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Forum on Innovative Approaches to Outer Planetary Exploration 2001–2020

February 21–22, 2001

Lunar and Planetary Institute
Houston, Texas

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William Jeffrey, *Defense Advanced Research Projects Agency*
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Preface

This volume contains abstracts that have been accepted for presentation at the Forum on Innovative Approaches to Outer Planetary Exploration 2001–2020, February 21–22, 2001. The meeting was organized by Dr. Colleen Hartman *(NASA Headquarters)*. The Panel Chairs consisted of Michael Drake *(University of Arizona),* William Jeffrey *(Defense Advanced Research Projects Agency),* Jonathan Lunine *(University of Arizona),* William McKinnon *(Washington University),* Brad Parkinson *(Stanford University),* and Lisa Porter *(Defense Advanced Research Projects Agency).*

Logistics, administrative, and publications support were provided by the Publications and Program Services Department of the Lunar and Planetary Institute.

Contents

HIGHLY SURVIVABLE AVIONICS SYSTEMS FOR LONG-TERM DEEP SPACE EXPLORATION

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Introduction. The design of highly survivable avionics systems for long-term (> 10 years) exploration of space is an essential technology for all current and future missions in the Outer Planets roadmap. Long-term exposure to extreme environmental conditions such as high radiation and low-temperatures make survivability in space a major challenge. Moreover, current and future missions are increasingly using commercial technology such as deep sub-micron (0.25 μ) fabrication processes with specialized circuit designs, commercial interfaces, processors, memory, and other commercial off the shelf components that were not designed for long-term survivability in space. Therefore, the design of highly reliable, and available systems for the exploration of Europa, Pluto and other destinations in deep-space require a comprehensive and fresh approach to this problem. This paper summarizes work in progress in three different areas: a **framework** for the design of highly reliable and highly available space avionics systems, **distributed** reliable computing architecture, and **Guarded Software Upgrading** (GSU) techniques for software upgrading during long-term missions.

Framework. Missions such as Cassini use highly reliable and expensive components organized into cross-strapped subsystems (prime and a backup). Missions such as the Europa Orbiter use advanced computing technologies such as the PowerPC 750 and other components that have much higher commercial heritage. As this trend continues, future deep-space missions will have to be designed to tolerate and survive higher number of failures, many of which will not be identified as during the qualification process. Our work considers a framework for the design of reliable systems that accommodates the use of advanced (and thus less known) technologies. This approach is based on a hierarchical methodology that starts from the physics of failure analysis at the materials and devices layer, and ranges to the hardware/software application or service layer. Reliable services are provided in a distributed fashion over a reliable network with a rich set of interconnections. Fault detection, containment and recovery are handled in a localized fashion, with hierarchical coordination with higher layers. In the limit, and at a very fine granularity, such an approach is also consistent with biological systems, which perform these functions very well.

Distributed Reliable Computing. Our work has shown that a distributed system that consists of a redundant and scaleable network with redundant storage devices and computing nodes, can provide an effective platform for the implementation of reliable network services. This work, funded jointly by NASA and DARPA, resulted in a commercial spin-off called *RAINfinity* which has applied these techniques to reliable services over the internet. Our current design of a distributed system uses the 1394 Firewire network to provide a rich set of redundant interconnects. Multiple nodes on the network provide backup services for both high-reliability and high-availability.

Guarded Software Upgrading. Long-term missions such as Pluto/Kuiper Express will benefit greatly from the proposed technology we refer to as "Guarded Software Upgrading." It is expected that during a mission that lasts 10-14 years, there will be plenty of opportunities to routinely upgrade the software. Currently, there is no known simple and reliable way to continuously upgrade software. In fact, it is quite difficult and risky. Together with IA Tech Inc, NASA has developed techniques to reliably upgrade software. GSU allows the old and reliable software to co-exist with the newly uploaded, and thus less reliable software. Using inherent redundancy (spare computer nodes), and distributed checkpoint and rollback techniques, the old software 'guards' the transition to the new software in a reliable fashion, until the right level of confidence is reached. At that point, the new software assumes control. A prototype of this exciting technology has been demonstrated, and is now in the latter stage of maturity.

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S. Chau, L. Alkalai, and A. Tai, "The Analysis of Multi-Level Fault-Tolerance Methodology for Applying COTS in Mission-Critical Systems," IEEE Workshop on Application-Specific Software Engineering and Technology, Dallas, TX, March 2000.

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A MINIATURIZED SEISMOMETER FOR SURFACE MEASUREMENTS IN THE OUTER SOLAR SYSTEM.

W. B. Banerdt and W. T. Pike, M.S. 183-501, Jet Propulsion Laboratory, Pasadena, CA 91109, bruce.banerdt@jpl.nasa.gov.

Introduction: Seismology is a powerful tool for investigating the inner structure and dynamic processes of a planetary body [1]. The interior structure information derived from seismic measurements is complementary to other methods of probing the subsurface (such as gravity and electromagnetics), both in terms of spatial and depth resolution and the relevant types of material properties being sensed. The propagation of seismic waves is sensitive to composition (via density and elastic parameters), temperature (via attenuation) and physical state (solid vs. liquid). In addition, the seismicity (level and distribution in space and time of seismic activity) provides information on the impact flux and tectonic forces currently active within the body.

The major satellites of the outer solar system provide obvious targets for seismic investigations. In addition, small bodies, such as asteroids and comets, can also benefit from seismic measurements [e.g., 2].

We have developed an extremely small, lightweight, low-power seismometer for planetary applications [see 1-4] which is ideally suited for use in the outer solar system. This instrument has previously been proposed and selected for use on a comet (on the Rosetta Lander [2], subsequently deselected for programmatic reasons) and Mars (on the NetLander mission [4]).

Seismometer Description: The seismometer, which is being developed by the Microdevices Laboratory of JPL, is designed to meet the constraints of extraterrestrial applications, in particular having very low mass, volume and power requirements, while delivering performance comparable to that of a conventional terrestrial seismometer ($5x10^{-9}$m/sec^2/Hz over a 0.05 to 100-Hz bandwidth). The design uses a micromachined mechanical structure consisting of the suspension mechanism, proof mass and capacitor plates, and a highly sensitive capacitive displacement transducer that employs a force-rebalance feedback system.

The suspension is of a symmetric design, incorporating three wafers bonded together (Fig. 1). The central wafer incorporates a set of flexures allowing motion of the proof mass in the plane of the wafer (Fig. 2). The flexure geometry is designed to maximize the robustness of the suspension; end-stops prevent any motion induced by accelerations greater than about 1 g. The proof mass is free to move under gravity (Earth gravity) to an equilibrium position. Capping wafers carry the metallized fixed electrodes. The displacement signal and feedback actuation result from the changing overlap between electrodes on the fixed plates and the patterned surface of the silicon proof mass. The use of a lateral detection scheme reduces damping effects and hence the fundamental noise floor by two orders of magnitude compared to the more conventional parallel opposed-plate approach.

The small volume available for the microseismometers limits the resonant frequency of the suspension to 10 Hz. This relatively stiff suspension requires a correspondingly sensitive position transducer to measure the deflection of the proof mass. A low-noise switched-capacitance transducer determines the lateral movement between the moving proof mass and fixed electrodes above and below the proof mass to a precision of about 10^{-14}m. The seismic signal from each axis is anti-alias filtered before being digitized with a multiplexed 16-bit analog-digital converter.

This device provides a high-quality seismic measurement which should be capable of elucidating many of the fundamental questions concerning the solid bodies of the outer solar system.

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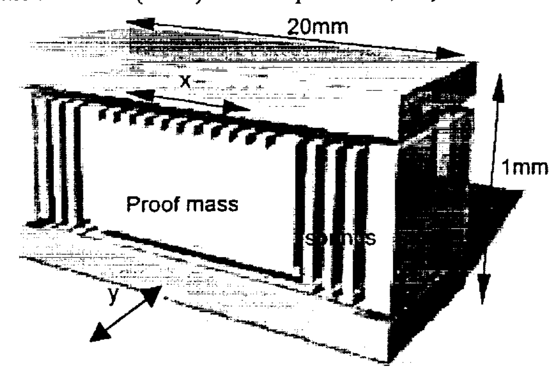

Fig.1: Cutaway drawing showing the geometry of the sensor.

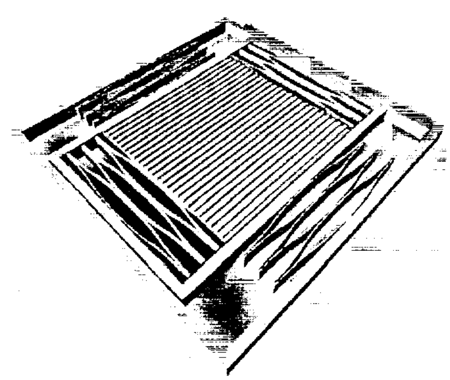

Fig.2: Central wafer, comprising proof mass and suspension.

APPROACHES FOR EXPLORING THE ORGANIC EVOLUTION OF TITAN'S SURFACE. P. Beauchamp[1], J. Beauchamp,[2], D. Dougherty,[2], F. Raulin[3], M. Smith[4], C. Welch[5], R. Shapiro[6], J.Lunine[7]. [1]Center for In-Situ Exploration and Sample Return, JPL 306-463, 4800 Oak Grove Dr, Pasadena CA 91109, pbeaucha@mail1.jpl.nasa.gov, [2]Noyes Laboratories, Caltech, Pasadena CA, [3]LISA, Univ. Paris, France, [4]Dept. Chemistry, Univ. of Arizona, Tucson, [5]Merck and Co., Rahway, NJ, [6]Dept. Chemistry, New York Univ., [7]LPL, Univ. Ariz.

Introduction: Saturn's largest moon Titan has a cold, very dense nitrogen atmosphere rich in methane and the hydrocarbon and nitrile products of methane photolysis (1). Sources of energy for atmospheric chemistry include solar ultraviolet radiation, Saturn magnetospheric particles, and galactic cosmic rays. The chemistry of Titan's atmosphere, while interesting from the point of view of planetary photochemistry, is largely free-radical driven and therefore not particularly suited to the synthesis of polymeric biomolecules or even their precursors. However, the nature of Titan's atmosphere, in particular its redox state (hydrogen escapes rapidly and is underabundant compared to in the giant planets), and the presence of a variegated surface (2) make consideration of surface chemistry on Titan interesting from an astrobiological viewpoint.

Surface sources of energy: Possible sources of surface energy include water ice (cryo) volcanism generated from interior heat sources (3), impact heating (4); (5), and stored chemical energy. This last source may come in the form of acetylene, which is the second most abundance product of Titan photochemistry (6) and an unsaturated hydrocarbon. Under appropriate conditions polymerization reactions can be trigger in acetylene, leading to release of heat and production of C-H or even elemental-C polymers. The amount of heat potentially releasable is less than that due to impacts or accretional heat, but still enough to be a potentially interesting source of energy.

Surface chemistry: Given a rich rainout of hydrocarbons and nitriles (liquid and solid), surface sources of energy and possibly transient episodes of near-surface liquid water on Titan, surface organic chemistry on Titan might be surprisingly rich and perhaps reflective of chemical evolution characterized by self-organizing or self-catalyzing processes. Ordered polymers (e.g., of particular tacticity) or amplification of enantiomeric excesses in chiral species might occur, as well as preferential abundance patterns of particular isomers or molecular weight distributions in organic polymers. The Cassini Orbiter will map the surface distribution of organics, perhaps finding areas of unusual composition, and the Huygens probe will sample atmospheric organics directly. These will provide sufficient information to target promising surface sites for a follow-on Titan organics explorer.

Organics explorer Investigations: Key investigations for a surface organics explorer must proceed in a stepwise fashion to locate and characterize sites of interest. Elemental and molecular analyses are required to assess whether a perticular orgnaic deposit was exposed to levels of oxygen (via, e.g., aqueous chemistry) well above those present in the atmosphere. Identification of metallic or other catalysis in the sample area, as well as determination of the presence of polymer products of acetylene, should provide information on energy sources available locally for chemistry. Chromatographic and mass spectrometer analyses should be undertaken to determine whether surface organics differ from the products of atmospheric photochemistry, as well as discern any non-random pattern in the molecular weight distribution of surface organics. Chiral chromatography, or other enantioselective diagnostic techniques, should be done to ascertain whether chiral species show strong enantiomeric excesses. Analysis of tacticity in complex polymers, for example acrylonitrile, is of interest to determine whether polymerization processes in the sample are random or not.

The Titan environment poses a challenge for most if not all of these tests. Most techniques for determining enantioenrichment are temperature sensitive, and while sensitivity improves as temperatures are lowered modestly below room temperature, the extreme cold of the Titan environment would pose severe challenges. Use of NMR to determine polymer tacticity, standard in the laboratory, requires concerted efforts in miniaturizing and automating the requisite technology.

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Acknowledgements: The work described herein is supported by a DDF grant to P.B. and Distinguished Visiting Scientist grant to J.L.

A RADIATION-TOLERANT, LOW-POWER NON-VOLATILE MEMORY BASED ON SILICON NANOCRYSTAL QUANTUM DOTS.

L.D. Bell[1], E. Boer[2], M. Ostraat[2], M. L. Brongersma[2], R. C. Flagan[2], H. A. Atwater[2], J. deBlauwe[3], and M. L. Green[3], [1]Jet Propulsion Laboratory, 4800 Oak Grove Dr, Pasadena, CA 91109, [2]Caltech, Pasadena, CA 91125, [3]Lucent Technologies, Murray Hill, NJ 07974.

Introduction: Nanocrystal nonvolatile floating-gate memories are a good candidate for space applications - initial results suggest they are fast, more reliable and consume less power than conventional floating gate memories.[1,2] In the nanocrystal based NVM device, charge is not stored on a continuous poly-silicon layer (so-called floating gate), but instead on a layer of discrete nanocrystals. Charge injection and storage in dense arrays of silicon nanocrystals in SiO_2 is a critical aspect of the performance of potential nanocrystal flash memory structures. The ultimate goal for this class of devices is few- or single-electron storage in a small number of nanocrystal elements. In addition, the nanocrystal layer fabrication technique should be simple, 8-inch wafer compatible and well controlled.

Technical Products: Formation of a nanocrystal aerosol is via the decomposition of silane at 950 C in an inert carrier gas, followed by an in-situ, pre-deposition thermal oxidation. This "discrete" method for aerosol synthesis allows unprecedented control of nanocrystal size and vertical positioning within the element gate stack. Dense ($5x10^{11}$ cm^{-2}), nearly co-planar nanocrystal layers have been obtained. We have then integrated nanocrystal layers in 0.20 micron nMOS-FETs to produce the first aerosol-nanocrystal floating-gate memory devices (Fig. 1). These devices exhibit threshold voltages of less than 5V with large threshold voltage shifts (~ 2 V), sub-microsecond program times and millisecond erase times. No decrease in program/erase threshold voltage swing was seen during 100,000 program and erase cycles. Additional near-term goals for this project include extensive testing for radiation hardness and the development of artificial layered tunnel barrier heterostructures [3] which have the potential for large speed enhancements for read/write of nanocrystal memory elements, compared with conventional flash devices.

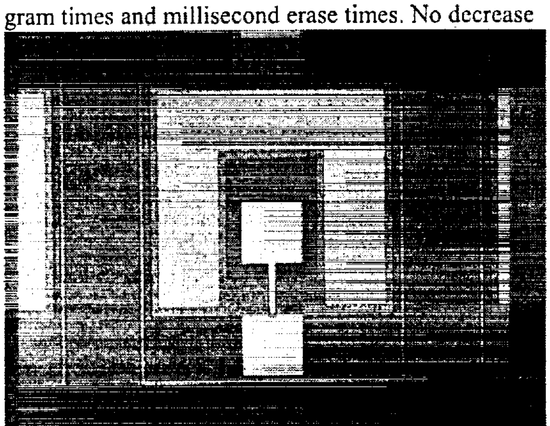

Figure 1: Scanning electron micrograph image of a nanocrystal floating gate memory test device.

NASA Relevance: NASA deep-space missions will require increased autonomy and capability without increased mass and power. Breakthrough small, low-power memory technologies are required to address this requirement. Nanocrystal-based flash memories are based on few- or single-electron storage per nanocrystal, offering the ultimate in low-power, ultrasmall storage. Moreover, many deep-space missions will demand radiation-tolerant electronics; high-radiation environments are especially demanding for memory technologies, often requiring massive shielding. Missions to the Jovian system, such as the Europa Lander or Titan Explorer, will require breakthroughs in memory radiation tolerance. The discreteness of charge storage in isolated nanocrystals instead of large, continuous floating gate offers an intrinsic tolerance to total-dose radiation damage. Thus, the implementation of flash memory designs using nanocrystal charge storage is extremely promising as an inexpensive and reliable way to address these challenges.

Nanocrystal-based flash memory elements, combined with layered tunnel barriers, can also be combined to produce wavelength-tunable imaging elements. The novel properties of these tunnel barriers enable voltage-tunable control of detected wavelength, combined with monolithic storage of multiple image frames (using nanocrystal storage) within the same microdevice. The end product is an autonomous, versatile imager/memory array which approaches the absolute limits of miniaturization.

References: [1] Yano K., Ishii T., Hashimoto T., Murai F., and Seki K. (1994) *IEEE Trans. Electron. Devices, 41,* 1628-1638. [2] Tiwari S., Rana F., Hanafi H., Hartstein A., Crabbe E. F., and Chan K. (1996) *Appl. Phys. Lett. 68,* 1377-1379. [3] Likharev K. K. (1998) *Appl. Phys. Lett. 73,* 2137-2139.

SEARCH FOR AMMONIA CONTAINING LIFE BUILDING BLOCKS IN OUTER SOLAR SYSTEM. Sz. Bérczi[1], and B. Lukács[2], [1]Eötvös University, Dept. G. Physics, Cosmic Materials Sp. Res. Gr. H-1117 Budapest, Pázmány Péter sétány 1/a. Hungary, (berczisz ani@ludens.elte.hu) [2]Central Research Institute for Physics RMKI, H-1525 Budapest-114. P.O.Box 49.

Introduction: Amino acids are critical building blocks for proteins. The most important ancient source for them could have been the ammonia ice which was a basic ice component in the models of the early Solar System. Outer Solar System bodies may have preserved ammonia and some of its compounds in ice form, or in the form of ammonia(um)-silicates. Ammonia could be the solvent for life molecules, too. The sources of the other, more important component and solvent for life molecules, water, are better known. We estimated simultaneous occurrence of ammonia and water: in atmospheres of Jupiter, Saturn, and Titan. For comparisons terrestrial planet possibilities are also shown.

Water examples and Ammonia sources in the Outer Solar system: Cosmic abundance of N is lower then that of O. Searching ammonium we follow the sources where water is present in Solar System materials. Two main sources of H_2O in Earth was 1) from condensation of hydrated silicates in Lewis-Barshay model (LBM, [1]); and water ice transport by cometary bodies from the outer Solar System. We look for the ammonia counterparts of these two cases [2].

Ammonia-silicates: In LBM serpentine and tremolite are the hydrosilicates. The fillosilicates have their ammonium silicate pseudo-counterparts: there the NH_4-ion substitutes K (as a pseudo-alkaline ion), i.e. *buddingtonite*: ammonium feldspar [3], *tobelite*: ammonium muscovite [4-5], *ammonioleucite*, [6], *ammonium-illite*, [7], and *ammonium-phlogopite*, [8]). They were probably observed in the infra-red spectrum of Ceres [9]. The LBM did not involved ammonia(um) silicates. Using data of [2, 3] and [10, 11] (decay temperatures for buddingtonite), we interpolated the buddingtonite approximate condensation line between FeS and FeO lines, somewhat above to tremolite [12] in LBM. (Cameron adiabat crossing of buddingtonite is at ca. 600 K)

Ammonia ices: In LBM the $NH_3.H_2O$ ammonia-hydrate condensation is calculated at 150 K (1 bar; 100 K at 10^{-5} bar, on the Cameron solar adiabata, Saturn vicinity [1]). According to this model Jovian and Saturnian satellites contain considerable ammonia ice components. Other N containing ices have similar or lower freezing points, and less probability to form in solar nebula conditions .)

Water and ammonia simultaneous solvents: a probable constraint to the formation of life in outer Solar System: Acidic carboxyl and basic amino radicals characterize amino acids. During their chain formation to build proteins the two types of radicals become neutralized by a reaction between these two different types of end-radicals. Neutralization produces peptide-link and results in water solvent. There are similarities between water and ammonia. They are dissociated into the solvent's radicals (H+, OH-, and H+, NH^{2-}). Because the characteristic radicals of amino acid molecules are carboxyl, hydroxyl, amine and amide ones, amino acid molecules can interact both with water and ammonia in a similar way in many reactions.

Overlapping liquid fields of ammonia and water in the p-T diagram: Because of the symmetry in solvent role of ammonia and water amino acid molecules were formed with high efficiency on those regions where both compounds were in liquid state [13]. There are two types of such regions in outer Solar System. One is the atmosphere of Jovian Planets, the other is the large satellites of outer planets. Fig. 1. shows the estimated range for the atmosphere of Jupiter and Saturn and together with the Venus-Earth-Mars) triplet for comparison the case of Titan. In the case of rocky planets the Tie-diagrams show the rage of atmosphere and hydrosphere extensions over the surface points.

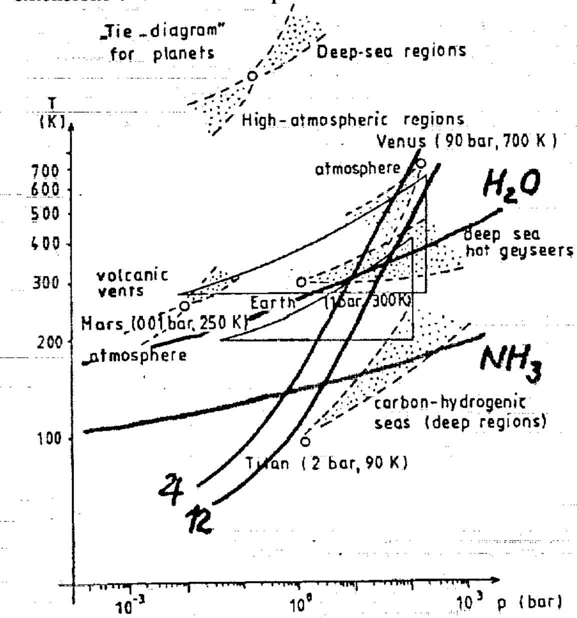

Fig. 1. P-T regions of outer Solar System bodies where ammonia and water may simultaneously occur: water phase line is from [1], ammonia line is from [2], others in [13, 14].

Conclusions, proposals: In search for basic life molecules - amino acids - the ammonia content and ammonia/water ratio seems critical. We suggest the measurement of the simultaneous occurrence of water and ammonia in comet nucleus, Europe subsurface, Titan atmosphere and Neptune/Triton environment. The occurrences may be not only in ice form but in ammonia-silicate form, too.

Acknowledgment: partly supported by OTKA T/26660.

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ADVANCED COMMUNICATION ARCHITECTURES AND TECHNOLOGIES FOR MISSIONS TO THE OUTER PLANETS.

