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RESEARCH PAPER

Single Aperture Large Telescope for Universe Studies: science overview

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ABSTRACT. The Single Aperture Large Telescope for Universe Studies (SALTUS) probe mission will provide a powerful far-infrared (far-IR) pointed space observatory to explore our cosmic origins and the possibility of life elsewhere. The observatory employs an innovative deployable 14-m aperture, with a sunshield that will radiatively cool the off-axis primary to <45 K. This cooled primary reflector works in tandem with cryogenic coherent and incoherent instruments that span 34- to 660-μm far-IR range at both high and moderate spectral resolutions. The mission architecture, using proven Northrop Grumman designs, provides visibility to the entire sky every 6 months with ~35% of the sky observable at any one time. SALTUS's spectral range is unavailable to any existing ground or current space observatory. SALTUS will have 16× the collecting area and 4× the angular resolution of Herschel and is designed for a lifetime of ≥5 years. The SALTUS science team has proposed a Guaranteed Time Observations program to demonstrate the observatory's capabilities and, at the same time, address high-priority questions from the Decadal survey that align with NASA's Astrophysics Roadmap. With a large aperture enabling high spatial resolution and sensitive instruments, SALTUS will offer >80% of its available observing time to Guest Observer programs, providing the science community with powerful capabilities to study the local and distant universe with observations of 1000s of

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diverse targets such as distant and nearby galaxies, star-forming regions, protoplanetary disks, and solar system objects.

Keywords: far-infrared observatory; cooled deployable antenna; cryogenic heterodyne instrument; MKID grating spectrometer

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1 Introduction

Single Aperture Large Telescope for Universe Studies (SALTUS) is a probe class far-infrared (far-IR) space observatory (Fig. 1) that will provide a new, powerful window to the universe through which we can explore our cosmic origins. The unprecedented sensitivity and angular resolution of SALTUS are achieved by combining a passively cooled (≤ 45 K), 14-m off-axis telescope with actively cooled instruments consisting of (1) a suite of superconductor insulator superconductor (SIS) and hot electron bolometer (HEB) heterodyne receivers (HiRX[1]) with resolving power $R = 10^6$ to 10^7 and (2) a broad-band, 34- to 230-μm grating spectrometer (SAFARI-Lite[2]) with a resolving power of $R \sim 300$. Instrument performances are summarized in Table 1. SALTUS can observe numerous atomic and molecular species, as well as lattice modes of ices and minerals, which, due to atmospheric absorption and/or wavelength coverage, are beyond the capabilities of existing ground-based or space-based observatories (Fig. 2). SALTUS provides a set of capabilities that directly complements James Webb Space Telescope (JWST) and atacama large millimeter/submillimeter array (ALMA) and provides access to an important FIR spectral region inaccessible to current space- or ground-based observatories (see Fig. 3).

With its large collecting area and high sensitivity, SALTUS is uniquely capable of advancing the Decadal Survey's[4] high-priority science themes of "Cosmic Ecosystems" and "Worlds and Suns in Context." The SALTUS science objectives are listed by theme in Table 2 and mapped directly to numerous Decadal questions (shown in brackets) and the NASA Astrophysics Roadmap.[5]

Fig. 1 SALTUS observatory uses a radiatively cooled, inflatable 14-m off-axis aperture with sensitive far-IR, high, and moderate resolving power systems to open a new window on our universe. See Sec. 3 for details on the SALTUS observatory architecture.

Table 1 Summary of the SALTUS observatory. SALTUS instruments perform observations over a wide wavelength range with both high-resolution coherent and moderate-resolution incoherent detectors at high spatial resolution. HiRX is the high resolution ($R = 10^6 - 10^7$) heterodyne instrument that covers four discrete wavelength bands (bands 1, 2, 3, 4a, and 4b), as shown in Fig. 2. HiRX bands 1 and 2 offer continuous tuning capability using solid-state local oscillators (LOs). Bands 3 and 4 use quantum cascade lasers's as LOs with more limited tuning ranges. SAFARI-Lite offers a constant resolving power ($R = 300$) over its entire operating wavelengths.

Observatory	Aperture	Operating temp.	Dry mass CBE (kg)	Mission life	Orbit
SALTUS	14 m	<45 K	3030	≥5 years	L2 Halo
Instrument	Wavelength (μm)	Spectral resolving power	Sensitivity ($5\sigma/1$ h)	Detector type	Beam size (arcsec)
SAFARI-Lite	34 to 230	300	$\sim 2 \times 10^{-20}$ W/m^2	Microwave kinetic inductance detector (MKID) arrays incoherent	0.6 to 4.1
HiRX	56 to 660	10^6 to 10^7	~100 mK (see also Fig. 3)	SIS/HEB mixers coherent	1 to 11.7

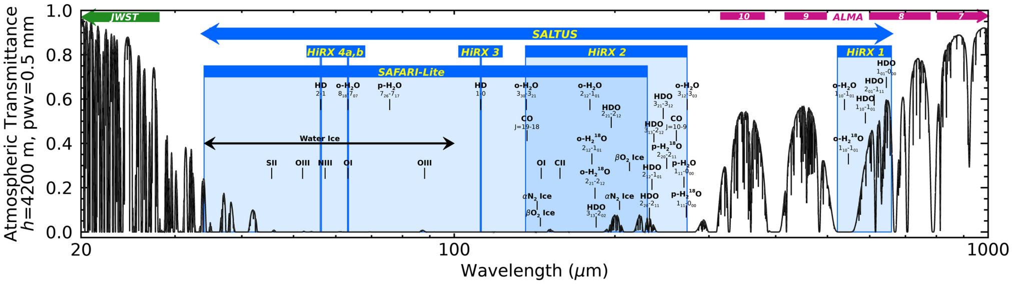

Fig. 2 Simulated terrestrial atmospheric transmission spectrum (black) demonstrating SALTUS's far-IR spectral region, inaccessible from the ground, and outside of JWST (green) and ALMA's (magenta) operational wavelengths. The tunable HiRX bands 1 to 4 with SAFARI-Lite (blue) target critically important wavelengths that are significantly or completely blocked from the ground; this includes low energy transitions of H_2O and its isotopologues and other species such as HD 1-0 and HD 2-1.

