The **S**pace **T**erahertz **O**bservatory (STO):
A 10-meter-class Far-Infrared Telescope for Origins Research

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1 Scientific Investigation

1.1 Overview

Here we describe the scientific motivation and technology for a 10-meter-class Space TeraHertz Observatory (STO) (Figure 1). STO would 1) conduct origin studies of planets, stars, and molecular clouds; 2) trace the life cycle of the Interstellar Medium (ISM) and star formation rate throughout the Galaxy; 3) determine the deuterium abundance in nearby molecular clouds and Galactic Center; and 4) observe the distribution of atomic and molecular gas in nearby and distant galaxies. STO will achieve these goals through high spectral and angular resolution observations of C, O, N, HD, and H_2O lines in the far-infrared. The science goals of STO can be achieved either through a dedicated mission or by implementing heterodyne instrumentation on SAFIR and extending its operational lifetime. STO science objectives are closely aligned with many of those found in the *Origins Roadmap* and drive the creation of a new generation of heterodyne instrumentation that benefits directly from technologies developed for the Herschel HIFI instrument.

Primary Mirror Diameter	9.0m
Angular resolution	1.7″ – 16″
Spectral resolution	$\lambda/\Delta\lambda = 10^6$
Wavelength range	60 – 540 μm
# of spectroscopic pixels	288
Lifetime	$>$5 yr
Orbit	L2

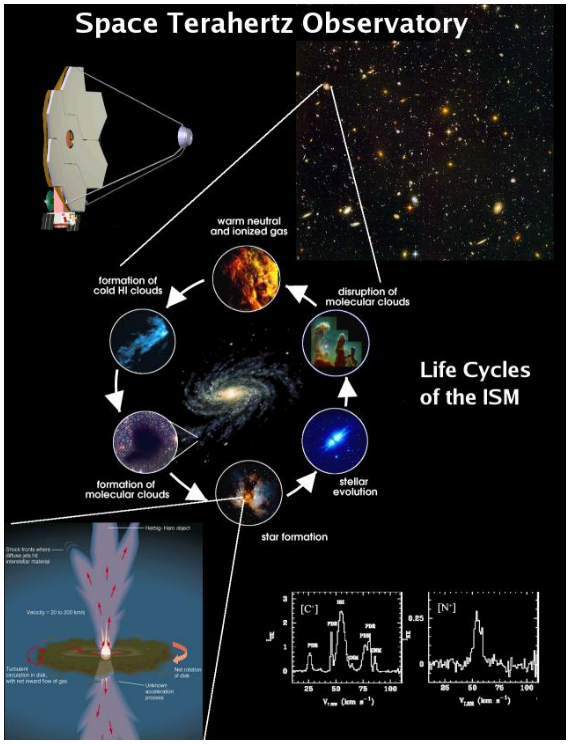

Figure 1: The Space Terahertz Observatory will provide a powerful probe of our cosmic origins; the evolution of galaxies, stars, planets, and the chemical elements of life.

1.2 Impact on Origins Research

STO addresses all major enterprise objectives in the 2003 Origins Roadmap:

A. *Understanding how today's Universe of galaxies, stars and planets came to be.* By exploring star formation throughout the Galaxy & nearby galaxies and the full life cycle of interstellar clouds, STO will directly quantify the feedback mechanisms connecting star formation with the interstellar environment; pivotal to the evolution of galaxies.

B. *Learning how stars and planetary systems form and evolve.* STO will explore the assembly of stars and planets from molecular cloud cores, and probe the detailed physics and chemistry of pre- and post-planetary disks. STO probes these environments in the spectral light of gaseous water, carbon, nitrogen, and oxygen – the elements of life on Earth. STO will be sensitive to the gas masses that circularize the orbits of terrestrial planets, and that form gas giants by core accretion.

C. *Exploring the diversity of other worlds and searching for those that might harbor life.* STO's unprecedented sensitivity to water and oxygen enables the search for extrasolar Kuiper Belts and residual cometary material in evolved stars, constraining the initial inputs to the chemistry of life on Earth.

STO will:

1. **Identify and characterize thousands of interstellar clouds, protostars and outflows in the Galactic Plane (Origins 2, 3)**
2. **Measure the abundance & role of water in the sculpting of hundreds of star-forming regions and circumstellar disks (Origins 3, 4)**
3. **Determine the life cycle of Galactic interstellar gas by studying the creation and disruption of star forming clouds in the Galaxy. (Origins 2)**
4. **Determine the parameters that affect the star formation rate in the Galaxy. (Origins 2, 3)**
5. **Provide and test templates for star formation and stellar/interstellar feedback in other galaxies. (Origins 2, 3)**

1.3 Mission Approach

The Space Terahertz Observatory (STO) will survey the Galactic Plane at 2-16$''$ angular resolution in far-infrared fine-structure emission lines of singly ionized carbon (C$^+$ 158 μm, the Galaxy's strongest IR emission line), nitrogen (N$^+$ 205 μm), neutral oxygen (O^0 63 μm), and ortho-water (H_2O 538 μm). It will obtain sensitive maps of selected clouds in the crucial lines of deuterated molecular hydrogen (HD 112 μm), H_2O, carbon, nitrogen, and oxygen. The STO heterodyne receivers provide sub-km/s velocity discrimination and bandwidths that encompass all clouds orbiting in the Galaxy. STO maps the structure, dynamics, energy balance, pressure, and evolution of the Milky Way's Interstellar Medium (ISM), as well as the Galactic star formation rate. STO possesses exceptional angular resolution that couples the life cycle of Milky Way interstellar clouds *inward* to the formation of individual stars, circumstellar disks, and planets – and *outward* to the global star-forming properties of nearby galaxies.

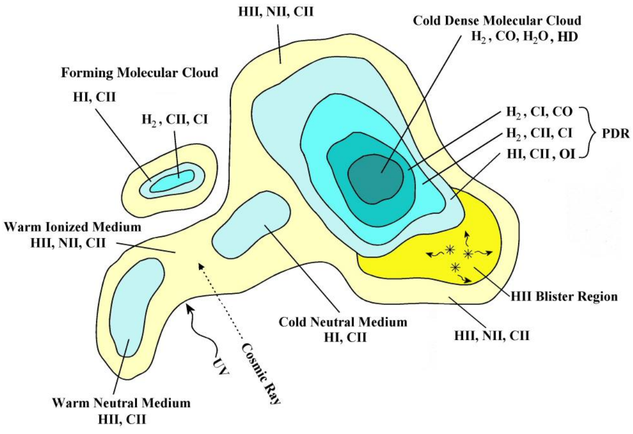

Figure 2: Schematic representation of ISM components.

The data are produced in both large scale and selective surveys, tabulated below. The data products from STO will be FITS data cubes of spectral line maps, a standard radio astronomy product.

STO Surveys:

1. **UGPS: An Unbiased Galactic Plane Survey:** $-180^o < l < 180^o$ **;** $-1^o < b < 1^o$ **in [C II] and [N II] line emission**
2. **TDS: Targeted Deep Surveys of selected interstellar clouds in [C II], [N II], [O I], HD, and H_2O line emission**
3. **PPD: A survey of 300 Pre-Planetary and Post-Planetary Circumstellar Disks (defined by the "C2D" and "FEPS" Spitzer Legacy programs) in HD, O^0, and H_2O lines.**
4. **NG: A Nearby Galaxy survey, based upon the "SINGS" Spitzer Legacy program, that maps a few galaxies of late-Hubble types in [C II], [N II] and [O I] line emission**

2 Science Goals and Objectives

Via resolved C^+, N^+ and O^0 line emission, STO uniquely probes the pivotal formative and disruptive stages in the **life cycles of interstellar clouds** and sheds crucial light on the **formation of stars and pre-planetary disks**. It provides new insight into the relationship between interstellar clouds and the stars that form in them; a central component of **galactic evolution**. One of the products is a detailed study of the Milky Way Galaxy, which is then applied as a template or standard to **interpret global star formation in other spiral galaxies**.

