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ARKSAT-1, 1U CubeSatellite Developed at the University of Arkansas

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ABSTRACT

ARKSAT-1 is a 1U CubeSatellite developed at the University of Arkansas (UA). The primary mission of the satellite, in addition to being the first student satellite in the State, is to operate a bright LED hosted on the satellite in conjunction with a ground-based tracking system. A secondary objective is to perform space environment testing of a deorbiting module applicable to small satellites (<180kg). This paper will discuss the satellite design, development, build, and expected operations in the context of ongoing work at the UA.

ARKSAT-1 OVERVIEW

ARKSAT-1 (Figure 1) is a 1U CubeSat potentially scheduled to launch to the International Space Station on SpaceX SpX-22 mission launching from Kennedy Space Center 12 Mar 2021, as part of NASA's 8th Cubesat Launch Initiative (CSLI-8). ARKSAT-1 was previously manifested on SpX-21, but has been pushed into early 2021 due to COVID-19 related delays in the development and production of the flight unit.

ARKSAT-1 will feature a high-powered LED, which will be visible on the ground from Low Earth Orbit and tracked via a ground tracking system. The payload also includes a simple, reliable, low-cost, and lightweight Solid State Inflatable Balloon (SSIB) deorbiting system applicable to small satellites. The SSIB is comprised of a printed circuit board (PCB) solid state gas generator chip (SSGG) based on a previously developed Micro-Electro-Mechanical Systems (MEMS) prototype, space compatible balloon film structure, and spacecraft integration subsystem.

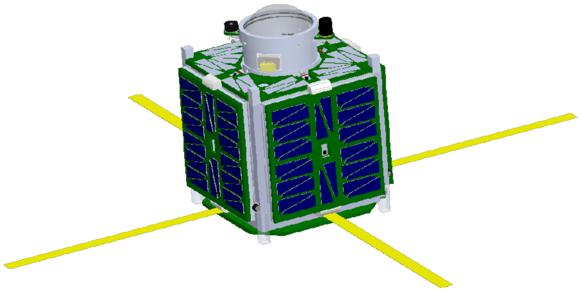

Figure 1: Rendering of ARKSAT-1

Satellite Development at the University of Arkansas

The initial spaceflight performance of ARKSAT-1 is the first step in enabling a state of the art, low cost atmospheric detection platform, the Diurnal Atmospheric Surveyor CubeSats (DAS-Cubes), consisting of an emitter with a source of known intensity and spectrum (DAS-E), and a chaser (DAS-C), with receiving and tracking capabilities. Combined, the system will be capable of achieving high quality measurements of atmospheric or other material between pairs or multiple spacecraft in formation flight. Components and capabilities of the system will be developed and tested as part of phased satellite projects, starting with ARKSAT-1 featuring LED as a source emitter and followed on by ARKSAT-2 with tracking capability provided by microthrusters. Both satellites will be tested in Low Earth Orbit at or near the International Space Station orbits.

SPACECRAFT DESIGN AND HARDWARE

Figure 2 shows an exploded solid model view of ARKSAT-1 and its components and subsystems. The axis (+Z and –Z) nomenclature will be referenced throughout the remainder of the paper.

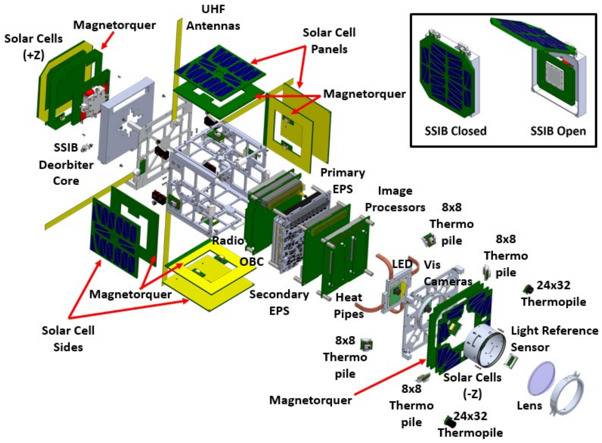

Figure 2: Detailed view of ARKSAT-1

Power Systems

The satellite is powered by 3J GaAs scrap solar cells mounted on all six faces of the spacecraft, shown in blue in Figure 1. These directly charge the primary Clydespace 3G EPS with integrated 20 Whr batteries. ARKSAT-1 also hosts a small bank of ten 100mAh lithium-ion polymer batteries, powering a secondary EPS which will exclusively drive and control the satellite's high-powered LED nominally at 36V. The secondary batteries and EPS are charged only by the primary EPS and include integrated solid-state switches as inhibits and control.

