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# Lunar Ice Cube: Determining Volatile Systematics Via Lunar Orbiting Cubesat

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## Abstract

We have applied the CubeSat Paradigm to science requirements-driven deep space exploration mission, Lunar Ice Cube, and are developing a compact 'workhorse' instrument for a high priority science application, which has just been selected for the HEOMD NextSTEP program for EM1 launch. Lunar Ice Cube complements Lunar Flashlight, a mission previously selected for EM1, by focusing on the abundance, location and transportation physics of water forms and components on the lunar surface at a variety of latitudes and terminator crossings not restricted to Permanently Shadowed Regions.

## 1. Introduction

We focus on measurement of lunar volatiles because of their apparently important role, based on recent lunar orbital measurements (1-9), with implications for environmental processes on the atmosphereless bodies that account for most of the surface area in the solar system. In addition, the Moon's accessibility as a stepping stone to the rest of the solar system, combined with its suitability as an analog with extreme range of conditions and thus an ideal technology testbed for much of the solar system, make it an ideal candidate for exploration. The recent announcements of opportunities to propose to fly cubesats on EM1 (e.g., NASA NextSTEP BAA, NASA SIMPLEx NRA) have generated a plethora of proposals for 'lunar cubes'.

## 2. Payload and Spacecraft Descriptions

Over the course of this year, we have conducted the equivalent of a pre-phase A study for a lunar orbital mission with a focus on the payload instrument. Subsystems required for deep space operation include state of the art active cubesat attitude control, propulsion (for transportation from GEO, GTO or Earth escape to lunar capture), communication, power, thermal and radiation protection systems providing lunar orbital operation of a cubesat bus. Based on this work, we have concluded that a 6U bus with state of the art cubesat systems already available or now being built and tested can support a high priority science orbiter in cislunar space. Particular challenges for lunar cubesats are remote communication, navigation and tracking, thermal and radiation protection in a volume, power, and bandwidth constrained environment.

Despite the fact that 6U deep space capable cubesat buses and deployers are now available, the development of CubeSat instruments capable of providing focused, high priority science, so critical to achieving the potential for low cost planetary exploration promised by the CubeSat paradigm, has evolved more slowly. A major challenge is the development of compact yet sufficiently robust and sensitive versions of successful instruments in a 'funding starved' environment. In response to both of these challenges, we are developing BIRCHES, Broadband InfraRed Compact, High-resolution Exploration Spectrometer, a miniaturized version of OVIRS on OSIRIS-REx a compact version of the successful volatile-seeking GSFC-designed OSIRIS Rex OVIRS leveraging extensive heritage and previous work on its components. BIRCHES is a compact (1.5U, 2 kg, <5W) point spectrometer with a compact cryocooled HgCdTe detector for broadband (1 to 4 micron) measurements at sufficient resolution (10 nm) to characterize and distinguish important volatiles (water, $H_2S$, $NH_3$, $CO_2$, $CH_4$, OH, organics) and mineral bands. It has built-in flexibility, using an adjustable 4-sided iris, to maintain the same spot size regardless of variations in altitude (by up to a factor of 5) or to vary spot size at a given altitude, as the application requires.

Lunar Ice Cube will be developed and managed by Morehead State University and include radiationhardened subsystems, GSFC designed payload thermal protection system, the JPL Iris transceiver, a high power solar panel/actuator system and a robust multiple-processor based payload processor. The Busek Iodine-based Ion Drive will provide propulsion necessary to achieve the science orbit from EM-1 release. GSFC Flight Dynamics will manage and execute trajectory modeling and navigation.

## 3. Science Measurements

BIRCHES will provide IR spectral measurements of major forms and components of volatiles, including the entire 3 um region associated with water ice and hydroxyl, to 1) reveal water and other volatiles distribution as a function of time of day, latitude, and terrain; 2) provide a geological context for those measurements through simultaneous spectral determination of mineralogical composition, and maturity; and 3) expand understanding of volatile sources, sinks, and processes with implications for the distribution, abundance, origin, and evolution of lunar and other atmosphereless bodies, surfaces and interiors.

## 4. Conclusions

Lunar Ice Cube addresses the broad strategic objectives of advancing understanding of solar system formation and evolution, and interaction and evolution of chemical and physical processes on the Moon, and by implication other small atmosphereless bodies, surfaces and interiors, by establishing the basis of intriguing evidence for surface volatiles, cold traps, and 'wetter' interiors from previous missions (1-9). In particular, we address the question: What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play? Lunar Ice Cube augments, complements, provides a context for, and utilizes measurements from previous (Chandrayaan, LCROSS, LRO, LADEE) and planned (Lunar Flashlight) missions by capturing the 'systematics' of volatile form and component distribution, defined as their specific character and abundance (OH versus $H_2O$ as ice or various forms of bound water and other volatiles) as a function of surface temperature (diurnal variation and average), illumination geometry (latitude and average slope), particle exposure, and regolith character. Lunar Ice Cube will thus provide input crucial for understanding the role of external sources, internal sources, solar wind proton and micrometeorite bombardment in formation, trapping, and release of water and exosphere formation.

## Acknowledgements

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# MEMS Fabrication of Micro Cylindrical Ion Trap (μCIT) Mass Spectrometer for CubeSats Application

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## Abstract

Microelectromechanical Systems (MEMS) technology is used to fabricate arrays of micro Cylindrical Ion Traps (μCIT) which are integrated into a miniaturized mass spectrometer (MS). The micro μCITs are built from silicon wafers and requires high machining precision, smooth surface, and high dimensional uniformity across the array for optimum mass spectrometer performance. In order to build these 3D miniature structures several MEMS processing techniques were explored and a process was developed and tested. By using the developed MEMS process, the required μCIT 4 x 4 arrays were fabricated. This included a chip design variation in which mechanical locking pits and posts were machined in the Ring Electrode (RE) chip and End Plate (EP) chips respectively, for self-assembly. The size of the assembled μCIT is only 12 mm x 12 mm x 1.5 mm. It is a key component for the miniature mass spectrometer. The micro cylindrical ion trap mass spectrometer has the advantages of low-power operation, simpler electronics and less-stringent vacuum system requirements. The MEMS batch production capabilities will also greatly lower the cost. It is a promising candidate for CubeSat and nanoSats applications for exploration of chemical distributions in space.

## 1. Introduction

Mass spectrometry plays an important instrumental role in planetary science**.** There were many different mass spectrometers used in NASA's space flight missions, include Mars exploration and other planetary scientific missions. For CubeSats and NanoSats applications, reduction in mass, power consumption and cost are required. A miniaturized mass spectrometer which could be used on a CubeSat or NanoSats is in ever-increasing demand to do *in situ* analysis for a wide range of applications including astro-biology research.

