Detection of lensing substructure using ALMA observations of the dusty galaxy SDP.81," Y. D. Hezaveh, N. Dalal, D. P. Marrone, et al., 2016, The Astrophysical Journal, 823, 37.
4. "First Results from COPSS: The CO Power Spectrum Survey," G. K. Keating, G. C. Bower, D. P. Marrone, et al., 2015, The Astrophysical Journal, 814, 140
5. "The Rest-Frame Submillimeter Spectrum of High-Redshift, Dusty, Star-Forming Galaxies," J. S. Spilker, D. P. Marrone, et al., 2014, The Astrophysical Journal, 785, 149
6. "Dusty starburst galaxies in the early universe as revealed by gravitational lensing," J. D. Vieira, D. P. Marrone, et al., 2013, Nature, 495, 344
7. "ALMA Observations of SPT-Discovered, Strongly Lensed, Dusty, Star-Forming Galaxies," Y. Hezaveh, D. P. Marrone, et al., 2013, The Astrophysical Journal, 767, 132
8. "ALMA Redshifts of Millimeter-Selected Galaxies from the SPT Survey: The Redshift Distribution of Dusty Star-Forming Galaxies," A. Weiss, C. De Breuck, D. P. Marrone, et al., 2013, The Astrophysical Journal, 767, 88
9. "SPT 0538–50: Physical Conditions in the ISM of a strongly lensed dusty star-forming galaxy at z = 2.8," M. S. Bothwell, J. E. Aguirre, S. C. Chapman, D. P. Marrone, et al., 2013, The Astrophysical Journal, 779, 67

Desika Narayanan *Biographical Sketch*

Professional Preparation

University of Florida, Gainesville, FL, USA	Astronomy	B.S., Highest Honors	2003
University of Florida, Gainesville, FL, USA	Physics	B.S., High Honors	2003
University of Arizona, Tucson, AZ, USA	Astronomy	Ph.D	2008
Harvard-Smithsonian CfA, Cambridge, MA, USA	CfA Fellow		2008-2010
University of Arizona, Tucson, AZ, USA	Bart J. Bok Fellow		2010-2014

Appointments

University of Florida, Department of Astronomy		Gainesville, FL USA
Assistant Professor	January 2017-Present	
Haverford College, Departments of Physics and Astronomy		Haverford, PA, USA
Assistant Professor	January 2014-December 2016	
University of Arizona, Department of Astronomy		Tucson, AZ, USA
Bart J. Bok Fellow	October 2010-January 2014	
Harvard-Smithsonian Center for Astrophysics		Cambridge, MA, USA
CfA Postdoctoral Fellow	January 2008-October 2010	

Five Relevant Products

[1] Narayanan, D., Turk, M., Feldmann, R., Robitaille, T., Hopkins, P., Thompson, R., Hayward, C., Ball, D., Faucher-Giguere, C.-A., & Keres, D., 2015a, Nature , 525, 496, "Submilimetre Galaxies Formed in a Cosmological Hydrodynamic Simulation"

[2] Casey, C., Narayanan, D., & Cooray, A., 2014a, PhR., 541, 45, "Dusty star-forming galaxies at high redshift"

[3] Narayanan, D. & Krumholz, M., 2014, MNRAS, 442, 1411, "A Theory for the Excitation of CO in Star Forming Galaxies"

[4] Narayanan, D. & Hopkins, P., 2013a, MNRAS, 433, 1223, "Why is the Milky Way X-factor Constant?"

[5] Narayanan, D., Krumholz, M., Ostriker, E.C., & Hernquist, L., 2012a, MNRAS, 421,3127, "A General Model for the CO-H2 Conversion Factor in Galaxies with Applications to the Star Formation Law"

Synergistic Activities

Member of the Origins Space Telescope Science and Technology Definition Team

Lecturer, Chester County Family Academy (2015-2016)

Public Lecturer, Arizona Senior Academy (2009)

Public Lecturer, Cambridge Senior Center (Fall 2009-Fall 2010)

Conference Organizer, Aspen Senior School on Galaxy Evolution, Spring 2011

Curriculum Vitae

Dr. Gopal Narayanan
Department of Astronomy,
University of Massachusetts, Amherst, MA 01002.
Tel: (413) 545 0925 Fax: (413) 545 4223.
Email: gopal@astro.umass.edu

Prof. Narayanan works on the intersection of design and construction of high frequency radio receivers, large-scale data analysis and visualization software, and use of such sensitive receivers for the study of star-formation in our own galaxy and external galaxies.

Education
Nov., 1997: Ph. D. in Astronomy, University of Arizona.
June 1990: M.S. in Electrical Engineering, California Institute of Technology.
June 1989: B.S. in Electronics and Communication Engineering, Anna University, Madras, India.

Experience
Sep 2016 - current: Research Professor, University of Massachusetts.
July 2009 - Aug 2016: Research Associate Professor, University of Massachusetts.
June 2000 - June 2009: Research Asst. Professor, University of Massachusetts.
December 1997 - May 2000: Postdoctoral Research Associate, Five College Radio Astronomy Observatory, University of Massachusetts.

Selected Publications

1. **G. Narayanan**, R. L. Snell, and A. Bemis, “Molecular outflows identified in the FCRAO CO survey of the Taurus Molecular Cloud”, 2012, MNRAS, Volume 425, Issue 4, pp. 2641-2667.

2. J.C. Bardin, M. Yogeesh, N. R. Erickson, and **G. Narayanan**, “A 7095 GHz SiGe Down-converter IC for Large-N Focal Plane Arrays,” Proc. 2014 IEEE IMS, accepted (2014).

3. R. L. Snell, **G. Narayanan**, M. S. Yun, M. Heyer, A. Chung, W. Irvine, N. R. Erickson, and G. Liu, “The Redshift Search Receiver 3 mm Wavelength Spectra of 10 Galaxies”, 2011, AJ, Volume 141, Issue 2, article id. 38, 12 pp

4. **G. Narayanan**, M. H. Heyer, C. Brunt, P. F. Goldsmith, R. L. Snell, Y. Tang, and D. Li, 2008, “The Five College Radio Astronomy Observatory CO Mapping Survey of the Taurus Molecular Cloud. ”Astrophysical Journal Supplement”, vol 177, number 1, 2008, Pages 341-361.

5. N. R. Erickson, **G. Narayanan**, R. Goeller, and R. Grosselein, 2007, “An Ultra-Wideband Receiver and Spectrometer for 74-110 GHz,” Proceedings of the Astronomical Society. of the Pacific, v375, pp71-+.

CURRICULUM VITAE

Yancy L. Shirley

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& Steward Observatory
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EDUCATION

1997 **BS in Astronomy & Physics with Honors, The University of Arizona**

1997 **BS in Applied Mathematics, The University of Arizona**

2002 **PhD in Astronomy, The University of Texas**
Thesis: *Tracing the Mass During Star Formation: Studies of Dust Continuum and Dense Gas*
Supervised by Neal J. Evans II & Daniel T. Jaffe

EMPLOYMENT

1997 - 2002	Graduate Research Assistant, Astronomy Department, The University of Texas
2002 - 2005	Jansky Postdoctoral Fellow, National Radio Astronomy Observatory
2005 - 2008	Bok Postdoctoral Fellow, Steward Observatory, The University of Arizona
2014	Sabbatical, Visiting Scientist, Max Planck Institut für Astronomie (Heidelberg, Germany)
2008 - *Present*	Adjunct Astronomer, National Radio Astronomy Observatory
2008 - *Present*	Associate Professor, Astronomy Department, The University of Arizona

CURRENT GRANTS AND CONTRACTS

2015 - 2017 PI (100%) on NSF AAG Grant ”Starless Cores and Clunps: The Physical and Kinematic Structure of the Incipient Phase of Star Formation” ($252,000)

RECENT PUBLICATIONS (Author or coauthor on 71 refereed journal papers)

1. Svoboda, B. E., Shirley, Y. L., Battersby, C., Rosolowsky, E., Ginsburg, A., Ellsworth-Bowers, T., Pestalozzi, M., Dunham, M., Evans, N. J., Bally, J., & Glenn, J. ”The Bolocam Galactic Plane Survey. XIV. Physical Properties of Massive Starless and Star-forming Clumps” 2016, ApJ, 822, 59

2. Seo, Y. M., Shirley, Y. L., Goldsmith, P., Ward-Thompson, D., Kirk, J., Schmalzl, M., Lee, J.-E., Friesen, R., Langston, G., Masters, J., & Garwood, R. ”An Ammonia Spectral Map of the L1495-B218 Filaments in the Taurus Molecular Cloud. I. Physical Properties of Filaments and Dense Cores” 2015, ApJ, 805, 185

3. Shirley, Y. L. ”The Critical Density and the Effective Excitation Density of Commonly Observed Molecular Dense Gas Tracers” 2015, PASP, 127, 299

4. Shirley, Y. L., Ellsworth-Bowers, T. P., Svoboda, B., Schlingman, W., Ginsburg, A., Rosolowsky, E., Gerner, T. Mairs, S. Battersby, C., Stringfellow, G., Dunham, M. K., Glenn, J., & Bally, J. ”The Bolocam Galactic Plane Survey. X. A Complete Spectroscopic Catalog of Dense Molecular Gas Observed toward 1.1 mm Dust Continuum Sources with $7.5 \leq l \leq 194$” 2013, ApJS, 209, 2

5. Shirley, Y. L., Huard, T. L., Pontoppidan, K. M., Wilner, D. J., Stutz, A. M., Bieging, J. H., & Evans N. J. ”Observational Constraints on Submillimter Dust Opacity” 2011, ApJ, 728, 143

ANTONY A. STARK

EDUCATION

California Institute of Technology, B.S. with honors, 1975 (Physics and Astronomy)
Princeton University, Ph.D. 1979, (Astrophysical Sciences)
Advisor: Arno Penzias, Thesis: "Galactic Kinematics of Molecular Clouds"

EXPERIENCE

2014– Senior Astronomer, Harvard-Smithsonian Center for Astrophysics
1991–2014 Astronomer, Harvard-Smithsonian Center for Astrophysics
1988–2006 P.I., Antarctic Submillimeter Telescope and Remote Observatory (AST/RO)
1980–1992 Visting Lecturer, Department of Astrophysical Sciences, Princeton University
1979–1991 Member of Technical Staff, Radio Physics Research Department, Bell Labs
1975–1976 Physicist, Lawrence Livermore National Laboratory
1974–1975 Programmer, Space Radiation Laboratory, Caltech
1973–1974 Observing Assistant, Owens Valley Radio Observatory

SAMPLE PUBLICATIONS (280+ authored/co-authored publications)

1. Martin, C. L., Walsh, W. M., Xiao, K., Lane, A. P., Walker, C. K., and Stark, A. A. 2004, "The AST/RO Survey of the Galactic Center Region. I. The Inner 3 Degrees", ApJS, 150, 239.

2. Stark, A. A. and Lee, Y. 2005, "The Scaleheight of Giant Molecular Clouds is Less than that of Smaller Clouds", ApJL 619, L159

3. Stark, A. A., Gammie, C. F., Wilson, R. W., Bally, J., Linke, R. A., Heiles, C., and Hurwitz, M. 1992, "The Bell Laboratories H I Survey", ApJS, 79, 77.

4. Lee, Y., Stark, A. A., Kim, H. G., and Moon, D. 2001, "The Bell Laboratories ^{13}CO Survey: Longitude-Velocity Maps", ApJS, 136, 137.

5. Stark, A. A., Bally, J., Balm, S. P., Bania, T. M., Bolatto, A. D., Chamberlin, R. A., Engargiola, G., Huang, M., Ingalls, J. G., Jacobs, K., Jackson, J. M., Kooi, J. W., Lane, A. P., Lo, K.-Y., Marks, R. D., Martin, C. L., Mumma, D., Ojha, R., Schieder, R., Staguhn, J., Stutzki, J., Walker, C. K., Wilson, R. W., Wright, G. A., Zhang, X., Zimmermann, P., and Zimmermann, R. 2001, "The Antarctic Submillimeter Telescope and Remote Observatory (AST/RO)", PASP, 113, 567

6. Stalder, Brian; Stark, Antony A.; Amato, Stephen M.; Geary, John; Shectman, Stephen A.; Stubbs, Christopher W.; Szentgyorgyi, Andrew, 2014, "PISCO: the Parallel Imager for Southern Cosmology Observations", SPIE, 9147, 3Y

7. Stark, A. A., 2000 "Design Considerations for Large Detector Arrays on Submillimeter-wave Telescopes" in H. R. Butcher, ed. *Radio Telescopes*, vol. 4015 of *Proceedings of SPIE*, 434.