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Introduction: Missions to the outer planets would be considerably enhanced by the implementation of a future space communication infrastructure that utilizes relay stations placed at strategic locations in the solar system. These relay stations would operate autonomously and handle remote mission command and data traffic on a prioritized demand access basis. Such a system would enhance communications from that of the current direct communications between the planet and Earth. The system would also provide high rate data communications to outer planet missions, clear communications paths during times when the sun occults the mission spacecraft as viewed from Earth, and navigational "lighthouses" for missions utilizing on-board autonomous operations.

Relay Network: An outer planet communication network is shown in Figure 1. To implement this system, it is assumed that most of the large flexible structure technologies are in place so that large but lightweight communications systems can be placed in space at reasonable cost. In this concept, large antenna structures are tethered together with a control spacecraft and a large solar array. The solar array powers all the units through wires in the tethers. The control unit acts as a router for sending data received from earth through the appropriate antenna or optical telescope to a mission's spacecraft and for handling the mission's data return route. All units handle their own pointing and the central control unit ensures that the units don't collide.

Tethered relay stations are placed at the various Lagrangian libration points such as the Earth, Jupiter, and Saturn L3, L4 and L5 points. Such relay stations vastly improve the communications data rates to distant locations in the solar system by using shorter transmission distances between relay points. The relay stations utilize microwave frequencies from 8 to 120 GHz and optical communications. The lower frequencies provide health, housekeeping, low rate command, and emergency data services. The higher frequencies enable very high-resolution hyperspectral imaging, synthetic aperture radar, and video files to be sent back to Earth. Such an infrastructure can also provide high rate data services to manned missions to Mars and beyond.

Europa Mission: Operations for the landed Europa mission are expected to require rather intense control and monitoring as the activities will likely be complex and difficult to make fully autonomous. Direct communications to Earth are hampered by occultation periods due to masking by Jupiter and due to the rotation of Europa. In this presentation we will compare the features of direct-to-earth, lander-to-orbiter-to-Earth, and the lander-to-relay network-to Earth architectural infrastructure shown in Figure 2. We will also discuss new and in-process communications technologies pertinent to the support of the Outer Planet Program.

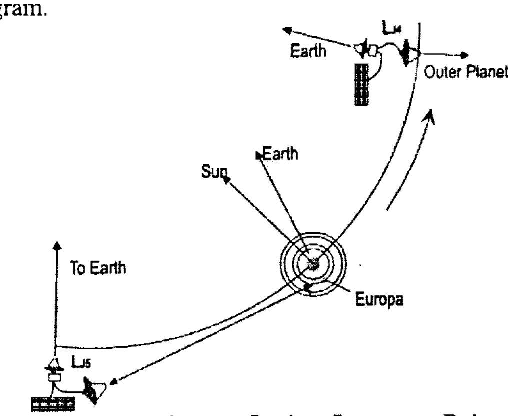

Figure 2, Relays at Jupiter Lagrange Points

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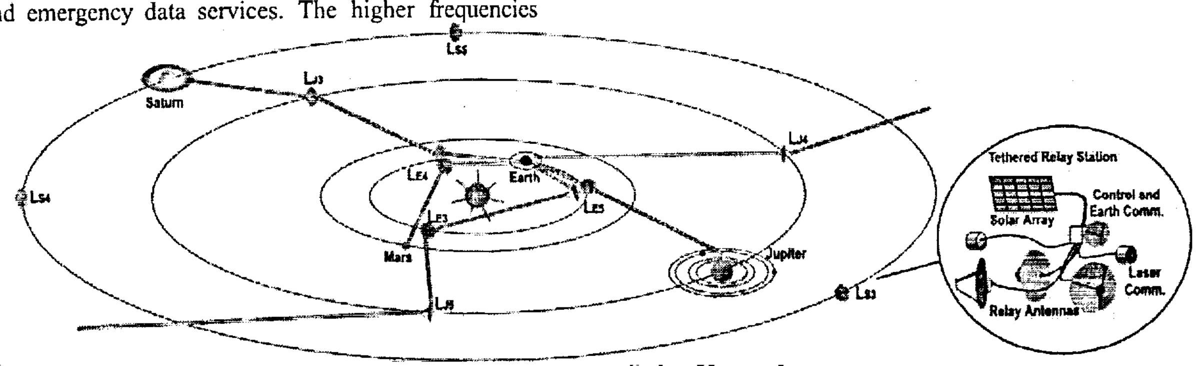

Figure 1, Outer Planet Relay Network

MICRO-AVIONICS NODE FOR DISTRIBUTED AVIONICS SYSTEM. B. R. Blaes, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove, Pasadena, CA 91109, brblaes@jpl.nasa.gov

An avionics system is a platform residing on a flight vehicle that provides the resources (hardware and software) needed to manage the flight mission. Distributing the avionics system components, both functionally and spatially, can provide characteristics that benefit the overall system robustness, reliability, testability, and maintainability. This abstract discusses the concept of a distributed avionics system consisting of a network of micro-avionics nodes.

A micro-avionics node contains all the electronics needed to support the interfacing needs of local sensors, instruments and effectors as well as providing local data processing and storage, and inter-node communication. A micro-avionics node consists of the smallest avionics system that fits on a single silicon chip. In fact, a single node could provide sufficient avionics resources for small systems such as micro rovers, free flyers, or science probes. System-On-A-Chip (SOAC) technology would allow this functionality to reside on a single chip, or a few chips.

The processing performed at the avionics node would take care of low-level signal conditioning, low latency real-time control loops, and reduction (compression) of sensor data communicated to other nodes. A network of micro-avionics nodes results in a distributed data collection, processing, and control system that is highly fault tolerant, providing graceful degradation of the overall system to multiple faults. The nodes would support the transfer of data at all levels of abstraction (raw to highly compressed). A node could be viewed as a software object by the system software. This is particularly beneficial for object-oriented software architectures that are used in advanced spacecraft. Communicating the compressed (pre-processed) sensor data relieves the bandwidth requirements of the interconnecting network during normal operation. The raw sensor data can however be communicated across the network to provide testability and to allow other nodes to function as backup processors to provide computational fault tolerance.

The ability to reconfigure node resources through software is a desired attribute of the micro-avionics node. This would allow the node to be configured for multiple sensor, effector, processing functions. These functions could be static (preprogrammed) or dynamically altered during operation to accommodate real-time adaptability and fault tolerance.

The technical challenges facing the development of the micro-avionics node include extremely low power consumption, high analog resolution and high data rates in a noisy environment, ability to handle high voltages (up to 60 V) and isolated grounds at the sensor/effector interfaces, and the ability to withstand harsh mission environments (radiation, high and low temperature). A strawman architecture for the micro-avionics node is shown in Fig. 1. This SOAC node contains a CPU, volatile and nonvolatile memory, a clock, timers and event handlers (capture registers), analog and digital I/O, and a short-range wireless transceiver. The transceiver can be used for backup communication in a hard-wired network or for wireless communication between isolated self-powered nodes on one vehicle or between multiple vehicles. The SOAC would be fabricated through a radiation hard SOI process.

A distributed avionics system architecture offers many benefits in realizing extremely reliable systems. The performance of such a system scales linearity with size (number of nodes) and offers functional redundancy in a spatially distributed system for enhanced node decoupling and hence high fault tolerance. The micro-avionics node is a flexible building block for constructing distributed avionics systems.

Acknowledgement:

The research described in this paper was performed at the Center for Integrated Space Microsystems, Jet Propulsion Lab, California Institute of Technology, and was sponsored by the National Aeronautics and Space Administration.

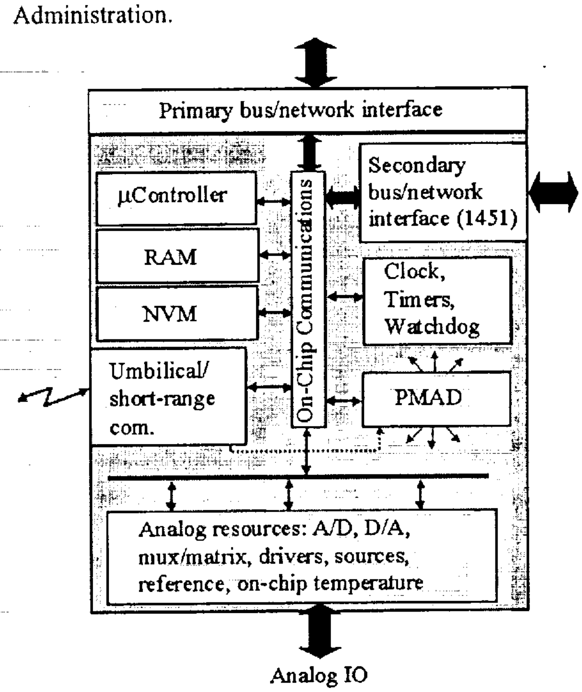

Fig. 1 Micro-avionics node SOAC architecture

MINIATURE FREE-FLYING MAGNETOMETER UTILIZING SYSTEM-ON-A-CHIP TECHNOLOGY.

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Four Free-Flying Magnetometers (FFMs), developed at the Jet Propulsion Laboratory (JPL) for the Enstrophy mission (lead by University of New Hampshire), were successfully deployed from the payload of a sounding rocket launched from Poker Flats, Alaska on February 11, 1999 [1]. The FFMs functioned successfully by synchronously measuring the vector magnetic field at 4 points separate from the payload and at relative distances up to 3 km, and communicated their data, in bursts, to the ground. This is the first time synchronized in-situ multipoint measurements of the Earth's magnetic field utilizing miniature spin-stabilized "sensorcraft" have been performed. The data they provided have enabled, for the first time, the direct measure of field-aligned current density and are enabling new science by determining the fine-scale structure of the currents in the Earth's ionosphere involved in the production of aurora.

These proof-of-concept "hockey puck" (80 mm diameter, 38 mm height, 250 gram mass) FFMs were built using off-the-shelf commercial, industrial, and military grade surface-mount electronic components. Radiation-hard electronics was not required for the Enstrophy mission's short sub-orbital flight. The successful design, implementation, and flight demonstration of this 1st generation FFM design has provided a solid base for further development of a 2nd generation FFM design for planetary science applications. A reliable ultra-miniature radiation-hard 2nd-generation FFM utilizing System-On-A-Chip (SOAC) technologies is proposed [2]. This design would be targeted for long-term planetary missions to investigate magnetospheric field configurations in regions having small-scale structure and to separate spatial and temporal variations. A fleet of short-lived (expendable) FFMs would be deployed into a targeted region to gather multiprobe vector magnetic field data. The FFMs would be ejected from a parent spacecraft at a speed of a few m/sec and would cover spatial volumes of order tens of kilometers for times of order one hour. The parent spacecraft would carry a sufficient number of FFMs for multiple deployments.

The FFM consists of 1) a sensitive 3-axis magnetometer sensor; 2) synchronized 3-channel Analog-To-Digital Converter (ADC); 3) an accurate clock used to determine the attitude of the FFM; 4) sun sensor used in conjunction with the clock for determining the spin orientation of the FFM; 5) Radio-Frequency (RF) transmitter to relay data to parent spacecraft; 6) a wireless umbilical interface used to communicate with the FFM prior to deployment; 7) a data subsystem for acquiring, formatting, and storing data in memory and controlling power and data transmission; and 8) power source with conditioning and management, electronics. The eight components are integrated into the architecture shown in Fig. 1. The data subsystem manages continuous data acquisition from magnetometers, sun sensors, and system health monitoring. Data is communicated to the deploying parent spacecraft via a RF transmitter whose carrier frequency is programmable prior to deployment.

High-level SOAC integration of all FFM electronics onto one or a few silicon chips utilizing a radiation-hard SOI foundry is technically feasible. The development of a 3-axis magnetic field sensor meeting the FFM application requirements is the greatest challenge. Presently a high-sensitivity MEMS Lorentz-force-oscillator based magnetometer is being considered for the FFM.

Acknowledgement:
The work described in this abstact was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References:

[1]Blaes B. et al (1999) Proc. DASC 0-7803-5749-3 7.D.4-1

[2]Blaes B. et al (1999) Proc. AIAA Space Tech. Conf. 9-28

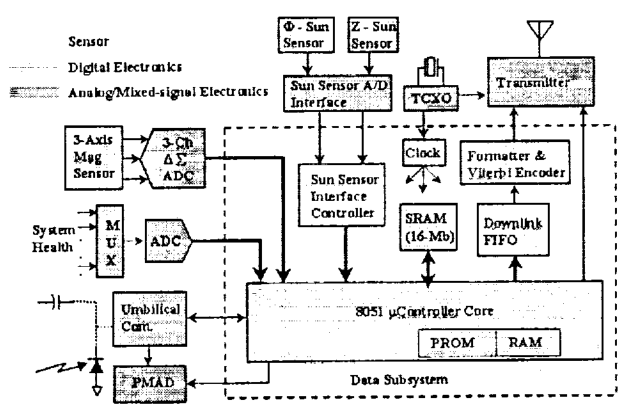

Fig. 1 FFM architecture

MICRO NAVIGATOR. B. R. Blaes[1] , S. N. Chau[2], and T. Kia[3], [1, 2, 3] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove, Pasadena, CA 91109, brblaes@jpl.nasa.gov, Savio.N.Chau@jpl.nasa.gov, Tooraj.Kia@jpl.nasa.gov

Miniature high-performance low-mass space avionics systems are desired for planned future outer planetary exploration missions (i.e. Europa Orbiter/Lander, Pluto-Kuiper Express). The spacecraft fuel and mass requirements enabling orbit insertion is the driving requirement. The Micro Navigator is an integrated autonomous Guidance, Navigation & Control (GN&C) micro-system that would provide the critical avionics function for navigation, pointing, and precision landing. The Micro Navigator hardware and software allow fusion of data from multiple sensors to provide a single integrated vehicle state vector necessary for six degrees of freedom GN&C. The benefits of this Micro Navigator include:

1. The Micro Navigator employs MEMS devices that promise orders of magnitude reductions in mass power and volume of inertial sensors (accelerometers and gyroscopes), celestial sensing devices (star tracker, sun sensor), and computing elements.
2. The highly integrated nature of the unit will reduce the cost of flight missions.
   a. The advanced miniaturization technologies employed by the Micro Navigator lend themselves to mass production, and therefore will reduce production cost of spacecraft.
   b. The integral approach simplifies interface issues associated with discrete components and reduces cost associated with integration and test of multiple components.
3. The integration of sensors and processing elements into a single unit will allow the Micro Navigator to encapsulate attitude information and determination functions into a single object. This is particularly beneficial for object-oriented software architectures that are used in advanced spacecraft.

Inertial and celestial sensors used in current spacecraft designs are typically heavy, physically large and consume large amounts of power. Miniature inertial sensors, such as micro gyros and micro accelerometers in the form of MEMS, miniature celestial sensors such as Active Pixel Sensor (APS), and miniaturized GPS sensors are currently in development and are targeted for the Micro Navigator system.

Current spacecrafts utilize discrete components to gather measurement data to a central processor that uses onboard algorithms to provide separate attitude information. This approach leads to many hardware and software interface problems during integration and test and in-flight operations. The concept of an integrated system that fuses multiple sensor data and outputs a single state vector facilitas easy integration, test and operation. This capability enables independence from the sensor suite and frees the mission designers from producing new algorithms and software every time they adapt hardware to meet mission needs. The Micro Navigator contains the computing resources needed to implement a state estimator to fuse data from multiple sensors and to output the vehicles position-attitude (6-DOF) state vector at high resolution (0.1° attitude and 50 meters position, 10 with GPS) and at update rates of less that 1 second. The Micro Navigator is targeted for a mass of less than 0.5 kg, a volume of ~8 in^3, and a power requirement of less than 5 watts. A packaging concept for the Micro Navigator is illustrated in Fig. 1.

Acknowledgement:

The research described in this paper was performed at the Center for Integrated Space Microsystems, Jet Propulsion Lab, California Institute of Technology, and was sponsored by the National Aeronautics and Space Administration.

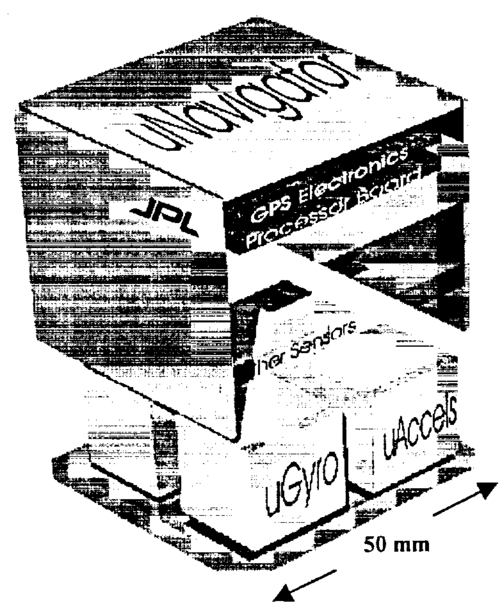

Fig. 1 Micro Gyro packaging concept.

Advanced THEMIS for Multispectral Thermal IR Imaging. K. R. Blasius[1], S. H. Silverman[1], and P. R. Christensen[2] [1]Raytheon Santa Barbara Remote Sensing, 75 Coromar Dr., Goleta, CA 93117, e-mail: kblasius@west.raytheon.com [2]Arizona State University, Tempe, AZ 85284.

Introduction: Advanced THEMIS is a project [1] to define and develop to breadboard stage, a miniature infrared imaging radiometer with applications to Mars orbiter and lander missions and missions to other bodies of the outer and inner solar system. The goal is to maintain or enhance functionality of the Thermal Emission Imaging System (THEMIS), recently delivered to the Mars 2001 Odyssey Orbiter, while reducing volume by ~75%. Other improvements expected are a broadened spectral range and improved radiometric calibration. A new generation of microbolometer detectors will be tested and further developed. These detectors have a new structure and smaller pitch, 25 microns vs. 50 microns used for THEMIS.

Advanced THEMIS will be a substantially smaller instrument than THEMIS, so it will reduce the cost of multispectral thermal emission imaging on future missions. Candidate missions include future landed and orbiting platforms at Mars and other solar system objects where priority science requires multispectral imaging in the thermal infrared. The reduction in instrument mass may greatly improve mission science return compared to previous technical approaches. Advanced THEMIS offers opportunities for science data return in at least three areas: surface mineralology, surface temperature dynamics, and atmospheric phenomena, similar to the return from Mars Global Surveyor Thermal Emission Spectrometer (TES) now in operation [2].

Key Developmental Tasks: The Advanced THEMIS Project has three hardware-related tasks.

1. *Detector Spectral Response Characterization and Design Modifications.* We will characterize the spectral-radiometric response of the new 25μm microbolometer detectors developed by Raytheon Infrared Operations (RIO) and investigate/implement design changes to improve sensitivity in specific regions of the spectrum. Response will be measured over the spectral range 1 to 30 μm.
2. *Detector Noise Characterization.* Uncooled microbolometer detectors have been developed primarily for terrestrial real-time imaging applications. These detectors typically operate at frame rates of either 30 Hz or 60 Hz. The pixel structure has been optimized to have short thermal time. For space remote sensing applications, it is often desirable to increase sensitivity by employing pixel averaging techniques, such as time-delay-and-integration (TDI), for sensors operating in a push-broom scanning mode, or frame-averaging. In either case the detectors must have good 1/f noise characteristics as well as low overall system drift in the output signal. This task will characterize the 1/f noise and output drift of the microbolometer detectors in order to determine the effectiveness of signal averaging.
3. *Radiometric Calibration Approaches.* Absolute IR radiometry requires at a minimum minimum two-point calibration (to yield gain and offset), while relative radiometric calibration may succeed with single-point (offset) calibration. We will evaluate a variety of calibration approaches, including internal single and dual temperature references, external single and dual temperature references, partially transparent radiance references, ground truth, and combinations of the above.

Instrument Concept: Advanced THEMIS is expected to allow future missions in the post-2003 era to perform multispectral thermal imaging with lower launch and spacecraft costs. Table 1 is a comparison of estimated masses of a miniature Advanced THEMIS with THEMIS.

The shown reduction in mass of 79% would make this Advanced THEMIS suitable for a low mass flyby, orbiter, or lander. If only a limited IR spectral range is required, say 7 to 16 μm, and a shorter focal length can meet mission requirements, then the reflective telescope could be replaced with a refractive Ge lens for an additional savings of about 0.9 kg.

Table 1 Mass Comparisons (kg)	**THEMIS (w/o VIS camera)**	**Advanced THEMIS**
Refl. Telescope	4.4	1.1
Shutter Assembly	0.3	0.02
Electronics, Cables	4.6	0.7
Sunshade	0.7	0.2
Thermal Blankets	0.5	0.2
Misc.	0.4	0.1
Total	**10.9 kg**	**2.3 kg**

References: [1] approved for funding in 2000 by NASA's Planetary Instrument Design and Definition Program [2] Christensen, P.R. (1992) JGR, 97, 7719-7734.

ENABLING TECHNOLOGIES FOR HIGH SCIENCE RETURN AND LOW-POWER, LOW-MASS COMMUNICATIONS ON OUTER PLANET MISSIONS.

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Introduction: This paper provides an overview of enabling RF technologies and architectures, developed recently at the Applied Physics Laboratory (APL), that can serve to the benefit of the Outer Planets Program. The close proximity of flight programs and technology development programs at APL has enabled the rapid infusion of innovative new RF technologies into deep space missions such as CONTOUR and MESSENGER. These technologies serve to improve the science return either directly (antennas, power amplifiers) or indirectly (low-power, low mass electronics). Our approach is forward thinking and aggressive, yet grounded in technical and fiscal reality.

Hybrid Inflatable Antenna: Inflatable antennas have long been considered by mission planners as an enabling technology for increasing the science return of imaging missions. However, the infusion of this technology has been stymied by concerns over reliability. The "all-or-nothing" scenario evokes memories of the failed high gain antenna deployment on Galileo. Under the NASA Advanced Technology Development (ATD) Program, we have begun the development of a "hybrid" inflatable antenna that provides a credible backup capability in the event of an inflation failure. This antenna combines a rigid reflector with an inflatable annulus to achieve this goal. Should inflation of the annulus fail, the mission retains a reduced but credible high gain capability. Alternatively, the antenna can be used on outer planet missions to provide a science "bonus." In this scenario, the inflated annulus enhances the science return above the minimum level already provided by an existing rigid dish. For example, a 1-m diameter rigid dish that is extended to 4-m diameter could potentially increase the downlink science return by a factor of 16 at Neptune. We hope that this promising technology will enable the incorporation of inflatable antennas into flight programs by 2005. A breadboard hybrid inflatable antenna is currently being fabricated by ILC Dover, Inc. with the goal of verifying a surface accuracy that is compatible with K_a-band operation.

Low-Power, Low-Mass Transceiver Systems: A significant problem in achieving a low-power, low mass communication system is in the improvement of the transponder hardware. The nature of microwave circuitry and the stringent requirements of deep space communications make significant transponder improvements expensive. An alternative approach pioneered by APL is to change the fundamental architecture of the hardware, so that miniaturization and lower power operation can occur more readily. We have developed a noncoherent RF transceiver architecture as an alternative to the coherent transponder for some deep space missions. This architecture is readily incorporated onto plug-in cards so that it can be integrated into a common housing with the other spacecraft electronics. The first flight of a deep space transceiver-based communication system will occur on CONTOUR in 2002. We have advanced this work under the NASA ATD program and have developed a breadboard X-band receiver that draws an average power of less than 1.5 W. This is significantly lower than the power consumption of current and planned X-band receivers (see table). The ATD receiver is a potential enabling technology that can provide low-power interplanetary communications by 2004-2005.