Neutral interstellar gas is the dominant mass component of the ISM, and exists as two phases in rough thermal pressure equilibrium: a diffuse warm neutral medium (WNM) with hydrogen densities at the solar circle of n$\sim$0.3 cm^{-3} and T$\sim$8000 K, and a denser cold neutral medium (CNM) with n$\sim$40 cm^{-3} and T$\sim$70 K(Wolfire, McKee, Hollenbach, & Tielens, 2003). With sufficient shielding column, $N > 10^{20-21}$ cm^{-2} of hydrogen nuclei, the CNM clouds begin to include molecular interiors. Above $N \sim 10^{22}$ cm^{-2} they become fully-molecular, gravitationally bound, and stars may form in their interiors(McKee, 1989). The largest condensations take the form of giant molecular clouds (GMCs) with large masses $M \sim 10^{5-6} M_{\mathrm{sun}}$ and are responsible for most of the star formation in the Galaxy. These ISM components are shown schematically in Figure 2. The spectral probes provided by STO span an enormous dynamic range of physical conditions in the Galaxy and uniquely probe all of these components.

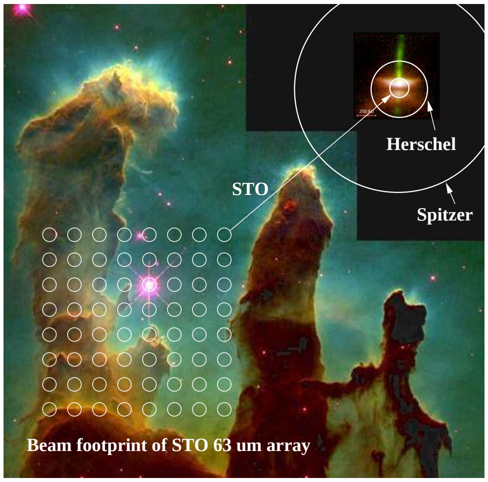

Figure 3: **The importance of high angular resolution**. Footprint of STO's 63 μm heterodyne array on M16 and HH30, in comparison to that of previous observatories. The combination of high angular resolution and large-format spectroscopic imaging opens up new frontiers for planet formation and external galaxies.

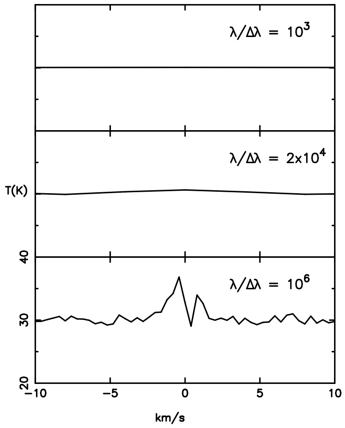

Figure 4: **The importance of high spectral resolution.** Synthetic emission & absorption of the HD J=1-0 transition (112 μm) observed at different resolving powers demonstrates that high spectral resolution increases the line-to-continuum contrast vital to the detection of narrow interstellar lines embedded in a bright infrared continuum.

Joined with other surveys, STO will:

1. Constrain planet formation models by spectroscopically probing disks in oxygen and water lines inaccessible from the ground. With the high spectral resolution of heterodyne instruments we can detect the clearing of gas and dust in circumstellar disks due to planetary accretion or disk instabilities. Constrain the frequency of "Kuiper Belt" like reservoirs of frozen water in post-main-sequence stars.
2. Map as a function of Galactic position the size and mass distribution and internal velocity dispersion of interstellar clouds in the Galaxy.
3. Construct the first barometric map of the Galaxy, the first map of the gas heating rate, and a more detailed map of the star formation rate.
4. Probe the relation between the mass surface density (on kpc scales) and the star formation rate, so that we may be able to understand the empirical Schmidt Law used to estimate the star formation rate in galaxies.
5. Reveal clouds clustering and forming in spiral arms and supershells, and follow the growth of clouds to sufficient column densities to shield molecules and to become gravitationally bound.
6. Observe the formation and destruction of

clouds throughout the Galaxy, and directly observe the feedback caused by supernovae and the ultraviolet radiation from massive stars. Measure the destruction rate of clouds via the conversion to warm ($\sim 10^4$ K), diffuse neutral and ionized gas.

7. Construct a Milky Way template connecting the line emission from C^+, N^+, O^0, CO, H_2O, and far-IR continuum to star formation properties and state of the ISM; apply this template to nearby star-forming galaxies.

2.1 *Overview of STO Capabilities*

The combination of high sensitivity, angular and spectral resolution gives the Space Terahertz Observatory unprecedented power to unlock important mysteries of our cosmic origins (Figure 3).

The main features of STO surveying modes are:

1. **High spatial resolution; 1.7″–16″**
2. **Very high spectral resolution, < 1 km s^{-1}.**
3. **High dynamic range; $\sim 10^4$ spatially and 10^3 spectrally**
4. **More than 10^7 spatial pixels of data, each with a high resolution spectrum**
5. **High sensitivity: 10^6 times better than FIRAS/COBE. STO will catalog neutral clouds with columns $N > 10^{20}$ cm^{-2}, all ionized clouds with EM > 10 cm^{-6} pc, circumstellar disk gas masses to $< 10^{-3}$ M$_{\rm Jup}$ for nearby star forming regions, and water abundances to $< 10^{-10}$ of H_2.**

STO will have the ability to detect (at 3σ) C^+ emission from CNM clouds with columns of $N > 10^{20}$ cm^{-2}, or $A_V > 0.07$ mag. Such clouds typically subtend $> 1'$ of angle at d =8.5 kpc, and will be spatially and spectrally resolved. Figure 5 demonstrates the beam sensitivity of STO; for large-scale Galactic clouds, STO's high angular resolution can be traded for greater sensitivity, allowing the measurement of even the most tenuous, elusive phases of the warm and cold interstellar medium.

2.2 *Specific Science Goals and Objectives*

Of the numerous science aims outlined in Section 2, five will now be discussed in more detail.

2.2.1 *Goal 1: Protostellar Evolution & Planetary Systems*

H_2O and O^0:

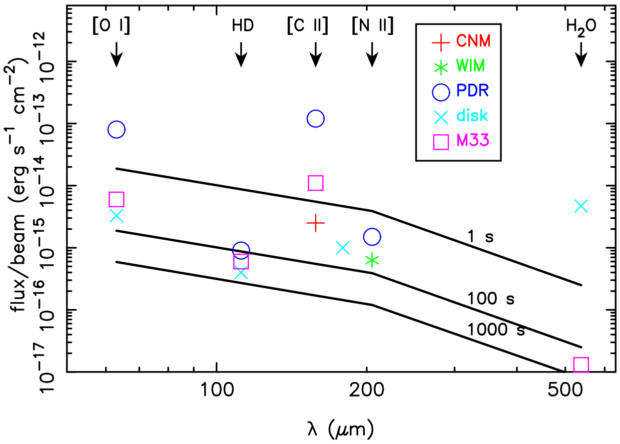

Figure 5: 3σ sensitivity of STO to spectral lines from Galactic clouds and interstellar components (see Section 2 for definitions) at 10 kpc, circumstellar disks at 150 pc, and GMC's in M33. Much greater sensitivities can be reached in the case of nearby Galactic clouds by smoothing the data in angular resolution.