High-Power LED

ARKSAT-1's primary payload is a high power light source, a Luminus CXM-27 Gen 1 COB Arrays White LED. This LED has 11-12,000 lumens output and 119-130 lumen/watt brightness. A 50mm diameter condenser lens is used on the –Z face, its housing and aperture occupying the "tuna-can" space. At the expected orbital altitude of 410km, the light intensity to an observer on the ground corresponds to an apparent magnitude of approximately 3. Due to the amount of heat rejected by the LED, only brief (on the order of 10 seconds) continuous operations will be possible. Four heat pipes will be used as passive thermal control, as shown in Figure 2, by enhancing the spread of heat generated by the LED to the side-frames.

Sensors & Imaging

ARKSAT-1 has a series of sensors for use as part of the attitude determination and control system (ADCS) as well as IR and optical image collection and being downlinked. Each of the five faces (less the -Z face) has an 8x8 pixel Panasonic AMG88 thermopile IR sensor, while the -Z face has four of the same sensor, mounted at 60 degree angles to capture the sphere of the Earth at the orbital altitude, allowing further feedback to achieve nadir-pointing of the spacecraft. This provides the satellites and ADCS system with more input into a filter algorithm, allowing for finer pointing accuracy when used in conjunction with magnetometer and rate gyro data, rather than sun sensors utilized by many CubeSats[1,2]. The -Z face also hosts two higher resolution IR cameras (Melexis MLX90640 32x24 thermopile) to be used for more accurate pointing to our ground station during the mission as well as two optical standard definition TTL cameras (Putal PTC06, JPEG output) used for finer pointing and daytime ground tracking. Additionally, each face of the satellite has a 9-axis MEMS gyro, accelerometer, and compass (TDK ICM-20948).

The attitude determination and utilizes rate gyro, magnetometer, and IR camera data to achieve its nominal operational mode of nadir-pointing. Attitude control for ARKSAT-1 is achieved via printed copper magnetic coils in separate PCBs under the solar array PCBs on all six faces of the satellite. Detumbling will be achieved shortly after deployment, with multiple variations of a Bdot controller currently under investigation. After detumbling the spacecraft, operations will proceed to free-flight until nadir-pointing is required.

Radio

ARKSAT-1 hosts 2 radios: an Astrodev Lithium-1 half-duplex operating at 435.45 MHz, and an experimental LoRa RN2903 radio operating at 906.3 MHz which will be tested for basic uplink functionality in orbit. The Li-1 has flight heritage, and the experimental LoRa radio will be an operational test of that particular radio in a space environment.

The satellite has two 'tape measure' style dipole antennas sized for the frequencies of the respective radios. Nichrome burn wires are used to release the antennas after deployment. The ground station at the UA utilizes and builds upon existing amateur radio infrastructure on campus and consists of a transmitting Li-1 identical to the unit aboard the spacecraft, and an elliptically polarized Yagi antenna.

Figure 3: Machining frame prototype

Machining

All structure of the spacecraft, as well as the LED lens housing and cap are machined at the University of Arkansas's student machine shop facilities. The center frame of 6061 aluminum alloy is machined from 4" x 4" square stock extrusion with 1/8" thick sidewalls while the ends (+/- Z faces) are milled from solid billets of 6061 aluminum (The team based their structural fabrication concept on NASA Ames CubeSat designs using 10cm square tube 6060 aluminum extrusions). FIGURE 3 shows team member Jacob Fleming machining a prototype ARKSAT-1 frame. The red plastic material on the interior is a 3D printed insert to prevent warping of the frame during the machining process.

DEORBITING SYSTEM

As CubeSats and other small satellites are increasingly used as research platforms, there is a growing need to reduce the orbital lifespan of inactive spacecraft, reducing the probability of collision between spacecraft and orbital debris[3]. Because such satellites often do not have propulsion systems dedicated to deorbit, there is a need for novel non-propulsive deorbiting systems. Most CubeSats operate at 300-550km orbital altitude, where aerodynamic drag is the dominant force. ARKSAT-1's Solid-State Inflation Balloon (SSIB) deorbiting system utilizes this dominant force as an effective method to significantly reduce orbital lifetime of CubeSats and other small satellites (<180kg), including meeting FAA requirements to deorbit satellites within 25 years[4].