Deep Space Transponder Systems		($X/X/K_a$-Band)	
Program	**Launch**	**Mass (g)**	**Rcvr Power (W)**
NEAR	1996	5200	7.7
Deep Space 1	1998	3100	11
Space Transponding Modem (JPL)	2004 (est.)	1500 (est. from critical des. review)	10.8
Deep Space Transceiver Systems*		**(X/X-Band)**	
Program	**Launch**	**Mass (g)**	**Rcvr Power (W)**
CONTOUR	2002	1440	8.5
ATD Transceiver (APL)	2004-2005 (est.)	430 (est.)	1.5 (breadboard)
"Transceiver-on-a-Chip"	2015 (est.)	200 (est.)	≤ 0.5 (est.)
*Plug-in card architecture. Excludes shared resources such as crystal oscillator, power converter, and chassis.			

Solid State Power Amplifiers: Solid state power amplifiers continue to be in high demand for deep space missions due to their relatively low cost and small size relative to traveling wave tube amplifiers. Through our work at X-band on the MESSENGER program and K_a-band on the ATD program, APL has developed a center of expertise in solid state power amplifier (SSPA) design. We have created a long-term plan designed to advance the efficiency of K_a-band power amplifiers through an emphasis on advanced materials and advanced matching techniques. This enabling technology will benefit future power and mass-limited outer planet missions.

JUPITER: ATMOSPHERIC SOUNDING AND SENSING OF THE INTERIOR (JASSI). S. J. Bolton[1], T. Owen[2], D. Gautier[3], S. Gulkis[1], M. Janssen[1], S. Atreya[4], T. Guillot[5], J. Anderson[6], M. Allison[7], and J. Lunine[8], [1]JPL(scott.j.bolton@jpl.nasa.gov), [2]U.Hawaii, [3]Obs. Paris, [4]U.Michigan,[5]Obs.Coted'Azur,[6]GISS/NASA, [7]U.Arizona.

Introduction: The formation of the giant planets is one of the most fundamental questions in solar system exploration. Understanding the process that led to the creation of Jupiter is essential to understanding the nature of the primordial solar nebula, and the formation of our solar system and others currently being discovered. Data from Galileo combined with HST and Ulysses results validated our basic understanding of Jupiter as a giant planet whose gaseous envelope consists of solar nebula gas enriched in elements heavier than He by infalling icy planetesimals [1]. However, the current Galileo Probe data set does not itself allow firm conclusions about the original planetesimal composition or the process of giant planet formation - we crucially need the O and N abundances that Galileo could not determine (Fig 1). We propose a new and simple concept capable of determining these abundance in Jupiter plus substantial gravity science.

Mission Description: The concept utilizes a close polar flyby using a solar powered spacecraft to measure the microwave brightness temperature of Jupiter's atmosphere at multiple radio frequencies, corresponding to multiple depths ranging from <1 bar to > 500 bars. Because the measurements are related explicitly to the opacity and temperature profile of the atmosphere, the retrieval of the water (oxygen) and ammonia (nitrogen) abundance is straightforward. In addition, Doppler measurements during the flyby define Jupiter's gravitational moments with sufficient accuracy to determine the properties of Jupiter's internal structure.

The broader scope and resources associated with the Outer Planets program (relative to Discovery) may allow us to extend the mission concept to include both Jupiter and Saturn (and possibly Uranus and Neptune). A single spacecraft could conduct a comparative study of the outer planet atmospheres addressing formation questions as well. A brief JPL study identified a number of launch date opportunities during the next two decades for a Jupiter-Saturn mission using a ballistic trajectory with flight times between 4-8 years.

Science Goals and Objectives: The chemical inventories of the deep atmospheres of the giant planets contain key evidence regarding the nature of the protoplanetary disk and how planetary systems form and evolve. The amounts of water and ammonia in Jupiter are essential to interpreting the atmospheric abundances in terms of the primordial reservoirs. Based on heavy element abundances returned by the Galileo Probe, scientists have developed a number of Jupiter formation theories [2,3]. The proposed theories differ in the source, role and composition of icy planetesimals, as well as the temperature and location of Jupiter's formation. The O and N abundances are a primary discriminator among the theories [4,5,6]. The data obtained by this mission will answer the following questions:

- How, where & what temperature did Jupiter form?
- What was the composition and proportion of icy planetesimals that formed Jupiter?
- What is total mass of heavy elements in Jupiter?
- Does Jupiter have a solid core? (of what size?)
- Does Jupiter contain a radiative zone?
- What is the internal structure of Jupiter?

Significance of the Science: This mission concept addresses the major science goals of the COMPLEX Report, an Integrated Strategy for the Planetary Sciences 1995-2010, and the Origins Roadmap. These goals are; (1) how planetary systems originate and evolve, (2) how physical and chemical processes determine the characteristics of the planets; and (3) how the basic laws of physics and chemistry lead to diverse phenomena in complex systems.

References: [1] Mahaffy et al. (1998) *Space Sci. Rev., 84,* 251. [2] Owen et al. (1999) *Nature, 402,* 269. [3] Mahaffy et al. (2000).*JGR, 105,* 15061. [4] Owen, T. and Bar Nun, A. (1995), *Icarus, 116*, 215. [5] Drouart et al. (1999), *Icarus, 140*, 155. [6] Lunine et al, (1991), *Plan. Sp. Sci. 46,* 1099.

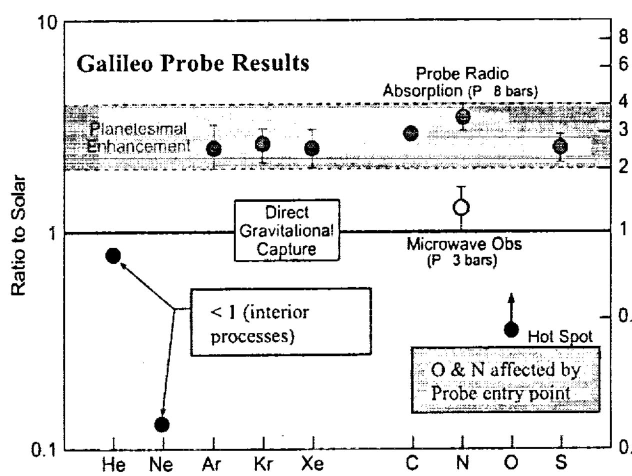

Figure 1. Galileo probe data showing the measured elemental ratios (to H) in Jupiter's atmosphere compared to solar values. O is important as the carrier of the heavy elements. N constrains the formation temperature of the icy planetesimals. Together these two abundances hold the key to how the solar system was formed.

Nuclear Thermal Rocket (NTR) Propulsion and Power Systems for Outer Planetary Exploration Missions.
Stanley K. Borowski and Robert L. Cataldo, Space Transportation and Power Projects Offices, NASA Glenn Research Center, Cleveland Ohio, 44135

Abstract: The high specific impulse (Isp) and engine thrust generated using liquid hydrogen (LH_2)-cooled NTR propulsion makes them attractive for upper stage applications for difficult robotic science missions to the outer planets. Besides high Isp and thrust, NTR engines can also be designed for "bimodal" operation allowing substantial amounts of electrical power (10's of kW_e) to be generated for onboard spacecraft systems and high data rate communications with Earth during the course of the mission. Two possible options for using the NTR are examined here. A high performance injection stage utilizing a single 15 klbf thrust engine can inject large payloads to the outer planets using a 20 t-class launch vehicle when operated in an "expendable mode". A smaller bimodal NTR stage generating ~1 klbf of thrust and 20 to 40 kWe for electric propulsion can deliver ~100 kg using lower cost launch vehicles.

Results: Small NTR engines (with thrust levels <15 klbf) can be used individually or in clusters for a variety of applications ranging from robotic science missions to human exploration missions to the Moon, Mars and near Earth asteroids. Using a single Titan IV or Delta IV-H launch vehicle with a 20 t payload capability, an expendable NTR upper stage can inject two Pluto "Fast Flyby" spacecraft (combined mass over 500 kg) on high energy, short transit time (~6.5 - 9.2 year) direct trajectories to Pluto. A 15 klbf NTR engine, using uranium-zirconium-niobium "ternary carbide" fuel, would have an engine thrust-to-weight ratio of ~3.1 providing a Isp of ~960 seconds with a hydrogen exhaust temperature of ~3025 K. A "standardized" NTR injection stage using the same engine and 20 t launch vehicle can enable yearly "direct flight" orbiter missions to Saturn, Uranus and Neptune with transit times of 2.3, 6.6 and 12.6 years, respectively. Injected mass includes a small storable N_2O_4/MMH capture stage (Isp~330 seconds) and orbiter payloads 340 to 820% larger than that achievable using a LOX/LH_2-fueled injection stage. Figure 1 and Table 1 shows the features and mass properties for a Neptune orbiter mission. The 15 klbf NTR shown here is configured as a "bimodal" engine capable of also producing ~10 kilowatts of electrical power (kW_e) during the coast phase of the mission. A small bimodal NTR vehicle providing ~1000 lbf of thrust for Earth departure and ~20 to 40 kW_e for powering xenon ion thrusters during the interplanetary transfer has also been studied. Launched on a lower cost Atlas III, this "hybrid" stage is capable of delivering ~100 kg of payload mass to Pluto orbit in ~17 years using a direct trajectory.

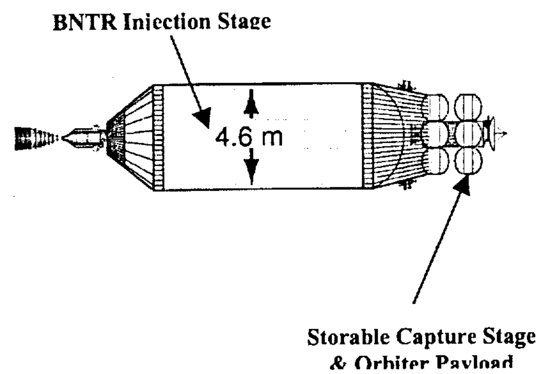

Figure 1. Bimodal NTR Neptune Orbiter Mission Vehicle Configuration

Total Mass (kg)		20,000
15 klb_f NTR	2225	
10 kW_e Brayton	210	
"Dry" Injection Stage	2240	
LH_2 Propellant	13050	
		17,725
"Dry" Capture Stage	110	
(8% Stage MF/ Isp ~330 s)		
Storable Prop (N_2O_4/ MMH)	1270	
Orbiter Payload*	895	
	2,275	

TABLE 1. Mission Mass Breakdown for Bimodal NTR Neptune Orbiter Mission

References: (1) S.K. Borowski, "Robotic Planetary Science Missions Enabled with Small NTR Engine/Stage Technologies", 12th Symposium on Space Nuclear Power and Propulsion, Albuquerque, NM, Jan. 8-12, 1995 and NASA TM--107094.
(2) J.P. Riehl, S.K. Borowski and L.A. Dudzinski, "Application of a Small Nuclear Thermal/Electric Bimodal Vehicle for Planetary Exploration", 34th Joint Propulsion Conference Paper, AIAA 98-3882, July 13-15, 1998.

ELECTRICALLY ISOLATING SUBSYSTEMS IN SOAC TECHNOLOGIES. R. M. Boyd[1], W. B. Kuhn[1], M. M. Mojarradi[2], and E. A. Shumaker[1], [1]Kansas State University, wkuhn@ksu.edu, [2]Center for Integrated Space Microsystems, Jet Propulsion Laboratory, California Institute of Technology, Mohammad.M.Mojarradi@jpl.nasa.gov.

Introduction: Integrated circuit fabrication technology has evolved to the point that it is possible to construct complete systems, including power, data processing, and communications, on a single chip. Such System-on-a-chip (SOAC) technologies can enable drastic reductions in spacecraft size and weight, lowering the cost of missions and presenting new mission opportunities. This paper overviews some key enabling technologies unique to the needs of spacecraft for outer-planet exploration and missions requiring extreme resistance to radiation such as Europa orbiters and Europa Landers. The work is being carried out by Kansas State University (KSU) under direction of the Center for Integrated Space Microsystems (CISM) at NASA's Jet Propulsion Laboratory.

Electrical Isolation using SOI Technologies: Missions such as the Europa Lander must withstand extreme radiation environments, demanding the use of hardened IC technologies. Silicon-on-Insulator (SOI) CMOS provides good hardness while permitting circuit densities compatible with SOAC design. In addition, SOI offers the unique opportunity to build spacecraft subsystems that are electrically isolated from one another. Since circuits are insulated from the underlying mechanical support structure (substrate), there is no need for a chip-wide common ground as there is in traditional CMOS design. Such isolation is essential in many system designs, including the IEEE 1394 data bus being adopted in X2000 spacecraft.

IEEE standard 1394 defines a high-speed (100 to 400 Mb/s) serial 6-wire bus and an associated parallel backplane bus operating at 12.5 to 50 MB/s. Included in the standard is a power/ground isolation boundary between systems communicating over the parallel bus. This isolation allows connected subsystems with power or ground potential differences and/or noise problems to pass bi-directional data at the full bus speed. The standard provides a suggested method of implementation utilizing transformers and associated driver/receiver circuits. Unfortunately, the physical size, weight, and power consumption implied by this solution is incompatible with the goals of SOAC technologies.

Beginning in the summer of 1999, CISM initiated a research program with KSU's department of Electrical and Computer Engineering to design a fully-integrated solution to the IEEE 1394 isolation requirement. A block diagram of the isolator circuits currently under development is shown in Figure 1. This design provides isolation by transmitting data across a transformer interface, as in the 1394 standard, but uses radio technology to allow significantly smaller transformers to be used. The data is modulated onto a high-frequency carrier, up-converting the spectrum from baseband to approximately 1 GHz. On-chip transformers measuring approximately 200x200 microns square then pass this RF signal across the boundary where it is demodulated and converted back to standard digital levels. The complete system is simple and robust, providing an effective solution that meets all 1394 requirements. Key circuits, including the required transformers have been prototyped in Honeywell's RICMOS IV 0.8um SOI process and are currently in test. A revised design targeting Honeywell RICMOS V (0.35um SOI) is also under development.

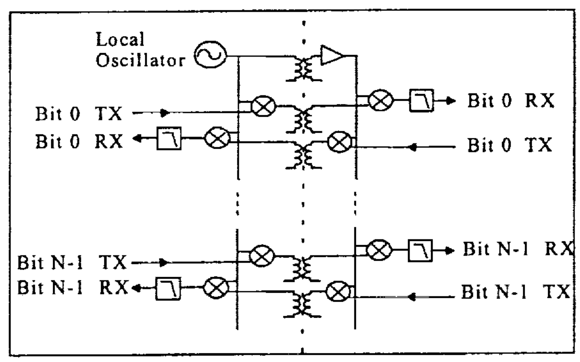

Figure 1. Block diagram of isolator circuits.

Conclusions: The integrated electrical isolation technique under development substantially outperforms all alternatives considered. It is faster and lower power than both traditional (non-integrated) electro-optic methods and recent MEMs based products [1]. Using 0.35um SOI, the design will operate at 2 GHz, consume approximately 15 mA total power (for 12 bi-directional channels), and occupy $1mm^2$ of die area. Electrical breakdown is expected to exceed 50V, while noise immunity should exceed 10V/ns. Full-scale prototyping is scheduled to be completed in the 2002 to 2003 timeframe.

Acknowledgements: The research described in this paper was performed at the Center for Integrated Space Microsystems, Jet Propulsion Lab, California Institute of Technology, and was sponsored by the National Aeronoutics and Space Administration.

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INTEGRATION OF PASSIVE COMPONENTS FOR SPACECRAFT AVIONICS. E.J. Brandon[1], E. Wesseling[1], V. White[1], U. Lieneweg[1], M. Mojarradi[1], R. Ulrich[2], M. Wascf[2] and A. Mantooth[2], [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, erik.j.brandon@jpl.nasa.gov, [2] University of Arkansas, Fayetteville, AR 72701.

Introduction: The NASA roadmap outlining future deep space missions to Europa and other outer planetary destinations calls for continued reductions in the mass and volume of the spacecraft avionics [1]. Spacecraft power electronics, including the power switches and converters, remain difficult to miniaturize due to the need for large numbers of discrete passive components such as resistors, capacitors, inductors and transformers.

As part of the System-on-a-chip program at the Center for Integrated Space Microsystems and at the University of Arkansas, we are working to develop integrated or embedded passive components geared specifically for use in power management and distribution (PMAD) in future avionics over the next five to ten years. This will not only enable a scaling down of the power subsystems, but will make possible new architectures such as "distributed" PMAD.

Resistors and Capacitors: Surface mount resistors and capacitors are used for a wide range of applications including current sensing, decoupling, filtering, and energy storage. We are investigating a variety of materials and integration options to replace these discrete components with thin film passives which are integrated with the interconnect substrate, the packaging or even the silicon die [2]. For maximum compatibility with heat sensitive substrates, low temperature processes are used. Resistors are deposited and patterned from sputtered Cr-Si films or screen-printed inks and thick films. Anodized tantalum oxide is used as a dielectric for thin film capacitors. These capacitors can even be used to construct efficient, on-chip charge pumps (Figure 1). Challenges include developing resistors rated for high power handling and capacitors that can handle relatively large transient voltages of 100 V or more.

Inductors: The miniaturization of DC-DC converters presents a particular challenge due to the need for numerous magnetic-based passive components such as inductors and transformers. Inductors play an integral role in converters, serving as both energy storage and filtering elements. As DC-DC converters move to higher operating frequencies and as the output voltages migrate to lower levels, smaller inductive elements can be implemented.

Planar inductors can be fabricated on various substrates, including directly on a silicon die next to active devices, by using a metal spiral patterned from one or more of the metallization layers. These inductors are typically used in microwave applications at frequencies of 1 GHz or higher. These spirals are unsuitable for power converters, however, that usually operate in the 250 kHz to 1 MHz range.

Higher value "microinductors" that can operate at lower frequencies may be fabricated using standard microelectronic fabrication techniques. To enhance performance, magnetic films are deposited above and below the spiral plane. Since the ferrite materials which are used in conventional power magnetics require high temperature processing, electroplated ferromagnetic films are used (Figure 2).

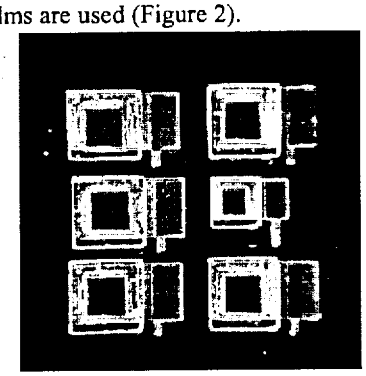

Figure 1. Anodized tantalum oxide on a silicon substrate.

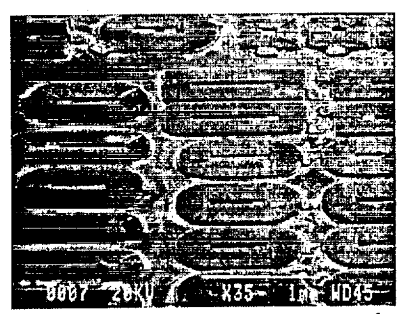

Figure 2. An array of microinductors on a glass substrate.

Acknowledgement: The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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LASER TOF-MS FOR *IN SITU* ANALYSIS OF OUTER PLANETARY MOONS AND SMALL BODIES.

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Introduction: The in-depth exploration of the moons and small bodies of the outer solar system represents an enormously exciting and challenging long-term vision for planetary science. Such missions will require increasingly sophisticated and miniaturized robotic analytical tools for *in situ* sampling and composition studies [1]. Surface and subsurface rock, ice, and fine samples will be accessed and studied on a range of spatial scales. Microscopy, mineralogy, and molecular/organic, elemental, and isotopic analyses are all needed to address *in situ* goals. These techniques must work as an efficient suite to provide complementary and cross-calibrated data. Toward such a suite, we are developing miniature time-of-flight mass spectrometers (TOF-MS) for microanalysis of minimally-prepared samples. An adjustable-energy pulsed laser volatilizes and ionizes material from a small region on the sample. Ions enter the instrument and are detected at a sequence of times proportional to the square root of their mass-to-charge ratios. Thus, each laser pulse produces a complete mass spectrum (in less than 50 μs). These instruments can now be significantly miniaturized while maintaining high performance.

Laser TOF-MS Instruments: Prototypes at JHU/APL include the following features pertinent to *in situ* analysis:

1. The laser spot diameter is adjustable between 10 μm and 500 μm, for nested microprobing.
2. Sample preparation is usually not required.
3. A micro-imager with a few-mm FOV permits the preselection of the laser analysis position.
4. Repeated laser pulses provide a layer-by-layer analysis (and can access unweathered material).
5. TOF-MS has an unbounded mass range: elements through large organic molecules (10^2 - 10^5 amu).
6. Detection limits are 0.1-10 ppm for most elements.
7. Mass resolution up to 1000 (FWHM) is achieved.
8. Precision of rock-forming abundance ratios, such as Mg:Si, Al:Si, Mg*, (Na+K):Si, Fe:Si, and Fe:Mn, is sufficient to distinguish general classes.
9. Isotope ratios are < 3% RSD for many elements.
10. Organic molecules may be analyzed with a range of samples and inlet systems, including use of direct and matrix assisted laser desorption methods
11. Mass (< 2 kg) and power (few W peak) are low enough for multiple deployment scenarios.

Laser Ablation TOF-MS: Work with a laser ablation mass spectrometer (LAMS) [2] has shown that elemental and isotopic analyses of rocks, ice, and fines can be obtained with a Nd:YAG laser focused to 10^9 W cm^{-2}, in a TOF-MS less than 20 cm in length. Such high irradiance produces a large flux of prompt atomic ions (and essentially no molecules). Precision of Mg, Al, S, Ca, and Fe ratios to Si permitted differentiation between chondrite classes [3]. On an airless body, no sample contact is required.

Laser Desorption TOF-MS: While LAMS is particularly useful for bulk and microprobe elemental analysis with minimal fractionation, and for depth profiling, the lower-irradiance regime termed laser desorption (LD) is ideal for organic/molecular analysis and some isotope and trace element studies. Prototype miniature LD TOF-MS instruments at JHU/APL can detect organic species of hundreds to thousands of amu with high mass resolutions (> 1000 FWHM).

Combined LA/LD on a Europa Lander: A new prototype TOF-MS at JHU/APL combines LA and LD in one instrument (Fig. 1). This is an important direction for extremely-constrained missions such as a Europa lander. Using a simple, coaxial geometry and novel, monolithic reflectron designs [4], this TOF-MS may be able to correlate elemental and organic/molecular composition in sequences of spectra from a co-imaged field of view (Fig. 2).

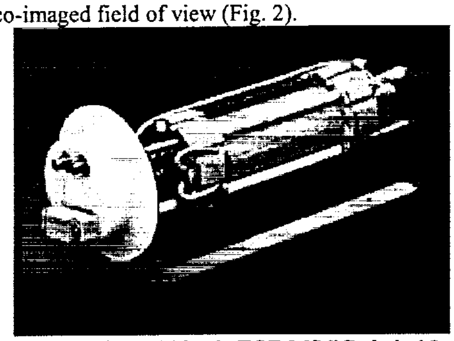

Figure 1 JHU/APL "Plastic TOF-MS." Rule is 15 cm.