EXAMPLES OF SYNERGISTIC ACTIVITIES:

PI and designer of AST/RO and PISCO, collaborated in design of SPT3g and the SPT component of the Event Horizon Telescope; Chair of South Pole Users' Committee, 1998-2004; supervised graduate and undergraduate students in Astronomy and Engineering at Princeton University, Boston University, Northeastern University, and Harvard University; supervised students as part of CARA REU program; member of telescope design advisory panel of Paul Allen Telescope.

October 2016

Douglas S. Stetson
douglas.stetson@gmail.com

Current Position

Founder and President, Space Science and Exploration Consulting Group

- Consultant to the space science community for mission and system development, strategic planning, proposals, university programs
- Project manager for LightSail Cubesat flight under contract to The Planetary Society

Prior Experience (Jet Propulsion Laboratory, 6/83 – 7/08)

Manager, JPL Solar System Mission Formulation Office (10/06 – 7/08)

Manager, JPL Strategic Planning Office (6/05 – 10/06)

Deputy Manager, NASA Advanced Planning and Integration Office, (3/04 – 6/05)

Manager, JPL Planetary Program Development Office (3/01 – 3/04)

Manager, JPL Solar System Exploration/Deep Space Systems Program (9/98 – 10/01)

Systems Engineer and Program Architect, NASA New Millennium Program and JPL Mars Micromissions Office (March 1998 – October 1998)

Special Assignment for Solar System Roadmap Development (3/96-3/98)

Manager, JPL Planetary Advanced Concepts Office (11/93-3/96)

Technical Group Supervisor, JPL Advanced Projects Group (11/93-9/95)

JPL Detailee to Solar System Exploration Division, NASA HQ (3/92-11/93)

Technical Group Supervisor, JPL Outer Planets Mission Design Group (3/90-2/92)

Member of the Technical Staff, JPL Mission Design Section (6/83-3/90); systems engineer for multiple missions; mission design lead for Cassini Saturn Orbiter

Significant Awards and Other Activities

- NASA Exceptional Achievement Medal (2) and Group Achievement Award (3)
- JPL Award for Excellence in Leadership
- NRC committee member: Solar System Decadal Survey (2010), Planetary Protection for Icy Bodies (2010-11), Human Space Flight Technical Panel (co-chair 2012)
- Approx. 25 technical publications in planetary mission design and orbital mechanics

Citizenship: USA

Education: Stanford University, Stanford, California
1983, Master of Science (Aeronautics and Astronautics)
1981, Bachelor of Science (Physics)

MARK B. TAPLEY, Ph.D.

Staff Engineer
Space Systems Directorate
Department of Space Engineering
Space Science and Engineering Division

Ph.D., Aerospace Engineering, Stanford University, 1993
M.S., Aerospace Engineering, Massachusetts Institute of Technology, 1986
B.S., Engineering Science, University of Texas at Austin, 1984

Dr. Tapley's final education centered on analysis of geodetic missions. He worked with the Gravity Probe B mission at Stanford University, in utilizing its extremely quiet dynamic environment to enhance recovery of gravitational field observations with the gyroscope suspension and GPS navigation systems. Dr. Tapley also served as a Systems Engineer on that extremely challenging mission. Beginning in 1996, Dr. Tapley became the Mission System Engineer for the very successful IMAGE mission for ionospheric and magnetic imaging. His responsibilities for IMAGE included requirements tracking and verification for which he oversaw development of a database system later used on other GSFC missions. He also wrote and conducted payload functional tests and served as second shift Mission Operations Manager for the 40-day IMAGE in orbit checkout period, and later automated much of the routine command generation process for the IMAGE science payload. He also worked in System Engineering for the IBEX Small Explorer mission, using energetic neutral atoms to image the heliopause from a highly eccentric Earth orbit. He served as PI for the F6WICS element of the DARPA System F6 project, wherein SwRI supplied prototypes for the omnidirectional cross-link radio, a crucial element of the fractionated-satellite mission concept. He is currently Deputy Payload System Engineer on the New Horizons mission to Pluto and the Kuiper Belt, due to encounter Pluto in July 2015. His primary area of interest is mission design and systems engineering as well as astrodynamical research. His experience has been diverse, including experimental work in low-gravity fluid slosh, electronic system development and test, software engineering, analysis of mission design, and analysis of spacecraft dynamics.

Currently, Dr. Tapley is serving as the Deputy Payload Systems Engineer for the New Horizons mission and collaborating on multiple proposals for NASA planetary and near-Earth missions.

PUBLICATIONS: Dr. Tapley's work to-date has resulted in publications in professional journals.

PROFESSIONAL CHRONOLOGY: University of Texas Center for Space Research: laboratory assistant, 1978-84; NavAstro: systems engineer, 1993-6; Southwest Research Institute: 1996-[senior research engineer, 1996-2000; principal engineer, 2000-5; staff engineer, 2005-present].

MEMBERSHIPS: American Geophysical Union; American Institute of Aeronautics and Astronautics (AIAA).

May 2015

Appendices J4, J5, J6.

Not applicable to SLS.

Appendix J.7
Discussion of End-of-Mission Spacecraft Disposal Requirements

SLS will deorbit naturally within the prescribed 25 years after End-of-Mission.

SwRI performed orbit lifetime analyses for the SLS CubeSats to show compliance with the end-of-mission (EOM) disposal requirements, specifically deorbit within 25 years of the EOM. While the two spacecraft have limited propulsion capability, both vehicles deorbit naturally within the required time-frame. Phase A analysis will determine any additional margin due to remaining propellant. The lifetimes of these vehicles were calculated using the NASA Debris Assessment Software 2.0.2 tool with the maximum allowable variation in mass to determine how robust the calculations were. Given initial conditions matching the science orbits of 650 km, we analyzed the deorbit parameters for the limiting case of MEV mass (full contingency and margin) of 9.115 kg at a conservative altitude of 674 km demonstrating that both SLS spacecraft will reenter within the prescribed 25 years after EOM. Additionally any lower mass or lower altitude will result in a shorter spacecraft lifetime.

We calculate the average cross-sectional area based on the average area of the three faces. Based on the dimensions shown in in Figure J.7-1, we calculate the average frontal area as 1285 cm^2 in this configuration.

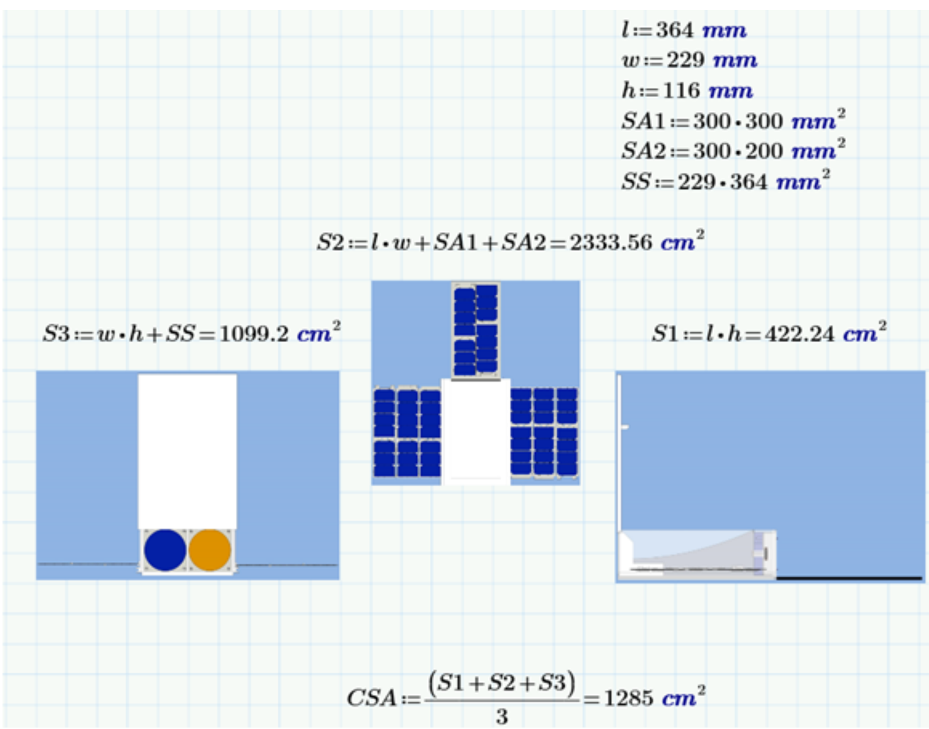


Figure J.7-1: Cross-Sectional area calculation of SLS spacecraft for de-orbit analysis.

Table J.7-1 provides the SLS lifetime analysis results. The predicted minimum Observatory lifetime is 6.0 years (MEV mass for the lowest orbit: 600 x 600 km), while the longest possible lifetime is <27.17 years (MEV mass for the highest orbit: 674 x 674 km). These results comply with the EOL disposal requirements of 25 years after EOM (27.17 years after launch, including a 2-year mission and 2 month commissioning until EOM).

All simulations were conducted using the NASA DAS 2.0.2 software with January 2015 update for the solar activity (F10.7) parameters, the latest available as of April 2016. The mass and drag area inputs used for each simulation are listed in Table J.7-1 with the resulting lifetime.

Table J.7-1: SLS Orbit Lifetime Analyses Inputs and Results		
Observatory Lifetime for Highest BOL Altitude 674 km		
Mass (kg)	**Area (m^2)**	**Maximum Lifetime (yr)**
9.115	0.1285 m^2	27.17 (25 after EOM)
Observatory Lifetime for Nominal BOL Altitude 650 km		
9.115	0.1285 m^2	~18
Observatory Lifetime for Lowest BOL Altitude 600 km		
9.115	0.1285 m^2	~6

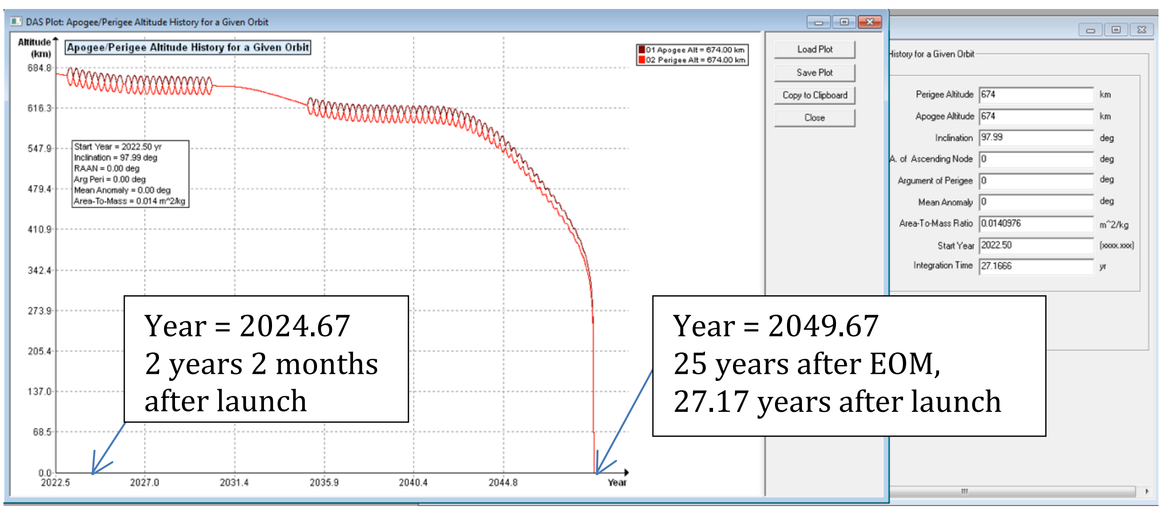


Figure J.7-2: Maximum lifetime for SLS spacecraft. Plot (left) and input parameters (right) for DAS 2.0 analysis of maximum 674 km altitude and an MEV mass of 9.115 kg limiting the de-orbiting to 27.17 years (2 year mission, + 2 month commissioning + 25 year de-orbit).

In addition to the lifetime survey, during Phase-A analysis, SwRI will conduct a DAS 2.0 analyses for all other EOM requirements, excepting collision with tethers (since SLS has no tethers). This analysis will be based on a complete breakdown according to the MEL.