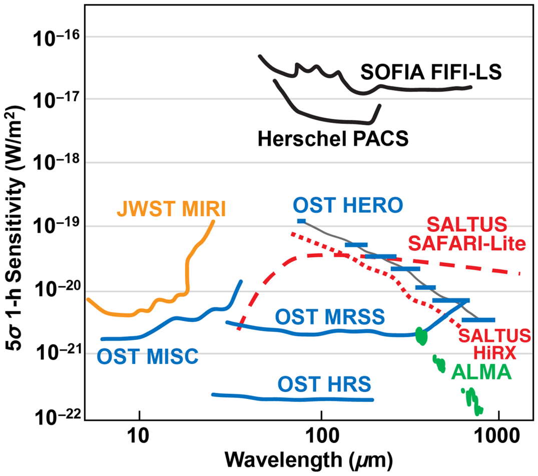

Fig. 3 SALTUS complements the capabilities of JWST and ALMA and exceeds the achievable performances of the Herschel[3] and SOFIA observatories by more than two orders of magnitude. It provides sensitivities comparable to the Origins Space Telescope flagship concept.

SALTUS's capabilities will enable significant progress toward resolving high-priority Decadal Survey questions in the areas of:

1. measuring the formation and buildup of galaxies, heavy elements, and interstellar dust from the first galaxies to today, probing the co-evolution of galaxies and their supermassive black holes across cosmic time, and,
2. tracing the astrochemical signatures of planet formation (within and outside the solar system).

The SALTUS observatory's flexible capabilities provide the astrophysics community with a robust Guest Observer (GO) program during a baseline 5-year mission, which could be extended by a factor of 2 or longer. The PI-led, Guaranteed Time Observations (GTO) discussed briefly in Sec. 4 aim to highlight SALTUS's capabilities, promising high-impact science, with illustrative GO science objective examples offered in Sec. 5. In addition, all SALTUS observations will be archived and made available to the science community through Caltech/IPAC after a 6-month latency period and will be a valuable dataset to be mined by Guest Investigator (GI) programs. More than 80% of the available observational time will be allocated for the GO program, which will foster unexpected explorations and a rich harvest of unforeseen discoveries (see Sec. 6).

The SALTUS observatory's robust design margins allow for the accommodation of a complementary, contributed third instrument that benefits from a large, cooled, diffraction-limited aperture. During a potential phase A study, SALTUS will investigate the feasibility of adding the B-BOP[6] as an additional instrument. B-BOP is a FIR polarimetric camera originally formulated for the ESA-JAXA SPICA observatory. It is designed to investigate the magnetic field in astrophysical environments by mapping the total power, degree, and angle of linear polarization in three bands at 70, 200, and 350 μm. The B-BOP cryogenically cooled array of silicon bolometers has an NEP of $\sim 10^{-18}$ $\mathrm{W/Hz^{1/2}}$, and its location on the observatory will be identified during the phase A study.

2 Need for Aperture

SALTUS will be the first far-IR space observatory with a large enough aperture to provide arcsec-scale spatial resolution (0.66 to 10 arcsec) in the far-IR. This will permit the unmasking of the true nature of the cold universe, which holds the answers to many of the questions concerning our cosmic origins. SALTUS will break through the confusion limit in extragalactic observations (see below), which plague smaller apertures[7] and probe the far-IR universe at unprecedented detail (Fig. 4). The SALTUS aperture allows attaining sensitivity performance close to the proposed

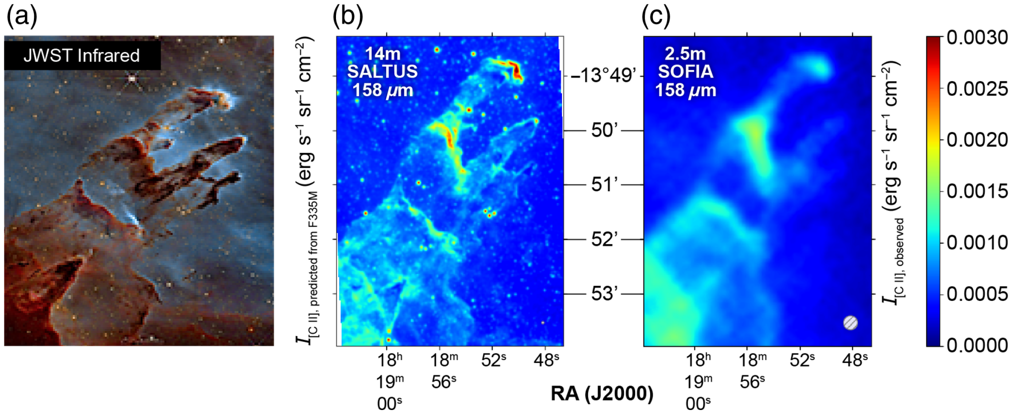

Fig. 4 Simulated SALTUS image at 2.5″ angular resolution (b) of the [CII] 158 μm emission in NGC 6611 (pillars of creation) is similar to the JWST image (a) and compared with the SOFIA-created map (c). SAFARI-Lite can map this 10-arcmin^2 region in 10 h and simultaneously provide maps in all diagnostic lines of photo-dissociation regions (PDRs) and HII regions in our galaxy and the local group, probing the physical environment produced by radiation feedback of massive stars and its link to stellar clusters and its molecular core. SOFIA image simulated by A. Tielens.

Origins Space Telescope and 31 times greater than that of SOFIA and 16 times greater than that of Herschel (Fig. 3). This increase in sensitivity means that SALTUS will be able to probe orders of magnitude deeper than any past far-IR mission. A large aperture also helps minimize the impact of beam dilution on spectral line observations when targeting objects smaller than the telescope's diffraction-limited beam.

Beam size and confusion noise are fundamental limits to the sensitivity and information content of far-IR observations. Confusion noise is defined to be the spatial variation of the sky intensity in the limit of infinite integration time and can only be directly addressed by increased telescope aperture size.

An observatory's minimum beam area is set by diffraction, which depends on the inverse square of the ratio of the aperture and wavelength. At some sensitivity levels, the number of distant galaxies will exceed the number of beams, and the sensitivity cannot be improved with better instrumentation or longer integration times.