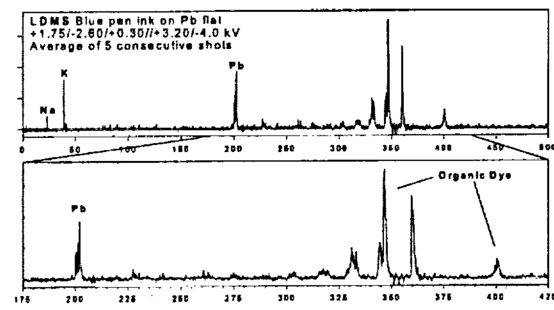

Figure 2 LD TOF-MS data showing simultaneous detection of elemental (Pb) and organic (ink) composition.

The laser probe could directly remove and ionize particles from the Europa surface. TOF-MS would thus perform a rapid chemical assay of selected surface materials, addressing issues such as the makeup of ice and the chemical identity of S-bearing phases. Significantly, with minor tuning, this same instrument could then focus on detecting higher mass organics in samples chosen for intensive study.

The authors wish to thank S. Ecelberger, P. Mahaffy, and L. Prockter. Support was provided in part by NASA PIDDP Grant #NAG5-4548. [1] Meyer C. et al., eds. (1996) *Planetary Surface Instruments Workshop,* LPI Tech. Rpt. 95-05. [2] Brinckerhoff W. et al. (2000) *Rev. Sci. Instrum., 71,* 536. [3] Brinckerhoff W. et al. (1998) *LPS XXIX,* 1789; [4] Cornish T. et al. (2000) *Rapid Commun. Mass Spectrom., 14,* 2408.

TECHNOLOGIES FOR ICY BODIES' ACCESS, OPERATIONS AND SCIENCE. F. D. Carsey [1], F. S. Anderson[2], L. C. French[3], J. R. Green[4], J. A. Jones[5], A. L. Lane [6], P. C. Leger[7], and W. F. Zimmerman[8], Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA 91109 (1: fcarsey@jpl.nasa.gov; 2: Fletcher.S.Anderson@jpl.nasa.gov; 3: lloyd.c.french@jpl.nasa.gov; 4: Jacklyn.R.Green@jpl.nasa.gov; 5:jack.a.jones@jpl.nasa.gov; 6: Arthur.L.Lane@jpl.nasa.gov; 7: Patrick.C.Leger@jpl.nasa.gov 8: wayne.f.zimmerman@jpl.nasa.gov)

Introduction: Recent events in planetary exploration have profoundly changed the way both space scientists and the public regard the solar system and our place in it. These events include the Galileo data suggesting subsurface oceans in the Jovian system (1), ever stronger suggestions of near-surface water on Mars, as well as the complex structure observed for the Mars polar caps. And, of course, interest in icy cometary bodies is as old as humankind. Finally, the Mars north polar cap may conceivably cover and protect an ancient ocean floor, an obvious candidate ancient or extant habitat.

In short, our interest in searching for life embraced early on the search for liquid water, and that has led us to an additional appreciation for water ice as both a commonplace partner with liquid water and as an issue to be addressed in the exploration of a host of interesting sites. In general, the spectrum of specialized technology for space exploration has not yet been broadened to include the requirements brought about by exploration of icy sites. We argue that technologies for access, operations, and science in icy solar-system sites must be examined and their prioritized development initiated in order to successfully plan missions to these compelling sites over the next two decades.

Ice and Water: While our Earth experience leads us to focus on bulk surface water as the expected form, it is clear that it is rare; new results even suggest that in Earth's deep past there were episodes of a fully ice-covered or "Snowball" Earth. Liquid water is found in at least three other situations: Beneath an ice roof, interstitially in warm ice, and as ground-water (including interstitially in ground ice). Interstitial liquid water (2) is especially interesting. During ice growth this liquid is at saturation, and consequently not particularly attractive as microbial habitat, but it is a useful concentrator of material held in an ice mass; that is, it is a likely place to look for nutrients and therefore exobiological lifeforms may have inhabited the neighborhood.

Access: Exploration of many sites of present day or ancient liquid water involve moving through, and analyzing composition of, water ice. The ice can be present in significant amount; on Europa. Stevenson (1) has pointed out that an ice cover thinner (or even thicker) than 30 km is energetically unlikely. Even on Mars the polar cap thickness is several kilometers. Other ice sites are even less friendly; we note that comets are thought to be balls of violently sublimating, dirty ice. Clearly, access to icy surface and subsurface sites involve significant technology development as well as insight into the nature of the place.

Operations: Once we have achieved access to a site, we want to perform operations: move about, determine our location, communicate and exercise control, take scientific data, and look after the health of the exploration vehicle. On Europa, each of these simple needs is a significant challenge. It is interesting to note that scientific and operational autonomy are debated as to need for solar system exploration in general, but they are essential to a trip to the Europa Ocean, because of all that ice among other reasons.

Planetary Protection: Working without contamination is obviously essential in all life-detection explorations. In an icy environment, this requirement will profoundly impact vehicle fabrication.

Science: Taking data in or on an ice cap will bring special constraints to in-situ science. The issues for consideration include pressure, structure and chemistry in the deep subsurface, radiation on the surface, documentation of context and sample handing.

Testing Needs and Opportunities: Development of technologies for planetary ice explorations require testing to an extreme degree, especially for devices under consideration for deployment to the Outer Planets.

A Cryofacility, collaborative among technology developers and scientists, is a desired testbed tool to enable technology developers to test concepts, validate processes and verify performance parameters. A Cryofacility would provide resources to develop multi-variable ices in density, contaminants, and temperature. This would assist in designing insitu instrument robustness, sample handling and return, and instrument validation and verification. Currently, this facility does not exist, and without it, mission planning to these remote sites will be at an impasse.

At the same time, ice on Earth can supply excellent sites for this testing, and, in many cases, the technology being developed will have application in Earth science such that the testing situations involve interesting Earth science sites. We note an interesting example, that of the study of subglacial lakes, that has recently become an Earth science priority (3) and requires many technologies of planetary ice missions.

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COMPACT HOLOGRAPHIC DATA STORAGE. T. H. Chao[1], G. F. Reyes[2], and Hanying Zhou[3], [1]Jet Propulsion Laboratory, M/S 303-300, 4800 Oak Grove Drive, CA 91109, Tien-Hsin.Chao@jpl.nasa.gov, [2]Jet Propulsion Laboratory, M/S 303-300, 4800 Oak Grove Drive, CA 91109, George.A.Reyes@jpl.nasa.gov, [3]Jet Propulsion Laboratory, M/S 303-300, 4800 Oak Grove Drive, CA 91109, Hanying.Zhou@jpl.nasa.gov

Introduction: NASA's future missions would require massive high-speed onboard data storage capability to Space Science missions. For Space Science, such as the Europa Lander mission, the onboard data storage requirements would be focused on maximizing the spacecraft's ability to survive fault conditions (i.e. no loss in stored science data when spacecraft enters the "safe mode") and autonomously recover from them during NASA's long-life and deep space missions. This would require the development of non-volatile memory. In order to survive in the stringent environment during space exploration missions, onboard memory requirements would also include: survive a high radiation environment (1 Mrad), operate effectively and efficiently for a very long time (10 years), and sustain at least a billion (10^9) write cycles. Therefore, memory technologies requirements of NASA's Earth Science and Space Science missions are: large capacity, non-volatility, high-transfer rate, high radiation resistance, high storage density, and high power efficiency. JPL, under current sponsorship from NASA Space Science and Earth Science Programs, is developing a high-density, nonvolatile and rad-hard Compact Holographic Data Storage (CHDS) system to enable large-capacity, high-speed, low power consumption, and read/write of data in a space environment. The entire read/write operation will be controlled with electro-optic mechanism without any moving parts. This CHDS will consist of laser diodes, photorefractive crystal, spatial light modulator, photodetector array, and I/O electronic interface. In operation, pages of information would be recorded and retrieved with random access and high-speed. The nonvolatile, rad-hard characteristics of the holographic memory will provide a revolutionary memory technology meeting the high radiation challenge facing the Europa Lander mission.

CHDS System Architecture And Recent Progress: The CHDS architecture, under development at JPL, as shown in Figure 1, consists of a writing module for multiple holograms recording and a readout module for hologram readout. The writing module include a laser diode as the coherent light source, a pair of cascaded beam steering Spatial Light Modulators (BSSLM), one transmissive and one reflective in each pair, for angular multiplexed beam steering, an input SLM for electronic-to-optical data conversion and a photorefractive crystal for hologram recording and storage. The readout module includes a laser diode with the same wavelength as the writing one, a pair of cascaded BSSLMs to generate phase conjugated readout beam (i.e. the readout beam is directed in opposite direction of that of the writing beam and a photodetector array for recording the readout holograms. The system uses angle multiplexing scheme to store multiple holograms and phase-conjugated beams to readout each hologram.

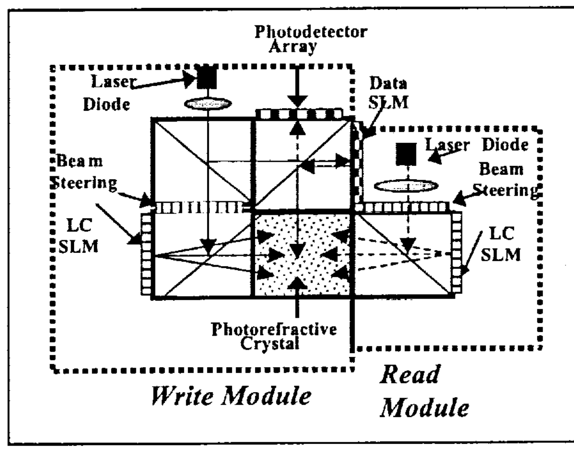

Figure 1. System schematic architecture of Compact Holographic Data Storage System.

In this paper, recent technology progress in developing this CHDS at JPL is will be presented. The potential future application of this rad-hard, nonvolatile memory technology to NASA's future space science mission such as the Europa Lander will also be discussed.

References

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CHALLENGING TECHNOLOGY, AND TECHNOLOGY INFUSION INTO 21ST CENTURY

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Introduction: In preparing for the space exploration challenges of the next century, the National Aeronautics and Space Administration (NASA) Center for Integrated Space Micro-Systems (CISM) is chartered to develop advanced spacecraft systems that can be adapted for a large spectrum of future space missions. Enabling this task are revolutions in the miniaturization of electrical, mechanical and computational functions. On the other hand, these revolutionary technologies usually have much lower readiness levels than those required by flight projects. The mission of the Advanced Micro Spacecraft (AMS) task in CISM is to bridge the readiness gap between advanced technologies and flight projects.

Objectives and Approach: One of the key objectives of the AMS as a focused technology development program is to infuse technologies into target missions under NASA's mission themes. In order to ensure a gradual and smooth transition of technologies from research and development environment to flight project environment, the AMS will develop two stages of testbeds to facilitate the technology infusion: the Proof-of Concept Testbed and the Engineering Testbed. These testbeds are developed by the Advanced System Development Team (ASDT) and the Advanced System Infusion Team (ASIT), respectively, under the AMS task [1].

The Proof-of Concept (POC) Testbed has flexible configuration and uses prototype flight software to create a realistic system environment to validate the advanced technologies. The POC Testbed can also be used to perform experiments for advanced system architecture concepts.

The Engineering Testbed will merge POC technologies to technology readiness level 6 hardware or qualifiable system hardware that meets the form factor, thermal, power and other requirements of flight projects. As part of CISM's commitment to technology infusion, a major focus of ASIT is to understand mission needs verses technology capabilities and implementation trade-off studies for the flight projects.

Moreover, it should be mentioned that the technology infusion process is not merely a reactive response to mission requirements. Innovations are used throughout the process to fuel the advancement of the state-of-the-art of avionics systems.

The technology infusion process is depicted in Figure 1, and the interfaces between the elements in this process are explained in the following sections.

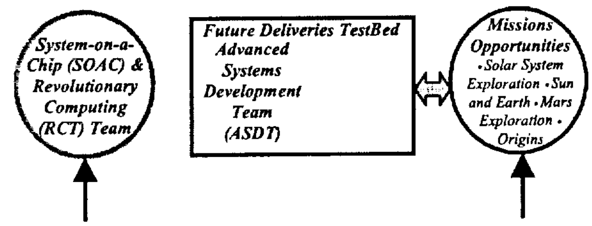

Figure 1

SOAC/RCT and ASDT Interface: The System-on-a-chip (SOAC) and the Revolutionary Computing Technology (RCT) Teams are two other elements in CISM that develops advanced technologies. These two teams provide technology products that are compliant with the POC Testbed interfaces to the ASDT. The ASDT then validates these technologies within the POC Testbed.

ASDT and ASIT Interface: The ASDT provides POC validated system technologies to the ASIT. The ASIT synthesizes a mechanical / packaging system consistent with a candidate mission's system wide architecture. Additionally provides a platform for complete environmental testing and develops a test infrastructure to support the new technologies. Both teams' work interactively together to performing trade-off studies and implementation approaches that best meet mission needs and requirements.

ASIT and Flight Project Interface: The ASIT encourages user interactive participation to solve design challenges in a system environment. The goal is to provide a user based Testbed. Focus on mission needs and requirements by providing Product Specification documents and tools for bench marking and validation.

Conclusion: Technology infusion into flight missions has always been a difficult problem. To capitalize on NASA's technology investment it is believed that the process outlined in this paper will improve the technology infusion into flight missions for NASA.

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Acknowledgement: The research described in this paper was performed at the Center for Integrated Space Microsystems, Jet Propulsion Lab, California Institute of Technology .

A MULTI-MISSION TESTBED FOR ADVANCED TECHNOLOGIES. S. N. Chau[1] and M. Lang[2], [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, Ca 91109 [2]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, Ca 91109

Introduction: The mission of the *Center for Space Integrated Microsystem (CSIM)* at the Jet Propulsion Laboratory is to develop advanced avionics systems for future deep space missions. The Advanced Micro Spacecraft (AMS) task is building a multi-mission testbed facility to enable the infusion of CISM technologies into future missions. The testbed facility will also perform experimentation for advanced avionics technologies and architectures to meet challenging power, performance, mass, volume, reliability and fault tolerance of future missions. The testbed facility has two levels of testbeds: a *Proof-of-Concept (POC) Testbed* and an *Engineering Model Testbed*. The methodology of the testbed development and the process of technology infusion are presented in a separate paper in this conference. This paper focuses only on the design, implementation, and application of the *POC testbed*.

Testbed Design: In order to be used by multiple missions, the *POC Testbed* has to accommodate various advanced technologies and perform a wide range of architecture experiments. Therefore, flexibility is the primary concern in the design of the testbed. In order to maximize scalability, reconfigurability, and technology compatibility, the *POC Testbed* adopts a variety of commercial standard interfaces. Some of the standard interfaces are actually used in flight projects.

The initial configuration of the *POC Testbed* is based on the scalable, fault-tolerant, and distributed architecture developed by the X2000 project [1]. The architecture consists of a network of computing nodes and controllers that are connected by two redundant sets of buses; each set consists of an IEEE 1394 bus and an I^2C bus. Both of the buses are widely accepted industrial standards. When a node or bus media failure occurs, one of the redundant bus set can continue to operate while the failed bus set diagnoses and reconfigures itself. The bus architecture is designed to tolerate multiple faults.

In addition, each computing node has a Peripheral Component Interface (PCI) backplane bus that can accommodate a wide range of peripherals including other bus interfaces such as the 1553B or Ethernet. The PCI bus allows the IEEE 1394 or I^2C to be easily replaced by more advanced buses in the future.

The testbed can integrate with other advanced technologies developed by *CISM* through the standard interfaces. For example, a micro sensor can choose to use the IEEE 1394, I^2C, PCI, or any other available buses to interface with the testbed. The standard interfaces also enable the testbed to be configured into a variety of architectures to suit the needs of different flight missions.

Testbed Implementation: The current testbed has a network of five computing nodes, connected by two redundant sets of IEEE 1394 and I^2C buses [2]. The size of the testbed is chosen so that it can demonstrate interesting fault tolerance test cases. However, there is no restriction on the number of nodes in the testbed.

Physically, each computing node is a Compact PCI chassis housing two PowerPC 750 processors. One of the processors is the main processor of the node, while the other is used to simulate sensors, actuators, or other on-board instruments. Hence, experimentation of a flight system can proceed even if some of the hardware are not yet available. The PowerPC 750 processors also have UART ports and Ethernet. These standard interfaces enhance the flexibility of the testbed.

The testbed is supported by several testing and software development tools. This includes analyzers for the IEEE 1394, I2C, and PCI buses, and three Unix workstations. All the support equipment are connected to the testbed via the Ethernet. The implementation of the testbed is depicted in Figure 1. The implementation is expected to be completed by Spring 2001.

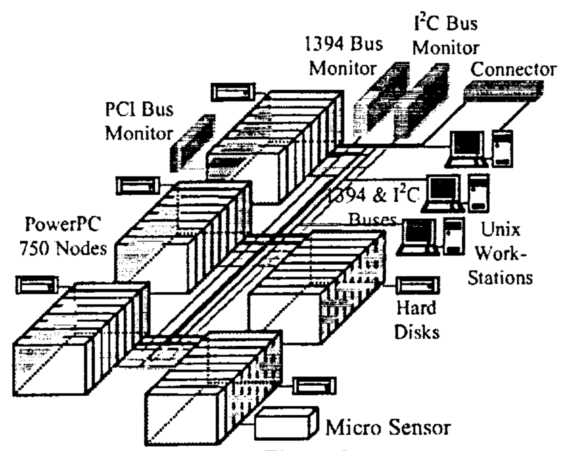

Figure 1

Testbed Application: The *POC Testbed* would be used to verify avionics systems for Europa Lander, Titan Explorer, Comet Nuclear Sample Return, and many other deep space missions.

References:

[1] S. Chau, L. Alkalai, A. Tai, and J. Burt, 351-359.
[2] S. Chau and Don Hunter, *X2000 Future Deliveries FY'01 Task Plan, JPL Internal Document.*

Acknowledgement: The research described in this paper was performed at the Center for Integrated Space Microsystems, Jet Propulsion Lab, California Institute of Technology, and was sponsored by the National Aeronoutics and Space Administration.

Jovian Moon Sampler. Benton C. Clark, Robert T. Gamber; Brian Sutter, Cynthia Faulconer.

Recently, a lot of interest has been focused on Europa and Ganymede due the evidence of subsurface water oceans. Unique methods of exploring the Jovian moons have been developed that allow sampling of the lunar surfaces. These methods include low cost concepts to collect a surface sample and return it to Earth using concepts similar to the Stardust Discovery mission.

The spacecraft can be placed on a ballistic trajectory that will carry it close to the surface of the moons of Jupiter. High resolution imaging of the surface can be collected during the approach phase. Small projectiles can be released and used to kick up a plume of surface material. Unique collectors can capture material from this plume as the spacecraft flies over the surface and through the plume of small particles. The spacecraft is protected from damage by shields. This material can then be retracted into a small Sample Return Capsule, SRC, similar to the Stardust capsule. Aerogel and other absorbant materials are used as the collecting medium. A ballistic return to Earth allows for tracking and capture of the capsule at Earth and return to the Utah Test and Training range.

Small hard-landing capsules can be dropped to the surface of the moons during the low flyby by using a retro rocket to slow the capsules. These small landers can also collect critical data on the surface composition and relay it to the flyby spacecraft.

MINIATURIZED, LOW-POWER LASER ALTIMETER (MLLA). Timothy D. Cole[1], R. A. Reiter, N. P. Paschalidis, A. F. Cheng, and D. Domingue, The Johns Hopkins University Applied Physics Laboratory, [1]tim.cole@jhuapl.edu.

Introduction: High accuracy measurements of surface elevations, slopes, and roughness from laser altimeters are primary datasets for geophysical and geological studies of planetary bodies. Surface elevations together with gravity measurements allow us to probe the internal structures (e.g., crustal thicknesses and density variations). These measurements can be used to relate crustal structures with the volcanic plumes on Triton, or with flexure due to a subsurface ocean as hypothesized on Europa. In addition, high-resolution measurements of surface topography reveal detailed geologic processes shaping the surface. To obtain these data, a miniaturized, low-power laser altimeter will be developed to provide high spatial and temporal resolution altimetry from an orbiting platform. The capability of this altimeter design, denoted MLLA, will lend itself to exploration of the outer planets by incorporating recent efforts to reduce both mass and power consumption of laser altimeters while enhancing measurement capability. In particular, to satisfy mission design requirements for the exploration of exceedingly distant objects from the sun, mass and power become premium commodities. For an altimeter associated with any outer planet missions, total mass should not exceed 3.5 kg and average power should be less than 6 W. In addition, altimeter designs must implement techniques to improve signal sampling while working at nadir ranges in excess of 100 km. The MLLA addresses each of these issues.

Focus Area: The focus of the MLLA is to continue work with those areas identified during the development of the NEAR Laser Rangefinder (NLR) to reduce mass and power usage, to increase measurement resolution, and to augment altimetry data with additional measurement (e.g., polarization) capabilities. Incorporating identified material changes selective machining, and redesign of support structures during the manufacture of the altimeter drastically reduces mass. With the judicious selection of interface electronics, the goal of 3 kg becomes achievable. Power consumption is reduced through increased efficiency in DC/DC converter technology, implementation of the APL-developed signal processing devices, and contextual-driven altimeter operation. The MLLA can operate in burst transmitter mode providing high rate measurements as necessary. The MLLA receiver is designed to allow backscatter waveform sampling to mitigate effects associated with pulse dilation while providing additional information associated with the target surface. By selection of transmitter materials, detector technologies and design modifications, this instrument can be adapted to a number of mission requirements and space environments, including surface exploration of comets, Europa, Titan, and Triton.

Key Technologies: The MLLA is a direct-detection laser altimeter capable of altimetry measurements from an orbiter spacecraft. Altimetry measurements are made using a compact Nd:YAG passively Q-switched, selectable pulse rate, laser transmitter (TX). Given adequate signal margin, and mission design, the backscattered signal can be introduced to an ellipsometer with the two orthogonal channels compared with that emitted by the TX to ascertain polarization characteristics (ergo structural aspects) of the target surface. Collection optics used with this detector employs a small aperture (<15 cm) Dall-Kirkham light-weighted beryllium telescope. Detection is accomplished through an IR-enhanced, radiation shielded, avalanche photodiode (APD) detector. Return signal processing incorporates a low-power, *enhanced*, time-of-flight (TOF) approach that provides high resolution of small-scale features and minimizes errors arising from pulse dilation effects. In contrast to the 1-W GaAs ASIC TOF device flown within the NLR, the MLLA CMOS TOF chips, require only a small fraction of the power while providing drastically increased temporal resolution capability. These devices employ a delay-locked loop (DLL) approach that stabilizes the TOF chip set against thermal, power, and radiation-induced errors. These TOF chipset provide multi-stop capability, precise to 2.5 ns (settable to ~50 ps).

Development Base: MLLA's design stems from experience gained throughout development of the very successful 5-kg NLR instrument. The NLR design was flown on 17 February 1996, and from 14 February 2000 through 12 February 2001, the NLR operated at a near continuous rate about the asteroid, 433 Eros. The radiation-hardened, tested to 4 Mrad, CMOS TOF design was flight qualified as part of NASA's High Energy Neutral Atom (HENA) instrument.

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Heterogeneous Integration, An Approach to High Density and High Flexibility Electronic Packaging. S. A. D'Agostino, D. Schatzel, Jet Propulsion Laboratory, 4800 Oak Grove Drive MS 83-204, Pasadena, CA 91109, saverio@jpl.nasa.gov.