SLS MASTER EQUIPMENT LIST

S/C Structure			# OF UNITS			FLIGHT HARDWARE MASSES			FLIGHT HARDWARE POWER			
Subsystem/Component	Unit Mass, Current Best Estimate (CBE Kg)	Unit Power, Current Best Estimate (CBE W)	Flight Units	Flight Spares	EMs & Proto-types	Total Mass, kg CBE	Contin-gency %	Total Mass w/ Contin-gency	Duty Cucle	Total Power W OAP CBE	Contin-gency %	Total Power W OAP MEV
Deck	0.50	---	1	0	1	0.5	*20%*	0.6	---	---	---	---
Side Walls (4mm)	0.12	---	2	0	1	0.2	*20%*	0.3	---	---	---	---
End Walls (4mm)	0.08	---	2	0	1	0.2	*20%*	0.2	---	---	---	---
Mounting Hardware	0.20	---	1	0	1	0.2	*20%*	0.2	---	---	---	---
Total Mass/Power						**1.1**	***20.0%***	**1.3**	***0.0%***	**0.0**	***0.0%***	**0.0**

S/C Attitude Control			# OF UNITS			FLIGHT HARDWARE MASSES			FLIGHT HARDWARE POWER			
Subsystem/Component	Unit Mass, Current Best Estimate (CBE)	Unit Power, Current Best Estimate (CBE)	Flight Units	Flight Spares	EMs & Proto-types	Total Mass, kg CBE	Contin-gency %	Total Mass w/ Contin-gency	Duty Cucle	Total Power W OAP CBE	Contin-gency %	Total Power W OAP MEV
Attitude Determination and Control System	0.91	2.8	1	0	0	0.9	*3%*	0.9	50%	1.4	*10%*	1.6
Total Mass/Power						**0.9**	***3.0%***	**0.9**	**---**	**1.4**	***10.0%***	**1.6**

S/C EPS			# OF UNITS			FLIGHT HARDWARE MASSES			FLIGHT HARDWARE POWER			
Subsystem/Component	Unit Mass, Current Best Estimate (CBE)	Unit Power, Current Best Estimate (CBE)	Flight Units	Flight Spares	EMs & Proto-types	Total Mass, kg CBE	Contin-gency %	Total Mass w/ Contin-gency	Duty Cucle	Total Power W OAP CBE	Contin-gency %	Total Power W OAP MEV
Clyde Space 3U triple-deployed solar array	0.44	---	2	0	0	0.9	*3%*	0.9	---	---	---	---
Clyde Space 3U x 2 solar array panel	0.25	---	1	0	0	0.3	*10%*	0.3	---	---	---	---
Clyde Space 3G Flex EPS Converter	0.15	---	1	0	0	0.1	*3%*	0.2	---	---	---	---
Clyde Space 40 WHr Battery Pack	0.35	---	2	0	0	0.7	*3%*	0.7	---	---	---	---
Total Mass/Power						**2.0**	***3.9%***	**2.1**	**---**	***0.0***	**---**	**0.0**

S/C C&DH			# OF UNITS			FLIGHT HARDWARE MASSES			FLIGHT HARDWARE POWER			
Subsystem/Component	Unit Mass, Current Best Estimate (CBE)	Unit Power, Current Best Estimate (CBE)	Flight Units	Flight Spares	EMs & Proto-types	Total Mass, kg CBE	Contin-gency %	Total Mass w/ Contin-gency	Duty Cucle	Total Power W OAP CBE	Contin-gency %	Total Power W OAP MEV
Southwest Research Institute Single Board Computer, CubeSat Format - SATYR	0.15	2.0	1	kit	1	0.1	*10%*	0.2	100%	2.0	*5%*	2.1
Total Mass/Power						**0.1**	***10.0%***	**0.2**	**---**	**2.0**	***5.0%***	**2.1**

S/C Propulsion			# OF UNITS			FLIGHT HARDWARE MASSES			FLIGHT HARDWARE POWER			
Subsystem/Component	Unit Mass, Current Best Estimate (CBE)	Unit Power, Current Best Estimate (CBE)	Flight Units	Flight Spares	EMs & Proto-types	Total Mass, kg CBE	Contin-gency %	Total Mass w/ Contin-gency	Duty Cucle	Total Power W OAP CBE	Contin-gency %	Total Power W OAP MEV
VACCO Cold Gas MiPS Thruster	0.92	10.0	1	0	0	0.92	*3%*	1.0	*0%*	0.0	*0%*	0.0
Total Mass/Power		0% duty only used BOL/EOL				**0.9**	***3.0%***	**1.0**	**---**	**0.0**	***0.0%***	**0.0**

S/C Thermal			# OF UNITS			FLIGHT HARDWARE MASSES			FLIGHT HARDWARE POWER			
Subsystem/Component	Unit Mass, Current Best Estimate (CBE)	Unit Power, Current Best Estimate (CBE)	Flight Units	Flight Spares	EMs & Proto-types	Total Mass, kg CBE	Contin-gency %	Total Mass w/ Contin-gency	Duty Cucle	Total Power W OAP CBE	Contin-gency %	Total Power W OAP MEV
6.5 Heater	0.05	1.5	5	2	0	0.25	*10%*	0.3	*50.0%*	3.8	*20%*	4.5
6.5 Temperature Sensor (Thermistor)	0.01	---	10	2	0	0.10	*10%*	0.1	---	---	---	---
6.5 MLI Blankets	0.07	---	1	0	0	0.07	*10%*	0.1	---	---	---	---
Total Mass/Power						**0.4**	***10.0%***	**0.5**	**---**	**3.8**	***20.0%***	**4.5**

S/C Communications			# OF UNITS			FLIGHT HARDWARE MASSES			FLIGHT HARDWARE POWER			
Subsystem/Component	Unit Mass, Current Best Estimate (CBE)	Unit Power, Current Best Estimate (CBE)	Flight Units	Flight Spares	EMs & Proto-types	Total Mass, kg CBE	Contin-gency %	Total Mass w/ Contin-gency	Duty Cucle	Total Power W OAP CBE	Contin-gency %	Total Power W OAP MEV
SYRLINKS S-Band Transceiver Receive	0.10	4.0	1	0	0	0.1	*3%*	0.1	*100%*	4.0	*10%*	4.4
S-Band Antenna	0.08	---	1	0	0	0.1	*10%*	0.1	---	---	---	---
SYRLINKS X-Band Transmitter	0.30	10.0	1	0	0	0.3	*3%*	0.3	*10.0%*	1.0	*10%*	1.1
X-band Patch Antenna	0.08	---	1	0	0	0.1	*10%*	0.1	---	---	---	---
Total Mass/Power						**0.6**	***5.0%***	**0.6**	**---**	**5.0**	***10.0%***	**5.5**

Science Payload			# OF UNITS			FLIGHT HARDWARE MASSES			FLIGHT HARDWARE POWER			
Subsystem/Component	Unit Mass, Current Best Estimate (CBE)	Unit Power, Current Best Estimate (CBE)	Flight Units	Flight Spares	EMs & Proto-types	Total Mass, kg CBE	Contin-gency %	Total Mass w/ Contin-gency	Duty Cucle	Total Power W OAP CBE	Contin-gency %	Total Power W OAP MEV
Telescope												
Receiver Module	1.50	16.00	1	0	0	1.500	*20%*	1.800	100.0%	16.0	*20%*	19.20
Reflector	0.50	---	1	0	0	0.500	*20%*	0.600	---	---	---	---
Secondary Reflector	0.20	---	1	0	0	0.200	*20%*	0.240	---	---	---	---
Total Mass/Power						**2.2**	***20.0%***	**2.6**	**---**	**16.0**	***20.0%***	**19.2**

Spacecraft and Instruments Mass and Power						**8.2**	***10.6%***	**9.1**		**28.2**	***16.7%***	**32.9**

J.9 Heritage

OVERVIEW

The SLS mission draws heavily from previous orbital and suborbital missions. These include SWAS, IceCube, CYGNSS, and STO. Heritage also applies from two missions in development, CuSP and GUSTO, as well as the in-house SwRI development of the SLX-6 Cubesat platform. For SLS we will also leverage the technology and software development our team has done on ground-based observatories in Antarctica (e.g. AST/RO and HEAT). Nearly all components, assemblies, and subassemblies of the SLS spacecraft are either built-to-print or commercial-off-the-shelf (COTS) hardware proven in previous CubeSAT missions. This greatly reduces the cost and risk associated with design and development. All technical processes, mission assurance practices, and management practices planned for SLS have been proven on multiple prior missions. This appendix focuses on instrument and spacecraft and related processes in order to demonstrate heritage for the most complex aspects of mission development.

Element	Basic Heritage
Program Management	Existing systems & controls in place from STO (UA), CYGNSS (SwRI), ICECUBE (VDI)
System Engineering	Existing systems & controls in place from STO (UA), CYGNSS (SwRI), ICECUBE (VDI)
Safety and Mission Assurance	Existing systems & controls in place from STO (UA), CYGNSS (SwRI), ICECUBE (VDI)
Science Payload	Similar design as used on ICECUBE (VDI), HEAT (UA), STO (UA), SWAS
Spacecraft & Subsystems General	Heritage drawn from progressive development of designs from SLX-6 (SwRI), ICECUBE (VDI), MINXX
Power Conversion Unit	SLX-6, CYGNSS, CuSP
Solar Arrays	SLX-6, CYGNSS, CuSP
Batteries	SLX-6, CYGNSS, CuSP
Attitude Determination and Control (ADCS)	Blue Canyon Technologies XACT, same as flown on MINXX CubeSat
Spacecraft Deck	SLX-6, CYGNSS, CuSP
Stow Latch	SLX-6, CYGNSS, CuSP
Flight Computer	SLX-6, CYGNSS, CuSP
Command & Control Software	SLX-6, CYGNSS, CuSP
Canisterized Satellite Dispenser	COTS
Ground Software	CYGNSS, CuSP with additional instrument control modules
Mission Operations	CYGNSS, CuSP with additional instrument control modules
Ground System	CYGNSS, CuSP with additional instrument control modules

Index and summary of heritage.

	Full	Partial			None
Design	Identical (off-the-shelf)	Minimal Modifications (<10%)	Moderate Modifications (<50%)	Major Modifications (>50%)	New Design
Manufacture	Identical Provider & Development Team	Minimal Modifications (<10%)	Moderate Modifications (<50%)	Major Modifications (>50%)	New Process
Software	Identical	Minimal Modifications (<10%)	Moderate Modifications (<50%)	Major Modifications (>50%)	New Process
Provider	Identical	Different with Substantial Involvement of Original Team			Different & Min/No Involvement of Original Team
Use	Identical	Same Interfaces and & Similar Use Within a Novel Overall Context			Significantly Different from Original
Operating Environment	Identical	Within Margins of Original			Significantly Different from Original
Referenced Prior Use	Flown	Built and Successfully Ground-Tested			Not Yet Successfully Ground-Tested

Heritage-level (HL) definitions.

I. Science and Instrument Heritage

WBS: 400	Title: Science

Description:
This section includes the managing, directing, and controlling of the science investigation aspects, as well as leading, managing, and performing the technology demonstration elements of the Project. Specific responsibilities include defining the science or demonstration requirements; ensuring the integration of these requirements with the payloads, spacecraft bus, ground systems, and mission operations; and providing the algorithms for data processing and scientific analyses. Included is the efforts of the Principal Investigator, Deputy Principal Investigator, Project Scientist and the remainder of the Science Team to develop sci ence requirements, performing science data collection, post-processes mission collected scientific data, archive the scientific data and publish the results of the scientific data analyses.

Science Operations Center (SOC): HL- Partial
The SOC will reside at UA. The ground data receiving workstation at the SOC will be a clone of the receiving station at the MOC with the same hardware and software used. From the ground receiving station the science data is piped to the Science data processing and data storage systems. UA will develop the SOC science data processing and storage component. SwRI will develop the data receiving workstation. The data processing and analysis portion of the SOC is closely similar to what was developed for the STO 2011/2016 Antarctic, high altitude balloon flight campaigns and the HEAT robotic observatory on Dome A, Antarctica. Data processing algorithms and software draw heritage from the Hershel mission. The SOC will be manned by UA personnel.