The performance of current instrumentation indicates that aperture size will be the key driver in probing deeper. Using SPIRE on Herschel (3.5 m), a confusion limit of 5.8, 6.3, and 6.8 mJy/beam at 250, 350, and 500 μm, respectively, was quickly reached.[8] This is illustrated in Fig. 5, showing the 3σ confusion noise curves for SALTUS, Herschel, and a possible 2.5-m class facility such as SPICA. Magnelli et al.[9] and Bethermin et al.[10] carried out a detailed analysis of the achieved confusion limits with Herschel at 70, 100, and 160 μm and at 250, 350, and 500 μm, respectively. They derived that the behavior corresponds to the photometric definition of confusion, not the source density criterion. We scaled for aperture from the values obtained in these studies as described by Condon[11] and Vaisanen et al.,[12] assuming an spectral energy distribution (SED) differential source count as a function of flux density S of $N(S) \sim S^{-\gamma}$, with $\gamma = 1.7$, which is a reasonable value based on Herschel data. Figure 5 illustrates two key points. First, the 3.5-m Herschel observatory had essentially reached the confusion limit and could not go deeper. Second, the 14-m SALTUS observatory will break the 1-mJy confusion limit achieved by Herschel at its short wavelength range (Fig. 5), and it is an appropriate metric to gauge SALTUS's improved performance. This enables SALTUS to understand the true nature of the distant far-IR universe and greatly outperform past and anticipated space-borne facilities. Moreover, SALTUS will probe much deeper than Herschel with only 10 h of observations assuming existing detector performance. SALTUS will be greater than two orders of magnitude more sensitive than a cooled 2.5-m class facility. The confusion limit not only is an issue for the cosmic far-IR background but also strikes at the heart of many key questions, including the

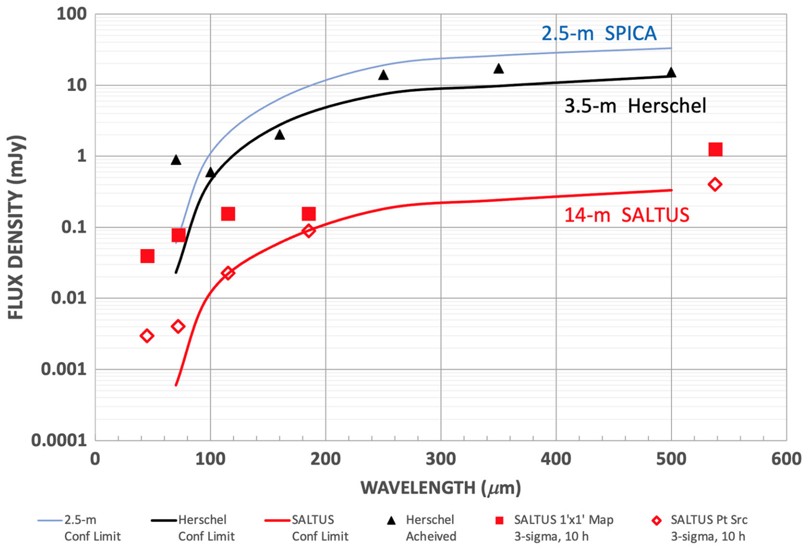

Fig. 5 Solid lines depict the 3-sigma confusion limits for telescopes of different sizes: the previously proposed 2.5-m SPICA (blue), the 3.5-m Herschel (black), and the 14-m SALTUS (red). The black triangles show the best-achieved sensitivity for Herschel. The red squares show the predicted SALTUS sensitivity for mapping a square arcminute in only 10 h of observations. The red diamonds show the predicted sensitivity of SALTUS for observing a point source for 10 h.

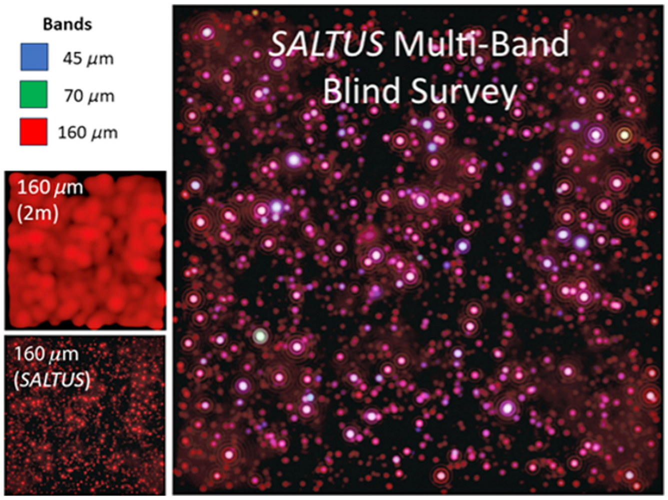

Fig. 6 Simulated SALTUS 4.74×4.74 arcmin COSMOS composite deep field; 45 μm (blue), 70 μm (green), and 160 μm (red) with logarithmic stretch from 0.2 to 1.2 mJy/beam (45 μm), 0.3 to 5.7 mJY/beam (70 μm), and 0.4 to 15 mJy/beam (160 μm). To produce the composite image, all three wavelength maps were convolved to the SALTUS resolution at 160 μm and combined. SALTUS will observe fewer than 1 galaxy per beam to a fraction of a mJy, even at 160 μm. To illustrate the resolving power of SALTUS, a native 160-μm SALTUS image is shown along with the same image convolved to the beam of a 2-telescope.

contribution of dust-obscured star formation to the star formation history of the universe and the rise of the PAH/dust abundance with cosmic time.

Existing extragalactic continuum far-infrared surveys are severely confusion-limited. Although low angular resolution surveys conducted with sufficiently high spectral resolution may address the confusion limit, they are biased by the emission from the brightest galaxies in a pixel. The contribution from fainter galaxies at a given wavelength will be easily lost in the glare of the continuum "headlight" of the dominant galaxy/ies. Spectral deconvolution techniques may be employed but require the character of the galaxies in the field (together with their infrared spectrum) to be understood to a high degree of confidence, which will often not be the case. Indeed, this is the information we seek to measure. Studies performed for the Origins mission concept demonstrated that, as there are many sources per beam, spatial blending is a significant issue for narrow band continuum SED images—even for a 5.9-m telescope—and simulations recover only 40% of the sources. Deblending techniques for emission line sources are slightly more effective as they recover ∼50% of the sources in narrow-band images.[13] Due to its native angular resolution, SALTUS can avoid many of the issues related to the far-IR continuum glare of the distant universe, which plagues smaller telescopes and, therefore, does not require *a priori* knowledge or assumptions to interpret its observations. Figure 6 is a simulated SALTUS multiband deep blind survey. Without the resolving power of SALTUS, the existence of the vast majority of low luminosity galaxies would be lost in the glare of the brighter objects, obscuring the true nature of the early universe. To understand galaxy evolution, it is imperative that we measure far-IR spectra of ordinary galaxies—not only exceptionally luminous galaxies—at redshifts out to the epoch of cosmic noon (i.e., $0 < z < 3$), which requires sensitivity of the order of tens of micro-Jy, a level attainable with SAFARI-Lite on SALTUS, but not with a Herschel-sized or smaller telescope.