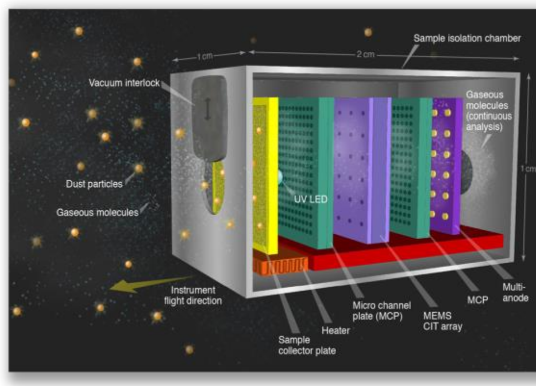


Figure 1: A concept of a μCIT mass spectrometer CubeSat which would provide in situ chemical analysis.

With the advantage of MEMS technology, it is possible to build extremely small structures. Several research groups have demonstrated the use of MEMS fabrication techniques to miniaturize MS components. For example, various mass analyzers, ionization sources, micromachined electrospray ionization devices, and microscale vacuum pumps have been successfully fabricated. A cylindrical ion trap mass spectrometer is a similar concept which uses MEMS fabrication to miniaturize a mass spectrometer.

One significant advantage that MEMS fabrication strategies have over conventional machining methods is that they enable low-cost batch production of high precision geometries and easy integration of these geometries to obtain millimeter-scale assemblies. MS miniaturization is typically accompanied by a reduction in sensitivity. In the case of miniature ion trap MSs, this loss of sensitivity results primarily from the lower transmission of ions and electrons into and out of the traps, as well as from the lower ion storage capacity of the smaller ion traps. Sensitivity can, in principle, be regained by using an array of miniature ion traps that operate in unison. Arrays of microfabricated miniature ion traps can also operate at much lower trapping voltages, thereby significantly reducing the overall power consumption of the MS system. The array approach has the additional advantage that MS arrays could be used to perform parallel analysis.

By leveraging prior MS miniaturization efforts at SRI, we have developed MEMS processing techniques and fabricated the required cylindrical ion trap for miniature mass spectrometer, which can be used for chemical analysis and astrobiology research.

## 2. MEMS Fabrication of µCIT

A simplification drawing of the cylindrical ion trap and a 4 x 4 array of µCIT are shown in Figure 2. It includes a Ring Electrode (RE) chip and two End Plate (EP) chips which are assembled into the uCIT. The RE chip is made of ~500 µm thick Si, and includes an array of thru-hole apertures ~600 µm in diameter. The EP chip is ~400 µm thick and includes an array of thru-hole apertures ~250 µm in diameter. There is a ~60 µm gap (set by the height of a post structure on the EP chip) between of the RE chip and each EP chips when they are assembled. Each of the EP and RE chips are coated with a metallization pattern, including coating of the thru-holes sidewalls. The fabrication of these miniature CITs, requires high machining precision, smooth surfaces, and dimensional uniformity across the array for optimum mass analysis performance.

Four inch silicon wafers were used for the fabrication these RE chip and EP chips. The thru-holes were etched using a Deep Reactive Ion Etch (DRIE) process and gold metallization of the electrodes accomplished via e-beam evaporation in a planetary deposition mode. We also designed two variations of pit and post structures which were etched into the RE chip and EP chips respectively to explore two methods for self-assembly.

After several fabrication iterations, in which several different DRIE, metallization patterning, and assembly and bonding techniques were explored we have arrived at a simplified fabrication strategy which allow us to achieve 1) good uniformity and smoothness of the cylindrical structures etched in Si; 2) minimal contamination across the chip; 3) good

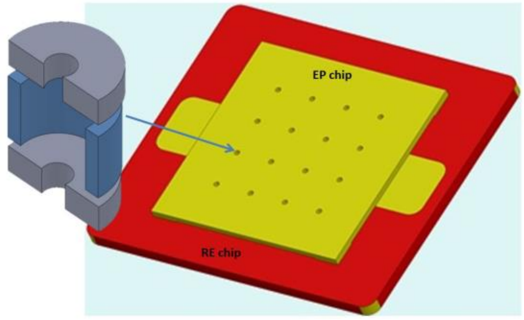


Figure 2: Drawing of µCIT and 4x4 array of µCIT.

metallization coverage; 4) high alignment accuracy (~3 µm, ~1% of thru-hole diameter) between the three trap electrodes after assembly; and 5) a reduction in the ion trap array chip capacitance to 25 pF. Figure 3 shows SEM images of fabricated RE and EP chips and an l image of an assembled µCIT.

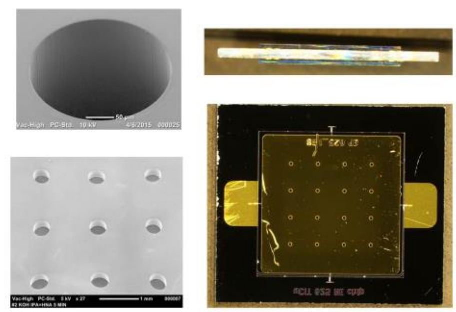

Figure 3: MEMS processed chips and assembled µCIT chip.

## 4. Summary and Conclusions

MEMS technology has proven to be extremely valuable for building miniature scale 3-D structures with an accuracy and ease not possible with conventional machining methods. We have fabricated and integrated a µCIT chip which is a key component for a miniaturized mass spectrometer. This technology development will likely lead to the development of next-generation low-power portable chemical analyzers, which can be mass produced in a cost-effective manner due to the batch production capabilities inherent in MEMS processing. The low power consumption and low cost of these miniature mass spectrometers make them a good candidate for CubeSats and NanoSats applications.

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# CubeSats to Explore Volatiles in Comets

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## Abstract

Close approach comets (<0.4 AU to Earth) are accessible to CubeSat and NanoSat missions that can return unique data not obtainable from ground-based telescopes. Primitive bodies such as comets are key to understanding Solar System formation. A low-risk, versatile, multispectral camera with integrated filters in a 6U spacecraft bus is capable of high spatial resolution mapping of the four primary volatile species $CO_2$, $H_2O$, CO, and organics. Simultaneous mapping of these bands and two thermal channels will enable studying the dynamical activity of the nucleus. Assuming deployment from a launch platform above the Earth's gravity well, we find intercept trajectories using current propulsion systems.

## 1. Introduction

The Dec-2018 apparition of comet 46P/Wirtanen (0.08 AU) and P/2014 U2 (Kowalski, 0.3 AU) in Sep-2019 present opportunities for a small satellite to perform a close flyby to study the nucleus and inner coma regions at high spatial resolution (Fig. 1). Measurements of volatiles in comets are required to establish their formation and evolution. For example, $CO_2$ is now recognized as one of the most abundant of volatiles in comets as a result of the *Akari* and *Deep Impact* mission results, yet we know relatively little of its diversity among comets. The target volatile have spectral signatures are best observed in the 2-5 µm Mid-Wave Infrared (MWIR) spectral region. Thermal emission dominates spectral wavelengths >5µm in the inner coma, which enables the Comet Camera (ComCAM) to map the inner coma temperature distribution by measuring 7-10 and 8-14 µm Long-Wave InfraRed (LWIR) emission. In the case of 46P/Wirtanen, the flyby will discriminate measured quantities at high spatial resolution of ~0.3 km, comparable to 0.005" angular resolution for a ground-based observatory when the comet is nearest to Earth.