The SSIB deorbiter was funded from NASA's Small Satellite Technology Program under the Space Technology Mission Directorate and developed at the University of Arkansas. The SSIB consists of Solid-State Gas Generator (SSGG) chip containing 1 2D array of Sodium Azide (NaN_3) wells, relevant control electronics, and a balloon material surrounding the SSGG. The original manufacturing, design, and testing featured a MEMS SSGG chip, though ARKSAT-1 will utilize a PCB version to better match the less-stringent requirements of ARKSAT-1. When activated, the wells are heated to >350C, releasing N_2 gas which inflates a balloon. This process uses ~ 1W of power for ~10 seconds, and the N_2 gas is released within milliseconds of heating[4]. The modular sub-system package fits within a 10cm x 10cm x 2cm envelope. The NaN_3 in the wells is coated with a ~15μm thick parylene coating[4]. Figure 5 shows the PCB-based SSIB subsystem and Figure 5 shows a rendering of the inflated ($0.1m^2$) balloon for scale.

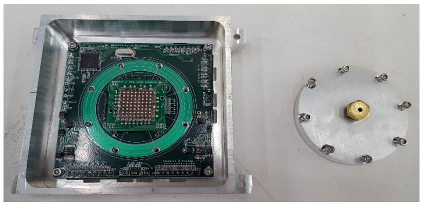

Figure 4: MEMS SSIB subsystem prototype

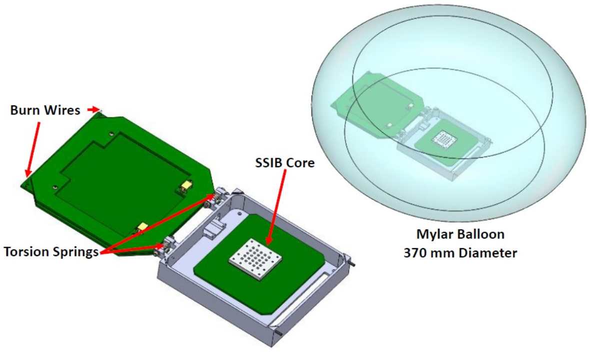

Figure 5: ARKSAT-1's PCB deorbiter design with 37cm diameter balloon

Simulations on the performance of the SSIB with different balloon cross sectional areas were determined using Analytical Graphics, Inc. Satellite Tool Kit (STK). Assumptions were: a 1.33 kg 1U CubeSat, circular orbit at 28.5° inclination, over a range of starting orbital altitudes. $0.01m^2$ area is the nominal cross sectional area of a 1U cubesat. As shown in Figure 6 the $0.1m^2$ area, corresponding to ~37cm diameter inflated balloon would reduce the orbital lifetime significantly, from about 40 years to less than 5 years at 700km initial orbit, and less than a year for a 550km orbital altitude[4].

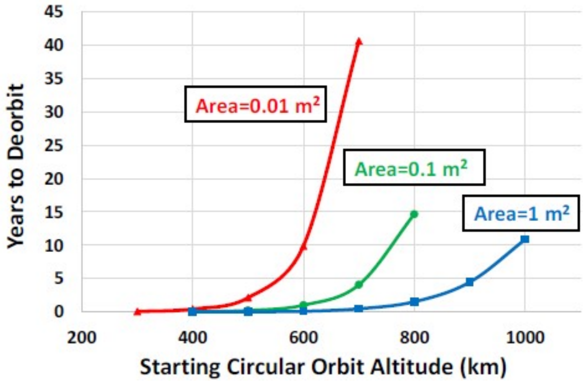

Figure 6: Orbital lifetime[4]

The SSIB system is designed to minimize complexity and utilize aerospace grade materials, with the exception of the Sodium Azide solid, which is slightly toxic and shock sensitive. The amount of NaN_3 used (~1-10 mg) is well below the toxic threshold, and shock tests were previously performed on the MEMS units with positive results showing no unintended dislodging of the material[4].

