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SmallSat Interferometry for THz Astrophysics

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ABSTRACT

While great strides have been made in far-infrared astrophysics with the NASA Spitzer and ESA Herschel missions, sub-arcsecond spatial resolution from space is still beyond the reach of current technologies. The Atacama Large Millimeter Array has produced stunning images from the ground of planetary systems in the process of formation but cannot observe the key molecules of water or O₂, due to the presence of Earth's atmosphere. The concept presented here will enable interferometric imaging with sub-arcsecond resolution of water and other key far infrared molecular species from space at a cost far lower than the flagship class interferometric missions previously proposed (i.e. ESA's ESPRIT). We present a concept for a far infrared interferometer based on a constellation of CubeSat antenna elements with a central ESPA-class correlator satellite optimized for the imaging of water in protoplanetary systems. Such a mission would produce groundbreaking images of newly forming planetary systems in a key astrophysical and astrobiological tracer, the 557 GHz ground state line of water. By leveraging recent developments in CubeSat technology, inflatable reflectors, miniaturized receiver systems and low power CMOS digital electronics, such a mission could be implemented at an Explorer level budget. In addition to the proposed astrophysics application, the developments proposed here could also find application in planetary science (FIR spectroscopy of comets and small bodies) and Earth observing (high resolution imaging of Earth from geostationary orbit).

Keywords: terahertz, cubesat, interferometry, water, mission concept

1. INTRODUCTION

Figure 1. An ALMA image of the protoplanetary system HL Tau at 233 GHz. The proposed concept could produce images of similar fidelity, but in the emission of water at 557 GHz. Credit: ALMA (NRAO/ESO/NAOJ); C. Brogan, B. Saxton (NRAO/AUI/NSF)

Water is an extremely powerful probe of conditions in the interstellar medium. The 557 GHz ground state transition is the optimal water line to probe the cold interstellar medium involved in the star formation process. Ground based observations of proxies for water (e.g. HDO) or optically thin lines of rare isotopologues (e.g. H_2^{18}O) have been attempted, but they are either non-optimal, very difficult to implement or both. Direct observations of the most important lines of water are impossible from the ground due to the presence of water vapor in Earth's atmosphere. Indeed, observation of the 557 GHz water line was a primary science driver for the SWAS, ODIN and Herschel missions. Recent observations of HDO by ALMA show that high spatial resolution observations of water in protostellar accretion disks will be an extremely powerful probe of the star and planet formation process [1].

In this concept, there are $\sim 12 \times 6\text{U}$ CubeSats, each equipped with a 2-meter diameter spherical inflatable antenna (1m effective aperture) feeding an ambient temperature Schottky diode-based terahertz receiver (See figure 2). This number of elements and reflector size provides the same collecting area as the Herschel space telescope, but with over three orders of magnitude higher spatial resolution. This inflatable spherical antenna concept has been developed as part of a recently completed NASA Innovative Advanced Concepts (NIAC) effort by Co-I Walker and his team and is continuing under a grant awarded to him by the Office of Naval Research (ONR). A laser or mm-wave metrology system used in conjunction with GPS will be used to triangulate and track the position of the CubeSats. In addition, each CubeSat will be equipped with a high-speed laser and/or radio communication system to transmit the received data to a central ESPA-class small spacecraft and receive a centrally generated local oscillator reference signal. An ESPA-class spacecraft is compatible with many different launch vehicles, including Minotaur I, Minotaur IV, Delta IV, Atlas V, Pegasus, Falcon 1/1e, and Falcon 9. This ESPA class spacecraft contains the master oscillator for local oscillator distribution to the CubeSats, the correlator used to process the data received from the CubeSats, and a Ka-band system to transmit the processed data to the ground. The remainder of each CubeSat contains commercial off-the shelf subsystems, which could be built with existing hardware. Each CubeSat would use a system similar to the Blue Canyon XACT platform for attitude determination and control. The XACT unit contains an integrated star tracker, sun-sensor, IMU, reaction-wheels and magneto-torquers to provide a 10-20 arcsecond pointing accuracy. Each CubeSat also contains a camera (e.g. the RocketCam from Ecliptic) for engineering and navigation, a pair of radiation shielded payload computers, (e.g. a Space Micro CSP based on the Xilinx Virtex-5 FPGA fabric and Tyvak Intrepid CD&H computers) and a secondary UHF communication system for spacecraft to ground backup communication. While absolute station keeping is not required, the CubeSat constellation must be kept in the same $\sim 5\text{ km}$ diameter volume throughout the mission. While a detailed study of the propulsion system requirements for the constellation is necessary, simple gas thrusters will likely be adequate to maintain the constellation in formation for reasonable mission durations.