3 SALTUS Observatory Architecture

SALTUS provides a powerful far-IR pointed observatory in a Sun–Earth Halo L2 orbit with a maximum Earth range of 1.8 million km. The observatory is comprised of the deployable telescope inflation control system, sunshield module (SM), cold corrector module (CCM), warm instrument electronics module, and primary reflector module (PRM). The primary reflector, M1, is a 14-m off-axis inflatable membrane building on decades of inflatable technology development heritage, including L'Garde's 14-m aperture reflector of similar design demonstrated on the Inflatable Antenna Experiment.[14] The PRM and instrument side of the observatory is radiatively cooled to <45 K by a ∼1000 m^2 two-layer sunshield, leveraging structural and thermal designs from NeXolve's heritage on the James Webb Space Telescope (JWST) and Solar Cruiser. The CCM corrects for residual aberrations from the primary reflector and delivers a focused beam to the two SALTUS instruments—the high-resolution receiver (HiRX) and SAFARI-Lite. The optical design and estimated wavefront error are further discussed in Kim et al.[15]

Similar to JWST, SALTUS can observe the entire sky in 6 months while also providing two continuous 20-deg viewing zones around the ecliptic poles. (An animation illustrating SALTUS sky coverage is located on the SALTUS web site, SALTUS.arizona.edu, under the "Next Generation Space Telescope" link.) Details of the SALTUS observatory architecture are presented by Harding et al.[16]

4 SALTUS Science Objectives

The PI-led GTO program addresses the SALTUS science objectives listed in Table 2. In Sec. 5, we provide examples of potential GO/GI programs enabled by SALTUS discovery space.

Table 3 highlights the traceability from the science objectives listed in Table 2 to the physical parameters and observables that the SALTUS GTO program will investigate.

4.1 SALTUS Theme 1: Cosmic Ecosystems

Theme 1 corresponds to the Decadal Survey's "Cosmic Ecosystems" theme and addresses the key science questions identified for a far-IR probe-class mission. As a versatile, sensitive observatory with arcsec-level spatial resolution, SALTUS is the natural complement to the near- and mid-IR capabilities of JWST. This theme outlines an ambitious science campaign designed to answer outstanding questions raised by the Decadal Survey, including: How do gas, metals, and dust flow into, through, and out of galaxies? How do supermassive black holes form, and how is their growth coupled with the growth of their host galaxies? Theme 1 will make use of SALTUS's unique capabilities to address science objective 1: Trace galaxy and black hole co-evolution and heavy element production over cosmic time, which comprises four key science investigations, listed in Tables 2 and 3, and expanded by Spilker et al.[17] and Levy et al.[18]

Thanks to the broad simultaneous wavelength coverage of the SAFARI-Lite, in particular, see Fig. 7, extragalactic observations of individual targets, pointed surveys of well-defined samples, and blank-field spectral mapping campaigns are all capable of addressing different aspects of the Cosmic Ecosystems science goals. Many of these goals (and beyond) will also be addressed by the wide variety of community GO observing programs enabled by the versatile and sensitive SALTUS capabilities. Moreover, SALTUS's nearby galaxy GTO observing program centers on star-forming spirals and starburst galaxies, but we expect the versatility of SALTUS to inspire a wide range of community GO programs targeting galaxies in the nearby

Table 2 SALTUS science objectives address relevant decadal themes and questions.

Decadal theme 1: cosmic ecosystems	Decadal theme 2: worlds and suns
SALTUS science objective 1:	SALTUS science objective 2:
Trace galaxy and black hole co-evolution and heavy element production over cosmic time.	Probe the physical structure of protoplanetary disks and follow the trail of water and organics from protoplanetary disks to the solar system.
1.1 What is the role of star formation in feedback in the local universe?	2.1 How does the mass distribution in protoplanetary disks affect planet formation?
1.2 When did metals and dust form in galaxies, affecting the process of star formation?	2.2 What is the spatial distribution and evolution of water vapor and ice in protoplanetary disks?
1.3 What are the roles of feeding black holes in galaxies from the early universe to today?	
1.4 Which feedback mechanism dominates as a function of time over cosmic history?	2.3 How did Earth and ocean worlds get their water?

Table 3 SALTUS science questions, physical parameters, and observations.

	SALTUS science investigation	Physical parameters	Observables
Theme 1: cosmic ecosystems	1.1 What is the role of star formation in feedback in the local universe?	Kinetic energy, momentum input, and shocked gas in star formation regions and nearby galaxies	Map star-forming regions in H_2O, [OI], [CII], [NII], [SII], H_2O, CO; 1 km/s velocity resolution Map shocks in high J CO and H_2O
	1.2 When did metals and dust form in galaxies, affecting the process of star formation?	Small carbon-bearing dust grains in galaxies from $z = 4$ to $z > 6$	Mid-IR PAH features from $z = 4$ to $z > 6$; 6.2/7 – 17 μm rest frame; $R \sim 300$
	1.3 What are the roles of feeding black holes in galaxies from the early universe to today?	High-velocity line wings in select star-forming galaxies and AGN at $0 < z < 2$	Molecular: H_2O/OH absorption, H_2 S(1) 17 μm at high-z end. Atomic: [CII] 158 to $z = 0.4$, [SiII] 35 to $z = 5.5$. Ionized: OIII 52/88, NeIII.
	1.4 Which feedback mechanism dominates as a function of time over cosmic history?	BH accretion rates and SFRs in large-volume surveys	Far-IR fine structure lines: [CII], [OI], [OIII], [NII], [NIII]; $R = 300$
Theme 2: Worlds and suns	2.1 How does the mass distribution in protoplanetary disks affect planet formation?	Mass and temperature structures of disks in a variety of environments	HD $J = 1 – 0$ and $2 – 1$; Far-IR H_2O and CO; 55 K < Tex < 1729 K Velocity resolved line profiles for selected sources
	2.2 What is the spatial distribution and evolution of water vapor and ice in protoplanetary disks?	Water vapor distribution and ice abundances in disks of various ages	Numerous far-IR transitions of H_2O vapor/far-IR phonon modes of H_2O ice
	2.3 How did Earth and ocean worlds get its water?	Abundances of molecular hydrogen, water vapor, and ices; Includes oxygen and hydrogen isotopologues	Far-IR transitions of H_2O, HD, HDO; CH_3OH and CH_4; $R \sim 10^6$ Far-IR phonon modes of H_2O, N_2, O_2, CO_2, CO, CH_3OH, CH_4, C_2H_6, H_2S, NH_3, and HCN ices Mineral spectral signatures; $R \sim 300$

universe. Such GO programs will greatly expand the range of physical conditions in which galactic feedback processes are characterized to include a range of galaxy mass, star formation rate, and metallicity compared with the GTO observing effort.