Water is a molecule of unique interest in astrophysics; its abundance and distribution provide information about the chemistry, composition, and physical conditions within the gas. Its powerful diagnostic capacity stems in part from the varied ways in which it is produced; (1) standard ion-neutral chemistry, (2) endothermic neutral-neutral reactions, and (3) processing on the icy surfaces of dust grains (Melnick et al., 2000). Precursor missions to STO, such as SWAS, ODIN, and Herschel, have provided and will provide a wealth of information about water on large scales. By virtue of its higher spatial resolution and greater sensitivity, STO will build on the knowledge gained from these prior missions by exploring regions of extreme interest that will remain largely unexplored even after Herschel flies. Two such examples are (1) water in circumstellar disks and (2) the forensics of dying planetary systems.

Water and Oxygen as Diagnostics of Planet Formation

The abundance of water in protostellar disks can yield important clues to the origin of water available to newly forming planets. Because it is so sensitive to its environment, water is a superb tracer of the physical, chemical structure and dynamics of (planet-forming) circumstellar disks.

In a "standard" model of a static flared circumstellar disk, the water emission is predicted to be weak due to the relatively small volume in which it exists in the gas phase. However, if vertical mixing within the disk is significant, ice-covered grains are regularly transported to warm regions where this water is liberated, increasing the gaseous water abundance by orders of magnitude. The presence of a high abundance of gaseous water can thus alter, and elucidate, the temperature structure and chemical evolution of the disk.

In contrast, O^0 emission at 63 μm provides an outstanding probe of radiation-heated gas in protostellar collapse (Ceccarelli, Hollenbach, & Tielens, 1996) and toward the "surfaces" of circumstellar disks. With a critical density of 5×10^5 cm^{-3}, [O I] is useful in probing denser regions than most fine structure lines. Very small gas masses, as small as $10^{-3}\ M_{\rm Jup}$ result in strong [O I] line luminosities of $10^{-6}\ L_{\rm sun}$ (Gorti & Hollenbach, 2004). STO's high angular resolution at 60 μm will permit easy detection of these gas masses in less than one minute toward the nearest star forming regions. Most critically, the [O I] line profiles will elucidate the overall physical structure of the disk, unveiling disk inhomogeneities such as gaps cleared by forming planets. STO will be able to detect whether there is enough gas for the formation of gas giant planets by core accretion in $10^6 - 10^7$ year old disks and whether there is enough gas in the terrestrial planet zone to circularize the orbits of terrestrial planets (Kokubo & Ida, 2002). Surveys of nearby clouds in 538/179 μm H_2O and 63 μm [O I] emission will provide a catalog of disk systems ripe for follow-up study.

Water as a Diagnostic of Planetary Death

To date, radial velocity techniques have been extremely successful at detecting large ($> 1 M_{\rm Jup}$) objects in relatively close orbits around more than 100 stars, but unfortunately lack sensitivity to analogues of the smaller constituents of our Solar System, such as Kuiper Belt objects. However, it is possible that the presence of smaller bodies in orbit around other stars may be detectable using the type of high spectral resolution, high sensitivity spectroscopy proposed for STO.

Specifically, as low-to-intermediate mass stars age and evolve off of the main sequence, they undergo a dramatic increase in their radius and luminosity. Orbiting bodies within 50 to 100 AU of the star that had previously been undisturbed by the star's radiation field will now be vaporized. If a star is orbited by a Kuiper Belt analog, results obtained from SWAS (Figure 6) have shown that – under the proper circumstances – it is possible to infer the presence of these icy bodies by means of water vapor enrichment in the stellar wind. Carbon stars are ideal candidates. For AGB stars like IRC+10216, which possess circumstellar envelopes in which carbon is the most abundant heavy element, it is predicted that the equilibrium chemistry will drive all of the oxygen into CO with little remaining to form other molecules. Thus, the detection of water vapor toward a carbon-rich AGB star raises the possibility that icy bodies are being vaporized. Toward IRC+10216, SWAS data imply a water vapor abundance 5 orders of magnitude greater than that predicted by chemical models of the outflow (Melnick et al., 2001).

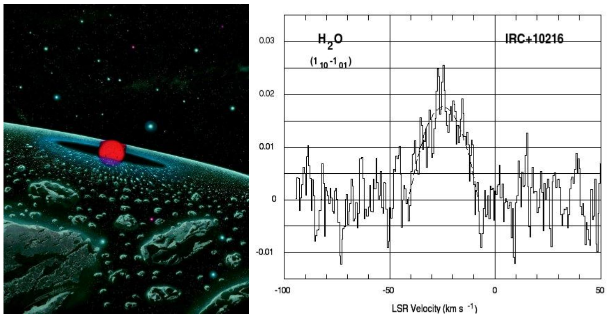

Figure 6: (left) Artist's conception of the evaporating comet hypothesis for the water vapor detection of Melnick et al. (2001) (right) toward IRC+10216. This result, obtained in ~200 hours of integration time with SWAS, is reproducible in 1 minute of integration time with STO.

STO will have the capability to survey the nearest carbon stars for evidence of vaporizing icy bodies. Further, the excitation conditions giving rise to a number of low-lying ortho- and para-H_2O lines accessible to STO will make it possible to determine where in the outflow the water is being injected. A determination of the presence and composition of the smaller constituents of other planetary systems is not possible using radial velocity or transit techniques and is beyond the capabilities envisioned for the Terrestrial Planet Finder. **By studying the contents of dying planetary systems spectroscopically, STO will make unique contributions to our understanding of extra-solar planetary architectures**.

HD and its Ions: No molecule is more crucial to star formation than molecular hydrogen (H_2); it comprises the vast majority of interstellar material from which all stars are born. However only its singly-deuterated form, HD, has permitted, energetically accessible transitions in molecular clouds. In warm (T>50 K) molecular environments, the J=1→0 transition (112 μm) of HD will accurately measure the mass of H_2 where $N_{\rm H} \geq 10^{22}$ cm^{-2}, and can be referenced to [C II], [C I], CO and [O I] emission observed in photodissociation regions, warm molecular clouds and disks adjacent to forming stars (Figure 4). Supplementary science studies include calibration of the D/H abundance in fully molecular gas and detailed measurement of the deuteration of star-forming cores that can ultimately serve as a "chemical clock" for their evolution. The latter studies will measure absorption lines from the ground states of HD (112 μm) (Caux et al., 2002), H_2D^+ (218 μm) (Boreiko & Betz, 1993) and D^2H^+ (203 μm) (Phillips, 2002) in targeted sources in combination with ground-based observations of infrared absorption lines (e.g. H_2) (Kulesa & Black, 2002).

Herschel and SOFIA will observe HD in clouds and (in part) will provide the sample of sources which STO will examine in dramatically better detail. In comparison with Herschel and SOFIA, STO has the unique combination of (1) a dedicated survey mission that will explore hundreds of star forming regions and disks in HD, (2) high angular resolution ($3''$ at 112 μm) that will disentangle the complex structure of star forming regions and provide up to an order of magnitude more sensitivity to absorption line measurements of ground-state HD, and (3) large-format arrays to provide a large simultaneous ($60'' \times 60''$) field of view.