Figure 2. The CubeSat THz interferometer concept. ~ 12 CubeSat elements with 2m spherical inflatable antennas feeding ambient temperature THz receivers communicate with a single ESPA-class central hub with a high-speed laser communications system. The central satellite contains the correlator system and ground communications. A laser metrology system tracks the position of each CubeSat to ~ 50 -micron accuracy.

Sensitivity calculations, following [2] assume a 12-element constellation with 1m effective aperture antennas, baselines up to 5 km (maximum spatial resolution of 50 mas) and 1000K noise temperature receivers. These specifications were chosen to provide similar total collecting area to Herschel and spatial resolution comparable to ALMA. With this strawman configuration, the proposed array can reach sensitivities assuming 1 MHz spectral channels of $1 \times 10^{-25} \text{ W m}^{-2} \text{ Hz}^{-1}$ in less than 2000s of integration time, and $1 \times 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$ in 54 hours of integration time in a 50 mas synthesized beam. This includes the effect of quantization efficiency for a 3-bit correlator (88%) and the efficiency effect of 30-degree rms phase decorrelation, in this case due to uncertainties in the positional metrology of the CubeSat elements (83%, [3]). While integration times are longer than with Herschel HIFI due to the ambient temperature receivers proposed here, the concept can deliver observations with depths equivalent to those achieved with Herschel in a reasonable amount of time, but with spatial resolution more than three orders of magnitude greater. Figure 3 shows a notional array configuration with 5 km maximum baselines and resulting UV plane coverage.

Figure 3. A possible 12 satellite constellation configuration (left), and the UV plane coverage (right) generated in half an orbit assuming the CubeSat elements are rotating about the center of the configuration during the observation.

2. TECHNOLOGICAL PATH

While many of the components necessary to implement the CubeSat antenna stations and the central correlator satellite already exist, several technologies would require significant development to make this concept a reality. Here is a sample illustration and caption for a multimedia file:

2.1 Primary Technical Challenges

The primary technical challenges for the realization of the proposed concept are:

- Development of a deployable antenna with ~1m effective aperture operating at 557 GHz frequency.
- Development of a miniaturized ambient temperature receiver that can simultaneously deliver state of the art noise temperature while being compatible with the mass, volume and power available on a 6U CubeSat.
- Low power, high speed digital electronics are needed to implement the digitizer, frequency synthesizer, correlator and data transmission subsystems.
- High speed, short range communications with bandwidths of several Gb/s are needed to transmit the received signals from each CubeSat to the central correlator in real time.
- Metrology with positional knowledge of ~50 microns is needed to measure the position of each CubeSat during observations.
- Advanced propulsion and formation flying technology is needed to maintain the constellation in a ~5 km diameter volume throughout the mission.

2.2 Antenna

A long-standing problem for using small satellites for astronomy at millimeter to far-infrared wavelengths is that of realizing a useful collecting area within the size and mass constraints imposed. This is not so much of a problem at e.g. optical wavelengths, where an aperture of a few cm diameter can carry out significant observations. At much longer

wavelengths, the lower brightness of typical signals means that collecting areas on the order of 1 m^2 are required for useful observations. Until now the parabola has been the shape of choice for space missions because it brings parallel rays to a single focus. However, the complexity and stow volume of the required back-up structure for a parabola makes it problematic for a CubeSat.

Here the proposed reflector is a balloon, made from thin dielectric material, that when inflated, takes on a spherical shape. One hemisphere of the sphere is fully or partly metallized. Electromagnetic waves pass through the dielectric, RF-transparent hemisphere of the sphere and reflect off the metallized hemisphere. The reflected waves come to a focal line approximately $\frac{1}{2}$ the way back towards the sphere's center. The focal line is then collapsed to a focal point by a spherical corrector. Multiple techniques exist for the correction of spherical aberration. Line feeds and both reflective and refractive spherical correctors can be implemented. Figure 4.1 is a photograph of a 3-meter diameter, rooftop inflatable spherical reflector (ISR) prototype. The prototype was constructed as part of a NASA NIAC study to gain experience with the technological approaches needed to realize a flight model of ISR. The prototype has all the key elements of the flight version. The sphere was purchased from a toy company and is formed from 0.8 mm thick, thermoplastic polyurethane (TPU) gores. As a test of optical performance, a Sun scan was made with the ISR at 115 GHz (see Figure 4). Since the projected size of the Sun on the sky is only $\sim 0.5^\circ$, the scan yields a faithful representation of the ISR main beam. From the Sun scan we measure, indicating the ISR prototype is providing diffraction limit performance. The fact that such a crude prototype works this well suggests the concept is robust and bodes well for the success of a full flight version.