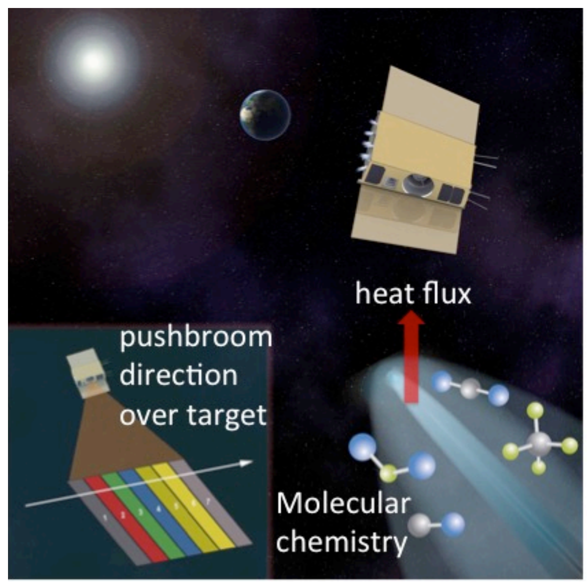


Figure 1: A close flyby of a comet yields unique and unprecedented mapping of the inner coma region.

## 2. ComCAM Concept

ComCAM is a low-risk multichannel multispectral camera concept based on a COTS product developed by Institut National d'Optique (INO), Canada. The baseline design uses an uncooled 384×288 pixel microbolometer array with an FPGA and digital processor (Fig. 2). The array is partitioned into seven 18×288 pixel spectral channels defined by filters mounted on the sensor array. The seven linear arrays are scanned across the target body as a push-broom to build spectral images, Fig. 1. The ComCAM payload, including 80 mm telescope and electronics, fits within a 1.3 U CubeSat volume (Fig. 2).

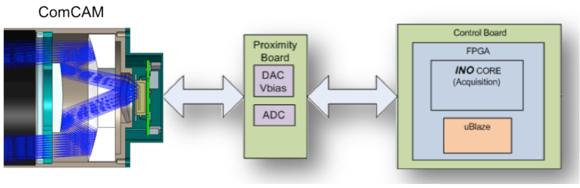


Figure 2: ComCAM telescope, sensor and electronics fits neatly into a 1.3 U volume.

## 3. Spacecraft Bus

The 6U CubeSat bus incorporates new nanosatellite technologies to mature an evolved, radiation-tolerant infrastructure designed to support interplanetary investigator science (Fig. 3). The 6U deep space design is based on Morehead State bus heritage and incorporates high power generation (72 W of continuous power), a radiation-tolerant, distributed multiple processor-based payload processor system, a highly-capable micronized GNC system designed for lunar missions, an innovative propulsion system, and a high throughput X-band communication system designed by JPL for lunar CubeSat missions.

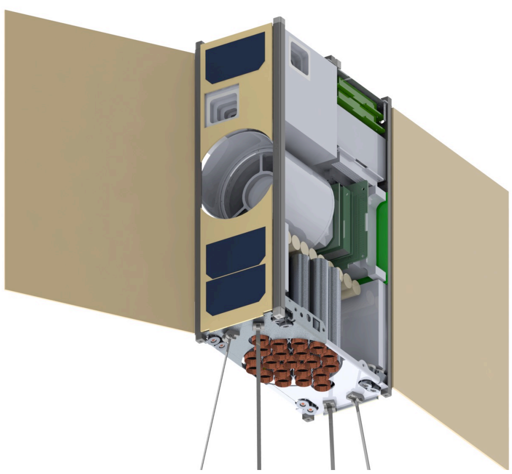

Figure 3: The 6U CubeSat bus with payload, propulsion, power, and other infrastructure.

## 4. Propulsion System

The Cubesat mission will utilize a multi-channel Micro-Cathode Arc Thruster (μCAT) micropropulsion subsystem that is an outgrowth of GWU Micropropulsion and Nanotechnology Laboratory (MpNL) research in scalable small spacecraft electric propulsion (Fig. 4). The μCAT is an electric propulsion device, based on the well-researched ablative vacuum arc process, enhanced by an external magnetic field that uses its own thruster cathode as propellant. The cathode terminal can be any conductive material. The applied magnetic field extends operation lifetime while reliance on a thruster element for propellant reduces system mass for micropropulsion compatible with 1-50 kg class satellites, including all CubeSat forms. The μCAT generic subsystem architecture consists of the controller incorporating control unit, power management, power distribution, and thruster boards incorporating plasma power units, and connections to off-board thruster heads, which contain: miniature anode/cathode elements, springs, insulators, electromagnet coils and connectors.

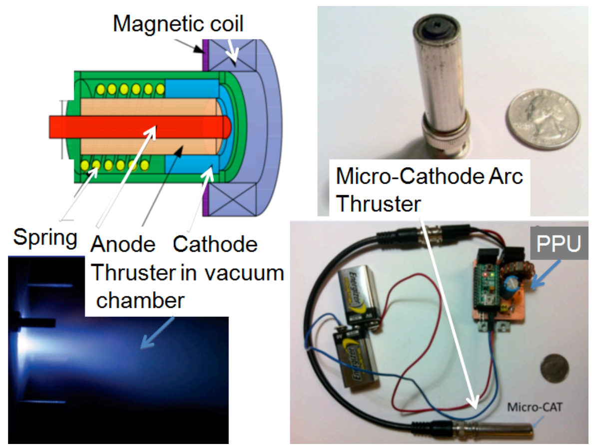


Figure 4: μCAT schematic and components.

## 5. Spacecraft Parameters

Payload: Multispectral camera
Mass: ~12.0 kg
Volume: 6U form factor
Prime Power: ~72 W
Data Rate: ~60 bps
Mission Data Volume: ~100 Mbits
Operational Lifetime: >2 years

## 6. Summary and Conclusions

We have designed a 6U CubeSat bus capable of interplanetary flight and close flyby of comets with Earth approaches of <0.4 AU to study volatile species and thermal structure of the nucleus and inner coma regions.

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# Radiation testing for the Jovian environment: in the laboratory and on CubeSats

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## Abstract

The harsh Jovian radiation environment is one of the main drivers for the design of instruments to be flown to Jupiter. Radiation testing of the instruments in the relevant environment is crucial, but challenging. We introduce RATEX-J, a radiation test setup dedicated for the JUICE mission that focuses on active radiation mitigation approaches and employs ground based and spaceborne testing platforms.