4.2 SALTUS Theme 2: Worlds and Suns in Context

The transformation of gas and dust clouds into stars and planetary systems is arguably the most important of astrophysical processes (Fig. 8). Star formation involves the full gamut of physical processes and a vast dynamic range in density and size scales. Much progress has been made in our understanding, but there are many gaps in our knowledge. The discovery of thousands of new planetary systems in recent decades has emphasized the amazing range and diversity of outcomes when building systems. What are the conditions that lead to these vastly different outcomes?

The aim of theme 2 is to study the structure and evolution of protoplanetary systems over a wide range of conditions and to understand the origin of Earth's water. This theme defines a

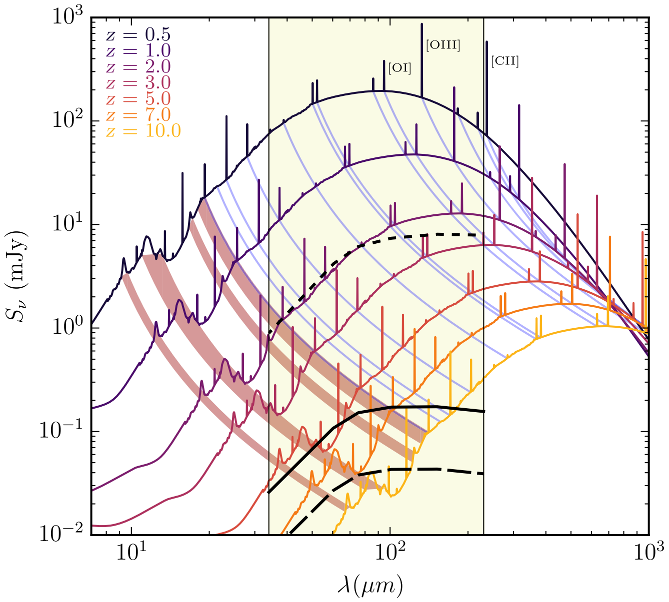

Fig. 7 Spectral range of SALTUS over cosmic time. Schematic representation of the spectral energy distribution of a dusty 3×10^{12} $L_\odot$ star-forming galaxy with redshift. Lines important to the science case and PAH features are traced through redshift, and dominant cooling lines ([OI], [OIII], [CII]) are labeled. Out to $z \sim 3$, SAFARI-Lite probes the peak of the dust continuum and the bulk of the dust emission. Beyond $z \sim 3$, SAFARI-Lite takes over from JWST/MIRI to probe the red-shifted mid-IR PAH emission features. The yellow color-coded region indicates the wavelength range of SAFARI-Lite. The lower solid black curve is the detection limit for SAFARI-Lite at $R = 300$ for pointed observations (1 h, 5σ). The lower long-dashed line approximates a detection limit for wide PAH features, which span many channels. The short-dashed line is the SAFARI-Lite detection limit in mapping mode (1 arcmin^2 area mapped in 1 h at 5σ).

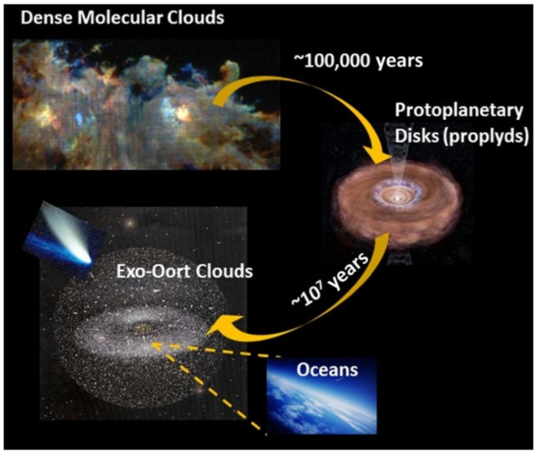

Fig. 8 SALTUS follows the water trail from molecular clouds to oceans. The habitability of planets is closely tied to the presence of H_2O, which is formed in the shielded interiors of molecular clouds, and transported to planet-forming disks where volatiles are further chemically processed before becoming part of planetesimals and comets beyond the snow line. Planetesimals and comets then deliver these volatiles to terrestrial planets and ocean worlds. SALTUS is designed to probe this important journey using low-lying rotational H_2O lines that probe cold gas with HiRX and the icy grain reservoir through their phonon modes in emission with SAFARI-Lite while we expect GOs to probe the later stages.

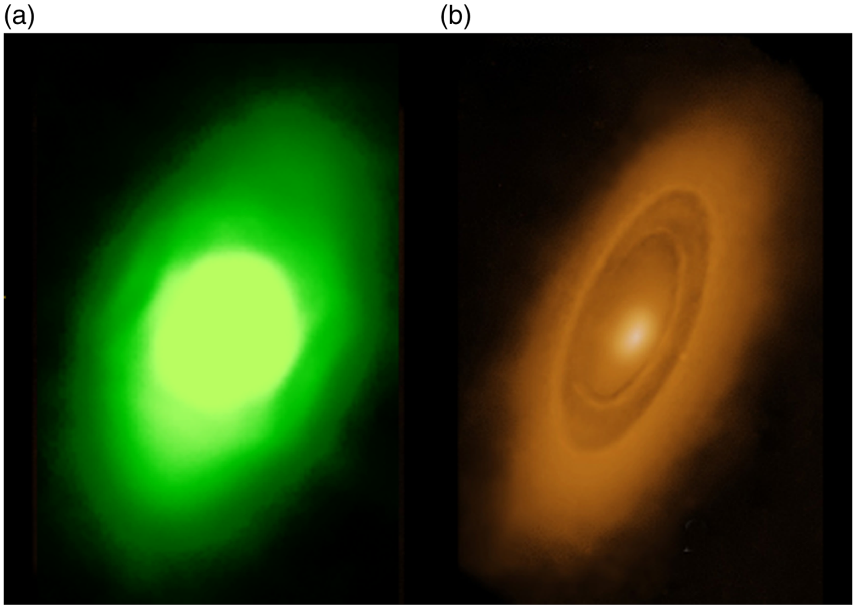

Fig. 9 Image of the Fomalhaut planetary debris system with Spitzer at 24 μm (a) and JWST at 25.5 μm (b). An increase in telescope aperture by a factor of seven (e.g., from 2 to 14 m in the far infrared) yields a huge increase in the information content of the images. Figure credit JPL (a) and Gaspar et al.[19] (b).

science campaign to answer several Decadal Survey questions[4] and enable significant progress toward resolving fundamental questions, such as: How do habitable environments arise and evolve within planetary systems? Where does Earth's water come from? How did we get here? SALTUS's large aperture provides high sensitivity and spatial resolution that is coupled with the high spectral resolution of the HiRX instrument and the broad spectral coverage of the SAFARI-Lite instrument; this allows SALTUS to address science objective 2: Probe the physical structure of protoplanetary disks and follow the trail of water and organics from protoplanetary disks to the solar system. Figure 9 shows the revolutionary impact of the SALTUS angular resolution on a protoplanetary disk in the far-IR.