Figure 4: 3-meter LBR rooftop prototype. The rooftop prototype is a fully functional model of the flight version of ISR designed to operate at 115 GHz (left). ISR Sun scan. A Gaussian fit yields a FWHM beam size of $\sim 0.8^\circ$, indicating the reflector is providing diffraction limited performance. (right)

Figure 5: Measured system noise temperature for a prototype 557 GHz receiver system measured at room temperature including optics losses and cooled to 180K developed as part of a NASA Small Satellite Technology Program award. The

system noise temperature measured without optics is $\sim 1000\text{K}$ at 300K . The rise in noise temperature at 557 GHz is due to water vapor in the laboratory and is not a feature of the receiver system.

2.3 Receiver System

All-solid-state heterodyne receivers using both MMIC Schottky diode based LO sources and mixers are uniquely suited for long-term planetary missions or Earth climate monitoring missions as they can operate for decades without the need for any active cryogenic cooling. With the recent advances in ultra-compact device microfabrication and device optimization, receivers beyond 1 THz are feasible. Our team was recently funded by the NASA Small Satellite Technology Program to develop the next generation of highly integrated Schottky diode receivers for use on CubeSats, with order of magnitude level improvements in mass, volume and power consumption compared to the current state of the art while maintaining or improving noise performance. This effort will focus on the design of receivers for the 557 GHz water line. We have demonstrated a compact, room-temperature, all-solid-state $520\text{--}600\text{ GHz}$ receiver featuring a minimum double side band (DSB) mixer noise temperature of 1000K , with DSB conversion losses of around 6 dB within an IF bandwidth of $1\text{--}11\text{ GHz}$. Further improvements in both compactness and performance are still possible using the latest device topologies and additional levels of integration. The existing SSTP effort will result in a receiver of TRL5 at the conclusion of the work in 2019. Figure 5 shows results from our SSTP work, developing a state of the art 550 GHz Schottky diode receiver consuming only 3.5W of power including the drive synthesizer. With a full IF chain and ASIC based backend, this would increase to no more than 4.5W .

2.4 Digital Electronics

Each CubeSat will require a high-speed analog to digital converter to digitize the downconverted signal from the THz receiver system. In addition, a total of $N(N-1)/2$ (where N is the total number of CubeSat elements) correlator boards to correlate the unique baselines between each CubeSat are required. Typically, these digital electronics are power hungry and large. Recently, JPL and UCLA have developed a 1.5 GS/s spectrometer using 65nm CMOS, all contained on a single $2\times 4\text{mm}$ chip, consuming significantly less than 200 mW of power (see figure 6). This chip includes both a high-speed ADC and a FFT processor. This technology could be further developed to produce the required wide band digitizers and correlator modules required for the proposed concept, with power consumptions suitable for use on CubeSats and the ESPA-class correlator satellite. Newer generations of this board now offer up to 3 GHz of RF input bandwidth.

Figure 6: A JPL developed 1.5 GS/s CMOS spectrometer board.

2.5 Metrology

While the proposed concept does not require ultra-precise station keeping, the positions of each of the CubeSats must be known and tracked in 3D space to within ~50 microns. Commercially available laser trackers (e.g. laser trackers from Faro and Leica) already offer the distance accuracy required for the proposed concept. We envision a system based on small optical retroreflectors mounted on each spacecraft, and pointable laser tracker(s) on the central satellite. Alternatively, mm-wave radar or tracking of the carrier of the mm-wave data link (see section 2.6) could be used to obtain accurate distance estimates. Measurements will be made continuously and used to update orbit models for each element to determine their relative positions. The derived time delays will then be compensated for digitally in the correlator system. Data will be digitally buffered to allow time for the orbit models to be measured and updated to achieve the required accuracy. This is likely the most challenging technology development area for this concept.

2.6 Satellite to Satellite Data Communications

Short range (km), very wide bandwidth (several Gb/s) communications are required between each CubeSat and the central satellite to transmit the received signals to the correlator in real time. This could be accomplished via two possible means: high speed optical communications using lasers or with millimeter-wave radio links (e.g. Ka band technology developed from JPL's ISARA CubeSat mission). Since the distances between elements and the central satellite are small and in the vacuum of space (no more than about 2.5 km), high power is not required. Therefore, inter-satellite links up to several 100 GHz are possible. This communications system will not only send data from the CubeSat elements to the central correlator satellite, it will also be used to distribute the master oscillator signal generated in the central satellite to the CubeSat elements. This master oscillator signal will be used to phase lock each of the CubeSat elements.

2.7 Propulsion and Formation Flying

While this concept does not require precise relative station keeping between constellation elements, it is necessary to keep the elements in a ~5 km diameter volume throughout the mission. This will require some level of propulsion. Formation flying of cubesats is an active area of research, with many missions proposed as demonstrations [4]. These missions demonstrate a TRL level for formation flying and propulsion technologies at TRL6 for the concept, but more likely TRL3 for the exact requirements of the proposed mission concept.

3. ACKNOWLEDGEMENTS

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