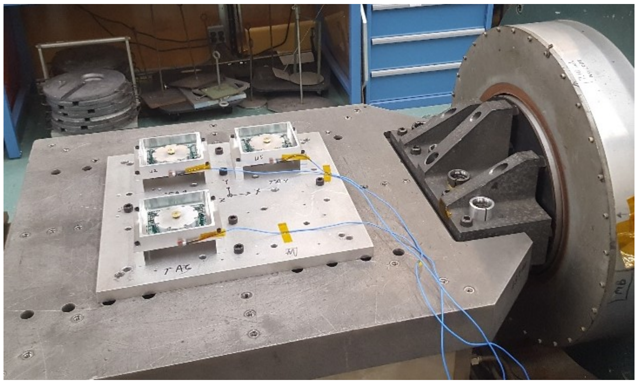

Figure 7: Test articles mounted for vibe testing[4]

Part of the development process included testing the SSIB system in a vacuum chamber. 10cm mylar balloon has been inflated at UA in a vacuum environment at ~5mTorr. While there were some issues achieving the desired full-inflation of the balloon (due to gravitational force exceeding pressure differentials on the balloon) in an Earth-based vacuum chamber, inflation of the SSIB in a space environment is expected to be less complicated than terrestrial vacuum chamber[4].

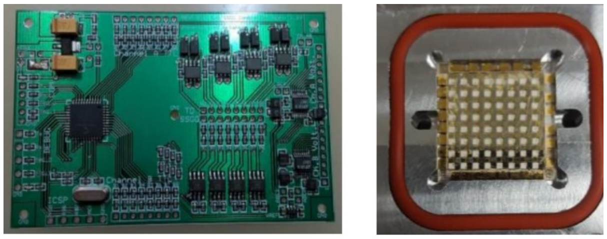
8x8 SSGG Driver
8x8 SSGG (with NaN_3)

Figure 8: SSGG and driver

TRACKING SYSTEM & SPECTROSCOPY

As part of the ongoing satellite development effort, a ground-based aerial-tracking open path spectroscopy system has been under development at the University of Arkansas. This system consists of two components: a Ground Tracker and an Emitter. The Emitter (ARKSAT-1 in the present case) package is comprised of an LED light source, and sends location data to and is kept in pointing alignment with the Ground Tracker. The Ground Tracker tracks the Emitter and utilizes a spectrometer to perform spectral measurements. The Ground Tracker is shown in Figure 9 and consists of a rifle scope, fiber optic cable, spectrometer, camera, two Nema high accuracy stepper motors for azimuth and elevation control, lightweight AL frames, and actuating mirror[5]. The spectrometer is an Ocean Optics USB 4000 UV-Vis -NIR collecting from about 350-1050nm.

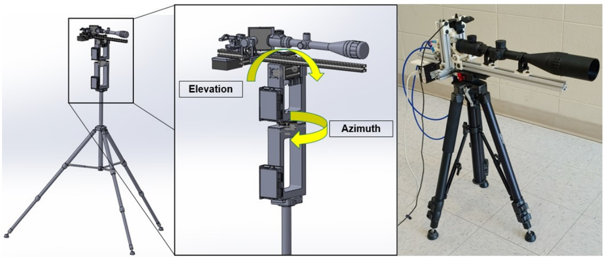

Figure 9: Automated ground tracking system design (left, center) and manual scope setup used for initial spectra measurements (right)

On June 17th, 2019, lunar spectra were taken using this system, and the spectra as well as lunar image are shown in Figure 10. The moon was taken into the field of view, and the spectra were recorded over an integration time of 1s. Ground truth measurements were taken with an LED flashlight with known spectrum at a distance of 25 feet over an integration time of 6000μs[5]. Multiple absorption bands from atmospheric constituents can be seen in the spectra, providing data on which compounds are present in the atmosphere using a spectroscopic database such as HITRAN. While this system is being developed first as a ground-based instrument, it is intended to be miniaturized and applied on a paired satellite system, which could be used to perform planetary atmospheric measurements not just at Earth, but other planets and moons in the solar system as well[6].