## 1. Introduction

ESA's JUICE (Jupiter Icy Moons Explorer) mission will be launched in 2022 and will experience the harsh radiation environment within the Jovian magnetosphere. This is dominated by high fluxes of energetic electrons in the MeV range that are not easily possible to shield against. Instruments of the Particle Environment Package (PEP) onboard JUICE commonly use microchannel plates (MCPs) and channel electron multipliers (CEMs) for particle detection. One example is the Jovian plasma Dynamics and Composition analyzer (JDC), one of six sensors within PEP. JDC measures 3D distribution functions of positive and negative ions. Penetrating electrons will disturb the measurements, decrease the signal-to-noise ratio and can partially even prevent any useful measurement.

Therefore radiation mitigation techniques need to be employed. This includes obviously passive shielding, but also active approaches.

Simulating Jupiter's radiation environment in order to verify the performance of the radiation mitigation techniques, is a complex experimental task due to the combination of electron energy and particle flux.

## 2. Radiation mitigation

### 2.1. Anti-coincidence system

For JDC an anti-coincidence system based on a semiconductor detector will be used. This system protects the stop signal of the time-of-flight chamber in the instrument. Particles selected by JDC's ion optics will hit a conversion surface and produce low energetic electrons that are detected as stop signal by an MCP. Energetic electrons will however as well produce a false stop signal as they penetrate the surface. As in this case the anti-coincidence shield will also show a signal, it can be discarded.

### 2.2. Characterization of MCP and CEM response to penetrating radiation

The second approach focuses on the characterization of the pulse height distribution of MCP and CEM outputs. As it is a semi-Gaussian for low energetic electrons, these detectors are usually run in counting mode. The pulse height distribution for penetrating particles is however expected to look different.

Furthermore efficiencies of MCPs and CEMs to penetrating radiation will be investigated, as little to nothing is known about the efficiencies to electrons with energies above 100 keV.

## 3. Experiment setup

The Radiation Test Experiment for JUICE (RATEX-J) uses three different particle detectors: one MCP, one CEM and two semiconductor detectors, which serve as the respective anti-coincidence shields, arranged in two detector stacks. The experiments setup houses the two detector stacks, front-end electronics, pulse height analysis, high voltage supply and a simple data processing unit. The setup's volume takes less than half a CubeSat and allows flexibility and mobility of the unit.

## 4. Radiation testing

Complementary ground based and spaceborne radiation tests are foreseen.

### 4.1. Accelerator

RATEX-J will be irradiated with energetic electrons in the MeV range at the microtron facility at Stockholm university. As drastic flux reduction and beam scattering are required to reach an adequate radiation environment, supporting Monte Carlo simulations are performed. We will show first results of these experiments.

### 4.2. CubeSats

CubeSats in Earth orbits provide a relatively easy-to-access platform to test small payloads in the natural radiation belt environment, in case of sun synchronous orbits. They are considered valuable for future instrument and subsystem testing to be employed on planetary missions, even for radiation environments as harsh as Jovian.

RATEX-J is selected payload on the 3-unit CubeSat MIST by Stockholm University, which will be launched in 2017. Also a dedicated 1-unit CubeSat mission is investigated.

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# CubeSats to study the Didymos asteroid system

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## Abstract

Among the growing interest about asteroid impact hazard mitigation in our community the Asteroid Impact & Deflection Assessment (AIDA) mission will be the first space experiment to use a kinetic impactor to demonstrate its capability as reliable deflection system [1]. As a part of the AIDA mission, we have proposed a set of two three-axis stabilized 3U CubeSats (with up to 5 science sensors) to simultaneously rendezvous at close range (<500m) with both the primary and the secondary component of the Didymos asteroid system. The CubeSats will be hosted on the ESA component of the AIDA mission, the monitoring satellite AIM (Asteroid Impact Mission). The CubeSats will characterise the magnetization, the main bulk chemical composition and presence of volatiles as well as do super-resolution surface imaging of the Didymos components. The CubeSats will also support the plume characterisation resulting from the DART impact (Double Asteroid Redirection Test, a NASA component of the AIDA mission) at much closer range than the AIM main spacecraft, and provide imaging, composition, and temperature of the plume material. At end of the mission, the two CubeSats can optionally land on one of the asteroids for continued science operation. The science sensors consist of a dual fluxgate magnetometer (MAG), one miniaturized volatile composition analyser (VCA), a narrow angle camera (NAC) and a Video Emission Spectrometer (VES) with a diffraction grating for allowing a sequential chemical study of the emission spectra associated with the impact flare and the expanding plume. Consequently, the different envisioned instruments onboard the CubeSats can provide significant insight into the complex response of asteroid materials during impacts that has been theoretically studied using different techniques [2].

The two CubeSats will remain stowed in CubeSat dispensers aboard the main AIM spacecraft. They will be deployed and commissioned before the AIM impactor reaches the secondary and record the impact event from a closer vantage point than the main spacecraft. The two CubeSats are equipped with relative navigation systems capable of estimating the spacecraft position relative to the asteroids and propulsion system that allow them to operate close to the asteroid bodies. The two CubeSats will rely on mapping data relayed via the AIM main spacecraft but operate autonomously and individually based on schedules and navigation maps uploaded from ground.

AIDA's target is the binary Apollo asteroid *65803 Didymos* that is also catalogued as Potentially Hazardous Asteroid (PHA) because it experiences close approaches to Earth. Didymos' primary has a diameter of ~800 meters and the secondary is ~150 m across. Both bodies are separated about 1.1 km [3]. The rotation period and asymmetry of the secondary object is unknown, and it might be tidally locked to the larger primary body. At least the primary body is expected to be associated with ordinary chondrite material, consisting mostly of silicates, and metal, but the earlier made Xk classification suggested a rubble-pile type with large amount of volatile content. The secondary companion spectral class is unknown, but the total mass of the system suggests that the secondary companion could be of similar class.

Detailed empirical information on the physical properties of the Didymos asteroid system, in particular the magnetic field, the (mineralogical) surface composition, the internal composition via the bulk density, the ages of surface units through crater counts and other morphological surface features is valuable in order to make progress in the asteroid field of science. Furthermore, the periodic effect of such a close dynamic system in the presence and temporal displacement of the surface regolith is unknown, and could be followed using close-up video systems provided by the CubeSats.

In conclusion, the proposed two CubeSats as part of the AIDA mission can therefore contribute significantly, since they can monitor the Didymos asteroid components at a very close range around hundred meters, and at the same time monitor in-situ an impact plume when it is created.