2.2.2 *Goal 2: The Life Cycle of Interstellar Clouds*

At a distance of 10 kpc, typical GMCs subtend 5 arcminutes, CNM clouds $\sim$1 arcminute, and diffuse HII regions, 10 arcminutes. STO resolves these objects spatially and spectrally, and will determine directly their size and internal velocity distribution as a function of Galactocentric radius (R) and height (z). STO's spatial resolution allows clusters of clouds to be discovered and their random velocity dispersion measured. The cloud to cloud velocity dispersion is the key parameter which determines when gravitational instabilities are able to collect clouds over huge ($\sim$1 kpc) regions to form GMC's.

These regions dominate 205 μm N^+ and 158 μm C^+ emission(McKee & Williams, 1997). Because STO can detect CNM clouds, GMC's, and diffuse HII regions throughout the Galaxy (ex. Figure 5), and because Galactic rotation generally allows velocity separation of the clouds along the line of sight, STO will provide an unprecedented global map of the distribution of clouds in the Galaxy. From the survey, which covers the majority of the cloud mass and the star forming regions of the Galaxy, we can see how clouds are clumped together in spiral arms or supershells. Similarly, the N^+ observations of diffuse HII clouds provide an unprecedented spectroscopic survey of the location and rate of star formation in the Galaxy. The rate of star formation is determined by using the N^+ luminosity to determine the ionizing luminosity of OB stars, a standard metric for the star formation rate. Since the C^+ emissivity per hydrogen atom rises monotonically with gas density and thermal gas pressure, the STO survey enables the construction of the first barometric maps of the Galactic disk, determining the ambient thermal pressure in different environments (e.g., the spiral arms versus interarm regions, the Galactic Center and higher Galactic latitudes), and probing and characterizing a turbulent medium stirred by e.g. young stellar outflows and supernovae. These pressure maps and the maps of cloud distributions and properties can be correlated with star formation rates to understand stellar/interstellar feedback mechanisms. Where extended emission is seen in HI with no C^+ counterpart, we can attribute the HI emission to extended low density gas – either WNM or thermally unstable gas with densities below that of CNM. Simultaneous N^+ measurements will disentangle the contribution to the C^+ emission from ionized gas. To achieve the required sensitivity, we will smooth the data to larger (10 km s^{-1}) velocity and spatial ($10'$) bins, as shown in Figure 5. In this way, STO can map the CNM/WNM mass fraction in the Galaxy, and determine how much of the neutral gas is in clouds. This ratio can be correlated to the thermal pressure, to the ultraviolet radiation field, and to the star formation rate to probe the stellar feedback processes that regulate star formation.

2.2.3 *Goal 3: The Formation and Destruction of Clouds*

The formation of interstellar clouds is a prerequisite for star formation, yet the process has not yet been observed! STO is designed with the unique combination of sensitivity and resolution needed to observe atomic clouds in the process of becoming giant molecular clouds (GMCs).

Theories of cloud formation are guided and constrained by observations of the atomic and molecular gas components. Based primarily on HI and CO observations, four mechanisms have been proposed to consolidate gas into GMC complexes (Figure 7): (1) gravitational-magnetothermal instabilities within the diffuse gas component, (2) collisional agglomeration of small, long lived molecular clouds, (3) accumulation of material within high pressure environments such as shells and rings generated by OB associations, and (4) compression in the randomly converging parts of a turbulent medium. STO's surveys, particularly in the C^+, N^+ and O^0 lines can distinguish these processes by:

1. Accounting for all the molecular hydrogen mass (the H_2/C^+ clouds as well as the H_2/CO clouds) when computing global measures of the interstellar medium.
2. Making a more complete, better characterized catalogue of interstellar clouds than CO or HI surveys.
3. Constructing spatial and kinematic comparisons of sufficient resolution, spatial coverage and dynamic range to probe a wide range of interstellar phases and environments.

In particular, C^+ emission barometrically picks out clouds of atomic gas and H_2 clouds with little CO. Regions of GMC formation may therefore be tracked by a large density of clouds per beam, or regions with individual clouds with higher than average columns or pressures. With STO's superlative spectral resolution, these regions can be identified with superrings or spiral arms or convergent parts of a turbulent medium. STO will follow the CNM clouds and H_2 clouds as they transit the spiral potential, and will witness the process of cloud formation directly from the atomic substrate or from small H_2 clouds. For example, dust lanes along the inner edges of spiral arms often show neither HI nor CO emission (Wiklind, Rydbeck, Hjalmarson, & Bergman, 1990) and are therefore likely to be in an intermediate phase; sufficiently dense and self-shielded to harbor H_2, but not CO (see Figure 2) (Stacey et al., 1991). These clouds will be seen in C^+ line emission by STO. The high spectral resolution of STO enables crucial kinematic studies of the Galaxy to be made. The expansion of stellar outflows and supernova remnants create supershells that sweep up surrounding ISM and overrun surviving molecular clouds and cloud fragments. The high pressures in the shells convert swept-up WNM gas to CNM clouds via thermal instability. The resulting supershell can grow to several times the typical thickness of the gas layer in a galactic disk, creating superrings that can contain millions of solar masses of swept-up gas. Gravitational fragmentation of superrings may be an important mechanism for the formation of GMC's (McCray & Kafatos, 1987).

STO will determine the kinematics and thermal pressures of most supershells, fossil superrings, and molecular clouds just condensing via gravitational instability of old superrings and supershells. STO will detect the CNM clouds formed out of WNM in the shells, and the H_2 clouds which determine the role of OB association-driven supershells and superrings in the production of molecular clouds and the cycling of gas between the various phases of the ISM. STO witnesses the disruption of GMCs and all CNM or C^+/H_2 clouds with columns greater than about 10^{20} cm^{-2}, since N^+ measures the flux of ionizing photons, and C^+ measures their impact upon neighboring cloud surfaces. STO will measure the resolved photoevaporating atomic or ionized gas driven from clouds with UV-illuminated surfaces, thereby converting the clouds to WNM or to diffuse HII regions. Thus, STO can directly determine the rate of mass loss from all catalogued clouds, and their destruction timescales. STO's survey will correlate the star formation rate in a given OB association with the rate of destruction of the nearby (within 0.1-30 pc) natal GMC. It will demonstrate if CNM clouds are being effectively destroyed by the enhanced fluxes of UV coming from relatively nearby (50-200 pc) OB associations. Such measurements are crucial for models of star formation feedback and global galactic evolution.

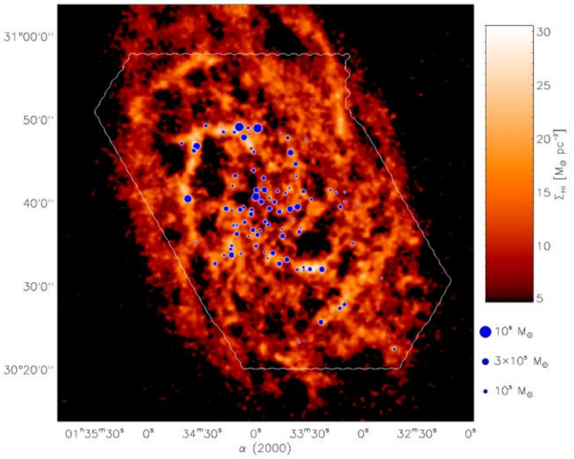

Figure 7: The location of GMC's in the nearby spiral galaxy M33 are overlaid upon an integrated intensity map of the HI 21 cm line (Engargiola, Plambeck, Rosolowsky, & Blitz, 2003). These observations show that GMC's are formed from large structure of atomic gas, foreshadowing the detailed study of GMC formation that STO will provide in the Milky Way and nearby galaxies like M33.