Component: SOC Aspect	Discussion and Level of Heritage		
Dates of use	January 2012/December 2016 STO Antarctica flight campaigns; HEAT from 2010-		
Developer institution	UA		
Differences from design basis	Modifications will be done to tailor the science data handling to the specific requirements of SLS. However SLS mission is very similar to STO and HEAT in terms of ground segment requirements.		
Development challenges	None anticipated. Ground segment is similar to what already developed for STO/HEAT		
Status	Proven for flight operations		
Highest assembly level	SOC		
Manufacture	Partial: new hardware will be used		
Software	Modification required to tailor the software to the specific requirements of SLS		
Provider	Identical: UA will develop the components of the SOC		
Use	Similar to STO/HEAT		
Operating environment	Similar to STO/HEAT		
Referenced prior use	STO balloon mission/HEAT automated observatory		
Is developer in proposing team?	YES	Individual(s) participating in heritage basis available to proposing team?	YES

492/460 GHz Mixers and Local Oscillators: HL-Moderate

Schottky diode mixers of the type to be flown on SLS have a long flight heritage, including the Submillimeter-wave Astronomical Satellite (SWAS), ODIN, and the Microwave Limb Sounder (MLS). More recently Virginia Diodes Inc., the mixer supplier for SLS, has delivered a complete 874 GHz Schottky diode receiver system with a subharmonically pumped local oscillator for GSFC's IceCube atmospheric science CubeSat mission. The SLS mixer is a scaled version of this successful design. The new generation of Schottky diode mixers is made photolithographically with beam lead whiskers, far more robust and reliable than the older point contact whisker diodes used in past missions.

Component: 492/460 GHz Mixers/LO's			
Aspect	**Discussion and Level of Heritage**		
Dates of use	2008-present		
Developer institution	Virginia Diodes Inc.		
Differences from design basis	SLS will largely utilize detailed designs previously used for IceCube, with modifications to the design to allow for operation at the lower frequency of SLS (centered at 472 GHz). SLS will use two mixers, one for each polarization. SLS will also use a programmable LO reference to allow frequency switching.		
Development challenges	Fabrication of the diodes, waveguides, and LO circuits at the lower frequency of SLS is straightforward. The challenge is in the packaging, i.e. mass and power. (Mitigation: early fabrication and lab/environmental testing)		
Status	Individual mixers have been designed, fabricated, and T-V tested at SLS frequencies.		
Highest assembly level	VDI 460/492 GHz mixers have been assembled and T-V tested at UA, successfully flown on the Stratospheric TeraHertz Observatory (STO), and used at the UA's High Elevation Antarctic TeraHertz (HEAT) robotic observatory on Dome A, Antarctica.		
Manufacture	Manufacture takes heritage from IceCube, STO, HEAT, and many other projects requiring cryogenically cooled mixers operating in a vacuum.		
Software	N/A		
Provider	Identical		
Use	Identical		
Operating environment	Identical		
Referenced prior use	IceCube spacecraft, STO balloon mission, HEAT		
Is developer in proposing team?	YES	Individual(s) participating in heritage basis available to proposing team?	YES

Digital Autocorrelator Spectrometers/IF System: HL- Moderate

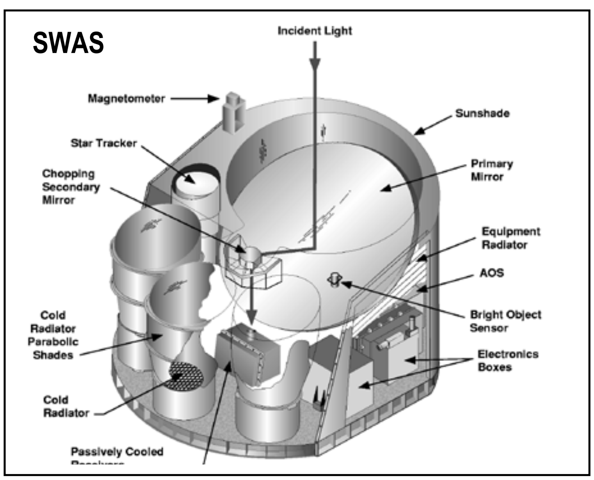
The SLS spectrometer will be provided by Omnisys Instruments. Omnisys spectrometers were successfully used on ODIN and on the STO test and science flights. For SLS an autocorrelator spectrometer approach (similar to that used on ODIN) will be utilized. This approach has the advantage of being both efficient and low power. A HIFAS ASIC is at the heart of the correlator. Omnisys has built and delivered autocorrelator spectrometers of this type. Together with Omnisys, we will environ- mentally test these units so that they are all at TRL 6 at the end of Phase B.

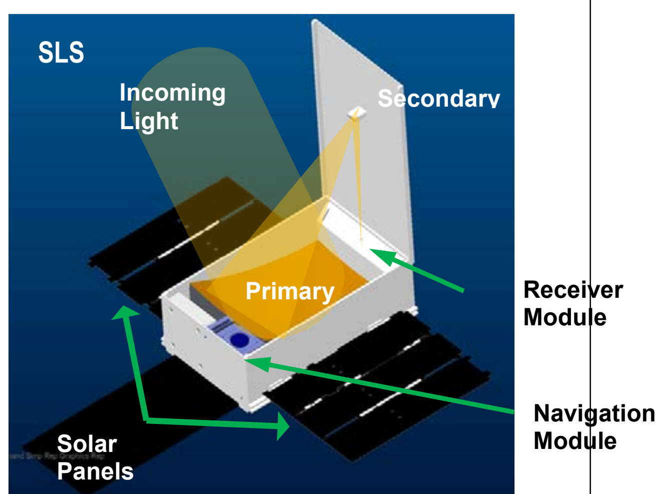
Component: Autocorrelator Spectrometer			
Aspect	**Discussion and Level of Heritage**		
Dates of use	2001-present		
Developer institution	Omnisys AB		
Differences from design basis	Flight qualified ASICs will be packaged in modules of 8 for SLS focal plane arrays. The exact ASIC for SLS is a newer generation from that used in ODIN, but is TRL 6		
Development challenges	Total data throughput over Spacewire bus needs to be verified		
Status	ASIC is spaceflight qualified		
Highest assembly level	Flight		
Manufacture	Partial: packaging of ASIC differs		
Software	N/A		
Provider	Identical		
Use	Identical		
Operating environment	Identical		
Referenced prior use	ODIN spacecraft/STO		
Is developer in proposing team?	YES	Individual(s) participating in heritage basis available to proposing team?	YES

SLS Telescope: HL-Partial/Moderate

The SLS telescope (Fold-Out E1.1; E1.2) is a simple off-axis Cassegrain design like SWAS, but ~1/2 the size and with larger, more tolerant f#'s, The SLS primary is a ~30 x 20 cm, f#1, parabaloid, and the secondary a ~2x1 cm, f#18, hyperboloid. . As on SWAS, both the primary and secondary are diamond turned aluminum, here with a surface accuracy of ~4μm rms. A figure comparing the SWAS telescope (ca. 1998) to SLS is shown below. The UA (a world leader in astronomical telescope design and construction) has designed the telescope and is responsible for overseeing its fabrication and payload integration.

Component: SLS 30x20 cm telescope			
Aspect	**Discussion and Level of Heritage**		
Dates of use	1998 (SWAS)		
Developer institution	GSFC		
Differences from design basis	~1/2 the size, more tolerant f#		
Development challenges	None		
Status	Standard design/fabrication approach used in Commercial and Industrial applications.		
Highest assembly level	Deployed telescope		
Manufacture	Diamond turned aluminum primary		
Software	FRED, Zemax		
Provider	SwRI precision machining facility		
Use	Identical		
Operating environment	Identical		
Referenced prior use	Same telescope design and manufacture approach used on SWAS.		
Is developer in proposing team?	NO	Individual(s) participating in heritage basis available to proposing team?	YES





SLS Onboard Processing Software: HL-Partial/Moderate

The SLS onboard software will benefit from a decade of development of similar data acquisition software for use in automated ground based (HEAT) and balloon-borne (STO) observatories utilizing the same or similar hardware components. The UA will work with SwRI to adapt the code for operation on the SLS spacecraft computer.

Component: Onboard Data processing Software			
Aspect	**Discussion and Level of Heritage**		
Dates of use	2011-present		
Developer institution	University of Arizona		
Differences from design basis	Modifications will be made to handle the differences between the data acquisition hardware (spectrometers) on SLS, calibration, and housekeeping telemetry injection into data headers. Expected about 80% reuse of the software currently used for the HEAT, with augmentations.		
Development challenges	Modifications are minor and do not affect the core algorithms and processes. The SLS DPI developed the data processing software and he will oversee the code modifications for SLS		
Status	Proven on robotic ground-based telescope & balloon-borne observatories		
Highest assembly level	In production		
Manufacture	N/A		
Software	Minor modifications required		
Provider	Identical		
Use	Identical		
Operating environment	Similar		
Referenced prior use	STO and HEAT, unattended robotic telescopes in near space and Antarctic plateau		
Is developer in proposing team?	YES	Individual(s) participating in heritage basis available to proposing team?	YES

II. Spacecraft and Operations Heritage

A. Spacecraft Management   Heritage Level: High

The SLS spacecraft management will follow the lead developed on Cyclone Global Navigation Satellite System (CYGNSS). CYGNSS has delivered a constellation of eight microsats on-time and on-budget for launch in December of 2016. Many key CYGNSS personnel maintain identical roles for SLS. In addition, the same schedule management, cost management, systems engineering, AI&T methods, and institutional interfaces will carry over as-is from CYGNSS.

Modifications for SLS

SLS has a different lead institution and PI, as well as a different instrument. Management and system engineering structures remain substantially intact and the spacecraft (SC) development and management are nearly identical.

Benefits of Heritage to SLS

Highly effective processes for managing payload/SwRI interfaces, as well as the design, assembly, integration, test, and verification of multiple observatories within a Class D mission have been developed for CYGNSS. Utilizing these same processes, along with the majority of the team that developed and implemented them, SLS realizes significant cost and risk reductions.

B. Spacecraft Development   Heritage Level: High

Description of Design Heritage: The SLS SC borrows heavily from past microsatellite and CubeSat missions. Table 1 gives a summary of the heritage of all major SC subsystems as well as the associated ground support equipment (GSE) and assembly, integration and test plan (AI&T). Subsequent subsections give details for each.
Modification for SLS: Targeted modifications to the SLS microsatellite heritage have been made only where absolutely necessary in order to reduce risk by using substitutions with more heritage and in order to increase SLS margin on key performance metrics – particularly power and thermal. See Table J.9.3-1 and the subsections below for details.
Benefits of heritage to SLS: The SLS requirements are well understood, as are differences from heritage microsatellite requirements. The comparison of the two has yielded a very strong case for the reuse of heritage components as given in this section in order to reduce SLS risk. As shown in Table 1, the majority of the SLS subsystems, integration flow, and processes come directly from CYGNSS. For those subsystems that differ, the replacements all have extensive heritage.

Table 1 SLS SC Component Heritage Summary

Subsystem	Heritage Source	Comments
SC (quantity 2)	CYGNSS	SLS will use design and fabrication flow from CYGNSS, which used a constellation of 8 satellites
PM, SE, Ma	CYGNSS	SLS uses similar PM, SE, and SMA processes and key personnel to that of CYGNSS
Command & Data Handling	CYGNSS, Syrlinks	SLS will use a reduced-I/O version of the CYGNSS C&DH board
Communications	Heritage Rosetta, Deep Impact, Myriade	Baselined EWC15, EWC29 from Syrlinks
SC Flight SW	CYGNSS	CYGNSS flight software will be modified for use with SLS using SwRI's standard FSW library and processes
Structure, Mechanisms, Thermal	CYGNSS, CuSP, ClydeSpace, Blue Canyon	CYGNSS and CuSP SMT will be modified for SLS use, including the Clyde Space Solar Array and deployer and the Planetary Systems Corp. deployment mechanism
Electrical Power	CuSP, Clyde Space	COTS unit

Subsystem		
ADCS	XACT	COTS unit
Ground GSE	CYGNSS	GSE philosophy and many components including dynamic simulator from CYGNSS will be reused for SLS
SC I&T	CYGNSS, CuSP	The constellation AI&T process from CYGNSS, will be reused for SLS (2 SC vs. 8 for CYGNSS).

B.1 SC Command and Data Handling (C&DH) Heritage level: High

The SLS Command and Data Handling Subsystem is composed of heritage components from SwRI's long history of space-proven spacecraft avionics. SwRI has provided avionics hardware for missions including NASA's CYGNSS, DS1, QuickScat, IMAGE, ICESat, Swift, WISE, Deep Impact, Kepler, NPP; DARPA's Orbital Express; commercial satellites WorldView1/2; and numerous other NASA and USAF programs. Many of these missions have lifetimes greater than 5 years. Through our extensive avionics work, we have developed significant catalog of interface, data storage, and data processing hardware designs. This core capability includes several different single-board computers, significant CCSDS compliant command and telemetry capability implemented in both ASIC and FPGA, interface designs for most ADCS components on the market, thermal control designs, safety-vetted actuator drive circuitry, and electrical power circuits (both charging control and distribution); all fully qualified to Level B and successfully flown.