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# Dellingr- A Path to Compelling Science with CubeSats

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## Abstract

Advancements in the capabilities of miniaturized systems are dramatically increasing interest in achieving science from CubeSats. The Dellingr project targets this interest. It will realize compelling science from a 6U spacecraft while developing human and spacecraft systems required to cost-efficiently deliver small satellites capable of reliably achieving mission objectives in divers environments—from low earth orbit to challenging radiation and thermal environments associated with lunar and planetary missions.

## 1. Introduction

Advancing capabilities of miniaturized systems is dramatically increasing interest in CubeSat-based missions, as the small size and low cost of these platforms relative to traditional spacecraft open new areas of science. For example, they can be deployed to venues and environments considered not reasonable or practical for larger more costly space assets. And the distributed architectures they enable can reveal new science by virtue of the increased temporal, spatial, and angular measurement resolution enabled by simultaneous multi-point observations. Furthermore, they can achieve certain science more cost effectively than traditional platforms.

Historical data shows however, that the potential of these platforms is often not realized due to mission failure. Among the contributing factors are cost-driven tradeoffs within one of more phases of the CubeSat mission life cycle.

Given the potential benefits of these platforms, NASA Goddard Space Flight Center is executing the Dellingr project. This initiative will achieve compelling science from a 6U CubeSat and define systems and processes for reliably *and* cost-efficiently achieving mission objectives in divers environments—from low earth orbit to lunar and planetary.

## 2. Dellingr Science

The Dellingr spacecraft is a 6U CubeSat that targets compelling Heliophysics science from its instrument complement—a compact Ion and Neutral Mass Spectrometer (INMS), and a 3-axis science magnetometer system comprised of boom- and body-mounted sensors. INMS will measure the composition and density of various ions and neutral elements in Earth's lower exosphere and upper ionosphere, a volatile region of the upper atmosphere that affects satellite communications and creates a drag that can degrade satellite orbits. [1]

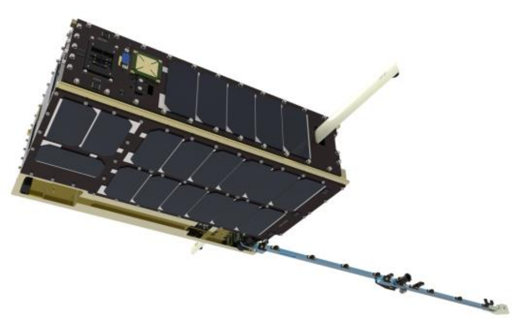

Figure 1. Computer model of the Dellingr 6U spacecraft with magnetometer boom and antennas deployed.

The science magnetometer is a miniaturized fluxgate with better than 0.1nT resolution at 3.5 Hz. The system is comprised of a sensor mounted at the end of a 76 cm boom and three sensors mounted within the spacecraft. The sensed field is comprised of two components—one attributable to science, and the other attributable to disturbances created by bus subsystems. Algorithms created by the science team will analyze field data, identify the disturbance component, and subtract it from the total field to yield the science data.

Dellingr flight readiness will occur late summer 2015.

## 3. Spacecraft Systems

Dellingr bus systems are partially comprised of commercial off the shelf (COTS) components. The components were selected based on their predicted compliance with mission goals over the six-month low earth orbit mission duration.

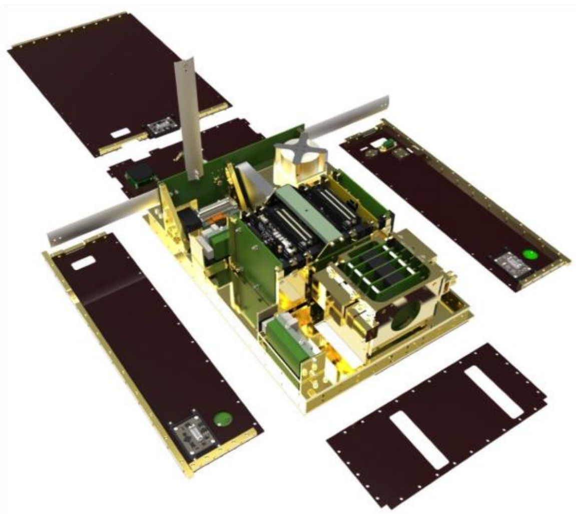

Figure 2- Dellingr computer model. Removing custom designed solar panels reveals Dellingr internal systems.

Selected systems, such as the boom, the antenna, deployment mechanisms, solar panels, the attitude determination and control components, and custom electronics were developed in-house in order to meet mission performance requirements or to realize cost or implementation benefits.

## 4. Concurrently Achieving Reliability and Cost Efficiency

In addition to the compelling science targeted by Dellingr, a critical project objective is to enable the development of cost-efficient CubeSats that can operate reliably in divers mission environments. Of particular interest are environments associated lunar and planetary missions.

The project targets this objective by leveraging decades of spaceflight systems best practices and lessons learned and by employing a "clean sheet" approach to define a framework that will guide CubeSat development. Lean processes will reduce the overhead typically associated with best practices. Tightly integrating and coordinating mission components—hardware, software, and human—across the full CubeSat project life cycle will yield additional efficiencies.

Project execution is also informing development of a flexible, modular, and extensible spacecraft architecture—the Goddard Modular Spacecraft Architecture or GMSA—that will further lower implementation costs and development risk. GMSA is being applied to GTOSat, a 6U mission concept targeting the severe radiation environment of a geosynchronous transfer orbit.

## 5. Summary and Conclusions

The Dellingr project will deliver a 6U CubeSat that achieves compelling Heliophysics science and lead to CubeSats that cost-efficiently accommodate divers mission environments and requirements. Of particular interest are missions that require reliable operations in challenging radiation and thermal environments beyond low Earth orbit. Findings are indicating that we can concurrently achieve system robustness and cost efficiency by employing a novel best practices-based framework that spans the full CubeSat life cycle and by basing CubeSat missions on GMSA, a flexible, modular, and extensible architecture.

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# Lunar Hydrospheric Explorer (HYDROX)

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## Abstract

The Lunar Hydrospheric Explorer (HYDROX) is a 6U CubeSat designed to further confirm the existence of lunar exospheric water, and to determine source processes and surface sites, through ion mass spectrometer measurements of water group ($O^+$, $OH^+$, $H_2O^+$) and related ions at energy/charge up to 2 keV/e. and mass/charge 1 – 40 amu/e. HYDROX would follow up on the now-concluded exospheric compositional measurements by the Neutral Mass Spectrometer on the NASA LADEE mission and on other remote sensing surface and exospheric measurements (LADEE, LRO, etc.).