2.2.4 *Goal 4: The Star Formation Rate in the Galaxy*

Star formation within galaxies is commonly described by two empirical relationships: the variation of the star formation rate per unit area with the (atomic + molecular) gas surface density (Schmidt, 1959; Kennicutt, 1998) and a surface density threshold below which star formation is suppressed (Martin & Kennicutt, 2001). The Schmidt Law has been evaluated from the radial profiles of H and HI, CO emissions for tens of galaxies. The mean value of the Schmidt index, n, is 1.4 ± 0.15 (Kennicutt, 1998), valid for kpc scales. This empirical relationship is used in most models of galaxy evolution with surprising success given its simplicity. Oddly, there has been little effort to evaluate the Schmidt Law in the Milky Way owing to the difficulty in deriving the star formation rate as a function of radius within the plane.

The STO survey of C^+ and N^+ emission provides the optimum set of data to calculate the Schmidt Law in the Galaxy. The N^+ line is an excellent tracer of the star formation rate as it measures ionizing luminosity with unmatched sensitivity, angular and spectral resolution, and is unaffected by extinction. The C^+ line, in conjunction with HI 21cm and CO line emission, provides the first coherent map of the neutral interstellar gas surface density and its variation with radius. STO's high spectral resolution allows one to assign a radial location of any emission feature assuming a rotation curve. The Schmidt Law is constructed from the radial profiles of the star formation rate derived from N^+ emission and the gas surface density. The column density threshold is inferred from the absence of star formation activity in the outer radii of galaxies where there is still a significant reservoir of gas (Kennicutt, 1998). It has been attributed to the conditions required for the gravitational instability associated with the Coriolis force to consolidate CNM clouds into GMC's (Kennicutt, 1998; Martin & Kennicutt, 2001). The velocity-resolved star formation rate indicators provided by STO will be invaluable in interpreting more traditional indicators, like the far-infrared continuum. With its resolution and ability to gauge thermal ISM pressure, STO evaluates this critical, regulatory process in the Milky Way.

2.2.5 *Goal 5: The Milky Way Template*

C^+ 158μm, the strongest Galactic cooling line, will be the premier diagnostic tool for studying external galaxies in the submillimeter for galaxies with large redshifts (Atacama Large Millimeter Array). In such spatially unresolved galaxies, however, only global properties can be measured. To interpret the measurement of extragalactic C^+, one must turn to the Milky Way for the spatial resolution needed to disentangle the various contributors to the total C^+ emission. The STO mission covers a broad range of density and UV intensity, establishing the relationship between physical properties, C^+, N^+, O^0, CO, HI, FIR emission, and star formation. This study will provide the "Rosetta Stone" for translating the global properties of distant galaxies into reliable estimators of star formation rate and state of the ISM.

The exceptional angular resolution that STO provides will be used to test and extend the Milky Way template against nearby galaxies where star forming complexes and GMC's can be resolved (Figure 7). The Milky Way template will first be expanded toward the low-metallicity limit by including star forming regions in the SMC and LMC. Application of the template to nearby star forming galaxies, such as IC 342 and dwarf irregular NGC 5253 will help elucidate the triggering mechanism(s) and evolution of the starburst phenomenon, and provide the necessary calibration and testing needed for application toward more distant, unresolved IR-luminous galaxies. These notions will be explored in further detail in the Concept Study.

2.3 *Comparison of STO with other Far-IR Spectroscopic Platforms*

STO is a powerful survey telescope capable of resolving clouds in crucial spectroscopic species and using Galactic rotation to place them along a line of sight. It builds upon the heritage of six pioneering telescopes: the Cosmic Background Explorer, the Balloon-borne Infrared Carbon Explorer (BICE), the Infrared Telescope in Space (IRTS), the Submillimeter Wave Astronomical Satellite (SWAS), the Infrared Space Observatory (ISO) and the Herschel Space Observatory. To the first five, STO adds many orders of magnitude in sensitivity, spatial, and spectral resolution. None of the C^+ and N^+ missions had sufficient spectral or spatial resolution to locate clouds, or separate one cloud from another along a given line of sight, and thus could not draw specific conclusions about cloud properties or distributions, or even the origin of the C^+ or N^+ emission(Petuchowski & Bennett, 1993). SWAS had two hundred times less collecting area, and Shottky receivers with 30 times the receiver noise as the cooled SIS mixers that will be used for the 0.6 THz channel in STO. Compared to Herschel, STO's integrated heterodyne receiver arrays increase mapping speed by two orders of magnitude and sensitivity to point sources by an order of magnitude.

It is illuminating to put the capabilities of STO in context with the successful Far Infrared Absolute Spectrophotometer (FIRAS) instrument on COBE. Convolved to the angular and spectral resolution of FIRAS, STO is $> 10^6$ times more sensitive, even in its moderate sensitivity (UGPS) survey mode. STO's sensitivity is therefore traded for angular and ve-

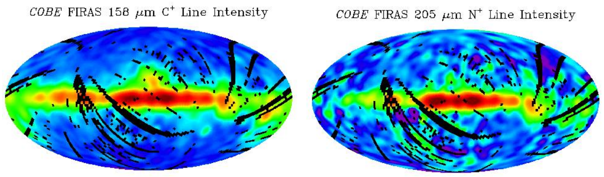

Figure 8: COBE FIRAS image of [C II] (top) and [N II] (bottom) integrated intensity at 7^o angular resolution. These data were taken with velocity resolution 3,000 km s^{-1}, greater than the Galactic velocity dispersion.

locity resolution that optimally couples to the physical scales of important interstellar components in the Galaxy. Even at at $5''$ angular resolution and 0.6 km s^{-1}velocity channels, the mean level of C^+ emission seen by FIRAS in the Galactic plane is detected by STO at the 5σ level in 1 second!

STO is unique and timely when compared with concurrent airborne and space observatories. The Spitzer Space Telescope (SST, formerly SIRTF) has no spectroscopic capability at these wavelengths. A series of balloon missions cannot provide the database essential for accomplishing STO's science goals. A prohibitive number, almost one hundred 10-day balloon flights, would be required to achieve equal sensitivity, and there is no long duration balloon flight capability in the northern hemisphere. STO is optimized to support large-format heterodyne arrays, with broad spectral coverage that includes interstellar water. The advantage of STO is its ability to provide large scale coverage, while simultaneously providing higher angular resolution than both Herschel and SOFIA. There will not be sufficient time on these other facilities to complete even a small fraction of the Galactic survey of the scale proposed for STO. We estimate that each facility will map approximately 1% of the area of STO's survey during their lifetimes. STO's database will provide important diagnostics to be used with future far-IR continuum surveys, such as those suggested for SAFIR.

3 Mission Concept

The scientific objectives of the STO can be achieved by having a dedicated mission or providing a comparable heterodyne instrument for SAFIR (Single Aperture Far-Infrared Observatory). Below we briefly discuss the advantages and disadvantages of each approach. The relative merits of the two mission concepts will be examined in detail during the concept study.

