SPECtroscopic TeRAhertz Satellite “SPECTRAS”

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The enormous success of Herschel has made it clear that the Terahertz frequency range (corresponding to submillimeter wavelengths) offers vastly powerful probes of astrophysical and planetary processes. Some of the most interesting and surprising results have emerged in the area of high-resolution spectroscopic study of the solar system objects, protoplanetary and protostellar disks, and the interstellar medium of the Milky Way, and nearby galaxies. The Probe concept described here, which builds on the discoveries made by Herschel, is exceptionally broad in its scientific reach, addressing critical questions from the origin of the Earth’s water to the dependence of star formation rate on the properties of galaxies.

A critical underpinning of the SPECTRAS concept is that for velocity-resolved studies of objects ranging from solar system comets to nearby galaxies, the telescope emission is unimportant compared to the quantum noise of heterodyne systems. Consequently, there is little advantage in cooling the telescope optics, in contrast to the situation for photometry and low-resolution spectroscopy. Thus, available funds can be focused on obtaining the maximum aperture size, without worrying about complex thermal shielding and cryogenic systems for keeping the telescope at 5 K – 10 K, as is being contemplated for a number of missions focusing on low-spectral resolution observations.

SPECTRAS is envisioned to be a 6-m class observatory, operating in the frequency range from 500 GHz to 3000 GHz (wavelengths from 0.6 mm to 0.1 mm). The angular resolution, ranging from ~25” down to 4” at the high-frequency end is critical for resolving structure in galaxies, in particular distinguishing spiral arm and inter-arm regions in such tracers as the ionized carbon fine structure line, [CII] 158 μm. SPECTRAS sensitivity will be a factor ~4 greater than that of Herschel in terms of collecting area, but the mapping speed will be dramatically increased by improvements in receiver sensitivity (by factor ~2-3 times better than HIFI), as well as employing large focal plane array receivers, which have been developed for balloon and airborne (SOFIA) use. With a 64-pixel array for the most important bands, the pixels per unit time mapping rate will be increased by a factor of 256 and the areal mapping speed by a factor of 64 relative to Herschel/HIFI.

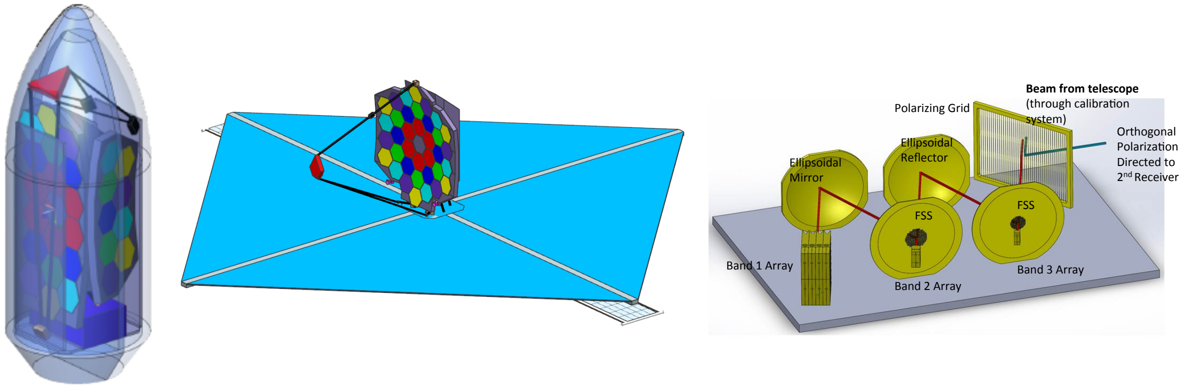
SPECTRAS will target the most important low-lying transitions of both HDO and other isotopologues of water, enabling accurate measurements of the D/H and oxygen isotopic ratios in a large number (on the order of 20) of comets. This measurement has been highlighted to be of prime interest to planetary science, as it can determine whether the Earth’s water came from comets. The limited set of Herschel HIFI measurements of HDO [1], [2] and in-situ measurements [3] suggest significant variations among comets, indicating that the only way to make progress is to measure a statistically significant sample. Water is also an exceptionally important astronomical molecule; its unique astrobiological role is supplemented by its being a critical coolant of the gas phase in star-forming regions. SWAS, Odin, and Herschel have studied water in a variety of astronomical and planetary regions. HIFI observations showed water to be a uniquely powerful tracer of the collapse of dense star-forming cores [4]. Extending this work with significantly higher angular resolution and sensitivity will enable determination of the full three-dimensional velocity field in star-forming cores. The result would be a major, fundamental advance in understanding how stars and planets form. Herschel detected water only in a single protostellar disk (TW Hydrae [5]), having a line width of only 1.5 km/s. With SPECTRAS’s higher sensitivity it will possible to survey many nearby disks and determine their gas-phase water content. Water is the second strongest molecular line emitter in nearby galaxies [6], but only with increased sensitivity, mapping speed and angular resolution can we use it to probe the physics and chemistry of star-forming regions in galaxies of different types. All of this work is impossible from SOFIA and almost so from a balloon.