SALTUS observations will obtain the disk gas masses in hundreds of protoplanetary systems without the need for ancillary data. Protoplanetary disks are much warmer than interstellar molecular clouds. Even for massive, large disks, which are also the coldest, nearly 50% of the disk by mass is warm enough for HD to emit.[20] The H_2/HD ratio in the local ISM is well constrained observationally.[21] The only isotope selective process that can substantially change this ratio in a protoplanetary disk is the continued dissociation of HD after H_2 has self-shielded, which can be corrected analytically for a known radiation field.[22] The largest source of uncertainty is then the temperature structure of the disk. Using simultaneous observations of optically thick lines of H_2O and CO spanning a wide range of upper-state energies, SALTUS will provide observational constraints on the disk temperature structure. The final uncertainty on the disk mass is expected to be a factor of ~ 3, based on past studies of sources with detected HD emission and an observationally constrained temperature structure.[23,24]

In a subset of the brightest disks, SALTUS HiRX will spectrally resolve strong HD lines at ~ 1 km/s velocity resolution. Because disk rotation follows a Keplerian velocity profile, the radius at which gas emission originates can be determined from the line profile. Thus, high spectral resolution observations of molecular lines in disks can be used to determine the radial location of the emission without having to spatially resolve the disk; a technique known as Doppler tomography or tomographic mapping. The spectral resolution of SALTUS HiRX is $<1\ \mathrm{km\,s^{-1}}$, sufficient to distinguish emission originating in the inner versus outer disk. With its 3.5-m aperture, Herschel was only able to detect a handful of protoplanetary disks in HD. A far-IR telescope with a significantly larger aperture than Herschel is essential to the success of such a study.

SALTUS is also well suited to answer a number of open questions in planetary science, including how did the Earth and ocean worlds get their water? SALTUS will address this by

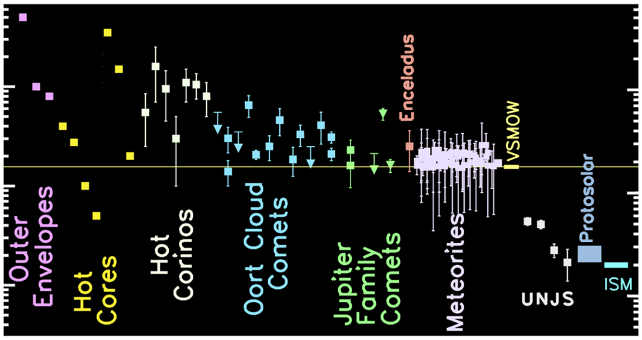

Fig. 10 D/H ratios record the low-temperature heritage of interstellar chemistry, modified by subsequent processing in planet-forming disks. The high resolving power of SALTUS HiRX will reveal the time evolution of the D/H ratio in planet-forming environments by measuring HDO and H_2O in various objects, and HD in the giant planets. These measurements provide critical insight into the earliest stages of planetesimal formation and the origin of Earth's water. This figure is adapted with permission from Anderson et al. (Ref. 20, figure 3), with data from Refs. 25–48.

measuring and comparing the HDO/H_2O ratio in a large sample of cometary reservoirs and planetary bodies (Fig. 10). This and other planned GTO science investigations are expanded by Schwarz et al.[20] and Anderson et al.[49]

4.3 Programmatic Value of SALTUS Science

SALTUS measurements extend the pioneering efforts of Herschel; enhance the scientific return of ground and space-borne observatories, such as ALMA and JWST; complement missions, such as GUSTO, SPHEREx, and Roman; and resonate with the science visions of SPICA, a joint ESA and JAXA mission, and NASA's Origins Space Telescope mission concepts.[13] As indicated in Table 2, SALTUS addresses crucial, high-priority scientific inquiries raised in the Decadal Survey.

5 Guest Observer/Guest Investigator Potential

The potential GO Science programs listed below were constructed to demonstrate the science capabilities of SALTUS beyond the GTO observational agenda. As such, these GO Science Investigations are by no means exhaustive, and we fully expect they will be modified during the GO program selection. Enabled by the large discovery space in sensitivity, spatial resolution, spectral coverage, and mapping speed, SALTUS is truly a community resource, and there are a significant number of high-impact investigations possible.

5.1 Debris Disk Architecture and Search for True Kuiper Belt Analogs

The debris disk phase follows the protoplanetary disk phase. Debris disks are gas-poor, with rings of second-generation dust thought to be influenced by the presence of planets; a ring-sculpting planet has been confirmed in at least one system. Debris disk observations allow us to study populations of small bodies around other stars and infer the presence of planets that otherwise evade detection. Debris disks also provide insight into the composition of solid bodies in other planetary systems. The detection frequency of debris disks decreases with system age. As the frequency of collisions drops, less observable dust is produced; thus, existing detections are biased toward young systems and the warmer dust around A and F stars.[50] Emission from true Kuiper Belt analogs, debris disks with the same intrinsic luminosity as the Solar System's Kuiper Belt, has yet to be observed because they are much too faint. These exo-Kuiper Belts have typical temperatures of 50 K, corresponding to a black-body emission peak in the far-IR. Updating sensitivity estimates from the original SPICA SAFARI[51] to SALTUS's SAFARI-Lite, SALTUS will reach the 5σ sensitivity threshold to detect exo-Kuiper belts around the nearest 30 G and K stars with known debris disks in 1 h of integration. SALTUS can determine the frequency of exo-Kuiper Belts, characterizing how common dust is in mature planetary systems, thus addressing Decadal Question E-Q1d. In addition, the angular resolution of SALTUS should enable the mapping of the dust in some of these systems (Fig. 10).