3.1 *Heterodyne Augmentation to SAFIR*

SAFIR is a large (10-m class), cold (4-10K) space telescope for wavelengths between 20 μm and 1 mm. This wavelength range encompasses that of STO, opening the possibility of combining the two missions. Indeed, SAFIR's telescope performance (e.g. surface quality, pointing) exceed those of STO. The only additional optical requirement would be to allow for the possibility of a chopping secondary or tertiary. The most significant mission impact would be increasing spacecraft power to cover the additional load of the heterodyne instrument and increasing the SAFIR mission lifetime to allow implementation of the STO science program. STO science investigations do not require a cooled aperture. Therefore one mission design approach could be to conduct investigations requiring a cooled aperture first and then shut-down the cryogenic systems responsible for cooling the aperture (and sun shield) for the heterodyne portion of the mission. The spacecraft power that was used to cool the aperture would then be used to meet the additional power needs of the heterodyne instrument package.

3.2 *Dedicated Mission - STO*

All science goals outlined in Section 1 are met with a purely heterodyne instrument. Heterodyne instruments are far less sensitive to telescope emissivity than broadband, incoherent detection systems. Indeed, there is no need to actively cool the telescope, resulting in a significant reduction in mission complexity and cost. With a heterodyne-only STO mission a deployable sunshade may not be needed. The additional cryogenics required by SAFIR to cool telescope optics are not required. Thermal blankets on the back of the reflector may be all that is needed to maintain the figure of the telescope in both targeted and survey modes. Furthermore, without the need for cooling, the STO reflector can be made of lightweight, relatively low-cost, temperature insensitive, carbon composite panels. A telescope design incorporating these simplifications is shown in Figure 14 in Section 4.4. The shortest wavelength at which STO will observe is 60 μm, 3× longer than that of SAFIR. This results in significantly reduced telescope surface and pointing requirements (see table in Section 4.2). Preliminary investigations suggest the pointing specification can be achieved using a standard Ball star tracker and reaction wheels; active control of the telescope surface is not required. The anticipated instrument power (1 kW) and data rates (0.5 Mbits/sec) can be supported by a JWST

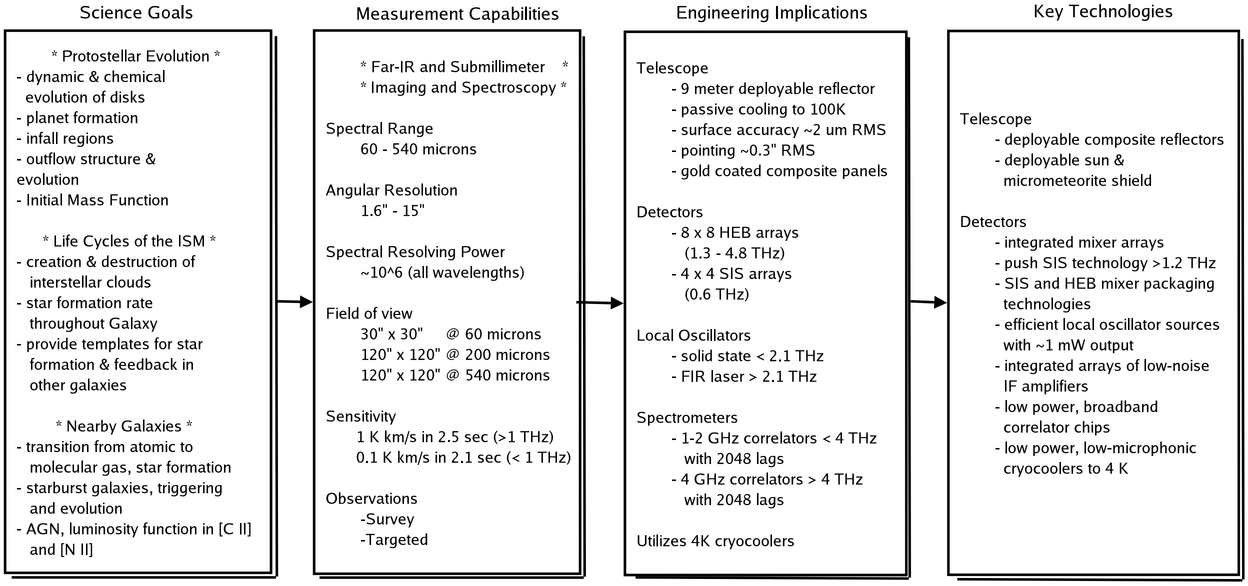

Figure 9: Flow of requirements

style spacecraft bus. Locating STO at L2 has several advantages. These include mission lifetime, the ability to radiatively cool portions of the instrument, low radiation environment, accessibility, and amenable data rates.

4 Instrument Roadmap

Figure 9 shows how the major science goals described in the previous sections define telescope and instrument capabilities and, ultimately, the key technology development areas. The proposed instrument concept greatly benefits from the heterodyne receiver technology developed for the HIFI instrument on Herschel. In the following sections we present an instrument concept for STO. The same concept could also be optimized for implementation on SAFIR. Together with a large aperture telescope, the instrument would provide a powerful, unique, capability for exploring the formation of stars and planetary systems, the life cycle of the ISM in the Milky Way and nearby galaxies, the starburst phenomenon, and [C II] and [N II] emission from more distant galaxies.

4.1 System Description

A schematic of the STO instrument concept is presented in Figure 10. The f/19 beam from the secondary passes through the apex hole of the 9m segmented carbon composite primary and encounters a fold mirror which directs it to the instrument cryostat. The fold mirror can be chopped at a 5 Hz rate. A vane chopper located between the fold mirror and cryostat is used to calibrate the observed intensity scale. Upon entering the cryostat the telescope beam passes through two frequency selective surfaces (FSS) and two wire grids that divide the light into 4 frequency sub-bands. Band 1 is optimized to observe the 557 GHz ground-state $(1_{10} - 1_{01})$ ortho water line. Band 2 covers the 1 to 2.1 THz band, which includes [C II], [N II], and the $(2_{12} - 1_{01})$ 1.69 THz water line. Band 3 is optimized for the 112 μm HD line and Band 4 for the 63 μm [O I] line. A third wire grid is used to divide Band 1 into orthogonally polarized components that are independently detected and co-added. Band 1 uses two, orthogonally polarized, 4x4 arrays of SIS mixers. Bands 2, 3, and 4 utilize single polarization, 8x8 arrays of HEB mixers. Below 2.1 THz solid-state sources provide the $\sim$ 1 mW of LO power needed to efficiently pump the arrays. Above 2.1 THz FIR or quantum cascade lasers serve as the LO sources. Low-noise, 4-8 GHz MMIC amplifiers are used to a boost the intermediate frequency (IF) output signal of each mixer to a power level suitable for processing by 2-4 GHz wide, 2048 lag, single-chip, correlators. The broadband IF output of each mixer will be detected and made available for continuum measurements of planets (calibration and pointing) and other astrophysical objects. The instrument architecture is flexible, allowing the user to configure the instrument to target the optimum lines for a particular observing program. We anticipate it will be possible to observe with ∼288 pixels at a time. The mixer arrays and IF amplifier arrays will be cooled to 4 and 15 K respectively by a low-power, low-microphonic cryocooler. The lifetime of all instrument components will be ≥5 years.