## 1. Introduction

Long after the Apollo lander missions, the Moon had been assumed to be dry until later findings were reported on epithermal-neutron detection of hydrogen in polar regions, trace water content of lunar rocks, remote observations of $H_2O$ and OH at the surface, and outgassing from the LCROSS satellite impact on Cabeus crater. The neutron measurements now suggest large deposits of ice-rich regolith in polar cold trap regions, equivalent in volume to many hours of peak water flow at Niagara Falls. Recent polar ice maps indicate that these deposits may have been present for billions of years after accumulation from global sources and exospheric transport to the poles. Final peer-reviewed reports from LADEE may confirm the presence of natural sources of exospheric water molecules in what could then be called the lunar hydrosphere. But the narrow field of view of the Neutral Mass Spectrometer (NMS) on LADEE samples only the cold exospheric neutrals and ions, not the hot pickup ion population accelerated in the local convective electric field. HYDROX would determine the full energy/charge and mass/charge spectra of both elemental and molecular ions, while also measuring the 3-D angular distributions providing information on source sites. HYDROX and WIMS are optimized for measurements of water group and related ions. HYDROX would be constructed, operated, and managed by NASA Goddard Space Flight Center.

## 2. Science Objectives

The three major science objectives of HYDROX are to (1) confirm exospheric water and measure molecular ion abundances, (2) follow spatial and temporal variations over at least six lunations (29.53 days) to determine source processes, and (3) determine surface source sites via numerical backtracking of ion beams resolved in energy/charge, incidence angle, and mass/charge at HYDROX. The principal sources are expected to be photo-stimulated desorption (PSD), meteoritic impact vaporization (MIV), and solar wind sputtering (SWS). Occasionally large energy fluxes of energetic particles could provide a fourth source via chemical radiolysis reactions and deep dielectric charging in the surface regolith. Fountain plumes from permanently shadowed regions of polar craters would also be detectable.

## 3. Implementation

HYDROX is 3-axis stabilized with solar electric propulsion to take it into 150 x 250 km polar orbit at the Moon after deployment into cis-lunar space from a NASA or other launch vehicle. The sole instrument is the Wide Field of View Ion Mass Spectrometer (WIMS) with high mass resolution M/dM ≥ 30 for elemental and molecular ions H+ - Ar+. The spacecraft and instrument are operated together as a closely coupled observational system to optimize detection of water group ions and to determine energy/charge-angle-mass/charge distributions as functions of spatial location and time.

Lunar pickup sons are detected at HYDROX after accumulation in the hydrosphere as neutrals from various potential sources, ionization by solar UV photons or hot plasma interactions, and subsequent acceleration on cycloidal trajectories to the spacecraft in the electric and magnetic field of the near-lunar solar wind. The angular resolution of the IMS and the 3-axis attitude maneuverability of the HYDROX CubeSat combine to allow maximum angular resolution of incident ions. With no other operational requirements than support of the IMS measurements, HYDROX is optimized for definitive determination of ion mass/charge abundances, source processes, and surface source sites. Although it carries no magnetic or electric field instruments, 3-D velocity and spatial distributions of lunar pickup ions would be used to estimate directions and magnitudes of these fields for ground-based computational modeling of lunar ion trajectories.

# 4. Supporting Measurements

Knowledge of the space weather environment around the Moon would be important to planning of HYDROX mission and science operations. Real-time upstream field, plasma, and energetic particle measurements would be available from the Advanced Composition Explorer (ACE) and DISCOVR spacecraft at L1. Although the composition and source process science objectives (see above) do not require precise knowledge of the local space weather environment, Daily cross-calibrations of magnetic-electric field and bulk plasma parameters with ARTEMIS P1 and P2 would be valuable for modeling of ion detection trajectories back to exospheric and surface source sites. If LRO were to continue, the CRaTER instrument would provide key local measurements of orbital radiation dosage rates that could be used to model surface radiolysis and deep dielectric charging as water ion contributors. Earth-based observations of meteoritic impacts and neutral cloud (Na, K) variations would also be useful for comparison to HYDROX observations.

Finally, HDROX is designed as a pathfinder for deployment of multiple-platform heliophysics and planetary instruments into lunar orbit. CubeSats have the advantage of highly focused operations in support of single instruments, or a highly complementary (e.g. field and plasma) suite of small instruments. Multiple CubeSats could be deployed at Explorer-level mission costs as lunar constellations to more fully survey the Moon and its space environment. Future science, exploration, and commercial operations at the Moon would most cost-effectively and efficiently be supported by constellations of small satellites. Although further exploration of the solar system would usually be led by single spacecraft missions, it may not be feasible to put these larger spacecraft into orbit around the bodies of interest, e.g. Europa and Enceladus, for highest resolution measurements of the interiors by gravity and magnetic field analysis. But this could alternatively be done by small subsats carried by the main mission spacecraft, such as Europa Clipper for Europa. Separation of field-plasma-particle from imaging and other remote-sensing instruments on different spacecraft would greatly simplify science operations planning and minimize mission cost. Flyby missions like Europa Clipper may be sufficient for global surface geologic and compositional coverage, but orbiters, however small, are needed for deep probing of interiors.

# 5. Summary and Impact

HYDROX would be the first lunar science mission to completely survey the composition, source processes, and surface source sites of lunar exospheric neutrals detected at the spacecraft as hot elemental and molecular pickup ions. It would significantly complement earlier cold exospheric neutral and ion measurements by LADEE. HYDROX would provide high-resolution hot ion mass spectrometry to any existing constellation (e.g., other CubeSats, ARTEMIS, LRO) of lunar-orbiting spacecraft to enable more comprehensive measurements of the lunar exosphere, surface, and remotely-probed interior. It would be a pathfinder to testing of the concept that constellations of small satellites, each with dedicated and highly complementary instruments, could be more efficient and cost effective than larger single satellites for exploration and survey of the Moon and other planetary bodies. Surface-based operations for science, exploration, eventual human habitation, infrastructure for Mars exploration, and commercial operations at Earth's nearest neighbour would be highly dependent on in-situ resource utilization, for which water to be probed by HYDROX would be an essential material.

Development and operation of small satellites also offers hands-on education and training opportunities for young scientists, engineers, and project managers that would otherwise be difficult to obtain. HYDROX for planetary science at the Moon follows from the successful respective flights and development of the ExoCube and Dellingr CubeSats for heliophysics science in low Earth orbit. NASA Goddard Space Flight is supporting CubeSat development and operations for all these applications.

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# Quantifying the Lunar Hydrogen Cycle: A Fast, Effective, and Economical CubeSat Approach

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## Abstract: The Lunar H Albedo

The Moon breathes hydrogen: solar wind protons and micro-meteoroids deliver hydrogen to the lunar surface at local rates that depend on surface composition, local topography, and the presence of structures such as magnetic anomalies. Because the lunar surface is generally saturated with hydrogen, the implanted hydrogen escapes the surface and forms the hydrogen exosphere through a variety of processes including sputtering, recoil, and diffusion - giving the surface an effective hydrogen "albedo." These processes can lead to hydrogen deposition into cold traps and the formation of OH, and possibly water, through chemical alteration of oxygen-bearing minerals. Exospheric hydrogen is reclaimed by the solar wind as picked-up photoions and charge-exchange products. *The exact pathway for each of these processes remains unknown, especially at regional scales, and quantifying each of these processes in this "lunar hydrogen cycle" as a function of solar zenith angle and plasma and space environment will lead to a unified understanding of the plasma, exospheric, and geologic Moon.* CubeSats provide a fast, effective, and economical approach to quantifying the currently unknown parameters in the lunar hydrogen cycle.