5.2 C/O Abundances at Late Stages

SALTUS can observe young debris disks, expected to contain detectable levels of carbon and oxygen based on the gas production model developed by Refs. 50 and 52. These observations, focusing on ionized carbon and neutral oxygen, will complement those made by ALMA, which targets CO and neutral carbon.[53,54] By doing so, SALTUS can gather valuable information about the carbon ionization fraction, a crucial factor in understanding the dynamics of gas, e.g., how well gas is coupled to the stellar wind. SALTUS's high spectral resolution (sub-km/s) can access spatial information such as the gas density and its position compared with dust. The ionization fraction and spatial information are essential for studying the transport of angular momentum in these disks and determining the electron density that influences non-LTE excitation. As gas is observed to be spreading from its original source (the planetesimals), it is important to understand if it is due to the magneto-rotational instability as discussed by Ref. 55 or MHD winds or even some hydrodynamic instabilities such as vertical shear instability (VSI) or Rossby Wave instability (RWI).[56,57]

The low surface density in debris disks allows a high photon flux from the central star, converting molecules such as CO, CO_2, and H_2O into C+ and O via photodissociation and photoionization. By targeting C+ and O in the far-IR, SALTUS users will gain insights into the initial species released from planetesimals by examining the C/O ratio, for example, investigating whether CO, CO_2, or H_2O is released. These observations will provide a comprehensive understanding of the gas disk composition at different radii from the central star. This knowledge is fundamentally important since there are indications that the late gas (detected in systems as old as 0.5 Gyr) can expand inward due to viscosity and reach the planets. Already-formed planets can then accrete this gas at a high rate, thereby altering their initial atmospheric compositions. The accretion of carbon and oxygen by young planets may play a pivotal role in the formation of the building blocks of life or affect the temperature through greenhouse effects, thus influencing its habitability.

Currently, debris disk studies have been mainly with A stars. SALTUS has the sensitivity to detect CII and OI in the more typical FGK stars. These observations will determine the C/O ratio across spectral type during the late stages of planet formation, when volatile gasses are delivered to terrestrial planets, and address Decadal question E-Q3a "How are potentially habitable environments formed?" SALTUS particularly can look at this question around solar mass stars.

5.3 Survey of Water Vapor in Planetary Atmospheres

With HiRX Bands 1 and 2, SALTUS will measure H_2O abundances in the stratospheres of the gas giants to determine whether planetary rings, icy moons, interplanetary dust particles, or comet impacts deliver water to these planets. Titan, another Ocean World, and the largest satellite of Saturn, has a complex atmosphere containing oxygen compounds that may have been delivered from the H_2O torus and, ultimately, from Enceladus. SALTUS will measure the vertical and horizontal distributions of H_2O in Jupiter and Saturn's stratospheres to constrain its external source. Gaseous H_2O emission has also been observed from the dwarf planet, Ceres; however, its source and spatial distribution are not known. The high sensitivity of SALTUS will permit the determination of whether cryo-volcanism or ice sublimation from localized regions is the source of water.[25,58] This addresses Decadal Question E-Q2c.

5.4 Stellar Feedback in Regions of Massive Star Formation

This topic aims to understand the role of stellar feedback in regions of massive star formation: How large is the kinetic energy input into the ISM, how does this depend on the characteristics of the region, and, connected to this, how does the surrounding medium react? This objective is addressed by spectral-spatial mapping of regions of massive star formation in the dominant far-IR cooling lines of PDR gas using both the SAFARI-Lite and HiRX instruments (c.f., the pillars of creation in Fig. 4). The sample consists of 25 regions with typical sizes of 25 arcmin^2, covering a range in stellar cluster properties (single stars to small clusters to superstar clusters), GLIMPSE bubble morphology (ring-like, bi- or multi-polar, complex), environment (isolated star-forming region, galactic mini starburst, nuclear starburst), and cluster age (0.1 to 5 Myr).

SAFARI-Lite will provide full spectra over the 34- to 230-μm range (see Table 1), containing the key diagnostic atomic fine-structure transitions, for example, [OI] 63, 145 μm, [CII] 158 μm,

[SiII] 34.5 μm, [OIII] 52, 88 μm, [NII], 122, 205 μm, and [NIII] 57 μm, as well as high J CO transitions, which provide the physical conditions in the neutral PDR gas as well as the photoionized gas. The HiRX–2 will measure the dynamics of the PDR gas by mapping the [CII] 158-μm line at km/s resolution and determine the expansion speed and turbulent line width of the swept-up, expanding shell. SOFIA/upGREAT studies of the [CII] 158-μm emission of regions of massive star formation have demonstrated the feasibility of this technique.[59] Together, these two data sets will quantify the kinetic energy of the expanding shell as well as the thermal, turbulent, and radiation pressures on the shell that can be directly compared with radiative and mechanical energy inputs of the stellar cluster.

5.5 Put Early-Universe Feedback in Context with Local Analogs of the First Galaxies

The first year of JWST observations revealed that early generations of galaxies were typically much lower in mass and significantly less metal-enriched compared with the massive star-forming spiral galaxies that dominate star formation today. Consequently, their ultraviolet (UV) radiation fields were harder,[60] which impacted the gas ionization state and cooling rate. The shallow gravitational potential wells also enhanced the effects of supernova-driven feedback as single supernovae could eject up to ∼95% of the heavy elements formed during the star's lifetime into the circum-galactic medium.[61,62] Although ALMA now allows the key far-IR fine structure diagnostic lines (e.g., [CII], [OIII]) to be detected at high redshifts, these lines still take several hours to detect even in the most massive and UV-luminous reionization-era galaxies[63] and are generally out of reach for the more typical galaxies thought to drive cosmic reionization.

Thanks to community efforts, many nearby galaxy populations have been identified bearing similarities to UV-bright reionization-era galaxies in terms of their mass, metallicity, and harsh UV radiation fields. Though rare locally and largely unknown during the time of Herschel, these low-redshift galaxies are plausible analogs to early star-forming galaxies. Such local low-metallicity dwarf galaxies are natural extensions to the SALTUS low-redshift GTO efforts to measure and resolve the injection of feedback energy on small spatial scales far beyond the capabilities of Herschel[63,64] or a 2-m-class far-IR mission. With the same observables as the GTO program of star-forming spirals and starbursts, and the most commonly detected lines found with ALMA at high redshifts, SALTUS will enable ∼200 pc-scale maps of the far-IR fine-structure lines and underlying dust continuum in low-redshift analogs of the first generation of galaxies.[65]

5.6 Spectral Line Survey

The benefits of performing high-frequency spectral line surveys were recognized and exploited by HIFI/Herschel. HIFI spectral surveys resulted in the first reported detections of SH^+, HCl^+, H_2O^+, and H_2Cl^+.[66–68] The formation of these small hydrides typically represents the first step in gas phase chemistry routes toward molecular complexity in space. However, the spectral surveys with HIFI were severely limited by sensitivity. SALTUS's increased aperture together with improved detector performance results in a >30 times increased sensitivity for these unresolved sources and can be expected to lead to an enhanced line density and discovery space.