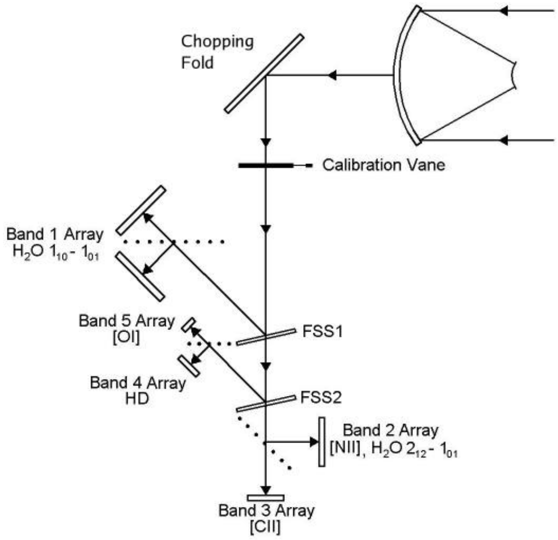

Figure 10: STO optical path

4.2 *Expected Sensitivity*

The Nb SIS device technology used in the Band 1 mixers is very mature. Lab measurements of waveguide mounted SIS devices routinely yield receiver double sideband (DSB) noise temperatures of ∼100K, with noise reductions to ∼60K expected in the near future (Kooi et al., 2003). Above ∼1 THz signal loss in the on-chip tuning structures required to neutralize device capacitance cause SIS noise temperatures to rise above ∼500 K. At these frequencies HEB mixers become competitive with SIS mixers. Lab measurements on waveguide and quasi-optical phonon-cooled HEB mixers in the 1.5 THz range have yielded DSB receiver noise temperatures in the 1000-1400K range (Tong et al. 2003; Yngvesson 2003). Using devices made with enhanced NbN HEB processing techniques and 2 μW of LO power, Baselmans et al. (2004) have recently demonstrated an HEB mixer (in this instance quasi-optical) with a DSB receiver noise temperatures of 950K. Unlike SIS devices, HEBs do not have a bandgap limitation or significant capacitance to tune out. As long as the signal is coupled to the device with low-loss transmission line (e.g. micromachined waveguide) the performance of HEB mixers is not expected to vary significantly with frequency (Yngvesson 2003). For sensitivity calculations for Bands 2, 3, and 4 we have assumed the receivers will have DSB noise temperatures of 1000K. This translates into a system noise temperature of ∼2000K. With the 10 sec integration time per pixel characteristic of the unbiased, galactic survey (UGS) mode, STO will be able to achieve an rms noise level of <0.25K at a 1 km s^{-1} velocity resolution in each pixel. The STO instrument characteristics are summarized in the table below.

Parameter	**Value**
Telescope	9m – deployable carbon composite reflector
Aperture Efficiency	66%
Main Beam Efficiency	90%
Mirror Surface Accuracy	$< \lambda/30$ total error @60 μm
Absolute Pointing	$< 0.3''$ (3σ)
Jitter	$< 0.3''$ (3σ)
Receiver Types	four 8×8 HEB arrays two 4×4 SIS arrays
RX Operating Temp	∼4 K
Target Frequencies	
Band 1: H_2O $1_{10} - 1_{01}$	557 GHz (538 μm)
Band 2: H_2O $1_{11} - 0_{00}$	1.11 GHz (269 μm)
Band 2: [N II]	1.46 THz (205 μm)
Band 2: H_2O $2_{12} - 1_{01}$	1.69 THz (179 μm)
Band 3: [C II]	1.90 THz (158 μm)
Band 4: HD	2.68 THz (112 μm)
Band 5: [O I]	4.76 THz (63 μm)
System Noise Temp.	<2000 K (DSB)
Backend Spectrometer	Autocorrelators 2-4 GHz BW (2048 lags)
Orbit	L2
Mission Lifetime	∼5 years

4.3 *Component Technologies*

4.3.1 *Mixers*

As discussed in Section 4.2, SIS and HEB device technologies have or are rapidly approaching the noise performance required by STO. The technological challenge will be in efficiently packaging the devices into integrated arrays. In Figure 11 we present photographs of laser etched feedhorns at 1.5 THz to illustrate the technologies available for the realization of THz arrays.

4.3.2 *Technical Approach for the LO Hardware*

The technical approach for developing and delivering the LO sources up to 2.1 THz is very similar to the approach being utilized by the Heterodyne Instrument (HIFI) on the Herschel Space Observatory (HSO). All of the recent work has concentrated on advancing planar technology into the THz range; but only single pixel applications have been considered. However, for array deployment, a paradigm

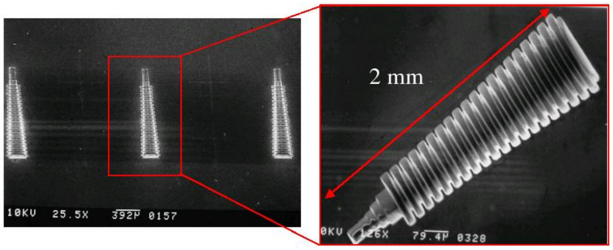

Figure 11: Laser Micromachined 1.5 THz corrugated feedhorn array

shift is necessary. Whereas before emphasis was placed on producing a handful of superbly working prototypes, now the requirement is to produce large format arrays without sacrificing sensitivity.

An example of an integrated LO topology is diagrammed in Figure 12. It consists of a "tray" containing a linear array of multiplier units. The savings in system assembly and operational logistics is substantial. A single LO chain similar to the type used by Herschel is about 9 cm long by 1.9 cm wide. The chain "tray" of Figure 12 produces four 1600 GHz outputs, and is only 0.5 by 0.8 cm. In order to produce a two-dimensional array, trays such as that in Figure 12 can be stacked vertically.

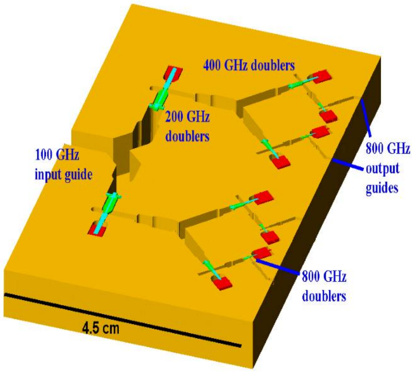

Figure 12: Heterodyne receiver array "tray" concept. Each tray will produce four 800 GHz 2 mW outputs from a single 500 mW 100 GHz input. The "trays" can be stacked to give a 2-D array.

Pumping mixers in the 2-4 THz range continues to pose a great challenge. Sufficient pump power beyond 2 THz from multiplied sources is difficult to achieve. The baseline approach would be to use FIR lasers which have been space qualified. Sideband generators could potentially be used with the FIR lasers to add a degree of tunability. Quantum Cascade Lasers (QCLs) are another promising technology. Test results suggest they have the potential of providing a compact low-power solid-state source for driving THz single pixel or array heterodyne receivers.

4.3.3 *IF Amplifiers*

During the past 4 years wideband, very low noise, cryogenic monolithic microwave integrated circuit (MMIC) amplifiers have been developed with design and testing at JPL and Caltech and foundry fabrication at TRW (now Northrop Grumman Space Systems, NGST) and HRL. These LNA's match the requirements needed for densely packed focal plane arrays in terms of noise temperature, chip size, DC power dissipation, yield, and bandwidth. A typical chip achieves noise temperature of < 5 K at 12 K when driven from a 50 ohm generator impedance.