Atomic fine structure lines are valuable probes of the interstellar medium and star formation. [CII] is the most important coolant of diffuse clouds and as such plays a key role in the atomic-to-molecular transition, which likely governs the rate of star formation. Observations of its 158 μm line directly measure the cooling rate, but high velocity resolution is essential to resolve kinematic structure and avoid problems with foreground absorption. [CII] 158 μm observations have allowed the first detailed look at the "CO Dark Molecular Gas", that adds about 30% to the molecular mass of the Milky Way [7], and have shown how this line traces star formation [8]. The spectral and angular resolution together with the mapping capability of SPECTRAS are essential to extend this study to a large sample of galaxies.

The SPECTRAS design is derived from JWST; as shown in the figure, it incorporates a deployable primary reflector having two folds with 36 hexagonal segments. A deployable tripod supports the hyperbolic secondary reflector. As a result of the ~100X longer operating wavelength, the mass and cost of the telescope are drastically less than JWST. A Falcon 9 Heavy can launch the mission mass of < 7000 kg directly to a Lissajous orbit around L2. A LEOstar-3 bus with upgraded dual star trackers will provide the 1" pointing accuracy. The shroud may be able to accommodate a 6.8-m diameter telescope, but more detailed analysis will be required to study the exact packing of telescope and sunshield. A single layer 34-m diameter sunshield is supported by 4 astromasts. Similar to Herschel, the sunshield and L2 orbit yield an extremely stable thermal environment, making the required 8 μm rms surface achievable without the use of exotic materials. The sunshield size needs further optimization, but the ability to point relatively close to the sun is desirable, and is essential for efficient study of comets.

The receiver system will have 5 bands of array receivers incorporating up to 64 pixels each. The receivers will employ SIS or HEB mixers, and the local oscillators will be produced by frequency multiplication from a precision low-frequency source. Similar single pixel systems were used in Herschel HIFI and small arrays in the upGREAT instrument on SOFIA at frequencies up to 4.7 THz (λ = 63 μm). The frontend components will be cooled by commercial 4 K closed cycle cryocooler. With no liquid cryogen, a minimum lifetime of 5 years can be expected. Spectral lines in multiple bands can be observed simultaneously if desired, as the different bands will be multiplexed using frequency selective surfaces. Dramatic advances in CMOS ASIC devices mean that a single chip 8192 channel digital FFT spectrometer covering 3 GHz bandwidth (450 km/s coverage and 0.06 km/s velocity resolution at the [CII] 1.9 THz line) and consuming only 200 mW (including digitizer, spectrometer, and memory) can serve as the full backend for each pixel.

A slightly different version of SPECTRAS was studied by Team-X at JPL, and the cost estimated to be $1.4B. This was based on conservative telescope design parameters and can likely be significantly reduced.



(Left) Stowed SPECTRAS configuration in Falcon 9 launch fairing; (Center) Deployed configuration (the solar panels on opposite side of sunshade are just visible at two corners); (Right) Multiband reimaging optics, frequency selective surfaces, and focal plane arrays for 3 bands, expandable to 5.

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