Introduction: Key to the design of spacecraft for exploration of the outer planets will be the development of highly integrated and mass/volume efficient electronic systems. Exploration of the outer planets will require optimized propulsion approaches which mandates mass minimization. If one looks at a mission such as the Europa Lander, a high mass/volume efficiency feeds back directly into lower mass for radiation shielding. Concurrently the long mission lengths will drive the need for fault isolation and fault tolerance. The ability to build distributed electronic systems is a inherent requirement and one which is enabled by heterogeneous integration. The electronic packaging approach must be capable of interconnecting various components at a scale comparable with that on the components themselves (chip scale) and it must facilitate efficient integration of the electronics with elements of the spacecraft such as structure or antennae. The concept of "Heterogeneous Integration" is being explored in the "System On A Chip (SOAC) Project at JPL. The goal, of this approach to electronic packaging, is to enable the fabrication and assembly of complete electronic subsystems from components fabricated by a range of processes. Included in such a system could be MEMS sensors, SOI mixed signal ASICs, micro scale passive components and micro power systems, Fig.-1. Secondarily the compact size will enable distributed architectures and integrated assemblies.

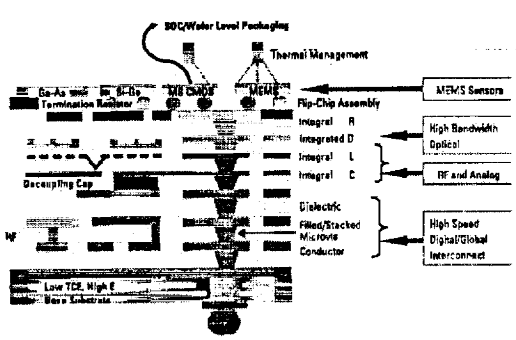

Figure-1. Concept of heterogeneous integration

Approach: There are several areas of technology development that are to be explored in bringing about the heterogeneous integration concept. The base-line technology is to incorporate "bump attachment" between the various components and the substrate. When possible this will entail wafer bumping prior to dicing and attachment. However, it is often the case with the stringent requirements of spacecraft electronics components will not be available as wafers and thus "single-point bumping" technologies will be a major area of development and validation testing. With the aim of enhancing long term reliability and to facilitate the adaptation of well understood processes the substrate for the integrated assembly is silicon. Currently a test structure combining thin film passive devices (part of another SOAC Task) test die from Sandia National Laboratories and the IEEE P1149.4 (analog boundary scan) is in design and will be fabricated this Spring with testing to follow in early summer. The next stage will the fabrication of a demonstration DC/DC converter incorporating integral passive devices and heterogeneous integration. Another area of research involves the study of thin film eutectic bonding for attachment of components to substrate and assembling MEMS integral hermetic packages. Prof. Chin C. Lee is pursuing this work at The University of California at Irvine through the System On A Chip Project.

Architecture Considerations: The development of effective heterogeneous integration technology enables the efficient incorporation of distributed architectures for spacecraft electronics systems and enhances the applicability of primary busses for power and data transmission. The approach of the "nano-avionics node" (under development in SOAC) utilizes an assembly containing digital control and communication, mixed signal capability and power control integrated at the chip scale. Distributed sensor nodes would be particularly advantageous for monitoring the "health" of a spacecraft. "Health monitoring" becomes particularly critical for long missions and where autonomous operation and fault tolerance/correction is required.

Also enabled by the combination of heterogeneous integration and distributed architectures is the development of a whole new class of instruments utilizing arrays of MEMS or electronic sensors. Each sensor node has its own signal processing, communication and power electronics.

Acknowledgement: The research described in this paper was performed at the Center for Integrated Space Microsystems, Jet Propulsion Lab, California Institute of Technology and was sponsored by the National Aeronautics and space Administration. The authors with to thank; B. Blaes, S. Chau, E. Kolawa and M Mojarradi of the SOAC Project for their ideas and contributions.

SYSTEM MINIATURIZATION VIA HETEROGENEOUS INTEGRATION OF ELECTRONIC DEVICES FOR DEEP SPACE MISSIONS L. Del Castillo, D. V. Schatzel, R. W. Graber and A. Mottiwala, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109.

Introduction: The scientific devices designed for each of the Outer Planets Program Focuses will likely be groundbreaking not only with respect to their scientific role but also regarding the electronics required to perform such investigations. In the past, the performance of packaged electronics was limited by the components themselves, with minimal influence of the packaging technology. The rapid development of integrated circuit technology, however, has drastically increased the importance of packaging technology in the ultimate performance of devices. If not carefully considered in the overall design, the packaging may become the limiting factor in the operation of the system. Although industry is responsible for several significant accomplishments in the field of electronics packaging, deep space/outer planet missions must take into account additional requirements such as extremely low temperatures, high radiation levels, hermetic sealing and severe size and weight limitations. Therefore, the present investigation has been designed to meet the needs of NASA's sensor intensive outer planets program by combining (using flip chip technology) an array of devices (including analog, digital, power voltage, passives and MEMS) into a miniaturized heterogeneous system and utilizing optical buses to enable autonomy.

Discussion: The increased functionality and performance of integrated circuits drastically increased the required number of input/output connections, requiring larger die sizes to accommodate the traditional wirebonding interconnection method. Such increases in die size led to larger substrate sizes and longer wire lengths (for bonding the die pads to the package). Increased wire lengths ultimately resulted in reduced electrical performance. Controlled collapse chip connection technology (flip chip technology), which has been successfully and reliably used by IBM for over 25 years, provides a viable solution to the performance limitations of traditional wirebonding. Area array flip chip technology can provide a 30-50% decrease in die size, while allowing a higher number of input/output connections.[1] Ultimately, this could result in a five fold reduction in the size and a significant reduction in the mass of the system. The use of flip chip technology would therefore reduce the size and weight of electronic systems, while concurrently improving their performance. As mentioned previously, however, commercial electronics packaging technology can only provide a starting point for the technology required of electronic systems intended for outer solar system missions. In addition to the traditional factors considered in electronic packaging, such as manufacturability, reliability, serviceability, size, weight, signal integrity, mechanical stability, power consumption, and heat dissipation problems, the present program offers unique challenges regarding the environment and conditions to be experienced by the devices. Size and mass must be minimized beyond the requirements of standard electronics, while obtaining 100% reliability due to the inability to repair devices.

To that end, the objective of the present project is to develop and optimize the interconnection technologies that are used to integrate active devices (microprocessors), passive integrated devices (capacitors, inductors, resistors), and Micro Electro-Mechanical Systems (microgyros, sensors) into a heterogeneous package configuration (using optical buses) that can be validated for space flight application. This will allow systems architectures capable of supporting multiple redundant computers for spacecraft autonomy. The interconnection development method will concentrate on the attachment interfaces that will allow the integration of an electrical system. Development efforts will include different pad metallurgies and connection materials as well as developing mechanical models to perform stress analysis and identify connection failure modes. Special coatings will be evaluated for cases in which radiation and hermeticity requirements are specified. To verify reliability, the fabricated packages will be subjected to potential mission environments, such as the extreme temperatures of Neptune and the high radiation of Europa. The deliverable output of the development efforts will incorporate an implementation requirements document that includes manufacturing and design guidelines to be used as an aid and reference for future electrical circuits using advanced integrated passive devices. Therefore, as an integral part of the infrastructure and multi-mission technologies focus, the presently proposed project will enhance outer solar system exploration for each of the missions.

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Low-Temperature Spacecraft: Challenges/Opportunities. J. E. Dickman, R. L. Patterson, and E. Overton[1], A. N. Hammoud[2], and S. S. Gerber[3], [1]NASA Glenn Research Center 21000 Brookpark Road M/S 309-2 Cleveland, Ohio 44135, John.E.Dickman@grc.nasa.gov, [2]Dynacs Engineering Inc., NASA Glenn Group, NASA Glenn Research 21000 Brookpark Road M/S 301-5, Cleveland, Ohio 44135, [3] Zin Technologies, NASA Glenn Research Center, 21000 Brookpark Road M/S 301-5, Cleveland, Ohio 44135.

Introduction: Imagine sending a spacecraft into deep space that operates at the ambient temperature of its environment rather than hundreds of degrees Kelvin warmer. The average temperature of a spacecraft warmed only by the sun drops from 279 K near the Earth's orbit to 90 K near the orbit of Saturn, and to 44 K near Pluto's orbit. At present, deep space probes struggle to maintain an operating temperature near 300 K for the onboard electronics. To warm the electronics without consuming vast amounts of electrical energy, radioisotope heater units (RHUs) are used in vast numbers. Unfortunately, since RHU are always "on", an active thermal management system is required to reject the excess heat. A spacecraft designed to operate at cryogenic temperatures and shielded from the sun by a large communication dish or solar cell array could be less complex, lighter, and cheaper than current deep space probes.

Before a complete low-temperature spacecraft becomes a reality, there are several challenges to be met. Reliable cryogenic power electronics is one of the major challenges. The Low-Temperature Power Electronics Research Group at NASA Glenn Research Center (GRC) has demonstrated the ability of some commercial off the shelf power electronic components to operate at temperatures approaching that of liquid nitrogen (77K). Below 77 K, there exists an opportunity for the development of reliable semiconductor power switching technologies other than bulk silicon CMOS. This paper will report on the results of NASA GRC's Low-Temperature Power Electronics Program and discuss the challenges to (opportunities for) the creation of a low-temperature spacecraft.

QUANTUM DOTS BASED RAD-HARD COMPUTING AND SENSORS. A. Fijany, G. Klimeck, R. Leon and Y. Qiu and N. Toomarian. MS 303-310, JPL/Caltech, 4800 Oak Grove Dr., Pasadena, CA 91109, Nikzad.Toomarian@jpl.nasa.gov.

Introduction: Quantum Dots (QDs) are solid-state structures made of semiconductors or metals that confine a small number of electrons into a small space. The confinement of electrons is achieved by the placement of some insulating material(s) around a central, well-conducting region. Thus, they can be viewed as artificial atoms. They therefore represent the ultimate limit of the semiconductor device scaling.

NASA Relevance: A survey of future deep space missions indicate a recurrent theme of the following technology needs: 1. Autonomous navigation and maneuvering, 2. Miniature *in-situ* sensors, 3. Radiation and temperature tolerant electronics. QDs will provide the underlying computing and sensing capabilities to satisfy the above needs. To achieve autonomous navigation and maneuvering one needs algorithms and high performance computing. It is obvious that the computing HW in addition to being high performance need to be low power, low mass, radiation and temperature tolerant. The ultra-small dimensions and very high packing densities, already achievable in QD structures, provide the bases for the projection that QDs based computing will be 10^5 times better than conventional CMOS technology. Furthermore, QDs will enable lasers and infrared photodetectors operating in 2 to 5um wavelength. For these reasons, QDs will be at the heart of Miniature *in-situ* sensors and lab on a chip. More important for deep space applications has been the finding that several of the optoelectronic devices with QDs in the active area show increased radiation tolerance [1-2]. Although, most of the current R&D focused in operating QDs base devices in room temperature, it is clear that the characteristics of these devices will improve in low temperature. Hence, QDs will play a key role in missions that will benefit from radiation & low-temperature tolerant electronics.

QD Applications of Relevant to Deep Space:

Sensor-optoelectronic detection and emission devices. Most atmospheric and planetary gases have strong absorption bands in the 2-5um wavelength range. Therefore, semiconductor laser diodes and detectors in this range are enabling technologies for detecting many organic and life-signature molecules. Research and development in this frequency range is specific to space science, and is not of great interest to the commercial sector. GaSb-based lasers are currently the choice for applications in this wavelength range, but they suffer from non-availability of high-quality substrates and immature growth processing technologies. On the other hand, there have been recent advances in the fabrication technology of both III-V semiconductor QDs and devices. Using the self-organized growth technique, InGaAs QDs on GaAs substrates have been exhibiting 3-D quantized confinement with sufficient material quality to obtain lasing. QDs promise several improvements in laser diode performance, including ultra-low threshold current density and temperature-insensitive threshold. GaAs-based QD lasers operating at 1.3um with a low threshold of 1.2 mA have recently been reported [3]. Temperature-insensitive low threshold has been obtained up to ~250K. Recently, InAs QDs of emission wavelength up to 2um have been demonstrated on InP substrates. We are developing long-wavelength (2~5um) InAsSb QD lasers on InP substrates. The formation of ternary InAsSb QDs will extend its emission wavelength beyond 2um.

Computing — logic/memory/computational devices. Several computational architectures based on QD arrays have been proposed in the past few years. Computing without transfer of charge (no current) provides the ultimate low power consumption [4]. Dense QD packing and low power properties along side of massively parallel and defect tolerant architecture[5} promise to provide extremely high performance computing, allowing for highly autonomous missions. While such computing systems has commercial relevance in terrestrial applications, NASA missions have the added requirement of radiation and temperature tolerant, which can be addressed in these technologies.

Design Tradeoffs: The solid-state-based confinement of electrons into a small spatial region can be implemented in a large variety of material systems and structural configurations. We focus on III-V semiconductor-based QDs due to their obvious advantage of co-integration into existing semiconductor technology. Even with this restriction, the exploration of the design space is an enormous task. Typical design parameters are QD compositions, sizes, doping, and confinement material. We therefore focused two of our task elements on this exploration:

1) Development and utilization of experimental nano-scale characterization technology [1-2].
2) Development of a comprehensive nano-scale electronic structure modeling and simulation tool [6].

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SOLID-STATE POWER GENERATING MICRODEVICES FOR DISTRIBUTED SPACE SYSTEM ARCHITECTURES. J.-P. Fleurial[1], J. Patel[1], G.J. Snyder[1], C.-K. Huang[1], R. Averback[2], C. Hill[2], G. Chen[3], [1]Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109, jean-pierre.fleurial@jpl.nasa.gov, [2]University of Illinois at Urbana, Dept. of Physics, 1304 W. Green St., Urbana, IL 61801, [3]University of California at Los Angeles, Mechanical & Aerospace Engineering Dept., Los Angeles, CA 90095-1597.

Introduction: Deep space missions have a strong need for compact, high power density, reliable and long life electrical power generation and storage under extreme temperature conditions. Conventional power generating devices become inefficient at very low temperatures (temperatures lower than 200K encountered during Mars missions for example) and rechargeable energy storage devices cannot be operated thereby limiting mission duration. At elevated temperatures (for example for planned solar probe or Venus lander missions) thin film interdiffusion destroy electronic devices used for generating and storing power. Solar power generation strongly depends upon the light intensity, which falls rapidly in deep interplanetary missions (beyond 5 a.u.), and in planetary missions in the sun shadow or in dusty environments (Mars, for example). Radioisotope thermoelectric generators (RTGs) have been successfully used for a number of deep space missions RTGs. However, their energy conversion efficiency and specific power characteristics are quite low, and this technology has been limited to relatively large systems (more than 100W). The National Aeronautics and Space Administration (NASA) and the Jet Propulsion Laboratory (JPL) have been planning the use of much smaller spacecrafts that will incorporate a variety of microdevices and miniature vehicles such as microdetectors, microsensors and microrovers. Except for electrochemical batteries and solar cells, there are currently no available miniaturized power sources. Novel technologies that will function reliably over a long duration mission (ten years and over), in harsh environments (temperature, pressure, and atmosphere) must be developed to enable the success of future space missions. It is also expected that such micro power sources could have a wide range of terrestrial applications, in particular when the limited lifetime and environmental limitations of batteries are key factors.

Technical Approach: Advanced solid-state thermoelectric or alpha-voltaic microdevices combined with radioisotope sources and energy storage devices such as capacitors are ideally suited for these applications [1, 2]. JPL is pursuing the development of novel thermoelectric microdevices using integrated-circuit type fabrication processes, electrochemical deposition techniques and high thermal conductivity substrate materials. An even higher degree of miniaturization and high specific power values (mW/mm^3) can be obtained when considering the potential use of radioisotope materials for an alpha-voltaic or a hybrid thermoelectric/alpha-voltaic power source. Some of the technical challenges associated with these concepts and initial experimental results are discussed in this paper.

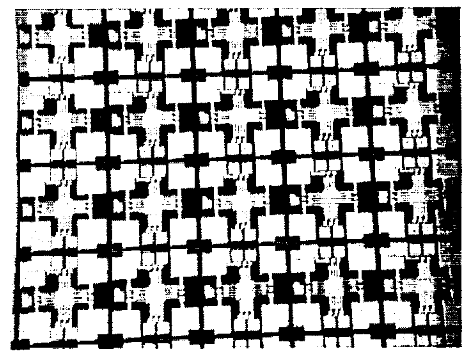

Figure 1: Array of 30 μm thick thermoelectric microdevice structures fabricated on SOI substrates.

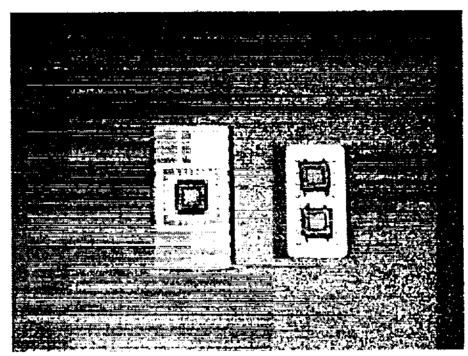

Figure 2: Protoptype alpha-voltaic devices based on GaAs heterostructures.

Mission insertion and benefits: This technology is expected to be ready for consideration within 4 to 5 years to address challenging power requirements in a variety of deep space missions such as planetary explorers for Europa (ice transceivers) or Mars.

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INDICATING THE DEEP STRUCTURE (BELOW THE ICY AND LIQUID LAYERS) OF EUROPA AND TITAN BY MEASUREMENTS WITH A GIANT SOLENOID SYSTEM ON BOARD OF AN ORBITING SPACE PROBE. T. Földi[1] and Sz. Bérczi[2], [1]FOELDIX, H-1117 Budapest, Irinyi J. u. 36/b. Hungary, (theo-foldi@ludens.elte.hu), [2]Eötvös University, Dept. G. Physics, Cosmic Mat. Sp. Res. Gr. H-1117 Budapest, Pázmány Péter sétány 1/a. (bercziszani@ludens.elte.hu).

Introduction: We propose a large, few wind solenoid experiment to measure on a circular orbit the depth of the ice crust of Europa and Titan. The solenoid is orbiting the Jovian or Saturnian satellite, it represents an oscillator with ultralong wavelength, (from 100 Hz to 40.000 Hz). The diameter of the few wind solenoid may be between 200 m and 800 m.[1]. The oscillator is established as a putch-hull oscillator. We use the solenoid as a special antenna. We do not use it as a radar, so we do not consider its far field. Instead of it, we use the near field of the antenna.

The near field of the antenna can be deduced from the emitted and received oscillation. In an ideal case the near field is $\pi/2$ phase delayed as compared to the far field of the antenna. In a real case the phase delay between the two fields (because of the losses in the near field) is a little bit different from $\pi/2$ phase delayed. This difference from $\pi/2$ is caused by the ice covered deep mountains (if they exist) below the icy crust of Europa or Titan. By this measurement it can be derived that how deep is the rocky material below the volatile ice and liquid spheres [2].

The arrangement of the oscillator on board of the probe: For example we show how the system works with a two-wind solenoid with 500 m diameter. There are 3 poles of the solenoid. First (1) at the output of the No. 1. Amplifier, second (2) at the positive pole of the Dc battery (some volts), and third (3) at the output of the No. 2. Amplifier. The pole (1) is connected to pole (2) through a capacitor, the pole (2) -as was shown, - is connected to the battery, and pole (3) is connected to pole (1) through a capacitor. The negative pole of the battery is connected to the common "earth" pole of the two amplifiers. The phase-measuring unit is attached to pole (1). This oscillator arrangement emits not a sinuous but a square signal.

This square signal can be summarized from sinuous ν signals with frequencies of 1ν , 3ν, 5ν, 7ν, ...The penetration depth of the various frequencies is different and the penetration depth decreases with the increasing frequency. We measure the amplitude and phase of the different harmonics. By this measurement the depth and the horizontal extension of the rocky medium below the icy+liquid crust can be calculated.

An estimated numeric example. With 500 m diameter solenoid and with 1000 Hz frequency the penetration depth of the basic harmonic component is 50 km. [3].

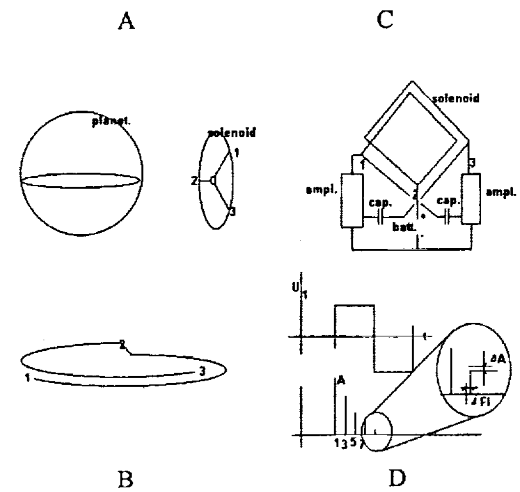

Fig. 1. A) The position of the solenoid as compared to the orbited satellite (Europa or Titan); B) The winding and poles of the solenoid; C) The circuit of connections of the Amplifiers and the Battery; D) upper function: the shape of the time function of the potential between the poles 1 and 3 of the solenoid; lower function: the Fourier spectra of the earlier function: enlarged is difference of phase and amplitude caused by the loss of the near filed power induced [3].

Technological realization: When operates in measuring mode the solenoid is embedded into a plastic torus which forms a hermetically closed container under pressure. In transportation mode the solenoid and its torus-conatiner is folded arranged in a Technologically the great circular solenoid consists of three geometrical constituents. 1) the circular winds of the solenoid [3], 2) the radial spokes with poles described, arranged with a 120 meeting angle at center of the ring, finally, 3) the central oscillator and measuring unit with radio connection to the on board telemetry.

Summary: The harmonics of the near field induced by the solenoid will change in amplitude (decreasing) and in phase (plus or minus) implicates the rocky surface below the ice and water spheres on the observed satellites because of the dissipation of energy from the near field. This effect is very different from the long wavelength radar and our method works with far lower energy consumption [3].

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Introduction: Since their initial discovery in 1992, to date only a relatively small number of Kuiper Belt Objects (KBO's) have been discovered [1]. Current detection techniques rely on frame-to-frame comparisons of images collected by optical telescopes such as Hubble, to detect KBO's as they move against the background stellar field. Another technique involving studies of KBO's through occultation of known stars has been proposed [2]. Such techniques are serendipitous, not systematic, and may lead to an inadequate understanding of the size, range and distribution of KBO's.

In this paper, a future Kuiper Belt Mapping Radar is proposed as a solution to the problem of mapping the size distribution, extent and range of KBO's. This approach can also be used to recover radar albedo and object rotation rates.

Background: Radar mapping of bodies in the solar system has allowed scientists to study the Moon, the inner planets, the Galilean satellites and, more recently Near Earth Asteroids [3]. Radar astronomy measurements have been made at several facilities, notably the 70 m Deep Space Network (DSN) antenna at Goldstone and the Arecibo radio telescope. Planetary radar measurements have not been targeted at bodies in the outr solar system because of the prohibitively large distances involved in studying more remote objects. Large distances to the objects under observation lead to severely attenuated signals due to the R-to-the-fourth-power law for two-way propagation of electromagnetic waves, and the wide angular beam of the radar antenna.