## 1. Recent Results: A Paradigm Shift

The last 6 years have been paradigm-changing in lunar science, with the discovery of an active water and hydroxyl environment (i.e., water cycle) at the Moon. Besides the LCROSS confirmation of water existing within the lunar polar cold traps [2, 10], a set of IR sensors discovered an OH veneer that extends all the way down to the lunar equator, and which may even possess a modern, dynamic diurnal component [1, 8, 11]. The solar wind is on the "short list" of sources for this OH veneer (see review by McCord et al. [7]), yet the solar wind has its own cycle of H implantation and release that has yet to be fully investigated/quantified. If solar wind H is a component of the larger lunar water cycle, quantifying the amount that is lost back into space is vital in order to gain insights and understanding on the amount of H retained.

There are tantalizing recent observations of the complexity of the solar wind H/regolith interaction that suggest a large reflected hydrogen albedo. Using the ion analyzer onboard Kaguya, Saito et al. [9] detected a near mono-energetic population of backscattered protons off the lunar surface, in non-magnetic regions being a few percent of the incident solar wind. However, in magnetic anomaly regions, this reflected ion density increased to over 50% of the inflowing solar wind protons.

While surface-facing ion spectrometers observe an anomalous $H^+$ emission, the low energy neutral atom spectrometers onboard IBEX [6] and Chandrayaan-1 [5, 12] revealed the presence of non-thermal neutral H atom emission, with surface emission flux levels at ~10-35% of solar wind influx at energies >30 eV. The H atom emission also exhibits strong spatial variations with a significant reduction in neutral reflection within magnetic anomalies.

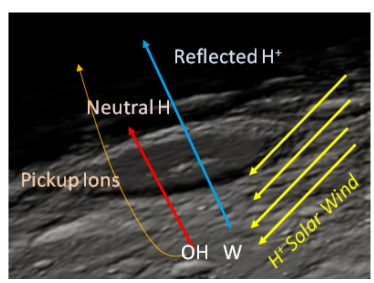


Figure 1: Surface-reflected hydrogen components.

A picture is developing (see **Figure 1**) in which incoming solar wind hydrogen seeds the lunar surface with OH (as a source of water) but also is backscattered from the surface to form an H-exosphere. A hydrogen budget has yet to be quantified, and is necessary to determine the amount of OH (and water) created by the solar wind. For example, Crider and Vondrak [3, 4] found that the solar wind was an adequate singular source of polar water if 100% of the solar wind is converted to water (to subsequently migrate to the poles). However, observations suggest that a substantial portion of solar wind may not be retained to form OH and water.

## 2. A CubeSat Approach

A 6U CubeSat with an ion spectrometer that observes simultaneously the impinging solar wind and the reflected ion component and a nadir-facing low-energy neutral atom imager that observes the upward moving neutral hydrogen will provide quantitative answers to important outstanding questions regarding the lunar hydrogen cycle by: (1) Obtaining a time-averaged back-scattered proton and hydrogen value from the lunar surface integrated over the mission lifetime with the spacecraft in close proximity to the surface, (2) Determining the regional mineralogy influence on proton and hydrogen albedo, (3) Quantifying the signatures of the putative diurnal migration of hydrogen products and determining their origin and (4) Deriving the space environment (i.e., impactors and solar storms) effects on anomalous escape of hydrogen.

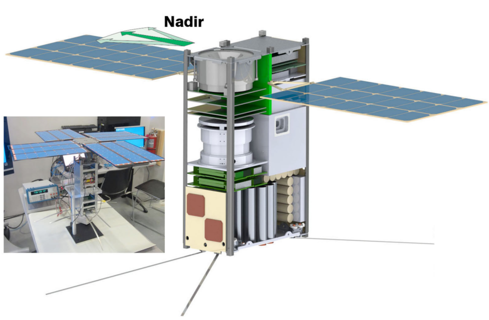


Figure 2: A CubeSat to quantify the lunar H cycle.

To this end, we have developed a CubeSat concept shown in **Figure 2**.

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# Exploiting Artificial Intelligence for Analysis and Data Selection on-board the Puerto Rico CubeSat

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## Abstract

CubeSat missions are constrained by the limited resources provided by the platform. Many payload providers have learned to cope with the low mass and power but the poor telemetry allocation remains a bottleneck. In the end, it is the data delivered to ground which determines the value of the mission. However, transmitting more data does not necessarily guarantee high value, since the value also depends on the data quality. By exploiting fast on-board computing and efficient artificial intelligence (AI) algorithms for analysis and data selection one could optimize the usage of the telemetry link and so increase the value of the mission. In a pilot project, we attempt to do this on the Puerto Rico CubeSat, where science objectives include the acquisition of space weather data to aid better understanding of the Sun to Earth connection.

## 1. Introduction

We focus on detecting and investigating strong natural [1] and artificially induced [2] radio emissions in the Earth's ionosphere. Artificially induced emissions are driven by a high-power radio transmitter on the ground and occur only in the antenna beam. Natural emissions occur unpredictably over long periods of time in the auroral zones and possibly at the equator. The Puerto Rico 3U CubeSat (Figure 1) will carry two scientific payloads: CARLO (Charge Analyzer Responsive to Local Oscillation), which is a Faraday cup designed to measure ion turbulence from 0 to 10 kHz, and GIMME-RF, which consists of four electrically short monopole antennas and a miniaturized digital receiver for measurement of radio waves in the 0 to 30 MHz range.

## 2. On-board signal processing

The GIMME-RF receiver incorporates massively parallelized hardware for digital signal processing at up to 2 TFLOPS [3]. The four antenna inputs, filters, amplifiers, and 14-bit 250 MHz ADCs are located on a carrier board, with a processor daughterboard on one side and a science module on the other. GIMME-RF can accommodate internal data rates of up to 40 Gb/s and we expect to collect about 5 Tb of data per orbit. This is a factor $10^6$ to $10^7$ larger than the amount of data that can be transmitted to ground. AI methods and techniques will therefore be used to automatically identify and select interesting events. In addition to using well-known spectral characteristics to classify the signals, we will take full advantage of the instrument's capability to measure the 3D electric field vector, which, in turn, makes it possible to characterize the radio emissions in terms of the four Stokes parameters and to perform direction finding. The AI algorithms, and specifically Case-Based Reasoning, designed to learn from examples [4], will be used to separate uninteresting data from interesting data. Also, knowledge discovery algorithms [5] will be used to detect new interesting features in data. After automatic classification, an importance ranking will determine which data to transmit to the ground. The CARLO and GIMME-RF payloads are complementary instruments, as CARLO will measure low-frequency plasma turbulence, which affects radio propagation in the high-frequency radio band. Radio data can therefore be correlated with ion turbulence data from CARLO and subsequently, on the ground, with geophysical data from instruments such as radars, magnetometers, and optical imagers.