SLS C&DH requirements are virtually identical to those of CYGNSS and are significantly simpler than SwRI's typical spacecraft applications. CYGNSS combined existing, fully qualified circuit designs to meet its requirements on a smaller board form factor with fewer interface quantities. This new board is called the Centaur, and the reduced I/O version compatible with Cubesat form factor and serving as the CuSP C&DH, is the Satyr. SLS directly leverages the Satyr. Table 3 provides a summary of the C&DH and Communications hardware.

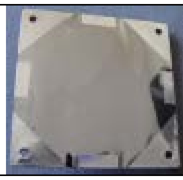
Modification for SLS: The only modifications are for the interface to the ADCS, which, as described below, has been condensed to the XACT unit for the SLS spacecraft using a COTS unit with extensive heritage and a well-defined ICD.

Benefits of heritage to SLS: There are clear benefits in using heritage CYGNSS designs for the SLS C&DH, including: 1) risk reduction, 2) cost reduction and 3) increased reliability, 4) software commonality. All of the C&DH sub-components have been designed, built, tested and flown on previous missions. Though CYGNSS has not launched as of this writing, a considerable amount of the mission was based on adapting heritage design elements, each at TRL 9, into a smaller form factor. Many of the CYGNSS system components have already been advanced to TRL 8 as part of the production effort and present the minimal engineering risk approach and a clear path to a reliable flight product.

Cost Comparison to Heritage: SwRI has extensive C&DH development experience from several past missions including IMAGE and MMS as lead of payload command and data handling subsystem, as well as sounding rockets and balloon payloads where SwRI served as communications lead. SwRI's high-TRL solutions for C&DH hardware greatly reduce NRE and overall risk to SLS. Labor hours in the cost estimate are based on grass roots estimates validated by heritage projects and an Independent Cost Estimate. Subsystem engineering labor costs are based on a CDS lead (PL-2) full time in phase B and C and half time in Phase D.

Table 3. Communication and Data Subsystem Heritage Table

Subsystem	Image	Design	Manufacture	Provider	Use	Operating Environment	Prior Use	TRL
Satyr Processing Unit		**Full** SwRI design identical to prior use	**Full** SwRI manufacture facilities, identical processes and procedures.	**Full** SwRI	**Partial** Juno JADE IPB in operation, CYGNSS near launch, Cusp in Fabrication	**Partial** Prior use envelopes SLS (Juno, CYGNSS)	**Full** Juno JADE IPB in operation, CYGNSS near laurch	**8**
S-Band Transceiver		**Full** SyrLinks design identical to prior use	**Full** SyrLinks manufacture facilities, identical processes and procedures.	**Full** SyrLinks	**Full** EYE-SAT (CNES), OPS-SAT (ESA/TU-Graz)	**Full** Qualified for EYE-SAT, OPS-SAT	**Partial** Qualified for EYE-SAT, OPS-SAT (Launch 2017)	**7**
X-Band Transmitter		**Full** SyrLinks design identical to prior use	**Full** SyrLinks manufacture facilities, identical processes and procedures.	**Full** SyrLinks	**Full** GOMX-3 (ESA/Gomspace)	**Full** GOMX-3 (ESA/Gomspace)	**Full** GOMX-3 (ESA/Gomspac e)	**9**

S-Band Patch Antenna		**Full** Build to print, design to prior use	**Full** AntDevCo manufacture facilities identical to prior use	**Full** AnDevCo supplier	**Full** Identical to prior use	**Full** Identical to prior use	**Full** Numerous	**9**
X-Band Patch Antenna		**Full** Build to print, design to prior use	**Full** AntDevCo manufacture facilities identical to prior use	**Full** AnDevCo supplier	**Full** Identical to prior use	**Full** Identical to prior use	**Full** Numerous	**9**

B.2 Satyr Heritage level: High

The SLS program will be using the Satyr (derived from the Centaur) board as a major element of the C&DH. In implementing the nanosatellite architecture of CYGNSS, a subset of existing TRL 9 board elements were tailored for a significantly simplified spacecraft into the Centaur board. A brief description of the Centaur avionics functions and their heritage are given below, and a photograph of a Satyr board appears in Figure 1.

- Processor Core (Aeroflex LEON3-FT FPGA core): Instantiated in the Centaur FPGA, the LEON3 core is the spacecraft computer. The computer provides all resources for onboard SLS Spacecraft flight software processing. This includes science data collection, on-board data storage, and thermal control as well as higher level command and telemetry processing. The LEON3 core is the successor to the LEON2 and has flown on multiple space missions, including UK-DMC. The IP core is procured from Aeroflex as a gate- level programming file, tailored to include the desired peripheral interfaces.
- Processor Support Circuitry: Processors require additional parts including memories, clock, reset, power management and interface drivers. The Satyr processor support circuitry is identical to that on the Centaur which in turn were identical to the Juno JADE Instrument Processor Board. Memory resources include MRAM for code storage, SDRAM for code execution, and Flash memory for data storage. The same radiation tested Flash parts are being used on MMS.
- CCSDS Command and Telemetry Core (CTC): The CTC function is heritage HDL resident in the Centaur FPGA. The CTC autonomously receives and routes ground commands from the transceiver, assembles and packetizes science data, and autonomously collects and formats housekeeping telemetry for transmission via the transceiver. The CTC significantly reduces flight software processing loads.

For downlink, the telemetry algorithms to perform the CCSDS packetization are identical to those used on the WISE Mission Unique Board, which produce CCSDS Telemetry TM Source Packets and Transfer Frames with Reed-Solomon Codeblocks (E-16, I=5). MMS heritage hardware acceleration of the CCSDS File Delivery Protocol (CFDP) File Protocol for of CFDP Protocol Data Units (PDUs) is also provided. The downlink processor also autonomously collects low level telemetry, formats and forwards to the transceiver via virtual channel 0 without processor interaction.

For uplink, the CTC command decoder algorithms are identical to those used on Deep Impact, Orbital Express, Kepler, and WISE. The CTC accepts CCSDS TC Transfer Frames with BCH check bits, determines where the command is directed (Level-0, FSW, etc.) and either executes the low level command or forwards it to a FSW command buffer. Level 0 telemetry and commanded resets are generated by the CTC without intervention from the processor. Through the CTC, the ground station can reset the spacecraft, even with the processor in a non-responsive state.

- General Purpose Interfaces. The Centaur design includes LVDS, RS422, analog, and discrete (low-level) interfaces. The Blue Canyon ADCS and SLS instrument are compatible with these interfaces and will not require Centaur modification to accommodate.


Figure 1. Satyr C&DH board

B.3 Telecommunications Subsystem Heritage level: High

Description of Design Heritage: SLS will use the Syrlinks EWC31 S-band transceiver combined with heritage RF hardware from the CYGNSS mission for telecommunications. The EWC31 is based heavily upon the Syrlinks EWC15, which has flown on over 40 space- craft including Rosetta, Deep Impact, and the CNES Myriade series of satellites. The EWC31 increases performance over the EWC15 to meet the size, power, and data rate requirements of missions like SLS. In addition to design heritage from the EWC15, it inherits design elements from the EWC29 S-band transceiver, which is ESA Class 3 compliant. The EWC31 has been selected to fly on the EYE-SAT and OPS-SAT missions, with the units are currently at TRL 8.

The SyrLinks EWC27 X-band transmitter provides SLS with a high-rate science data downlink. In flight on GOMX-3 since 2015, the transmitter is capable of data rates up to 100 Mbps although SLS will utilize only a 10 Mbps bandwidth. The S-band transceiver, and X-band transmitter, combined with necessary RF components (all at TRL 9), comprise the SLS Communications hardware complement. Table 3 provides a summary of this hardware.

Modification for SLS: The COTS parts used for SLS telecommunications will be used as is, although the interfaces (electrical, electronic, mechanical, and thermal) will be unique to SLS. All COTS components come with well-defined ICDs.

Benefits of heritage to SLS: The use of these high-heritage components will provide a low-risk, low-power telecommunications solution for SLS to help ensure mission success.

Rationale Supporting Achievement of Heritage: The Syrlinks EWC31 and EWC27 and the associated RF hardware meet SLS communications requirements with significant margin. All components of the communications system have been verified with their respective vendors as being fully compatible. Given the high heritage of each, they provide a low-risk, highly capable communications subsystem to ensure SLS success

Cost Comparison to Heritage: Costs are based on vendor quotes for the delivery of EM and flight units of the Syrlinks S-band transceiver boards, and COTS communications H/W including antennas (see MEL). Labor hours associated with the management of the communications sub- system requirements and interfaces in the cost estimate are based on grass roots estimates validated by heritage projects and Independent Cost Estimate. Costs also include an RF analyst (PL- 3), 80 hours each for the following activities: mission PDR, EM testing, CDR, FM-1 testing and PSR.

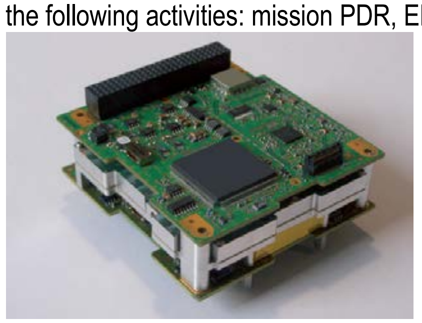


Figure 2. SyrLinks X/S Band Transceiver

B.4 S/C Flight Software Heritage level: High

Description of Design Heritage: The SLS SC FSW will derive significant heritage from the CYGNSS S/C FSW which was itself based on the MMS CIDP FSW and other missions. Table 4 summarizes the anticipated Computer Software Components (CSCs) and their reuse. Source lines of code (SLOC) estimates are based largely on CYGNSS code generated using David A. Wheeler's 'SLOCCount'. Where full reuse is anticipated, the actual reuse SLOCs are reported; where modifications are expected, SLOCs are estimated to the nearest 100 or 1000 SLOCs, as applicable..

Modification for SLS: The SLS spacecraft is based extensively on that developed for the CYGNSS mission and the Satyr SBC hardware/software interface is identical to the Centaur with significant functional reuse. As such, the CYGNSS FSW is the obvious basis for the SLS FSW and modifications are made only where absolutely necessary to accommodate the new instrument on SLS, with the single exception of the ADCS FSW. For ADCS, SLS uses the Blue Canyon Technologies XACT system described below. This provides a high heritage, low mass and volume system much more aligned with SLS requirements than the CYGNSS ADCS. SLS will use the Blue Canyon Technologies flight-proven heritage embedded FSW designed for this unit..

Benefits of heritage to SLS: SwRI has a Reusable Flight Software (RFS) library that implements many common FSW functions, such as an absolute and relative time sequence library, a software data bus library, a time conversion library and a number of device drivers for most spacecraft interfaces such as RS-422, LVDS, MIL-STD-1553 and SpaceWire.

The benefits of flight software heritage are threefold: 1) reduced cost, 2) more predictable development schedule, and 3) reduced technical risk. Since many of the flight software components already exist and have been either flight proven or flight qualified, the non-recurring engineering effort is substantially reduced. Reusing software components from prior missions allows the FSW team to focus their efforts on those elements of the software that are unique to SLS, such as instrument operations, on-board science data processing, and mission-specific fault management functions.

As described previously, the SLS FSW is based extensively on the CYGNSS FSW, which itself drew heritage from a number of prior missions including the MMS Central Instrument Data Processor (CIDP), Fermi (formerly GLAST), Juno, and the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) CIDP.