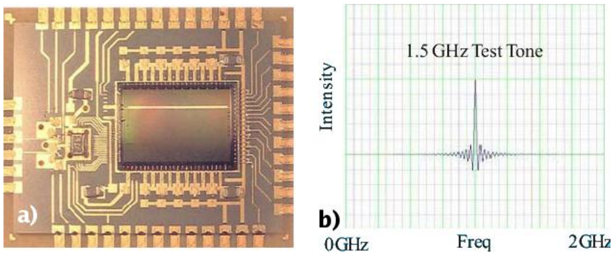

Figure 13: The Spaceborne digital autocorrelator provides an ideal "off-the-shelf" multichannel spectrometer for STO. a) 2 GHz Spaceborne correlator chip. b) Laboratory measurement of spectral response to single frequency input.

4.3.4 *Array Spectrometers*

Rapid advances in autocorrelator and high-speed, analog-to-digital(A/D) converter technology enables multi-pixel systems to be used on STO. Modern correlators incorporate a 2-bit/4-level digitizer and a 2048-lag auto-correlator on a single chip. Figure 13 is a laboratory measurement of the response of a modern 2 GHz correlator chip, manufactured by Spaceborne Inc. A full 2 GHz bandwidth is achieved. A similar result has been achieved by another firm, OmniSys Inc, who have constructed a 2 bit/3 level correlator chip with 1 watt power dissipation. Within a 7-10 year time frame, the expected power requirements of these correlator chips is projected to be reduced by an order of magnitude.

Within the past year high-speed A/D converters coupled with FPGAs have also been demonstrated to provide a full 1 GHz of spectral coverage. This approach has several advantages over using autocorrelators: 1) essentially no loss in signal-to-noise ratio due to digitization, 2) as much as an order of magnitude improvement in spectral resolution, and 3) the capability of being reconfigured through software once constructed. The power requirements of these devices (now ∼10W) are also expected to drop significantly with time.

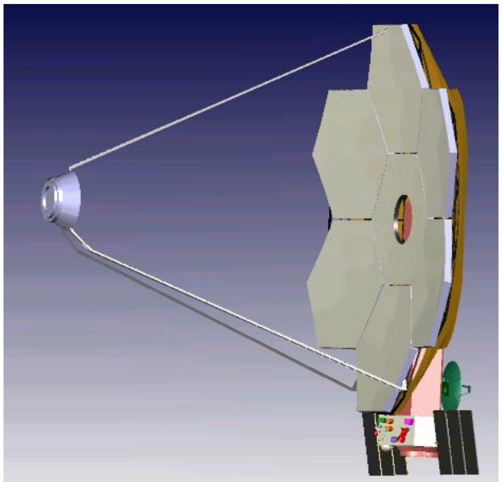

Figure 14: The deployed STO spacecraft and telescope.

4.3.5 *Cryocoolers*

The STO instrument will use long-life, low-power, low-microphonic cryocoolers to achieve the optimum operating environment (~ 4 K) for the THz array receivers. An Engineering Unit of a cryocooler is under development at Ball for the NASA/JPL ACTDP (Advanced Cryocooler Technology Development Program). The foundation of the Ball Cryocooler design is component and system development proven in test verification from Ball programs such as the ACTDP Study Phase, the Ball Aerospace SB235, the NASA Explorer 6 K, the AFRL 10 K, and the DOD COOLLAR, in combination with technology proven on external programs such as the RAL 4 K Cooler and JPL Planck programs. Cooling capacities in excess of 25 mW were measured for temperatures down to 5 K.

4.4 *STO Telescope Description*

The STO provides a $120'' \times 120''$ field of view to the heterodyne spectrometer arrays at a focal ratio of f/19 from a 9-meter f/1 primary mirror composed of seven hexagonal segments (Figure 14). STO's primary mirror is maintained at a uniform temperature with minimal thermal gradients by thermal blanketing on the primary mirror support. The secondary and its support structure are shielded from the Sun by the primary's thermal blanket for Sun-Earth off-axis angles $\leq 45°$. To package STO for launch in a 5-meter Delta-IV or Atlas V faring, the 9-meter primary mirror incorporates a deployment scheme identical to the James Webb Space Telescope concept; the primary mirror articulates in two locations to fold in thirds, one of the three support spiders for the secondary mirror folds in half, and the other two support spiders hinge at the primary mirror attachment points (Figure 15). Once the primary mirror is deployed the segments are adjusted in tip, tilt, and piston by mirror-mounted actuators using mirror edge sensor position feedback to position them accurately. The surface figure can be independently verified by measuring the quality of the diffraction limited telescope beam on astrophysical objects (e.g. planets). Carbon fiber reinforced polymer composites are used to replicate the hexagonal segments for the primary and secondary mirrors, a technique similar to construction techniques used for ground-based radio astronomy telescope manufacture and a method that will allow significant cost savings in comparison to the cost of beryllium mirror manufacture for JWST. A comparison of STO and JWST performance requirements is provided in the following table.

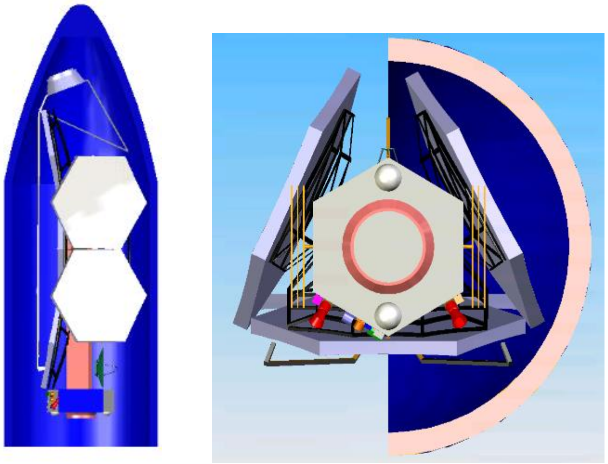

Figure 15: Side and top views of the STO spacecraft. Telescope & spacecraft fit in the smallest available 5m fairing.

Parameter	**STO 2004**	**JWST 2004 (1998)**
Primary Mirror Diameter	9.0m	6.4m (8.4m)
Primary Mirror Material	Carbon composite	Beryllium
Sunshade vanes	0	5
Mirror surface figure	2 μm	0.023 μm
Pointing Requirements	$0.5''$	$0.15''$
Telescope temperature	100-300 K	40 K
Segment actuators	rigid body	rigid body & radius of curvature
Number of Instruments	1	3
Mission life	5 yr	5 yr
Orbit	L2	L2
Daily Data Volume	22 Gb/day	33 Gb/day
Ground Testing	warm	cold
Mass	2500 kg	(4100 kg)
Power	1400 W	(570 W)

5 Summary

The Space Terahertz Observatory (STO) is a deployable, uncooled, 10-meter-class, far infrared space telescope optimized to 1) conduct origin studies of planets, stars, and molecular clouds; 2) trace the life cycle of the Interstellar Medium (ISM) and star formation rate throughout the Galaxy; 3) measure the gas content of formative pre-planetary disks; and 4) observe the distribution of atomic and molecular gas in both nearby and distant galaxies. STO will achieve these scientific objectives through high spectral and angular resolution observations of C+, O, N+, HD, and H2O lines in the far-infrared. The science goals of STO can be achieved either through a dedicated mission with an uncooled 8-10 meter primary or by implementing heterodyne instrumentation on SAFIR and extending its operational lifetime.

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