Synthetic Aperture Radar (SAR) is a mature technique used in imaging radars for mapping [4]. The relative Doppler between the SAR antenna and the observed features is filtered in order to construct a 'synthetic aperture' image of the object with dramatically sharper resolution than the angular beamwidth of the illuminating antenna provides. Inverse Synthetic Aperture Radar (ISAR) operates under the same principle [5], except that in ISAR the radar is stationary and the observed feature moves, e.g. through rotation or translation. The signal processing involved in either case achieves two objectives: i) significantly enhanced angular resolution along the arc of relative motion; and ii) significant increase in Signal-to-Noise (S/N) for isolated point-like targets within the radar's field-of-view. Both are achieved by coherent integration of radar returns collected over a given time interval.

Measurement Concept: The proposed Kuiper Belt Mapping radar would be positioned in an Earth-trailing orbit or at L2. This would allow it to be targeted at successive patches of sky for long observation intervals without interference from the gravitational pull of the Earth-Moon The operations scenario for the proposed system would be to scan a segment of the sky for periods up to 2 days. [This period of sustained observation precludes a ground-based radar solution.] After the radar transmits one pulse, the expected round-trip delay for returns from the far edges of the Kuiper Belt would be as long as one earth day. Returns would be coherently processed for integration times of up to 12 hours. The limits of performance of one design for the proposed space-based radar system are given in Table I, where it is shown that a 25 km diameter object would be detectable at ranges up to 100 AU.

Parameter	Value
Range	< 100 AU
Object diameter	25 km
Object σ^o	- 10 dB
Radar wavelength	10 cm
Antenna diameter	1 km
Antenna beamwidth	0.1 mrad
Peak Transmit power	10 MW
Avg.Transmit power	12.5MW
Pulse repetition freq.	1 Hz
Pulse Bandwidth	1 kHz
Integration time	0.5 days
Single-pulse S/N	-73 dB
Integrated S/N	11 dB

Table I: Parameters for the Kuiper Belt Mapping Radar

Challenges: The concept described here offers a number of implementation challenges. Not the least of these is the need for a lightweight reflector antenna with 1 km diameter and surface control to +/- 1 cm. The high power levels required and the narrow bandwidths would drive the development of new RF technologies. [The current state-of-the-art for ground-based radars is Arecibo, which has a 305 m antenna and a transmit power of 1 MW.] Another challenge would be signal processing, given unknown motion characteristics (rotation, translation) of the KBO's which can be resolved by applying high-speed computing capability.

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SUBSURFACE EXPLORATION TECHNOLOGIES AND STRATEGIES FOR EUROPA L. C. French [1], F. S. Anderson [2]; F. D. Carsey [3], J. R. Green[4], A. L. Lane[5], W. F. Zimmerman[6], Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA 91109 (1: lloyd.c.french@jpl.nasa.gov; 2: Fletcher.S.Anderson@jpl.nasa.gov; 3: fcarsey@jpl.nasa.gov; 4: Jacklyn.R.Green@jpl.nasa.gov; 5: Arthur.L.Lane@jpl.nasa.gov; 6: wayne.f.zimmerman@jpl.nasa.gov)

Introduction: The Galileo data from Europa has resulted in the strong suggestion of a large, cold, salty, old subglacial ocean (1) and is of great importance. We have examined technology requirements (2) for subsurface exploration of Europa and determined that scientific access to the hypothesized Europa ocean is a key requirement. By "scientific access" we intend to direct attention to the fact that several aspects of exploration of a site such as Europa must be addressed at the system level. Specifically needed are: a robotic vehicle that can descend through ice, scientific instrumentation that can interrogate the ice near the vehicle (but largely unaffected by its presence), scientific instrumentation for the subglacial ocean, communication for data and control, chemical analysis of the environment of the vehicle in the ice as well as the ocean, and methods for conducting the mission without contamination. We have embarked on a part of this extremely ambitious development sequence by developing the Active Thermal Probe, or Cryobot.

Design and Status of Cryobot: The Cryobot is the descendant of the Phiberth Probe concept (3) of the 1960's; we have updated the subsystems and integrated into the design a miniature hot-water jet derived from the highly successful glacial drilling technology. The Cryobot works by melting ice beneath its nose and descending into the space generated; the meltwater refreezes behind the probe so that the Cryobot is descending in a lozenge of meltwater. The Cryobot design is complete, and fabrication has begun on the first complete vehicle, which does not at this time carry scientific instrumentation. For Earth testing, the Cryobot is about 12 cm diameter and 1-2 m long and is powered through a tether; in planetary application it may be smaller and will probably carry its own power source.

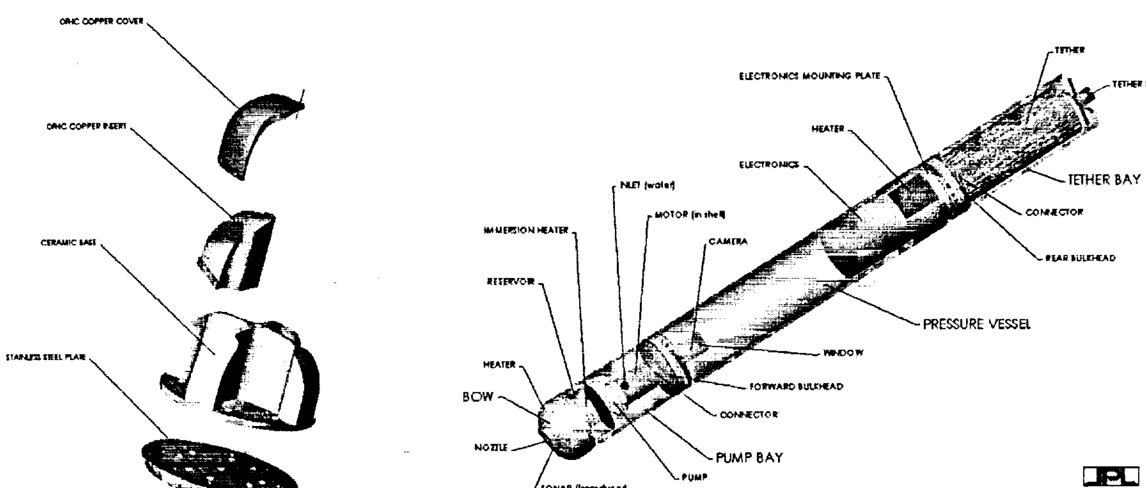
Cryobot Instrumentation Opportunities: A logical beginning for subglacial scientific observations is the installation of simple optical systems for visible-light imaging and UV fluorescence analysis. More demanding instruments can be anticipated in future.

Subsystem Testing Needs and Opportunities: Clearly, testing of novel and challenging systems such as the Cryobot is essential prior to planetary deployment, and opportunities are developing in the Earth science community in such areas as the study of subglacial lakes (4).

A Europa Subsurface Mission: Cryobot technology is an approach to a Europa subsurface mission in which only a communications antenna is left on the surface.

References: 1. .Stevenson, D., *Science, 289*, 1305-1307, 2000. 2. Carsey, F., and others, *Journ. Marine Tech.*, 33, 34-40, 2000. 3. Kelty, J., *An In-situ Sampling Thermal Probe for Studying Global ice Sheets*, PhD dissertation, University of Nebraska, 189 p. 1995. 4. SCAR, 1999, *Subglacial Lake Exploration Workshop Report and Recommendations*, Scientific Committee on Antarctic Research, 2000

Figure 1 The Cryobot design with an exploded view of the nose, at left.



Initial results from the Jovian Electrodynamic Tether Systems (JETS) study

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J. Moore, C. Talley
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The Jovian system with its rapid planetary rotation and strong magnetic field presents exciting opportunities for the use of electrodynamic (EM) tethers in system applications on a Jovian spacecraft. Previous analysis for a radial, 10-km length tether demonstrated the possibility of propulsive forces as large as 50 N and power generation levels as high as 10^6 W for low perijov passing trajectories. For orbital positions beyond approximately 2.5 Jovian radii, JETS can be used simultaneously for power and increases in the orbital altitude. Previous study demonstrated the physical feasibility of EM tether use at Jupiter, but did not address the issues of limited gravity gradient force for tether extension and power regulation needed before JETS can be implemented as a practical spacecraft system. This presentation will discuss these issues and current progress in an ongoing systems feasibility study.

Sub-Kilowatt Radioisotope Electric Propulsion for Outer Solar System Exploration

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Introduction: An activity has begun to perform a multi-mission trajectory/systems analysis study that examines the combined benefit of three key technology development areas. The three key technologies leveraged in the study include sub-kilowatt ion propulsion, Stirling radioisotope power systems and microelectronics/lightweight spacecraft bus technologies. This study is being performed jointly by NASA Glenn Research Center and the Applied Physics Laboratory to leverage their combined areas of expertise in advanced power/propulsion and spacecraft design. Missions examined in this study include missions to outer planets' moons, such as, Europa, Titan, and Triton, and a Comet Nucleus Sample Return mission.

Technologies: The specific technologies included in the study will be ion thrusters with an operation power range of 100-500 W, stirling radioisotope power systems that can supply constant power of 100-500 W to the ion propulsion system and lightweight spacecraft bus technologies that enable revolutionary 100-200 kg spacecraft bus designs.

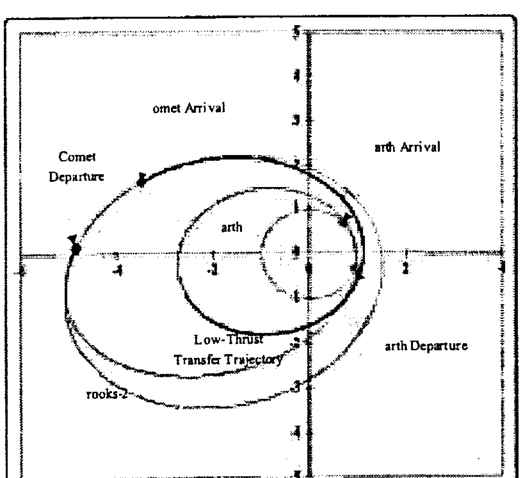
NASA Glenn Research Center is developing a lightweight (< 3.0 kg combined mass, representing a 5x reduction from state-of-the-art), sub-kilowatt thruster and power processor. Performance goals include 50% efficiency at 0.25 kW, representing a 2x increase over the state-of-the-art. The sub-kilowatt ion propulsion activity includes both an in-house hardware development element for the thruster and power processor, as well as a contracted system element.

The NASA Glenn Research Center and the Department of Energy (DOE) are developing a free-piston Stirling convertor for a Stirling Radioisotope Power System (SRPS) to provide on-board electric power for future NASA deep space missions. The SRPS currently being developed provides about 100 watts and reduces the amount of radioisotope fuel by a factor of four over conventional Radioisotope Thermoelectric Generators (RTG). The present SRPS design has a specific power of approximately 4 W/kg which is comparable to an RTG.

Advanced microelectronics/lightweight spacecraft bus development has been underway at the Applied Physics lab and will be leveraged toward the outer planet mission opportunities.

Preliminary Results: Mission results generated to date are encouraging regarding the combined technology application to the Comet Nucleus Sample Return (CNSR) mission. Initial results show that it may be possible to perform the CNSR mission using a Delta II 7925 launch vehicle. A mission summary of the preliminary CNSR results are shown below.

The results of these studies will be used to determine mission feasibility and determine refined technology requirements for the proposed technologies. Technology requirements will likely include things such as, the ion propulsion system operational specific impulse and lifetime, power system specific mass and allowable spacecraft science and bus mass.



Mission Timeline	
Launch Date	2-Sep-2005
Comet Arrival Date	18-Jul-2009
Comet Departure Date	14-May-2010
Earth Flyby/Sample Return Date	5-Nov-2013
Launch Summary	
Assumed Launch Vehicle Performance	Delta 7925H-9.5
Launch Vehicle Injection C_3	68.2 km^2/s^2
Launch Vehicle Injected Mass	307 kg
* assumes 10% LV reserves and 5% adapter mass	
Top Level System Breakdown	
Total Spacecraft Mass	307 kg
Lightweight Spacecraft Bus	123.6 kg
Micro-Lander	15 kg
Stirling Radioisotope Power Systems	60 kg
Ion Propulsion System	28.4 kg
Xenon Propellant	80 kg

HYPERSPECTRAL DATA COMPRESSION AS AN ENABLING TECHNOLOGY FOR DEEP SPACE MISSIONS. J.C. Granahan[1] and S.T. Rupert[1], [1]BAE SYSTEMS Mission Solutions, MZ 6300B, 16250 Technology Dr., San Diego, CA 92127. Phone: (858) 592-5198. E-mail: james.granahan@baesystems.com.

Introduction: Hyperspectral sensors have played an important roll in the exploration of the outer solar system. Hyperspectral sensors or imaging spectrometers have been flown on the Galileo and Cassini spacecraft to map the compositions of planetary surfaces and atmospheres. The Galileo Near Infrared Mapping Spectrometer (NIMS) discovered the presence and mapped the distribution of organics, hydrated sulfates, carbon dioxide, and sulfur dioxide on the surface of the icy Galilean satellites. The problem with sensors such as NIMS and the Cassini Visual Infrared Mapping Spectrometer (VIMS) is that they collect imaging with hundreds of bands of spectral data that can overload downlink bandwidths and onboard memory resources rapidly. Hence, an efficient data compression method for use with imaging spectrometers would enable more surfaces and atmospheres to be mapped during any given deep space planetary mission.

Hyperspectral Sensor Capabilities: Hyperspectral sensors can accomplish anything that the science of spectroscopy can do and place it in a spatial context. Galileo NIMS has been able to map the concentration and grain size of sulfur dioxide on Io, measure lava temperatures on Io, detect organics on Ganymede and Europa, map cloud composition and temperatures on Jupiter, and peer through the clouds at Venus. Deep Impact and the canceled Deep Space 4 missions have imaging spectrometers in their designs to study the compositions of comets. A Europa orbiter and Europa lander will most likely contain some imaging spectrometer capability to map the surface compositions (salts, water ice, acid, sulfur dioxide) and to look for fresh break outs of water. Cassini will use VIMS to examine the Titan atmosphere and hopefully to detect the presence of organics and other constituents there. In doing so, it may identify some infrared atmospheric windows that would allow direct imaging of the Titan surface. An imaging spectrometer system would also be very useful in detecting compositions and temperatures in the Neptune atmosphere, the variety of ices on Triton, Charon, and Pluto. Thus, imaging spectrometers have much to contribute to the outer planet space program.

Data Compression Capabilities: BAE SYSTEMS Mission Solutions has been actively researching hyperspectral data compression software technology. The current batch of compression schemes have been applied to terrestrial data sets such as those collected by Jet Propulsion Laboratory's AVIRIS (Airborne Visible InfraRed Imaging Spectrometer). Initial results have resulted in data compression values of 3:1 (with noisy data over urban silicon valley by Moffett Field, Naval Air Station) to 80:1 (with cleaner data acquired over Cuprite, Nevada). Typically, compression ratios between 20:1 to 30:1 were achieved with most AVIRIS data collects. We at BAE SYSTEMS are currently developing a technique called Residual Linear Unmixing Method (patent pending) that compresses spectral data types by breaking them down into mathematical constitute components. Current research includes the optimization of the prototype RLUM code and the addition of spatial data compression techniques to enhance the compression ratio performance.

Outer Planet Mission Enhancement: Any deep space mission will have to manage its data resources to maximize its science return. For orbiters and landers this will be of particular importance due to the fact that their sensors will be in continuous cycle of data collection, processing, and transmission. This is less critical on a flyby mission where there is only a finite opportunities for observations. On a flyby spacecraft the data return will be highly dependent upon the data memory of the spacecraft. Hyperspectral data compression technology, such as that described above, would allow one to manage the data output from an imaging spectrometer. This would enable more compositional maps of targets to be returned to Earth enhancing the science output of a spacecraft project.

The Galileo mission is an extreme example of this case. A multitude of compromises for data collection occurred due to the failure of the high gain antenna. On a good day some three images could be transmitted back to Earth during this mission. Only "postage stamps" of high spatial resolution spectral data and limited samples of low spatial resolution NIMS data were ever returned.

A typical compression ratio with the RLUM method combined with spatial compression techniques is estimated to be around 60:1. An imaging spectrometer such as Cassini VIMS has some 352 spectral channels. Imaging spectrometers can typically collect 256 spatial elements along with those 352 spectral channels on 16 bit detectors. That is about 180 kilobytes a line or 46 megabytes for a 256 x 256 image. A 1024 x 1024 CCD imager with 16 bit detector (like Cassini's ISS) would produce a 2 megabyte image. The RLUM technology could turn the 46 megabyte hyperspectral image into a 767 kilobyte one, making the imaging spectrometer data easier to sequence and to provide more complete spatial coverage of a target.

THE EXTRATERRESTRIAL MATERIALS SIMULATION LABORATORY J. R. Green[1], Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA 91109 (1: jacklyn.r.green@jpl.nasa.gov)

Challenges of In Situ Exploration in the Outer Solar System: In contrast to fly-by and orbital missions, in situ missions face an incredible array of challenges in near-target navigation, landing site selection, descent, landing, science operations, sample collection and handling, drilling, anchoring, sub-surface descent, communications, contamination. The wide range of materials characteristics and environments threaten mission safety and success. For example, many physical properties are poorly characterized, including strength, composition, heterogeneity, phase change, texture, thermal properties, terrain features, atmospheric interaction, and stratigraphy. Examples of the range of materials properties include, for example: (1) Comets, with a possible compressive strength ranging from a light fluff to harder than concrete: 10^2 – 10^8 Pa; (2) Europa, including a possible phase change at the surface, unknown strength and terrain roughness; and (3) Titan, with an completely unknown surface and possible liquid ocean.

The Extraterrestrial Materials Simulation Laboratory: A new laboratory for the physical simulation of extraterrestrial surface materials has been developed to support the development of upcoming in situ missions. In the Extraterrestrial Materials Simulation Laboratory (EMSiL) we develop new formulations, methodologies, and technologies to create ambient and cryogenic simulant materials for use in testing and validation of in situ surface systems and vehicles, such as In Situ Explorers, Subsurface Systems, Cryobots, Hydrobots, Moles, Anchoring Systems, and Drilling Systems for environments, such as the Galilean satellites (Europa, Ganymede, Callisto, and Io), Titan, comets, and asteroids, as well as Antarctica, Mars polar regions. The design and costs of in situ missions are significantly affected by the large uncertainties in our knowledge of the working environments and surface materials properties. In situ missions in the Outer Solar System will require realistic test materials and environments in which to test new technologies and systems as part of an active design and test cycle. The unknowns of the in situ environment can drive up costs and mass in order to reduce risks. A well-planned test program in relevant materials and conditions can reduce risk and foster Mission Safety. The importance of realistic testing and simulation capabilities was emphasized in the *Report on Project Management in NASA by the Mars Climate Orbiter Mishap Investigation Board* (Stephenson et al) which states "Conduct extensive testing and simulation in conditions as similar to actual flight conditions as possible." JPL's Extraterrestrial Materials Simulation Laboratory serves three functions: (1) Perform research to understand better the in situ surface environments and to predict expected physical properties; (2) Develop, formulate, and test terrestrial analog materials that will match the properties expected in the in situ environment; (3) Develop and deliver small- and large-scale test articles and materials to the test programs for in situ missions and associated technology programs to aid in the design and test cycle to reduce mission risk and cost.

Description: Over the past few years we have developed a variety of laboratory hardware and methodologies to: create cryogenic ice-dust mixtures, contain and process the materials in a specially designed cryogenic high vacuum chamber, and study the effects of insolation from measurements of the changing physical properties of a variety of ice/dusty mixtures. In particular, we create suspensions of water, minerals, and other relevant components with a composition similar to those expected of extraterrestrial environments, based on telescopic and spacecraft observations. We can finely specify the particle size range of the minerals through the use of an air jet sieve system that allows us to grade particles to sizes less than 5 microns. After a mixing procedure that includes the ultrasonic break-up of flocculated particles, the suspension is atomized and sprayed into a liquid nitrogen bath contained in a LN2-cooled, instrumented sample canister (cylinder: diameter = 0.20 m; depth = 0.25 m), which is adaptable enough to provide cooling for the back-plate only, sides only, or for the entire canister. Upon completion of the formation of the analog materials, we transfer the sample canister to the cryogenic vacuum chamber (10e-9 Torr). Once in the vacuum chamber, the canister can be oriented from 0-45 degrees with respect to the incoming insolation. The solar simulator output covers 0.1-2.1 Solar Constant. Temperatures are measured with 10 sensors in the mixture inside the canister. The gas release is monitored as a function of time with two mass spectrometers: one for the lower pressures and one for the higher pressures that may develop during an outburst. Dust release is recorded on videotape. A mechanical penetrator-scratcher measures penetrability and disturbs the surface for assessment of surface changes. At the end of the experiment, the sample is removed and core samples are taken for tests of compression strength, penetrability, porosity, density, and thin section analysis. Methods allowing detailed microscopic examination of the samples are under development. A freezing microtome for cutting thin sections of the sample and a freezing stage on a microscope are to be used for examination of the pore and grain structure of the icy mixtures. With all elements in place for the laboratory simulation of extraterrestrial materials, we are now performing our first experiments to simulate relevant in situ materials. The next steps in the process to support the test programs for upcoming in situ missions in the Outer Solar System is the development of low cost ambient, as well as cryogenic, test materials and the ability to produce the desired volumes of simulants, which can be very large. We have begun these steps and are currently supporting test and validation programs for advanced technologies, advanced mission studies, and flight projects.

Conclusion: The Extraterrestrial Materials Simulation Laboratory will play an important role in reducing risk and aiding mission success for upcoming in situ missions in the Outer Solar System. An active design and test cycle with tests in well-calibrated, reproducible, well-documented simulant materials will ensure optimized designs and reliability of spacecraft components and systems.

A NEED TO UPDATE THE EXPLORATION STRATEGY FOR EUROPA. R. Greenberg, B. R. Tufts, G.V. Hoppa, and P. Geissler, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721.

The current exploration strategy for Europa, for which the Europa orbiter is the next step, was predicated on a prevailing belief that Europa's ocean, if any, lies isolated from the surface beneath ~10 km or more of ice [1]. First, the orbiter would determine whether there indeed is a liquid water ocean. Then a lander would assess surface conditions, laying the groundwork for a subsequent mission to send a probe down through the ice to the ocean below. The ocean is the ultimate destination because of its appealing possibility as a site of life. In this scenario, the multiple missions and the central technological challenge of devising a way to penetrate the ice imply a timetable stretching over several decades.

During the past few years since that strategy was developed, our knowledge and understanding of Europa has increased dramatically. Evidence has mounted that there is in fact an ocean. Moreover, we have developed several lines of evidence that indicate the ice may be thin enough at various times and places for openings to link the ocean to the surface. That evidence suggests that most of the rapid and recent resurfacing of Europa involves interaction of the ocean with the surface. Understanding of tidally driven tectonics may identify sites of most recent activity. The picture emerging from that work is that the habitable zone of Europa may extend to within centimeters of the surface [2].

If we knew with certainty that conditions on Europa were like that, the strategy for exploration would be quite different from the current plan. A campaign laying the foundation for a deep penetration would be irrelevant. Instead, an orbiter (or several) might do detailed reconnaissance, so that a lander could be placed at a site where fresh oceanic material lies on (or perhaps is delivered in real-time to) the surface, readily accessible for investigations of composition or signs of life.