5.7 Broad and Versatile Follow-Up Capabilities for the 2030s

Thanks largely to the advent of the large imaging and spectroscopic components of the Sloan Digital Sky Survey, modern extragalactic astrophysics is awash in observational campaigns that target objects pre-selected from multiwavelength surveys. This trend shows no sign of slowing: the first year of JWST operations and the ongoing community planning exercises for Rubin's LSST and Roman emphasize that key advances in our understanding are often only made possible by pointed follow-up programs. Another early lesson from JWST's first year is that rapid advances are made possible when large windows in discovery space are opened: unexpected galaxy populations are found for the first time, objects that were once thought rare are revealed to be common, and flawed assumptions from previous galaxy evolution models are laid bare.[69,70]

SALTUS is the only far-IR observatory capable of delivering on this clear need from the community and is the only facility that allows for genuine discovery space similar to JWST. Smaller apertures are not sufficiently sensitive and are plagued by spatial and spectral confusion that precludes the detection of faint objects without *a priori* knowledge of the position and redshift of every galaxy within a given field of view.

This science objective encapsulates the enormous variety of extragalactic science programs we expect from the community, assembled in much the same way as HST and JWST observing programs. To illustrate one example, JWST and ALMA observations have revealed an astonishing number of obscured or heavily reddened active galactic nucleus (AGN) at $5 < z < 10$.[71] These spectroscopically confirmed AGNs are at least ∼30 to 100× more common than previously expected[71] and imply dramatic revisions to our understanding of early supermassive black hole growth. SALTUS is the only observatory sensitive enough to detect and measure the bolometric luminosities and black hole growth rates of this unexpected new population of reionization-era AGN. Even the longest wavelength band with JWST/MIRI (∼24 microns) only probes up to rest-frame three microns at $z \sim 7$, far bluer than the peak of AGN dust emission (∼10 to 30 microns rest or ∼70 to 200 microns observed-frame). Given recent number density measurements from JWST, we expect a single 10 h pointing with SALTUS to detect the far-IR continua of ∼10 to 30 obscured or heavily-reddened AGN at $5 < z < 10$.

We stress that characterization of these unexpectedly common reionization-era AGN is illustrative: SALTUS is sufficiently sensitive and has the spatial resolution required to disentangle the far-IR light from galaxies selected in very heterogeneous surveys, allowing the observatory to be nimble enough to address not just the open science questions of the year 2025 but also the new questions raised in the 2030s. SALTUS is a versatile far-IR observatory with unmatched sensitivity, enabling genuine discovery space in extragalactic astronomy, capable of responding to the current/future needs of the community.

6 Observing Allocations and Cadences

Table 4 shows the time allocated to achieve the SALTUS investigations for the threshold (1-year time frame) and baseline (5 years) mission. As indicated in Table 4, even with a conservatively estimated observatory operational efficiency of 60%, SALTUS will meet the AO requirement of greater than 70% devoted to GO time. The observing efficiency depends on the location of targets (see Sec. 5), observatory settling time,[16] and on-target observations before momentum unloading.[16] In practice, SALTUS will have an operational efficiency of between 60% and 80%, with the GO percentages in the baseline program varying between 77% and 83% of available

Table 4 SALTUS estimates >80% observing efficiency. If observing efficiency is as low as 60%, mission requirements will still be satisfied.

SALTUS investigation	GTO (h) threshold	Observing time (80% eff.) (%)	GTO (h) baseline	Observing time (80% eff.)
What is the role of star formation in feedback in the local universe?	250	4	550	2%
When did metals and dust form in galaxies, affecting the process of star formation?	100	1	500	1%
What are the roles of feeding black holes in galaxies from the early universe to today?	300	4	1500	4%
Which feedback mechanism dominates as a function of time over cosmic history?	100	1	1000	3%
How does the mass distribution in protoplanetary disks affect planet formation?	250	4	1250	4%
What is the spatial distribution and evolution of water vapor and ice in protoplanetary disks?	100	1	750	2%
How did Earth and ocean worlds get their water?	200	3	500	1%
Total SALTUS GTO program (percentage and hours)	1300	19	6050	17
Total GO program (percentage)		81		83

observing time. With each SALTUS investigation requiring less than ∼6% of available time, GO targets are available for observations so that GTO and GO programs can be supported almost simultaneously.

The current best estimate for SALTUS operational efficiency is 83.5%, based on a detailed analysis of expected observatory performances. This is calculated with an average observational duration of 4 h. SALTUS is capable of a 180-deg slew in 30 min. With a uniformly distributed set of targets over the sky, this gives a mean slew duration of 15 min and accounts for a 5.2% inefficiency. Momentum dumping adds 2.1% inefficiency. Up/downlinks take 4.2% overhead time and safe mode accounts for an additional 0.8% of observing time. With an estimated damping coefficient of $\zeta = 0.6\%$, a review of similar boom performances, SALTUS damping values of 0.5% to 0.7%, gives settling times of 9 and 17 min, respectively, giving an estimate required for settling time of 13 min and efficiency impact of 4.2%. If needed, settling time can be shortened and equipped with increased damping design features and jerk-limiting attitude control algorithms. With an allowable setting time of 13 min, observing time can be as short as 1 h while still meeting the >60% observing efficiency requirement. Given the current mean observation time is 5 h, SALTUS on-sky efficiency is largely insensitive to settling time (see Ref. 16). SALTUS's telecommunications architecture allows for continuous commanding, depending only on the availability of a ground station for command transmission. SALTUS's architecture does not limit time domain science cases that a GO might propose.

7 Summary

SALTUS has both the sensitivity and spatial resolution to address not just the open science questions of the year 2025 but also, more importantly, the unknown questions that will be raised in the 2030s. SALTUS is forward leaning and well suited to serve the current and future needs of the astronomical community.

Code and Data Availability

This paper reviews the science cases and potential observations for a future space mission so data sharing is not applicable at this time.

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