Rationale Supporting Achievement of Heritage: The SLS FSW will be modified in well-defined, well understood areas only as necessary to achieve unique SLS goals, which are very similar to the most recent heritage missions. Given the nature of the SwRI FSW development process through the RFS library, this process of software tailoring to the needs of a specific mission is well understood. Thus, the benefits of the heritage contained with the FSW can be achieved for SLS with minimal risk

Component	Est. Reuse SLOC	Est. Total SLOC	Design	Manufacture	Software	Provider	Use	Prior Use	TRL
Application									
Command Manager	1000	1400	Full	Full	Partial Update for <TBD>-specific commands	Full SwRI	Full	CYGNSS MMS-CIDP	9
Telemetry Manager	3000	5800	Full	Full	Partial Update for <TBD>-specific telemetry	Full SwRI	Full	CYGNSS	8
ATS/RTS Library	724	724	Full	Full	Full	Full SwRI	Full	CYGNSS	8
Storage Manager	1629	1629	Full	Full	Full	Full SwRI	Full	CYGNSS	8
Autonomy/ FDC	2500	4100	Full	Full	Partial Update for <TBD>-specific autonomy & fault monitors	Full SwRI	Full	CYGNSS	8
Thermal Manager	100	150	Full	Full	Partial Update for <TBD>-specific thermal design	Full SwRI	Full	CYGNSS IMAGE-CIDP	9
ADCS I/O Manager	2300	3000	Full	Full	Partial Update for <TBD>	Full SwRI	Full	CYGNSS	6
ADCS Algorithm	ADCS algorithmic code imbedded in XACT module, Blue Canyon COTS product.								

Component	Est. Reuse SLOC	Est. Total SLOC	Design	Manufacture	Software	Provider	Use	Prior Use	TRL
Position & Time Manager	650	1000	Full	Full	Partial Update for <TBD> GPS receiver	Full SwRI	Full	CYGNSS	8
Instrument Manager	0	2500	Partial Instrument Manager design patterns reused from prior missions	Full	None Mission-specific instrument	N/A SwRI	N/A	N/A	4
Data Compression	600	1000	Partial	Full	Partial Existing flight code from prior missions is available. Selection pending trade study.	Full SwRI	Partial	IMAGE-CIDP TBD others	9
System									
Bootstrap	2041	2041	Full	Full SwRI	Full	Full	Full	CYGNSS MMS-CIDP	9
RTEMS RTOS	COTS	COTS	Full	Full	Full	Full Gaisler	Full	CYGNSS MMS-CIDP Other	9
Centaur BSP	1800	2100	Full	Full	Partial <TBD>-specific updates	Full SwRI	Full	CYGNSS MMS-CIDP	9
UART Driver	891	891	Full	Full	Full	Full SwRI	Full	CYGNSS Others	9
Flash Driver	578	578	Full	Full	Full	Full SwRI	Full	CYGNSS	8
SpW Driver	463	463	Full	Full	Full	Full SwRI	Full	CYGNSS	8
Transceiver Driver	400	600	Full	Full	Partial Update for <TBD> transceiver	Full SwRI	Full	CYGNSS	8

B.5 Structure, Mechanisms and Thermal Engineering Heritage level: High/Medium

Description of Design Heritage: SwRI has 35+ years of successful instrument and avionics SMT design heritage. All of our hardware involves SMT development with numerous examples at the instrument level and exposed to the same environments as their host S/C. The SLS Spacecraft requirements for a milled aluminum, bolt-together structure represent an excellent match to this avionics heritage, as well as direct correlation to SwRI's design, fabrication, and test capabilities. A summary of heritage components used for the SLS SMT subsystem is provided in Table 5. SwRI has significant heritage in a wide range of both static and dynamic structural design/analysis capabilities related to SLS. SwRI has extensive experience modeling nonlinear responses of materials and structures (e.g., high strain rates, large deflections, anisotropic materials), using state-of-the-art analytical and computational modeling approaches.

While ProEngineer and ANSYS are typically used for SwRI space structural design/analyses iterations, SwRI maintains licenses for and staff experienced with a large variety of CAD and FEA tools (e.g., SolidWorks and NASTRAN). These design tools have been employed on a range of space structures from instruments (e.g., New Horizons SWAP & Alice) to large structures (e.g., RAISE, Space Shuttle).

The SLS structure is also based closely on the CuSP CubeSat structure, with a common backplane serving to transfer launch loads to the PSC separation mechanism as well as serving as radiation shielding. The layout simplifies

integration and test while providing a highly mass- and space-efficient enclosure.
Figure 3 provides an image of the CYGNSS 3U avionics chassis as integrated into the overall CYGNSS spacecraft before completing electronics integration. This chassis is an example of SwRI's standard avionics chassis used for numerous successful missions including Deep Impact, Orbital Express, and Kepler, and is capable of conduction cooling power loads over 100 W.

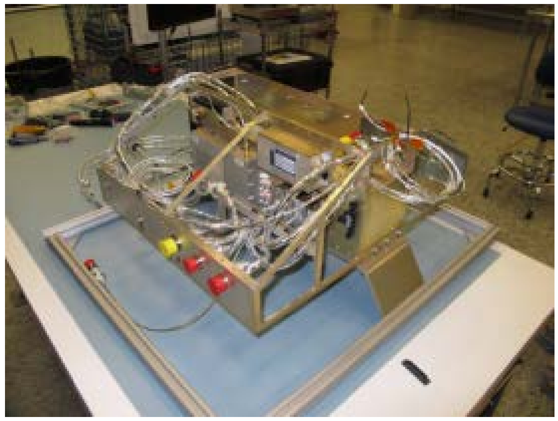


Figure 3. *CYGNSS Structure.*

SwRI Space Systems Division has extensive in-house manufacturing capabilities with division machinists who have accumulated a vast amount of experience producing flight hardware over the course of missions referenced in this document (e.g., CYGNSS, New Horizons, IMAGE, IBEX). SwRI's facility is capable of handling complex designs, exotic materials, and close-tolerance requirements. The machine shop craftsmen work closely with program engineers during the planning, design, and production phases of projects to ensure high-quality products that meet mission requirements, including schedule and cost targets. The shop processes hardware per the program Manufacturing Planning Sheet workflow instructions, carefully documenting each step of fabrication. The equipment available in the shop includes CNC three- and four-axis mills, manual mills, manual lathes, plunge EDM, welder, waterknife, and various saws. In addition to this resource, division facilities also include a Special Processes Laboratory used for painting, silk-screening, and applying surface treatments such as platings and coatings. SwRI also has a much larger and general-purpose machine shop as another cost-competitive resource for fabrication of quality parts with a short lead time.

Mechanisms. SLS uses solar array panel assemblies provided by Clyde Space, including ClydeSpace deployment mechanisms and hinges. Separation from the host mission is via a standard Planetary Systems Corporation 6U CubeSat deployer, again COTS TRL9 hardware.

Thermal. SwRI designs have been built, tested, and proven over a wide variety of thermal environments including earth orbit, lunar, and interplanetary missions. Like CYGNSS, the SLS spacecraft thermal design utilizes standard materials, sensors, and heaters. SwRI possesses a unique understanding of the collaboration and technical interchange that must take place between the spacecraft provider and the instrument team.

For the highly successful SwRI led IMAGE mission, SwRI played a system engineering and payload integration role bringing together 15 different instrument teams. The SwRI team was actively involved with the selection of control methods and materials used to manage the thermal performance of the spacecraft. On SWIFT, the SwRI-produced SWIFT-XRT electronics package was thermally isolated from the spacecraft and included dedicated radiators to dissipate internally generated heat to space. More recently, the SwRI led New Horizons spacecraft included the SWAP and ALICE instruments designed and built by SwRI. Each instrument included active and passive thermal control systems (MLI, heaters, radiators, etc.). A thermal analysis was completed for each instrument in full orbital environments with transient heating rates. While Thermal Desktop is the primary thermal analysis tool used at SwRI, other software packages such as ANSYS® and PCAnalyze are also used extensively. In addition to SINDA/ FLUINT (Thermal Desktop finite difference solver), models are hard-coded and solved in TAK 2000 without pre- and post-processors.

SLS will incorporate standard MLI blankets similar to those specified and procured for CYGNSS, IMAGE, LRO-LAMP, and Juno-UVS from established vendors (e.g., Mantech). Paints, tapes, and coatings will be used, such as the Z93 paint that was used on the Kepler SIB and SWIFT-XRT avionics boxes. Active control elements will be managed using circuits identical to CYGNSS that were derived from SwRI's heritage heater driver used on WISE, Orbital Express, and Kepler.

Modification for SLS:

Structure: The structural design for the SLS spacecraft is very similar to CuSP but there are exceptions to accommodate the instrumentation. The core machined aluminum structure is well within SwRI's avionics and instrument structure development heritage.

Mechanisms: The only significant modifications to the CYGNSS mechanism compliment are the use of the Planetary Systems Corporation separation mechanism for interfacing the SLS structure to the host mission and the use of ClydeSpace thread cutters for deployment of the solar array panels and the secondary reflector and heat shield. However, the CuSP mission, though still in integration, provides heritage and experience with these elements. The Cubesat dispenser has been used successfully in flight multiple times. Use of these mechanisms greatly simplifies the design of SLS while also increasing its flight heritage.

Thermal: The SLS thermal subsystem uses the same CYGNSS and CuSP SC standard thermal subsystem as SwRI avionics and critical instrument designs. The SLS SC thermal design employs SwRI's flight-proven, well-characterized thermal design techniques to ensure all components are maintained within their temperature limits throughout all modes of SLS operation. Each surface receives treatment tailored for its specific heat load and thermal radiation environment based on thermal analysis of all operational cases. Thermal blankets are custom designed, but use standard materials and SwRI processes. No modifications to SwRI standard materials or processes are required for SLS thermal control.

Benefits of Heritage to SLS:

Thermal: The SLS thermal design is based on CYGNSS and CuSP thermal designs, which were grounded in the experience, best practices and lessons learned from previous SwRI missions. Thermal control components (sensors, heaters, blankets and surface treatments) use proven TRL 9 hardware, materials and processes to reduce cost and schedule risk. Thermal control electronics are identical to CYGNSS and CuSP applications.

Rationale Supporting Achievement of Heritage:

Modifications for SLS from heritage SMT systems are very minimal. This maximizes the probability of realizing benefits from this heritage on SLS.

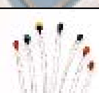
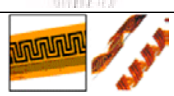
Cost Comparison to Heritage:

The SLS cost estimate for SMT is based on the CYGNSS development effort and several past avionics and instrument programs. The PM, PSE, and S/C Lead used actuals from heritage programs to estimate the needed resources and level of effort. A senior SMT lead is assigned half time for the duration of Phases A-C and quarter time in Phase D. The lead is supported by a thermal analyst and designer both quarter time in Phases A-D with 2 months full time in Phase D during thermal balance testing and thermal model correlation. The material and machining cost for the SLS structure is based on the cost of the electronics housing of the various CYGNSS chassis.

Costs associated with thermal engineering and thermal hardware are based on a ratio of the effort budgeted for the thermal design of CYGNSS.

Costs associated with the solar panel mechanisms are from vendor quotes for the delivery of EM and flight units from ClydeSpace. Use of heritage mechanisms reduces development risk and NRE cost. With COTS components, the unknowns associated with system development and qualification are greatly reduced. All mechanisms have been designed, built, and tested, and all have flight heritage.

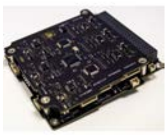
Table 5 Structure, Mechanisms, and Thermal

Subsystem	Image	Design	Manufacture	Provider	Use	Operating Environment	Prior Use	TRL
Structure		**Full** CYGNSS in I&T	**Full** SwRI standard design and processes with demonstrated expertise	**Full** SwRI	**Full** CYGNSS in I&T	**Full** Environment identical to CYGNSS	**Full** CYGNSS in I&T	**7**
Temperature Sensors		**Full** Off the shelf	**Full** Standard parts and processes	**Full** Measurement Specialties, Goodrich - Supplier	**Full** Identical to prior use	**Full** Identical to prior use	**Full** Identical to units flown on dozens of missions	**9**
Heaters		**Full** Off the shelf	**Full** Standard parts and processes	**Full** Watlo, Minco	**Full** Identical to prior use	**Full** Identical to prior use	**Full** Identical to units flown on dozens of missions	**9**
Surface Finishes		**Full**	**Full** SwRI standard materials and processes	**Full** SwRI	**Partial** Tailored for specific configuration	**Full** Within margins of capabilities	**Full** Identical to units flown on dozens of missions	**7**

B.6 Electrical Power Subsystem Heritage level: High

The COTS Clyde Space Electrical Power System (EPS) consists of Solar Arrays, 3G FlexU EPS converter, and two 0.3U 40WHr Lithium-Ion Polymer (LiPo) battery packs specifically designed for CubeSats. The 3G FlexU is a set of two joined boards and occupies 0.2U. The entire EPS is a commercial-off-the-shelf unit that is purchased in a tested configuration and requires no further development or testing other than Integration Testing. The 3G EPS is capable of drawing power from up to 9 1Ux3U solar panels. The CuSP Mission uses the identical hardware with the exception that two of the 3U panels are body mounted on CuSP and deployed together as a 6U panel on SLS. This allows for 100% reuse of the flight software used to command and monitor our unit. Table 6 describes the EPS components.