Because, at this time, we cannot be certain whether there is an ocean, or how thick the ice may be, we need to devise a strategy that is not predicated on one extreme model, but instead we should be designing a strategy that early-on resolves the issue of whether or not the interesting oceanic material is physically isolated from the surface. Then subsequent missions could follow a plan appropriate to that result. The currently conceived Europa Orbiter will partially address this problem by measuring ice thickness (assuming its radar remains adequate, or even better optimized, for this purpose). However, the Europa Orbiter imaging is unlikely to determine conclusively whether the ocean is responsible for resurfacing and where a lander might find oceanic material. High-resolution imaging over a substantial portion of the surface, under consistent conditions that eliminate observational selection biases, might help, but technological constraints are limiting. If oceanic material is naturally delivered to the surface and an early Europa orbiter cannot recognize it, we may waste decades following an exploration strategy optimized to solve an irrelevant problem.

Another related issue is the possibility that Europa's surface may be vulnerable to forward contamination by terrestrial organisms. This problem has not been given the analytical consideration that it deserves [3], especially given the possibility of a near-surface biosphere. Planning and policy for Europa exploration should include such considerations.

References: [1] Chyba, C., et al. (1999) State of knowledge of Europa, from the Report of the Europa Orbiter Science Definition Team, NASA. [2] Greenberg, R., et al. (2000) *JGR.-Planets, 105,* 17551-17562. [3] Greenberg, R., and B.R. Tufts (2001) *Eos, Transactions AGU*, 82, 26-28.

THE CASE FOR A NEPTUNE ORBITER/MULTI-PROBE MISSION. H. B. Hammel[1], C. C. Porco[2], and K. Rages[3] [1]Space Science Institute (CT Office, 72 Sarah Bishop Road, Ridgefield, CT, 06877, hbh@alum.mit.edu), [2]University of Arizona (LPL, Tucson, AZ, 85721, carolyn@raven.lpl.arizona.edu), [3]Space Physics Research Institute (NASA/Ames, MS 245-3, Moffett Field, CA, 94035-1000, krages@mail.arc.nasa.gov).

Introduction: We propose a mission to the Neptune system comprised of an orbiter with a Neptune atmospheric multi-probe. NASA's Solar System Exploration theme listed a Neptune mission as one of its top priorities for the mid-term (2008-2013) [1]. A recent NASA study also gave it top ranking for rich scientific return and connections to astrophysical problems outside the Solar System (atmospheric structure and dynamics; geology; ring systems/dynamics; magnetic fields/dynamos; pre-biotic chemistry on Triton; local extrasolar planet analog), calling it "almost Cassini-like in scope, near Discovery-like in cost" [2].

Neptune: In spite of (perhaps due to) Voyager's success at Neptune [3] and subsequent studies with HST [4], many questions about Neptune remain unanswered. *Atmospheric dynamics and structure.* What powers the winds, and why are the winds and thermal structure similar to those of Uranus, though the internal heat sources differ? How deep does the zonal structure go? Need: visible imaging and thermal mapping at various phase angles with scales down to 10 km; occultations of radio telemetry signals to probe atmosphere down to ~2 bar. *Atmospheric chemistry.* What is the composition of discrete features (bright and dark), and of the atmosphere as a function of altitude? Need: UV occultations to measure density, scale height, temperature and composition; compositional mapping at near-IR wavelengths. *Planetary interior and magnetic field environs.* Why are the magnetic fields much more asymmetric in ice giants than in gas giants? Need: measurements of magnetic field and magnetospheric particles at a variety of latitudes and longitudes.

Triton: Short of exploring Pluto, exploring Triton may provide our best opportunity to examine the surface and atmosphere of a Kuiper Belt Object analog. *Atmospheric structure and composition.* What is Triton's atmospheric composition and structure, and how has it changed since Voyager [5]? Need: radio occultations for atmospheric size/structure; high phase and high-res (100-300 m) limb imaging for hazes/plumes; UV occultations (density, scale height, temperature, composition); atmospheric sampling (fly-through). *Surface geology and composition.* Is there evidence for "recent" solid-state convective activity in an icy mantle? How does composition vary between/within surface features? What causes geologic structures on Triton's surface? Has the geyser distribution [3] changed since Voyager? Have atmospheric changes modified the surface? Need: UV to near-IR global imaging (<100 m); high-res imaging (10-30 m) of selected locales; thermal (50 and 100 μm) mapping; global 1-km imaging spectroscopy at 1-5 μm with $\lambda/\delta\lambda=300$.

Rings and small satellites: Are the ring arcs of Neptune a "major ring system waiting to happen"? Is a resonant model for arc stability correct? If not, how do arcs remain stable? Do Neptune's inner satellites show the effect of extreme tidal stress? Need: low-phase 100-m scale imaging of arcs to find embedded bodies; high-phase 1-km scale imaging to detect new rings/arcs and to characterize ring/arc morphology; spectroscopic capability to determine composition.

Neptune orbiter: The orbiter is the core of the mission, providing a remote sensing platform, *in situ* probes of the magnetic field and environs, and primary data links. A integrated imaging package would include: visible imager, IR imaging spectrometer, and UV imaging spectrometer. Other remote sensing devices are a thermal IR spectrometer and a microwave radiometer. Space physics detectors might include a magnetometer (and perhaps other instruments). Radio science instruments would also be necessary.

Atmospheric multi-probe: Multi-probes are an essential part of an investigation of the deep (~100 bar) atmospheric structure and chemistry on Neptune. However, significant technology advances would be required to enable high S/N transmission from depth in a cost-effective manner. An optimal probe package would include a main probe (GCMS; sensors for temperature, pressure, and acceleration; solar and IR radiometers; nephelometer) and at least three mini-probes (GCMS; temperature, pressure, and acceleration sensors) to sample diverse atmospheric regions.

Triton lander: A stretch goal would be a miniature surface lander to make *in situ* studies of the satellite's lower atmosphere and surface geology/composition.

Technological challenges: Recent studies indicate a Neptune mission with these capabilities is feasible given innovative technologies [2]: high-power lightweight SEP and solar sails; qualified aeroshells; aerocapture; autonomous spacecraft communications; advances in miniaturization; lightweight power generation systems; temperature-tolerant electronics (~50K); lightweight structures. These technology drivers are required for many outer planet missions; their solutions will be broadly applicable. The Neptune mission's unmatched diversity of science yield should place it at the top of the queue for outer planet exploration.

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A MULTIFUNCTIONAL, MULTISPECTRAL, OUTER PLANETARY IMAGER. R. M. Henshaw, *The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, 20723, USA*, E. H. Darlington, S. E. Hawkins, III, K. J. Heffernan, D. C. Humm, K. Strohbehn, P. Thompson.

Multispectral imaging systems are essential to any future planetary mission. The next generation of imaging systems need to provide high resolution spectral information at equivalent spatial resolution to current imaging systems. Any successful mission to the outer planets requires science payloads that are extremely frugal with resource utilization (such as mass, power, and volume). To achieve multispectral imaging systems which are low mass and power efficient, advanced technology must be applied to the design and development of the optical systems. Any mission to the inner Jovian system must have a high radiation tolerance. We propose a radiation tolerant, resource efficient, dual purpose scientific imager and star camera capable of electronic passband selection and active focus control. The Outer Planetary Imager (OPI) would meet these physical requirements, as well as any science and optical navigation requirements. By applying new technology currently under development at The Johns Hopkins University Applied Physics Laboratory (JHU/APL) to our existing remote sensing expertise, the OPI will feature low mass (~3 kg), low power (~3 W), radiation tolerant electronics and optics, image motion focus control, and electronically controlled optical filtering.

The OPI's potential science return provides a leap in our understanding of planetary surfaces and atmospheres. High resolution (spectrally and spatially), multispectral imaging not only provides images for interpreting geologic landforms, but also provides information for correlating mineral composition with geologic units *at the same spatial scales*, enabling unique insights into a surface's geologic history. For example, at Europa the OPI could measure the compositional variation along lineaments to help distinguishing between different formation models. At Triton this instrument could provide information needed for understanding Triton's sublimation/condensation cycle of ices. The OPI can also be used to study the meteorology of the gas giants.

JHU/APL has established itself as a significant contributor to interplanetary exploration. The Midcourse Space eXperiment and its comprehensive imaging science payload was one of the first closed-loop tracking space experiments for both hyper-spectral imaging and stellar occultation observations. The NEAR mission's Multi-Spectral Imager has demonstrated the extensive possibilities and scientific return from a fixed mounted camera. Current development of CONTOUR's CRISP imager and MESSENGER's Mercury Dual Imaging System represent varied environments and requirements that are being met by JHU/APL's team of engineers, technologists, and scientists. The OPI draws on this development heritage.

The OPI design is flexible and can be tailored to specific mission requirements while maintaining a common baseline design. Sensitivity is a major concern for any optical instrument. Traditionally optical instruments tend to be either large because of very weak illumination or alternatively require longer exposure times to detect weak signals. Long integration times constrain instrument pointing and tracking capabilities. We have developed image motion compensation techniques to improve signal strength and minimize image smear on projects like CONTOUR and the Instrument Incubation Program SCHOONERS.

Through various project funds and Advanced Technology Development (ATD) grants, we continue to develop radiation hardened electronic components such as the Temperature Remote Input/Output (TRIO) chip and the Micro Digital Sun Angle Detector (μDSAD). Radiation resistant glasses are available, but their limited choice of refractive indices results in heavy, complicated designs. Reflective designs have the advantage of being insensitive to radiation damage, and can have large apertures. Mirror design and fabrication advances using composites and silicon carbide make large area, light weight, high quality mirrors possible. The scientific objectives of any mission may demand a wide selection of spectral filters. Standard filter wheels offer a limited selection of wavelengths within detector spectral sensitivities. They typically involve motors and mechanisms that are generally cumbersome, and heavy. We propose using electro-optic tunable filters. Our current ATD research uses liquid-crystal display filters. These filters can be tailored to passbands extending from ~300 nm to ~1.1 μm, with bandwidths of ~5–10 nm. Acousto-optic tunable filters offer even greater spectral resolution.

The OPI detector system consists of an electronically shuttered camera with miniaturized radiation tolerant focal plane support electronics. A visible camera system would use a frame transfer Si CCD, sensitive from ~400–1100 nm, and is extendable into the blue by back-thinning. A modified long-wavelength detector design would use a passively cooled HgCdTe or InGaAs detector. Piezoelectric actuators on the detector mount will permit fine focus corrections and fine motion compensation, including blurring the imager so that the OPI may double as the spacecraft star camera.

ADVANCED RF FRONT END TECHNOLOGY. M. I. Herman[1], S. Valas[1] and L. P. B. Katehi.[2], [1]Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109 m/s 161-213 martin.i.herman@jpl.nasa.gov, [2] The Radiation Laboratory, Electrical Engineering and Computer Science Department, University of Michigan, Ann Arbor Michigan 48109

Introduction: The ability to achieve low-mass low-cost micro/nano-spacecraft for Deep Space exploration requires extensive miniaturization of all subsystems. The front end of the Telecommunication subsystem is an area in which major mass (factor of 10) and volume (factor of 100) reduction can be achieved via the development of new silicon based micromachined technology and devices. Major components that make up the front end include single-pole double-throw switches, diplexer and solid state power amplifier, Figure 1.

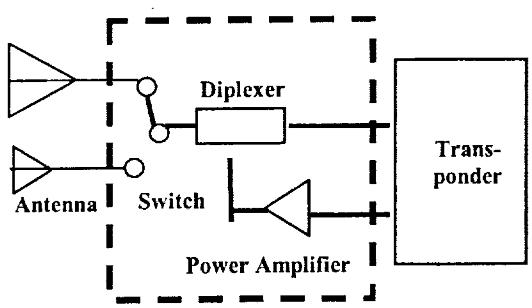


Figure 1. Inside the box outline are the basic front-end components of a Deep Space communication system.

JPL's Center For Space Microsystems - System On A Chip (SOAC) Program has addressed the challenges of front end miniaturization (switches and diplexers). Our objectives were to develop the main components that comprise a communication front end and enable integration in a single module that we refer to as a "cube". In this paper we will provide the latest status of our Microelectromechanical System (MEMS) switches and surface micromachined filter development. Based on the significant progress achieved we can begin to provide guidelines of the proper system insertion for these emerging technologies.

Approach: The baseline approach to our development is silicon technology. The advantages of using silicon are multifaceted Both the semiconductor and the MEMS community have baselined silicon as the dominant technology to develop. The use of silicon as a standard substrate can enable complex subsystem integration via advanced stacking of wafer sections to form complex 3-D components ("cubes"). Compatibility with silicon processing translates to lower manufacturing costs. A final advantage is that this approach is consistent with the other ongoing work in the SOAC program.

RF MEMS Switches: JPL[i] has developed a unique planar RF MEMS design that produces the broadest bandwidth, lowest insertion loss, and highest isolation of any other known single pole double throw (SPDT) switch. Using first order simulations, this design has demonstrated greater than 100 dB isolation and less than 0.6 dB insertion loss from DC to 30 GHz. As a benchmark, the best planar SPDT switches to date made using semiconductor devices provide 40 dB isolation and as much as 2.0 dB of loss with one third of the bandwidth capability of the JPL switch design.

The University of Michigan has been leading the development of core MEMS switch elements that can implement a variety of switch architectures.

Diplexers: The University of Michigan has been pioneering the development of X-band micromachined cavity resonators. The proper combination of resonators results in a filter. A diplexer is a combination of 2 filters to allow for a single physical connection to the antenna port and separate paths between the transmit and receive signals. For Deep Space applications an X-band (7.1 - 8.4 GHz) design has been pursued. Our work indicates that this technology more suitable for fulfilling the desired performance goals (high-isolation low-loss) at Ka-band (32 - 35 GHz).

Future Architecture: Based on progress from this task, advanced Si-based front-end components must be located very close to the radiating element and the transceiver/transponder (to reduce transmission-line loss). This is consistent with advanced nano-spacecraft concepts. The MEMS switches have wideband operation potential. However, the filter technology seems more applicable to future Ka-band applications.

Acknowledgement: The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

[i] NASA New Technology Report (NPO 20663) by Sam Valas, Jet Propulsion Laboratory

DMOSS: DUST MEASUREMENTS IN THE OUTER SOLAR SYSTEM. M.Horányi, G. Lawrence, P. Withnell, *LASP, U. of Colorado (horanyi@colorado.edu; George.Lawrence@lasp.colorado.edu, Peter.Withnell@lasp.colorado.edu)*, A. Tuzzolino, R.B. McKibben, *U. of Chicago (tuzzolino@odysseus.uchicago.edu; mckibben@odysseus.uchicago.edu)*, S. Auer, *A&M Associates (auer@astro.umd.edu)*, E. Grün, *MPIK, Germany (gruen@kosmo.mpi-hd.mpg.de)*, G. Schwehm, H. Svedhem, *ESTEC/ESA (gschwehm@estec.esa.nl; hsvedhem@estec.esa.nl)*.

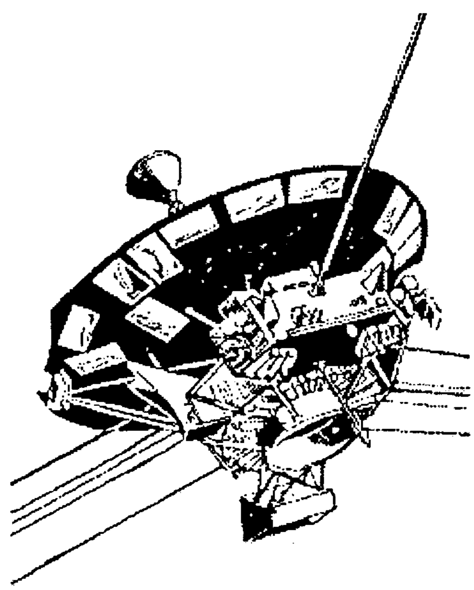
We propose a large surface area ($\simeq 0.5$ m^2), light-weight (< 0.5 kg) and low- power (< 1 w) dust detector to investigate the the dust distribution in the Solar System beyond the orbits of the giant planets.

DMOSS observations will greatly advance our understanding of the origin and evolution of our own Solar System and allow for comparative studies of planet formation in dust disks around other stars. The dust disk around β Pictoris is an example where the observed structure is thought to indicate the presence of planets. We know far more about the outer edges of the dust disks in these distant systems than about our own Solar System's dust disk. DMOSS will make significant contributions towards understanding the origin and evolution of our own Solar System and to compare it with planetary systems around other stars.

Considering the necessary power and weight constraints of an outer Solar System mission, PVDF (polyvinylidene fluoride) film sensors offer an unrivaled detector technology for a large surface area, low-weight and low-power dust experiment. Following the precedent of the dust experiments on the Pioneer 10 and 11 spacecraft, the DMOSS instrument will be mounted on the back-side of a communication antenna (HGA). For an impact speed of 10 km/s, DMOSS can determine the mass of the impacting dust particles in the range of $10^{-12} < m < 10^{-9}$g.

DMOSS is designed with two independent detectors, each comprised of 32 PVDF patches. Each patch is 75 cm^2 in area, resulting a total surface area $S = 2 \times 32 \times 75$ cm^2 = 0.48 m^2.

This 'dual' design allows for a higher level of reliability and also provides redundancy for the most critical components. Figure 1 shows the layout of the PVDF sheets on the HGA of a spacecraft. For a typical impact speed of 10 km/s, DMOSS will determine the mass of an impacting dust grain in the approximate range of $10^{-12} < m < 10^{-9}$ g within a factor of 2 and will provide count-rates for larger particles.



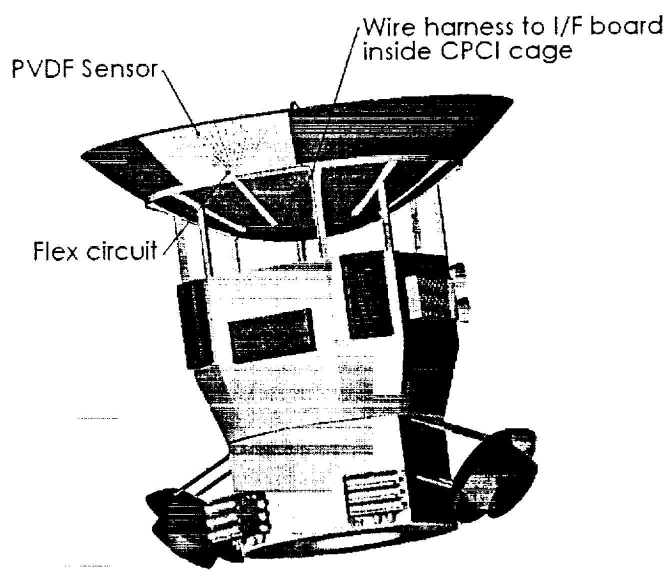


Figure 1: (*left:*) The backside of the Pioneer 10 HGA with the white boxes representing the dust detectors covering a total surface area of 0.57 m^2. (*right:*) One of 2 PVDF sensor sheets (yellow patche) on the back-side of an HGA (the antenna diameter was assumed to be 2 m).

ABSTRACT

Space Fission Propulsion System Development Status

Authors: Michael Houts, Melissa Van Dyke, Tom Godfroy, Kevin Pedersen, James Martin, Ricky Dickens, Eric Williams, Roger Harper, Pat Salvail, Ivana Hrbud, Arthur S. Kirkindall, Kirk Sorensen

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The world's first man-made self-sustaining fission reaction was achieved in 1942. Since then fission has been used to propel submarines, generate tremendous amounts of electricity, produce medical isotopes, and provide numerous other benefits to society. Fission systems operate independently of solar proximity or orientation, and are thus well suited for deep space or planetary surface missions. In addition, the fuel for fission systems (enriched uranium) is virtually non-radioactive. The primary safety issue with fission systems is avoiding inadvertent system start - addressing this issue through proper system design is straightforward.

Despite the relative simplicity and tremendous potential of space fission systems, the development and utilization of these systems has proven elusive. The first use of fission technology in space occurred 3 April 1965 with the US launch of the SNAP-10A reactor. There have been no additional US uses of space fission systems. While space fission systems were used extensively by the former Soviet Union, their application was limited to earth-orbital missions. Early space fission systems must be safely and affordably utilized if we are to reap the benefits of advanced space fission systems.

NASA's Marshall Space Flight Center, working with Los Alamos National Laboratory (LANL), Sandia National Laboratories, and others, has conducted preliminary research related to a Safe Affordable Fission Engine (SAFE). An unfueled core has been fabricated by LANL, and resistance heaters used to verify predicted core thermal performance by closely mimicking heat from fission. The core is designed to use only established nuclear technology and be highly testable. In FY01 an energy conversion system and thruster will be coupled to the core, resulting in an "end-to-end" nuclear electric propulsion demonstrator being tested using resistance heaters to closely mimic heat from fission. Results of the SAFE test program will be presented. The applicability of a SAFE-powered electric propulsion system to outer planet science missions will also be discussed.

Integrated Avionics System (IAS), Integrating 3D technology On a Spacecraft Panel. Don J. Hunter[1]
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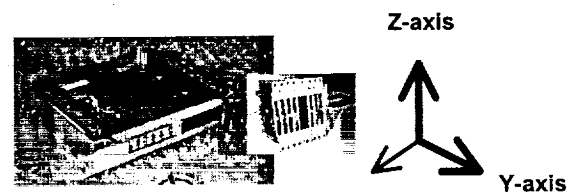
Introduction: As spacecraft designs converge toward miniaturization and with the volumetric and mass constraints placed on avionics, programs will continue to advance the "state of the art" in spacecraft systems development with new challenges to reduce power, mass and volume. Although new technologies have improved packaging densities, a total system packaging architecture is required that not only reduces spacecraft volume and mass budgets, but increase integration efficiencies, provide modularity and scalability to accommodate multiple missions. With these challenges in mind, a novel packaging approach incorporates solutions that provide broader environmental applications, more flexible system interconnectivity, scalability, and simplified assembly test and integration schemes.

This paper will describe the fundamental elements of the IAS, Horizontally Mounted Cube (HMC) hardware design, system and environmental test results.

Architecture: The combination of the New Millennium packaging technology with the X2000 system architecture will produce a product capable of meeting a wide range of mission requirements with a low system recurring cost. The architecture is capable of integrating different instruments, propulsion modules, power sources and telecommunication into a multiple mission platform. The goal is to develop and validate a modular building block design with standard interfaces, enabling this high level of integration with the foresight for future systems on a chip.

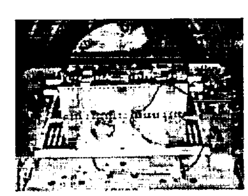
The electrical mechanical architecture is configured to accommodate three different bus configurations. A PCI Bus to handle the high speed Command and Data Handling functions. Signals are propagated across a Z-axis connection system. (Described in the mechanical architecture). The 1394 "firewire" Bus will provide the high data rate for science data acquisition. A third bus, I2C, is a low power bus that is used to accommodate power switching, pyro and temperature sensor interfaces. Both the 1394 and I2C signals propagate through an Y-axis connection system, and across an embedded bus which replaces the traditional spacecraft harness.

The mechanical architecture takes advantage of the technology synergism of the 3-D stack design developed for the X33 and Deep Space 1 programs. The mechanical configuration is made up of three major components. The Horizontal Mounted Cube (HMC), houses the command and data handling, power and attitude control electronics. The Embedded Bus, provides the system interconnectivity for the spacecraft. The third component, made up of a structural panel, integrates all three components. This structure is a load-carrying member of this system, and is used to conduct heat from the HMC to its radiative surface.