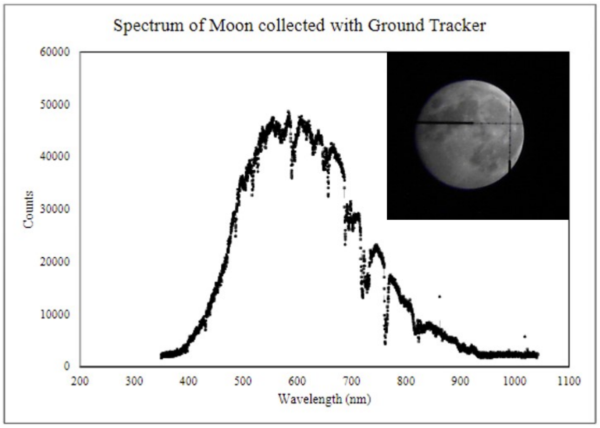

Figure 10: Lunar Image & Spectra[5]

ARKSAT-2

ARKSAT-2 is a 2U cubesat built on ARKSAT-1 infrastructure, designed for chasing and tracking demonstration. It utilizes the existing electronics stack, and the bulk of the remaining 1U of space is allocated for a novel CubeSat Agile Propulsion System (CSAPS), a water/propylene glycol based propulsion system for attitude control. The flight demonstration of ARKSAT-2 is expected to be in late 2021/early 2022.

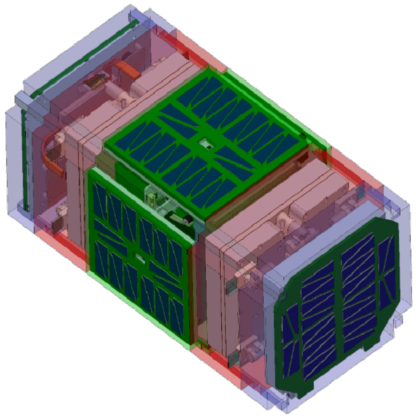

Figure 11: Rendering of ARKSAT-2

CSAPS Propulsion System

CSAPS is a low-cost, biocompatible, non-toxic, non-flammable, non-pressurized propulsion system applicable to nano-satellites (1-10kg), producing milli-Newton levels of thrust and ~100s of ISP, translating to a ΔV of about 114m/s[7]. Propylene glycol was chosen over pure water due to its properties of lowering the freezing point as well as limiting expansion. MEMS nano-channels are used as a passive throttling valve, effectively creating a simple cold-gas propulsion system. As shown in Figure 11, the CSAPS system has 2 modules, near the +Z and -Z ends. Each module has four 10mN nozzles, which provide four degrees of freedom of thrust. For maneuvers of up to 60s, no active heating is required[7]. For maneuvers requiring longer than 60s, an integrated 10W heater is present that will overcome heat loss due to vaporization.

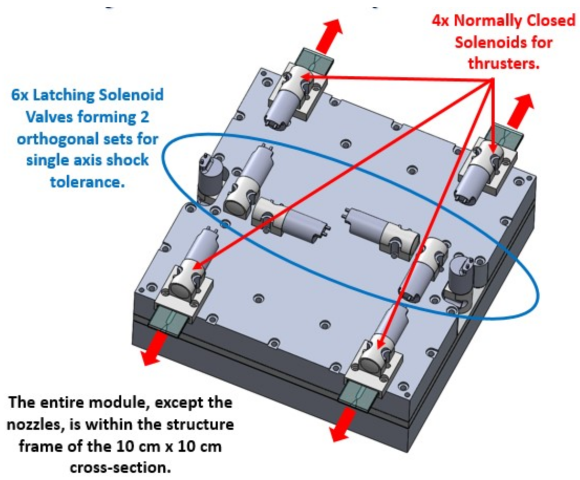

Figure 12: CSAPS Propulsion System

DAS-CUBES SYSTEM & PLANETARY SCIENCE APPLICATIONS

The DAS-Cubes system would remove many of the limitations inherent to the current standard of atmospheric measurements in planetary science exploration –stellar and solar occultations and nadir-pointing integrated column measurements. Data gathered via occultations are often restricted to limb measurements only, can have limited data acquisition times, and are dependent on the alignment of the sun and stars. Additionally, this method does not allow for night side measurements which give further insight into planetary processes and solar-atmospheric interactions. Nadir-pointing column measurements involve assumptions about atmospheric temperature and pressure, as well as surface conditions. While cubesats and other small satellites have primarily been used for Earth-orbiting missions, the recent use of the MarCo spacecraft as part of the InSight mission to Mars[8], as well as the planned INSPIRE mission to demonstrate the functionality of cubesats in deep space continue to make a strong case for cubesats as being capable of achieving objectives on an interplanetary scale, as a lower cost and more lightweight option in alignment with the goals of NASA's Space Technology Mission Directorate.