Table 6. Electrical Power Subsystem Component Heritage

Subsystem	Image	Design	Manufacture	Provider	Use	Operating Environment	Prior Use	TRL
Solar Panel and deployer		**Full** Existing heritage design	**Full** Clyde Space	**Full** Clyde Space	**Full** Identical interfaces and application	**Full** Identical, LEO	**Partial** CuSP	**7**
Battery 8SP3		**Full** Existing heritage design	**Full** Clyde Space	**Full** Clyde Space	**Full** Identical interfaces and application	**Full** Identical, LEO	**Partial** CuSP	**7**
PPT, LVPS		**Full** Existing heritage design	**Full** ClydeSpace	**Full** ClydeSpace	**Full** Identical interfaces and application	**Full** Identical, LEO	**Partial** CuSP	**7**

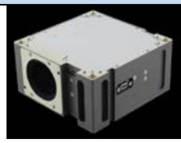
B.7 Attitude Determination and Control System (ADCS) Heritage level: High

The Blue Canyon Technologies (BCT) XACT, Attitude Determination and Control System (ADCS), is designed specifically for CubeSats. It is a complete ADCS in a 0.5U package. The XACT is a commercial-off-the-shelf unit that is purchased in a fully tested configuration and requires no further development or testing other than Integration Testing. The XACT uses a star tracker for 3-axis stellar attitude determination. BCT provides support in configuring the unit for its region of operation including defining the spacecraft axis and pointing vectors (such as FOV, antenna, and solar array directions) The CuSP Mission uses the exact same model and as such has the same command set. This allows for 100% reuse of the flight software used to command and monitor our unit. Table 7 gives its heritage.

This self-contained ADCS includes an embedded attitude processing computer, a star tracker, onboard star catalog, three-axis Reaction Wheel Assembly (RWA), sun sensors, Inertial Measurement Unit (IMU), a magnetometer and magnetorqurers. The XACT performs closed-loop momentum control with either the magnatorquers or a cold-gas thruster. The CuSP Mission uses the XACT to control a VACCO thruster directly for inertia shedding due to operation in deep space where there is a very low magnetic field. The XACT in SLS will use its integrated torque rods for momentum dumping and the thruster for decommissioning.

The XACT has Flight Heritage in the LASP/University of Colorado MinXSS mission launched June of 2016. The XACT is also supporting 16 CubeSat Missions scheduled to fly by 2018 including CuSP and the two JPL MaRCO CubeSats that will travel to Mars.

Table 7. Attitude Determination and Control System Heritage Table

Subsystem	Image	Design	Manufacture	Provider	Use	Operating Environment	Prior Use	TRL
XACT integrated ADCS unit including sensors and effectors		**Full** Identical to prior use	**Full** Manufacture facilities, identical processes and procedures.	**Full** Blue Canyon	**Full** Identical to prior use	**Full** Identical to prior use	**Full** MinXSS, UC/LASP	**9**

B.8 Propulsion Subsystem   Heritage level: High

The VACCO Standard Micro-Propulsion System (MiPS) is a low-cost, cold gas propulsion system designed specifically for CubeSats. Specifically a 0.5U MiPS thruster, one in a family of COTS thrusters from VACCO, is baselined for SLS. This commercial-off-the-shelf unit is purchased in a tested configuration and requires no further development or testing other than Integration Testing and fueling (adding cold-gas). The CuSP Mission uses a 0.3U thruster from the same family (the difference being only tank size) and as such has the same command set. This allows for 100% reuse of the flight software used to command and monitor our unit.

This self-contained, micro-propulsion system includes 5 thrusters to provide roll, pitch, yaw, and delta-V capability. It uses self-pressurizing, non-hazardous, green R236fa (used in fire extinguishers) as the propellant so is inherently safe. This unit contains 401g of propellant, providing 40-sec of Specific Impulse, 157N-sec of Total Impulse, and can provide our CubeSat with ~20m/s of delta-V. Table 8 shows heritage for the VACCO unit.

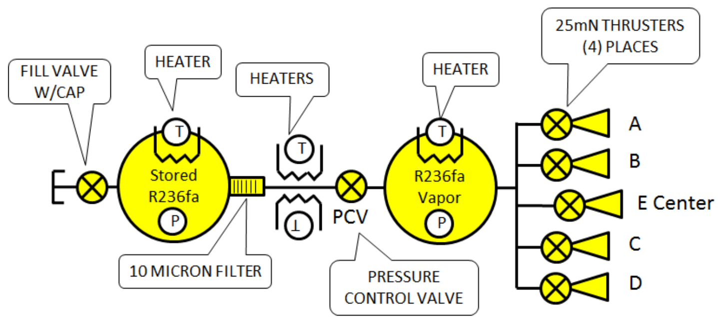


Table 8. Propulsion Heritage Table

Subsystem	Image	Design	Manufacture	Provider	Use	Operating Environment	Prior Use	TRL
VACCO integrated cold gás propulsion unit		**Full** Identical to prior use	**Full** Manufacture facilities, identical processes and procedures.	**Full** VACCO	**Full** Principally for delta-V with angular momentum capability backup.	**Full** Identical to prior use	**Partial** CuSP	**6**

B.9 Launch Vehicle/Services   Heritage level: High

SLS is using a NASA provided launch vehicle as a host mission. Costs for the launch vehicle and environmental assessment are per the AO. SLS launches inert, and will deploy to its mission orbit subsequent to deployment of the primary mission. A connector "Breakwire" opens on separation to activate the C&DH and begin the deployment sequence. Accommodations are in a standard Planetary Systems Corporation Canisterized Satellite Dispenser (PSC-CSD), requiring one 6U bay for each of the two SC.

B.10 SLS Deployment Module   Heritage level: High

Description of Design Heritage: The PSC-CSD Deployment Mechanism leverages a PSC history of more than 50 missions with no deployment failures. The 6U CSD was baselined for the SPARK* (Super Strypi) mission in 2015 (although a launch vehicle failure prevented activation of the CSD mechanism after launch). Prior to that, a 3U version of the CSD successfully separated the POPACS mission.

Modification for SLS: There are no modifications to the CSD for the SLS mission.

Benefits of heritage to SLS:. The benefits of reuse of the CSD system with no changes are threefold: 1) reduced cost, 2) enveloping environments as well as interfaces are already known and will not change during course of the project developmnt, and 3) reduced technical risk. Since the separation characteristics are already known, the non-recurring engineering effort is substantially reduced. In addition, the SLS mechanical configuration is designed to complement the CSD mechanical interface, providing optimal use of mass and volume in the SC design.

Table 9 Deployment System Heritage Table

Subsystem	Image	Design	Manufacture	Provider	Use	Operating Environment	Prior Use	TRL
Cannisterized Satellite Dispenser		**Full** Identical to prior use	**Full** Manufacture facilities, identical processes and procedures.	**Full** Planetary Systems Corporation	**Full** Identical to prior use	**Full** Identical to prior use	**Full** Super Strypi, POPACS	**9**

B.11 System Integration and Test   Heritage level: Medium/High

Description of Design Heritage: SwRI recently completed the Observatory AI&T campaign for the 8-S/C CYGNSS mission. Previous experience building S/C avionics, Spaceflight Instruments, payload I&T, and overall mission management made this milestone accomplishment possible. While CYGNSS was the first complete Observatory designed, integrated, and tested at SwRI, it was arguably less complicated and more easily managed than some prior payload AI&T activities performed by SwRI. For the IMAGE mission, SwRI was responsible for receiving, processing, installing, and testing over 15 individual instruments/electronics, from around the world, onto the flight honeycomb deck. For the MMS Mission, SwRI was responsible for receiving, processing, installing, and testing 30 components, including 25 instruments, on a flight deck. The MMS effort required tremendous coordination between the instrument suite team at SwRI and subcontracted institutions around the world. Additionally, MMS consisted of four identical observatories; the first payload deck was integrated at SwRI, and the remaining three payload decks were integrated at GSFC by SwRI personnel and instrument suite team members using SwRI processes and procedures. These recent projects have proven SwRI's capabilities with respect to parallel AI&T of multiple copies of instrument/component hardware as well as multiple observatories. The infrastructure at SwRI has been designed and implemented in support of NASA missions over more than 35 years. SwRI has the necessary processing facilities, the majority of the test facilities, and an experienced team of engineers and technicians. Given the simple S/C design, small bus size, and recent experience from the very similar CYGNSS and CuSP missions, SwRI is poised to execute an equally efficient AI&T campaign for SLS.

SwRI leads SLS AI&T. AI&T is set up similar to a matrix organization. SwRI costs are based on one AI&T lead (PL-2) full time for the duration of Phases A-D and three AI&T teams each comprised of a test conductor (PL-2) and an electrical technician full time during Phase D. The SC AI&T teams are also supported by a floating mechanical technician, a mission ops flight controller (PL-1) and a SC subsystem engineer (PL-2) throughout phase D. Each AI&T team is responsible for pushing their observatory completely through AI&T to be ready to be installed on the SM. In addition to the AI&T team, four each of facility engineers (PL-2) and facility technicians working full time during AI&T allow observatories to proceed through AI&T in parallel. The EM AI&T is staffed by the AI&T lead and mechanical technician. The number and type of personnel assigned as part of the AI&T teams and facility personnel is very similar to what SwRI typically staffs in complicated instrument or instrument suite integration and test campaigns.

Modification for the SLS Mission : SLS will be using SwRI's new thermal vacuum chamber that is configured to accommodate parallel testing like that required for the production of the CYGNSS Observatories without modification. The CYGNSS Dynamic simulator will be updated for the SLS spacecraft dynamic model. Much of the CYGNSS Test Suite, which itself used hardware from WISE, can be reused for SLS. In particular, many of the tests for the communication subsystem are identical; the SLS power and thermal interfaces are subsets of the CYGNSS and WISE capabilities. The SLS ADCS interfaces are slightly different from CYGNSS, but the support hardware will not have to change.

The SLS Dynamics Model will be adapted from one originally developed for CYGNSS. The MULTFLX dynamics library can be used to generate an attitude dynamics simulation in a highly schedule and cost efficient manner.

Benefits of Heritage to SLS: The processes used for previous missions are very similar to those used for the WISE and CYGNSS Observatories. The infrastructure at SwRI has been designed and implemented in support of NASA missions over more than 35 years.

The benefits of GSE heritage are twofold: 1) reduced cost and 2) reduced technical risk. Non- recurring engineering costs are much reduced as a result of heritage.

Rationale Supporting Achievement of Heritage: SLS system AI&T is very similar in scope and complexity to that of CYGNSS. Both combine multiple observatory builds of similar size and complexity. As such, the SLS AI&T team is in a unique position to reuse the very successful CYGNSS AI&T heritage to ensure mission success.

Cost Comparison to Heritage: The SLS SOC uses heritage from CYGNSS. As such, CYGNSS actuals, scaled for SLS complexity to account for the reduced number of spacecraft, have been used. All costs from other projects were inflated appropriately using NASA inflation factors. SLS costs are further reduced through the reuse of CYGNSS developed processes, facilities, and a modified version of the CYGNSS dynamic simulator updated to for the SLS spacecraft.

C. Mission Operations Heritage level: High

Description of Design Heritage: SwRI has extensive experience in mission operations, science operations, data processing and data archive preparation and submission. SwRI's operations team is currently using the Mission Operations Center (MOC) for the CYGNSS constellation – preparing and executing Mission Simulations interacting with the CYGNSS Observatories – and will be responsible for running Mission Operations starting from launch through the life of the mission. The SwRI team also has extensive experience gained from operating the New Horizons payload, LRO/LAMP, Rosetta/Alice, MRO/SHARAD, Cassini/IMNS, and Cassini/CAPS. The SwRI team is also heavily involved in operations for IBEX.

SwRI is responsible for developing all MOC capabilities for the CYGNSS constellation and for coordinating all operations of each of the Observatories within the constellation. The SwRI operations team is gaining experience in operating both a single observatory and a constellation through both the Observatory and Ground Segment integration and testing processes. SLS employs a similar operations concept, as well as using the same core observatory C&T system, ensuring the experience gained by the CYGNSS team will be directly applicable to the operations of the SLS observatories.