## 3. Summary and Conclusions

By using fast on-board computing and state-of-the-art AI algorithms, we intend to increase the science return of the Puerto Rico CubeSat mission, expected to be ready for launch in 2017. The methods and technologies developed in this pilot project could have applications in future planetary and interplanetary CubeSat missions, where telemetry is likely to remain a bottleneck.

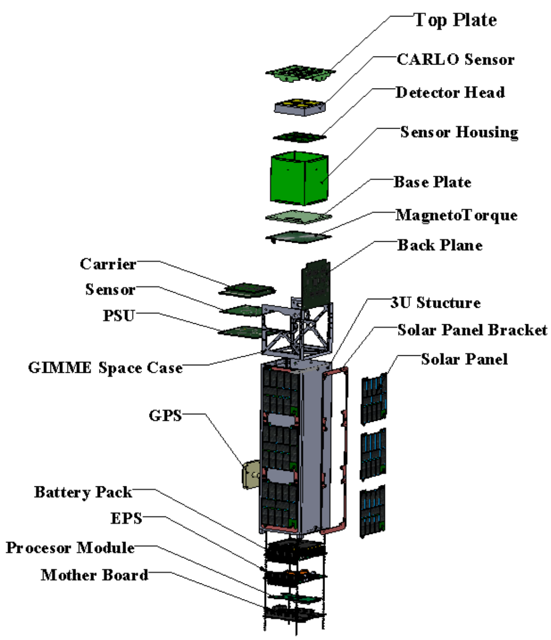


Figure 1: Exploded view of the Puerto Rico CubeSat.


## Acknowledgements

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# Nanosats for a Radio Interferometer Observatory in Space

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## Abstract

During the last decades, astronomy and space physics changed dramatically our knowledge of the evolution of the Universe. However, our view is still incomplete in the very low frequency range (1- 30 MHz), which is thus one of the last unexplored astrophysical spectral band. Below 30 MHz, ionospheric fluctuations severely perturb ground-based observations. They are impossible below 10 MHz due to the ionospheric cutoff. In addition, man made radio interferences makes it even more difficult to observe from ground at low frequencies. Deploying a radio instrument in space is the only way to open this new window on the Universe.

Among the many science objectives for such type of instrumentations, we can find cosmological studies such as the Dark Ages of the Universe, the remote astrophysical objects, pulsars and fast transients, the interstellar medium. The following Solar system and Planetary objectives are also very important:

- Sun-Earth Interactions: The Sun is strongly influencing the interplanetary medium (IPM) and the terrestrial geospatial environment. The evolution mechanisms of coronal mass ejections (CME) and their impact on solar system bodies are still not fully understood. This results in large inaccuracies on the eruption models and prediction tools, and their consequences on the Earth environment. Very low frequency radio imaging capabilities (especially for the Type II solar radio bursts, which are linked with interplanetary shocks) should allow the scientific community to make a big step forward in understanding of the physics and the dynamics of these phenomena, by observing the location of the radio source, how they correlate with their associated shocks and how they propagate within the IPM.
- Planets and Exoplanets: The Earth and the fourgiant planets are hosting strong magnetic fields producing large magnetospheres. Particle acceleration are very efficient therein and lead to emitting intense low frequency radio waves in their auroral regions. These radio emissions are produced through the Cyclotron Maser Instability (CMI). Locating the radio sources and tracing back their path along magnetic field lines leads to the particle acceleration regions. This diagnostic is powerful remote sensing tool for studying the dynamics of planetary magnetospheres. Planetary lightnings are also a source electromagnetic radiation, which allows us to sound both planetary atmospheric and ionospheric properties. Finally, the potential observations of exoplanetary radio emissions at low frequencies are a very promising way of getting intrinsic properties of exoplanets such as their sidereal rotation period, the inclination of their rotation axis or magnetic axis, the intensity of their internal magnetic field, etc…

## Current status

Dutch teams (Universities of Twente, Delft and Nijmegen, and the ASTRON institute in Dwingeloo) are leading a series of studies on space based radio interferometric instrumentation using miniaturized multiple platforms (swarms or constellations). These teams contributed to LOFAR instrument (30 MHz-250MHz), LOw Frequency ARray, which is the largest current low frequency instrument on Earth. Despite a limited space instrumentation expertise, these teams have built a serious road map towards a sapce based very low frequency radio interferometer (~1 kHz to ~100 MHz). Their archetypal project is OLFAR (Orbiting Low Frequency Array). This road map includes a series of technology demonstrators using cubesats (http://www.delfispace.nl). Many technical papers were published after their studies. Four PhD students are currently working on OLFAR at TU Twente, under the supervision of Mark Bentum. The OLFAR team is now seeking collaboration in Europe. Since the last two years, the NLAP (Netherland Low frequency Astromony Plateform) workshop is yearly organized and is dedicated to the study of very low frequency radio interferometry..

Within this collaboration platform, a space mission proposal was prepared for the ESA-CAS S2 call of 2015. The science objectives of the DSL (Discovering the Sky at the Longuest wavelengths) mission are those presented above. The proposal was unfortunately not selected by ESA, but other projects are in preparation.

## Proposed Study

We are proposing to prepare a road map to guide the community towards a space based radio interferometer. The following points will be studied:

- identification of the main science objectives, with a possible scaling in time: Sun-Earth interactions, planetary magnetospheres, Galactic mapping, astrophysical objects, cosmology…
- Instrumental requirements after these science objectives: Interferometer (size and array configur-ation, temporal, angular and spectral resolutions) ; effective area (number of array nodes) ; instantaneous sensitivity (performance of the receiving chain) ; integrated sensitivity (mission duration, duty cycling)
- Translation in terms of platform constraints: constellation or swarm, need for a mother spacecraft ? measurments and computations on the same nodes or usage of various type of nodes ; pointing, location, ranging performance ; inter-satellite communication ; dimensioning of the TC/TM link ; power dimensioning
- State of the art of the radio detector part. (on the shelf instrumentation or R&D needed). Additional constraints on power or EMC.
- State of the art of the platform part. nanosatellite ? standard nanosatellite (cubesat) ; specific nanosatellite?
- Assesment studies (power, swarm, downlink, inter-node communication, computing power, sampling, calibration…),
- Identification of existing software or algoritmic technologies useable for such an instrument,
- identification technological hard points : plateform, instrumentation, software

This series of study has been proposed to CNES under the name of the NOIRE proposal (Nanosats pour un Observatoire Interférométrique Radio dans l'Espace).

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