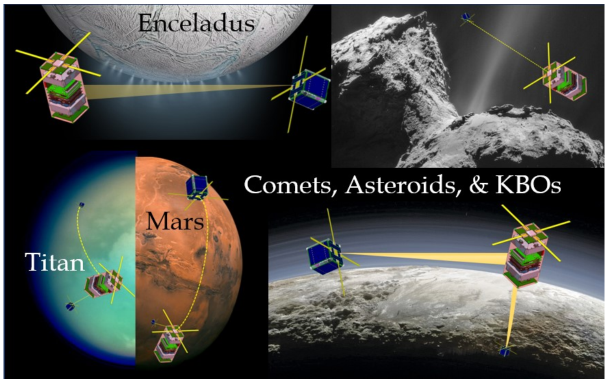

Figure 13: Applications of DAS-Cubes System[6]

Volatiles in the Martian atmosphere are an ideal candidate for the DAS-Cubes system. Detailed study of Mars' atmosphere is currently being done with a combination of general circulation models, spectroscopic data from occultation measurements, and nadir-pointing integrated column measurements. Multiple Mars missions have measured water vapor, primarily in the form of column abundances. This was achieved as part of the Viking program[9], and has more recently been completed on other missions, such as with ESA's SPICAM instrument and Mars Climate Sounder[10,11].These missions have found variance in total planetary water abundance, indicating H20 reservoirs, North-South hemisphere asymmetries in H_20

abundance, as well as seasonal variations in both hemispheres[10,11,12]. More detailed water measurements in the near IR at higher spatial and temporal resolution would both aid in our understanding of water as a resource for future habitation, as well as enhance our understanding of overall atmospheric dynamics and improve General Circulation Models. In addition to water vapor, the detection of methane from multiple observational platforms invites questions of its origin and is potentially indicative of an astrobiological source[13,14]. Variation in measurements from both orbiting spacecraft was well as in-situ measurements by the Curiosity Rover indicate that Mars' methane has local sources and/or sinks[13,14]. Measurements by the spacecraft system in the NIR would provide more data on the abundance and distribution of water vapor and methane, and ultimately enhance our understanding of the planet as a whole.

Another target planetary body for the DAS-Cubes system is Titan, which has some spacecraft-based occultation measurements from both the Voyager flyby and the Cassini mission[15,16], as well as a set of in situ measurements at the equatorial regions from the Huygens probe. While we have data on the bulk composition of the Titan atmosphere, much less is understood about the composition of specific aerosol and particulate species, as well as atmospheric dynamics of Titan as a whole[17]. Global mapping of atmospheric methane would be an important step in better understanding Titan's methane/ethane cycle. With the selection of the Dragonfly mission to Titan as part of NASA's New Frontiers program is an opportunity in the near future to further explore Titan and its atmosphere.

A successful paired dynamic emitter/receiver spacecraft system able to achieve high quality data would expand our horizons for low cost technology platforms, allow a more complete understanding of planetary atmospheric composition and dynamism, and aid in search for extraterrestrial life. To achieve global atmospheric measurements and higher spatial and temporal resolution of measurements on another planetary body will require longer data acquisition times than have previously been accomplished and could be greatly augmented by the flexibility of an independent spacecraft with an EM source of known intensity, spectrum, and source distance. The DAS-Cubes system is intended to investigate the applicability of this spacecraft concept to other bodies in the solar system, as well as ultimately demonstrate some of these capabilities in Low Earth Orbit. Volatiles on Mars as well as aerosols and methane on Titan are considered to be some of the most viable applications and these applications are under study at the UA.

CONCLUSIONS

ARKSAT-1, scheduled for launch in early 2021, is presented in this paper along with its associated technology developed by students and faculty at the University of Arkansas. Additionally, the follow on project of ARKSAT-2 2U satellite with a novel CubeSat attitude control system are presented here, in the context of a free-space spacecraft instrument concept of the DAS-Cubes system and its applications to planetary science.

Acknowledgments

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