SwRI operates the entire New Horizons science payload with responsibility for generating all commanding for the New Horizons instruments, including the commanding for the instrument, the SC pointing and SC recording operations necessary to perform each observation. SwRI designed and implemented the full observing timeline and all observations for the successful New Horizons Pluto encounter, including evaluating and staying within allocated SC resources.

On the New Horizons project, SwRI is also responsible for the development, maintenance, and execution of the data pipelines which process the raw data for each of the seven New Horizons instruments. The data pipelines convert the raw packets of data to functional data products by: assembling packets, detecting missing data, correlating housekeeping information and calibrating data and calculating geometry.

The IBEX Mission Operations Management office is run by SwRI. All aspects of operations are coordinated through the Mission Operations Manager including developing and maintaining the operations plan, coordinating communication between all ground segment elements (MOC, SOC, Ground Network), and providing oversight and review of the day to day operations schedules and command loads.

MOC components, as developed on CYGNSS, are deployed predominately on server based Virtual Machines (VMs). The VM architecture developed on CYGNSS is directly applicable to SLS.

MOC development includes the customization and deployment of the GOTS ITOS pack- age to support the CYGNSS mission operational concepts and to interface with the CYGNSS Observatories command and telemetry systems. The CYGNSS ITOS systems are used for FSW testing, Observatory AI&T, and Mission Operations. For SLS, the ITOS command and telemetry database information and utilities will be customized to support the unique aspects of the mission. With a similar operations concept and Observatory C&T Interface, modifications for SLS will be minor. The mission planning approach using a SwRI developed database front-end (SwRI Mission Planner – SIMPL) to the COTS STK Scheduler – STK tool-set will be directly applicable to SLS.

SwRI's operations experience prior to CYGNSS ranged from single instrument operations through full payload operations, providing a solid team experience basis for running the SLS mission. Tools and processes developed to perform operational planning and data processing tasks have formed the basis for the CYGNSS operations capabilities and will be used on SLS.

SwRI will use the successfully employed IBEX Mission Management approach to coordinate the SLS constellation operations efforts.

Modification for the SLS Mission: The SLS MOC is modified from the CYGNSS MOC only where necessary to meet SLS needs. The CYGNSS procedures and much of the CYGNSS code will be reused, but some tailoring will occur where needed to meet SLS specific SC and instrument needs.

Benefits of Heritage to SS: Reuse of SwRI MOC from multiple missions, including the very similar CYGNSS mission greatly reduces schedule, cost, and technical risk for SLS mission operations.

Rationale Supporting Achievement of Heritage: CYGNSS is a constellation of 8 micro- satellites similar in nature to the 2 SLS SC in terms of mission operations, operational concept, and data rates (see Section F). As such, reuse of the CYGNSS MOC provides a very low risk, high probability of success approach for SLS.

Cost Comparison to Heritage: The SLS MOC uses heritage from CYGNSS. As such, CYGNSS actuals, scaled for SLS complexity to account for the reduced number of spacecraft (down from 8 to 2), the increased number of instruments, and associated data rate changes relative to CYGNSS, have been used for the majority of the costs, with the exception of ground station contact costs, for which an estimate has been incorporated. All costs from other projects were inflated appropriately using NASA inflation factors. SLS MOC costs include SwRI and NEN costs in Phase E from WBS element 7, Mission Operations, as well as SwRI costs in Phases A through D for MOC development from WBS element 9, Ground Segment. SLS costs are further reduced through the reuse of CYGNSS developed processes, facilities, and software.

C.1 Ground Support Equipment (GSE) Heritage level: High

SwRI employs a “test as you fly and fly as you test” verification philosophy. Utilizing a requirements database, verification of requirements starts at the component level and continues throughout the integration and test flow utilizing SwRI’s coordinated test and verification environment (Figure J.9.6.2-1) to verify the SLS observatories. Early FSW development is performed on S/W development platforms using COTS processors. As EM H/W becomes available, FSW unit testing and verification transitions to SWTBs comprised of EM H/W and external interface simulators. Testing then transitions to the Systems Test Bench (STB) at SwRI where testing is performed on the EM S/C to provide full “test-as-you-fly” simulations that include pointing models for the S/C and RF stimulation of the DMR.

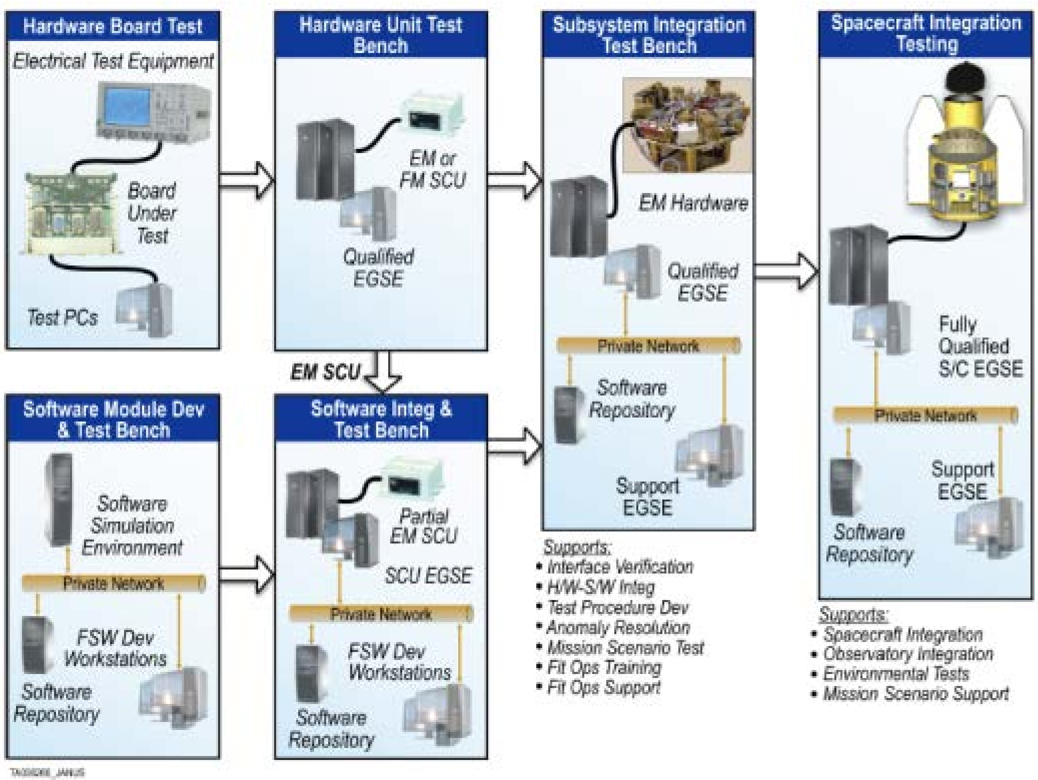


Figure 4 *. SwRI test and verification environment supports development through all phases of H/W and FSW development.*

Table 10 below lists the EGSE available for SLS Observatory I&T and verification

Table 10 *Electrical GSE List*

EGSE	Heritage Level	Comments
ITOS Workstation	High	COTS CDS Test System interface used on IMAGE, JANUS Phase A, and several internal development programs
Power Rack	Medium	EGSE rack based on WISE and Kepler test sets. Used for direct power when battery not installed. Requires addition of S/A simulation capability (available as COTS).
Telecom Rack	High	RF rack Based on COTS Cortex and Miteq RF equipment. Some modifications may be required for SLS antennae

ADCS Stimulator	High	Provided by Aerospace Corp, model by Draper Lab.
NTP Timebase	High	COTS Stratum 1 GPS-based timebase for system-wide synchronization
Spacewire I/F	High	SwRI custom I/F for loading/debugging Centaur S/W
Battery Surrogate	High	SwRI custom battery emulation for V&V under battery conditions (COTS batteries with custom enclosures and circuitry)
Telemetry Processor	High	COTS custom NetAcquire telemetry processor
Power Control	High	SwRI custom NI PXIe-based power, power sequencing and control for automated testing, including LV breakwire support

SwRI's test environment is based on two key elements; the Simulator Platform and the S/C Dynamic Simulator. These elements are used for all of the environments and are augmented as described above to form the specific test environment (H/W, FSW, Subsystem, and S/C) (Table 11 and 12 provide GSE Heritage summary)

Table 11 GSE Hardware Heritage Table

Subsystem	Image	Design	Manufacture	Provider	Use	Operating Environment	Prior Use	TRL
Centaur GSE Hardware		**Full** Identical	**Full** Identical	**Full** **SwRI**	**Full** Identical	**Full** **Identical**	**Full** WISE	**9**

Table 12 GSE Software Heritage Table

Component	Est. Reuse (SLOC)	Total SLOC	Design	Manufacture	Provider	Use	Prior Use	TRL
GSE Software	**84090**	**97120**						
Analog I/O and C&T Library	31300	31300	**Full** Library was developed for COTS NI PXI cards.	**Full** Identical processes and procedured	**Full** SwRI	**Full** Identical	**Full** From WISE codebase	**9**.
Test Suite	52790	65820	**Partial** Thermal subsystem tests will not be reused from WISE.	**Full** Identical processes and procedured	**Full** SwRI	**Full** Identical functions	**Full** From WISE codebase	**9**
Dynamics Simulator	**60000**	**84400**						
Aerospace Corp Simulation Toolset	50000	70000	**Full** Framework has been used effectively on several flight programs.	**Full** Identical processes and procedured	**Full** Aerospace; supplier	**Full** Identical functions	**Full** Reusable simulation executive used on SBIRS.	**9** Mature Asset
Dynamics Model	10000	14400	**Partial** GPS removed	**Full** Identical processes and procedured	**Full** Aerospace; supplier	**Partial** Identical functions	**Partial** Need to develop component models	**4**

C.2 Simulator Platform Heritage level: High

The Simulator Platform is the core hardware for all of the SwRI test environments except the FSW Development Workstation (which is based on standard computer workstations). It is derived from the test set built for the Wide-field Infrared Survey Explorer (WISE). SwRI was responsible for the WISE Spacecraft Control Assembly (SCA). The SwRI WISE SCA provided a feature set similar to SLS: C&T processing, ADCS interfaces, thermal control, battery conditioning, and power distribution. The Simulator Platform consists of a low-cost control PC, several National Instruments' COTS PXI components and Lab Windows/CVI software. It also includes a SwRI developed software library to support testing of full WISE SCA, which is available to the SLS mission.

Spacecraft Dynamic Simulator.

The test environment includes a S/C Dynamics Simulator developed by The Aerospace Corporation that is used to verify the S/C ADCS FSW and provide stimulation to the flight system during operational scenario testing. The simulator is a software-only real-time environment. It is based on the Aerospace Corporation Simulation Toolset, which includes COTS tools such as Simulink and Labview as well as custom tools developed by Aerospace such as the MultFlx multi-body dynamics simulation library. The Aerospace Corporation has used this toolset to develop ADCS validation platforms for a number of space programs including GPS, SBIRS, AEHF, DMSP, DSCS, Milstar, and the Boeing 702 commercial bus.

Appendix J10. Acronyms and Abbreviations

ALMA	Atacama Large Millimeter Array
APEX	Atacama Pathfinder Experiment
ASPECS	ALMA Spectroscopic Survey in the Hubble Ultra-Deep Field
CNM	Cold Neutral Medium
COBE	Cosmic Background Explorer
COTS	Commercial Off the Shelf
CSD	Canisterized Satellite Dispenser
CuSP	Cubesat for Solar Physics
DSB	Double Sideband
FIRAS	Far Infrared Absolute Spectrophotometer
FFT	Fast Fourier Transform
FOV	Field of View
FSOTF	Frequency Switched On the Fly mapping
FUV	Far Ultraviolet
GMC	Giant Molecular Cloud
GOTC+	Galactic Observations of Terahertz C+
GPS	Galactic Plane Survey
HEAT	High-Elevation Antarctic Terahertz telescope
IF	Intermediate Frequency
IRAS	Infrared Astronomy Satellite
IMF	Initial Mass Function
ISM	Interstellar Medium
JCMT	James Clerk Maxwell Telescope
LNA	Low Noise Amplifier
LO	Local Oscillator
LOS	Line of Sight
LSST	Large Synoptic Survey Telescope
MEV	Maximum Expected Value
SLED	Spectral Line Energy Distribution
SMG	Submillimeter Galaxy
SMT	Submillimeter Telescope
SSB	Single Sideband
STO	Stratospheric Terahertz Observatory
SWAS	Submillimeter Wave Astronomy Satellite
SwRI	Southwest Research Institute
TDS	Targeted Deep Survey

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