Features incorporated in this panel, provide access to the backside of the embedded bus, which maintains rework capability. Interchangeability between engineering or flight subsystems, which provides flexibility for the system design team to develop a spacecraft configuration independent of the Avionics. These components create the Integrated Avionics System (IAS). A unique multi-configurable system, which is designed across several engineering disciplines. The mission design, and the spacecraft, is optimized to reduce the workload and shorten the development, integration and test activities.

System Test and Conclusion: The dynamic and thermal environmental tests performed, validated that packaging design can meet or exceed predicted performance. The instu dynamics test results indicated no opens during the entire test duration, and the thermal vacuum test proved the 3-D stack and IAS design have been proven to efficiently reject heat to an external environment.



References:

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[1] Author Don Hunter. (1999) iMAPS,*MCM99,* 80–84

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Molecularly Imprinted Polymer Geochemical Detectors for Outer Solar System Exploration. N. R. Izenberg and O. M. Uy, JHU Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD, 20723. noam.izenberg@jhuapl.edu

Introduction: Molecularly imprinted polymer (MIP) geochemical detectors translate new fiber optic sensor technology to planetary and space environment applications. Characterization of planetary atmospheres, their variability with altitude, time, and geographic location, and their physical and chemical relationships with planetary surfaces are fundamental to the understanding of planetary geology, climate, and evolution. Solid state, low mass, low power, low volume tools for determining atmospheric constituents and activity will enable significant improvement in our understanding of the atmospheres of the outer planets and their moons, terrestrial planets, and other solar system bodies (e.g. active comets).

MIP Detectors: The development of optical fibers for the communications industry has provided a flexible means for sensing light [1]. Chemical sensing using fiber optic fluorimmunoassay to 10^{-12} molar levels has been demonstrated for some time [e.g. 2]. The direct sensing of specific gases based on their molecular structure using fiber optic sensors is a more recent development.

Direct sensing requires the synthesis of a polymer around a specific gaseous molecule of interest. After synthesis of the polymer, the target molecule (the analyte) is removed, leaving a three-dimensional imprint or template within the polymer [3, 4, 5]. The imprinted polymer is then coated on an optical fiber and used as an inexpensive yet highly sensitive chemical sensor [6].

A vast range of atmospheric or aqueous species can be detected directly by this simple, solid state sensor. When an imprinted species is present, its "key" fits into the MIP "lock," the change in reflectance altering the spectrum of reflected light. The wavelength and magnitude of the reflected light seen by a miniature spectrometer determine the abundance of the target species and differentiate possible contaminants. MIP technology is under active development at JHU/APL under Department of Energy and Independent Research and Development grants to create simple, reliable, portable detectors for nerve agents and explosive traces in water and air, and consumer-level food-spoilage indicators. Current R &D work focuses on space qualification of the technology for planetary exploration instrumentation.

Outer Planet Geochemistry: MIP geochemical detectors are designed to answer specific key questions such as: *What are the atmospheric constituents of the gas giant planets and their companion moons?* Key species such as water vapor and NH_3 are poorly constrained from earth and present spacecraft observations because they form condensation clouds, are easily photolyzed, and absorb onto internal surfaces of mass spectrometers [7]. Moons such as Europa and Titan likely possess oceans and/or atmospheres with complex chemical mixtures, and possibly organic constituents easily quantified by MIP detectors. Io and Triton have unique atmospheres generated by high temperature volcanism and cryovolcanism, respectively. MIP detectors should be sensitive enough to study constituents of thin, sputtered (Europa) or sublimated (comet) atmospheres. MIP-based atmosphere probe and/or lander instruments will provide a reliable, low cost, low mass sensor technology capable of answering these questions and more.

The translation of the sensor technology to a usable planetary geochemical sensor is ongoing, relying primarily on testing of key species at ambient planetary conditions. Mission-quality instruments will employ hundreds of these detectors, each keyed to target species, on descent vehicles, aerobots, landers, rovers, and/or microstations to study atmospheric properties at multiple altitudes and/or geographic locales on a planetary surface. Slight modifications would enable direct sensing of liquids (e.g. melted ices or liquid oceans on the Jovian and Saturnian moons) as well. A first generation 4"x2"x2" atmospheric MIP geochemical instrument is targeted to mass 1.5 kg, draw 1.5 W power, and detect sixteen unique species from percent levels to parts per billion by volume.

MIP detectors represent a true advance in geochemical sensors, with greater precision than gas chromatography (GC), and greater specificity than mass spectrometry (MS). Fiber optic detectors will have significantly lower mass, power, and cost requirements, and higher speed and robustness than current sensor types (including "hyphenated" GC-MS instrument combinations).

References: [1] JTEC Panel Report, S. Forest, Chair, ITRI, Loyola College, MD., Feb. 1996. [2] Walczak et al. *J. Biosensor and Bioelectronics* 7, 39-48, 1992. [3] Jenkins et al. *Analytical Comm.* 34, 221-224, 1997. [4] Murray et al. *JHU/APL Tech. Dig.* 18 (4), 464-472, 1997. [5] Arnold et al. *JHU/APL Tech. Dig.* 20 (2), 190-198, 1999. [6] Murray et al., Attorney Patent Docket 1290, filed April 28, 1999. [7] Lodders and Fegley, *The Planetary Scientist's Companion*, 371 pp., Oxford University Press, New York, NY, 1998.

AN ACTIVE SUBSTRATE DRIVER FOR ENABLING MIXED-VOLTAGE SOI SYSTEMS-ON-A-CHIP.

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Introduction: The current trend for space application systems is towards fully integrated systems-on-a-chip. To facilitate this drive, high-voltage transistors must reside on the same substrate as low-voltage transistors. These systems must also be radiation tolerant, particularly for space missions such as the Europa Lander and Titan Explorer. SOI CMOS technology offers high levels of radiation hardness. As a result, a high-voltage lateral MOSFET has been developed in a partially-depleted (PD) SOI technology [1]. Utilizing high voltages causes a parasitic transistor to have non-negligible effects on a circuit. Several circuit architectures have been used to compensate for the radiation induced threshold voltage shift of the parasitic back-channel transistor [2,3]. However, a new architecture for high-voltage systems must be employed to bias the substrate to voltage levels insuring all parasitic transistors remain off. An active substrate driver has been developed to accomplish task [4].

Circuit Description: The simplified architecture of the active substrate driver is provided in Figure 1. A 1μA current is forced through an *n*-type back-channel transistor (BCT). The associated top-channel channel (TCT) is connected ($V_{GS,TCT}$=0V) to remain off. The source of this BCT is biased to –5V (provided by an on-chip charge pump), insuring that its gate-source voltage is 5V greater than any other *n*-type BCT on the chip. Feedback will force this V_{GS} to a level allowing 1μA current to flow in this one BCT. This V_{GS} will be slightly larger than $V_{TN\text{-}BC}$, forcing the substrate voltage to be approximately 5V less than the $V_{TN\text{-}BC}$ of all other n-channel BCTs on the chip. With high levels of irradiation, both $V_{TN\text{-}BC}$ and $V_{TP\text{-}BC}$ will shift in the same direction by approximately the same amount. The active substrate driver will shift the substrate voltage by the same amount, keeping all *n*-type and *p*-type back-channel devices off.

The amplifier within Figure 1 has a low-voltage input stage (5V) and a high-voltage output stage (40V). The amplifier's output stage can provide a high-voltage output (approximately 2V to 38V). Since the amplifier directly drives the substrate and the substrate to ground capacitance can vary significantly with buried oxide thickness and die size, the stability requirements of the amplifier take into account substrate capacitance ranging from 10pF to 100pF.

Implementation and Simulation: The layout for the active substrate driver occupies a chip area of approximately 250 μm by 270 μm in a 0.8μm PD SOI technology. The high-voltage transistors are separated from low-voltage transistors by at least 10 μm. This insures thick insulating silicon dioxide between the transistors. The charge-pump has its own power supplies to reduce switching noise seen by the amplifier.

Figure 2 shows the simulation of the active-substrate driver tracking a shift in threshold voltage. BSIM3v3 device models were utilized. As V_{TH} changes, the substrate voltage follows. This simulation illustrates the fully functional active substrate driver tracking the parasitic back-channel threshold voltage shift.

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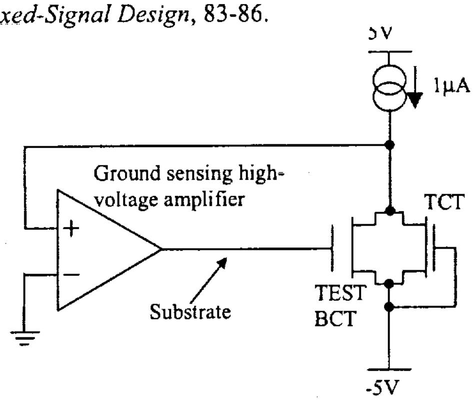
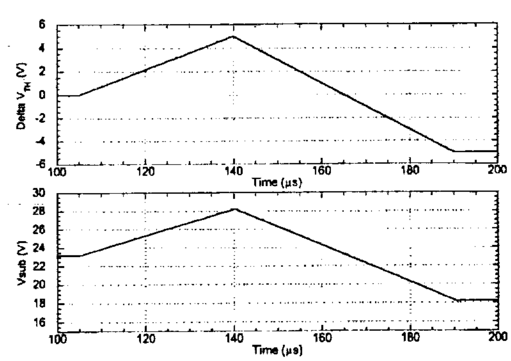


Figure 1. Active substrate driver architecture.
Figure 2. Simulated threshold voltage tracking.



Delay/Doppler Radar Altimetry for Outer Planet Applications. J. R. Jensen and R. K. Raney, The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel, Maryland, 20723, bob.jensen@jhuapl.edu.

Introduction: New concepts which improve the design and performance of spaceborne radar altimeters for remote sensing of the Earth can be applied to the mapping of extraterrestrial bodies. An inherent advantage of a radar altimeter is that it is capable of application where the atmosphere of the body being observed is opaque to micron-scale wavelengths. Furthermore, radar altimeters are typically pulse-limited, so the measurement area is determined by the intersection of the transmitted pulse with the surface. This limits the sensitivity of the altitude measurement to the spacecraft attitude knowledge. The recently developed and demonstrated delay/Doppler concept combines these advantages with a reduction in the size of the altimeter through more efficient use of the backscattered power and improvement in the along-track spatial resolution.

The delay/Doppler altimeter was originally proposed because of its many advantages in Earth altimetry (open water, sea ice, continental ice sheets, etc.), but the basic concept has wide application, including subsurface sounding as well as altimetry. This sounding application is being considered for the search for subsurface water on Mars and Europa. Altimetry is also a primary data set for geophysical studies (e.g., measurements of planetary tides, rotation state/libration) which provide fundamental constraints on origins and evolution, as well as geological processes (e.g., volcanic, tectonic) that affect topography. This instrument orbiting Europa or Triton can provide key measurements for the understanding of crustal tidal effects which have implications for geologic processes that may contribute to resurfacing. A delay/Doppler altimeter can distinguish between diffuses and specular reflecting surfaces and therefore between solid and liquid surfaces which can be useful in determining the presence of methane ponds on Titan.

The Delay/Doppler Altimeter Concept: The delay/Doppler altimeter differs from a more conventional radar altimeter in that it exploits coherent processing of groups of transmitted pulses and the full Doppler bandwidth is exploited to make the most efficient use of the power reflected from the surface [1]. This is a significant improvement over simple Doppler beam sharpening. In order to exploit this full bandwidth, the range variation that exists across the Doppler bins is removed as part of the data processing.

The reflected pulses from a given area of the observed surface are exploited over the entire time that that area is within the radar beamwidth. As a result, much more of the reflected energy is exploited and a smaller transmitted power is required to obtain a given level of performance.

Coherent processing reduces the along-track size of the measurement area from that which would otherwise be possible. This provides some immunity from errors that are introduced as a result of the along-track slope of the surface. The across-track dimension of the measurement is unaffected. Development and demonstration of a delay/Doppler radars altimeter has been supported by the NASA Instrument Incubator Program. This has resulted in a successful airborne flight of the instrument over the Greenland ice sheet.

Candidate Instrument Design: The parameters for a candidate instrument design for outer planet exploration are presented in Table 1. The transmit/receiver antenna is a patch array measuring 0.2 by 0.2 m that is flush mounted on a nadir pointing surface of the spacecraft. While the range samples are separated by 2 m, consistent with the 75 MHz pulse bandwidth, much finer range resolution of the final surface elevation is possible through analysis of the observed waveform shape [2]. This has been well demonstrated in Earth remote sensing where the 0.47 m range interval of the Topex altimeter, for example produces ocean altimetry precision at the 2- cm level.

Because the radar operates at 35 GHz, it is capable of operating over surfaces that are obscured by a dense atmosphere. Radar observations have succeeded in mapping the surface of Venus, for example.

Conclusions: Outer planet surface elevation can be measured with a radar altimeter that employs new concepts that have been developed and demonstrated for Earth remote sensing. It is now possible to make such measurements using less transmitted power and with greater spatial resolution and immunity to along-track slope effects than has been previously possible.

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Table 1. Candidate Delay/Doppler Altimeter

Parameter	Value
frequency	35 GHz, Ka-band
wavelength	0.008 m
antenna size	0.2 x 0.2 m
transmitted power	0.5 w peak, 0.05 w ave
transmitted pulse length	500 μs
pulse bandwidth	75 MHz
range interval	2 m
pulse rate	200 Hz
instrument mass	3 kg

A LARGE ARRAY OF SMALL ANTENNAS TO SUPPORT FUTURE NASA MISSIONS. D. L. Jones[1], S. Weinreb[2], and R. A. Preston[1], [1]Jet Propulsion Laboratory, California Institute of Technology, mail code 238-332, 4800 Oak Grove Drive, Pasadena, CA 91109 (dj@sgra.jpl.nasa.gov; rap@sgra.jpl.nasa.gov), [2]Jet Propulsion Laboratory, California Institute of Technology, mail code 168-214, 4800 Oak Grove Drive, Pasadena, CA 91109 (Sander.Weinreb@jpl.nasa.gov).

Introduction: A team of engineers and scientists at JPL is currently working on the design of an array of small radio antennas with a total collecting area up to twenty times that of the largest existing (70-m) DSN antennas. An array of this size would provide obvious advantages for high data rate telemetry reception and for spacecraft navigation. Among these advantages are an order-of-magnitude increase in sensitivity for telemetry downlink, flexible sub-arraying to track multiple spacecraft simultaneously, increased reliability through the use of large numbers of identical array elements, very accurate real-time angular spacecraft tracking, and a dramatic reduction in cost per unit area. NASA missions in many disciplines, including planetary science, would benefit from this increased DSN capability. The science return from planned missions could be increased, and opportunities for less expensive or completely new kinds of missions would be created. The DSN array would also be an immensely valuable instrument for radio astronomy. Indeed, it would be by far the most sensitive radio telescope in the world.

The Deep Space Network Array Concept: The current concept for the DSN array is based on 4000 commercially mass-produced parabolic antennas, each 5 meters in diameter, and operating at 8 and 32 GHz. The total cost for this array is estimated to be far less than the cost of an equivalent collecting area provided by traditional large-diameter (34-m or 70-m) antennas. If funding begins early in FY 2002, a two-element test interferometer could be running by December 2003, a prototype array with an area equivalent to a single 70-m diameter antenna could be finished by the middle of 2005, and construction of the full DSN array could be started in early 2007 and be completed by the end of 2009.

Advantages of a Large Array for the DSN: There are a number of reasons for DSN interest in a large array of many small antennas:

- Large decrease in cost per decibel of link margin
- Lighter, lower power, and less expensive spacecraft telemetry hardware
- Flexible scheduling – simultaneous tracking of multiple spacecraft over wide areas of the sky
- New spacecraft navigation capability: real time, high precision angular position measurements – complements range and Doppler data and provides full 3-D spacecraft positions without the need for trajectory modeling or for long tracking passes
- High reliability – graceful degradation of array performance if individual antenna elements fail; moving mechanical parts are small and light weight; simplified operations and low-tech maintenance
- Array is continuously expandable and upgradable
- Enable new types of mission: radio occultation measurements with very distant spacecraft, direct reception of lander/rover/penetrator signals on earth, multi-spacecraft interferometer arrays, spacecraft with no on-board data storage, down-links with both high data rates and high duty cycles

The most frequently discussed configuration for the DSN tracking array consists of a central region containing a dense network of array elements along with a smaller number of elements spread over a large (>100 km) geographic area. Such a configuration combines ease of phasing the central elements for telemetry reception and more precise spacecraft position measurements with the longer baselines. A separate, but potentially important, benefit for spacecraft navigation is the ability to detect and image the thermal emission from a large number of solar system targets, including asteroids and moons as well as planets. This will provide accurate positions for these targets in the same reference frame as the astrometric spacecraft tracking measurements.

Summary: Future NASA missions will require high downlink data rates to maximize their scientific productivity. Higher frequency RF and optical communication systems are being developed for this purpose, but it will probably be more cost effective to provide additional downlink data rate capability with a large increase in ground antenna area, especially if the cost per unit area is reduced significantly. In addition, missions with short-duration, high priority phases such as planetary flybys, radio occultations, atmospheric probe arrivals, etc., would require less on-board data storage if higher real-time downlink rates were available. Finally, very low power signals from landers, atmospheric probes, or ground penetrators could be received directly on Earth, giving additional geometric information and greater mission redundancy. Placing more of the complexity and mass of a communication link on Earth rather than on a spacecraft could open up entirely new ways of doing planetary science, and the cost of a ground array can be amortized over a large number of future NASA missions (not just planetary ones). For all of these reasons one or more large, low-cost arrays are a promising approach for NASA spacecraft tracking during the next decades.

INFLATABLE VEHICLES FOR IN-SITU EXPLORATION OF TITAN, TRITON, URANUS, NEPTUNE

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Background: Space Inflatable vehicles have been finding popularity in recent years for applications as varied as spacecraft antennas, space-based telescopes, solar sails, and manned habitats [1]. Another branch of space inflatable technology has also considered developing ambient-filled, solar balloons for Mars as well as ambient-filled inflatable rovers [2]. More recently, some of these inflatable technologies have been applied to the outer solar system bodies with the result that **there are some rather unique and compelling inflatable mission capabilities for in situ explorations of Titan, Triton, Uranus, and Neptune.**

Titan: Titan is the largest moon of Saturn and the only moon in our solar system with a significant atmosphere. The atmosphere is composed primarily of nitrogen and has a surface pressure of about 1.4 bar with a temperature of about 93K [3]. With a density of about four times that of Earth's surface atmosphere, Titan is ideal for ballooning. A relatively small helium balloon (3-m diameter) can easily lift a 50-kg payload to 10-km altitude. For one balloon mission on Titan, JPL has proposed filling helium into three large spherical tires (2-m diameter) of a 50-kg inflatable rover, such that the rover could be flown as a controllable aerovehicle. Using periodic venting and ballasting, the balloon could land and re-ascend numerous times before ultimately replacing the helium with ambient atmosphere (Figure 1). The heavier-than-air vehicle could then conduct an extensive amphibious surface exploration of Titan's solid surfaces, as well as of its anticipated liquid methane/ethane lakes and seas. A prototype inflatable rover presently exists at JPL and is being evaluated for airborne, as well as liquid mobility.

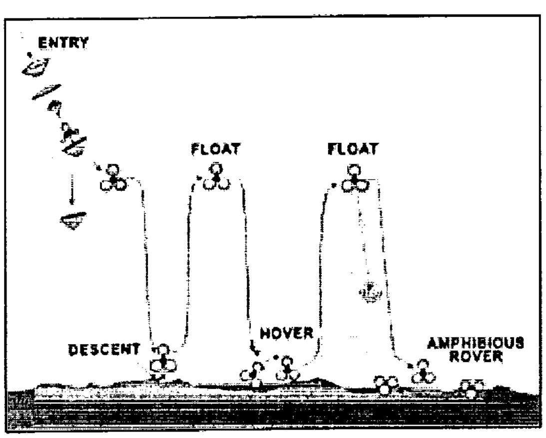

Figure 1. Titan Mission Sequence

Triton: The atmosphere of Neptune's largest moon, Triton, is also constituted primarily of nitrogen, although it is very thin (~ 17 microbar) and cold (38 K). Surface winds have been estimated to be about 5-15 m/sec [4], with locally stronger winds possible. Although an inflatable rover would generally be expected to function well on Triton's surface, the atmosphere is much too thin to support any balloon activity. One intriguing possibility for Triton, however, is to encase a small payload inside a spherical "beachball" that acts as a both a descent vehicle and a landing vehicle. A 3 m diameter sphere (~ 3 kg) could land a 3 kg payload with a terminal descent speed of about 100 m/sec, while a 10 m diameter thinner sphere (~8 kg) would have a terminal velocity of about 43 m/sec. **After acting as parachutes, the spheres could then act partially as airbags. Furthermore, upon landing, moderate winds could propel beachball payloads to explore new locations on Triton.**

Uranus and Neptune: Previous work has shown balloons may be possible at Jupiter and Saturn by using solar heat [5], but that Uranus and Neptune receive much too little sunlight. Of all the moons and planets in our solar system, however, only Uranus and Neptune possess the unusual characteristic that the molecular weight of the atmosphere in the upper stratosphere is significantly lower than that in the lower troposphere. This unique characteristic, which is due primarily to methane condensation, allows balloons to be filled while falling in the stratosphere, and then to be fully buoyant in the troposphere [6]. For example, a 5-kg balloon filled in the Neptune stratosphere can be used to easily float a ten-kg payload in the troposphere, from where deep atmosphere sondes could be dropped. **These balloons are, in fact, the only practical manner yet proposed to allow long-term in situ exploration of Uranus and Neptune.**

Acknowledgements: The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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TITAN AIRSHIP SURVEYOR. V.Kerzhanovich[1], A.Yavrouian[2], J.Cutts[3], A.Colozza[4], D.Fairbrother[5], [1] M/S 198-219 Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, E-mail: Viktor.V.Kerzhanovich@jpl.nasa.gov, [2] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, E-mail: Andre.H.Yavrouian@jpl.nasa.gov, [3] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, E-mail: James.A.Cutts@jpl.nasa.gov, [4] Mail Stop 301-3, NASA Glenn Research Center, 21000 Brookpark Rd., Cleveland, Ohio 44135, E-mail: Anthony.Colozza@grc.nasa.gov, [5]NASA Goddard Space Flight Center, Wallops Flight Facility, Balloon Program Office, Code 820, Bldg E-107, Room 313, Wallops Island, VA 23337
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Saturn's moon Titan is considered to be one of the prime candidates for studying prebiotic materials – the substances that precede the formation of life but have disappeared from the Earth as a result of the evolution of life. A unique combination of a dense, predominantly nitrogen, atmosphere (more than four times that of the Earth), low gravity (six times less than on the Earth) and small temperature variations makes the Titan almost ideal planet for studies with lighter-than-air aerial platforms (aerobots). Moreover, since methane clouds and photochemical haze obscure the surface, low-altitude aerial platforms are the only practical means that can provide global mapping of the Titan surface at visible and infrared wavelengths. One major challenge in Titan exploration is the extremely cold atmosphere (~ 90K). However, current material technology the capability to operate aerobots at these very low temperatures. A second challenge is the remoteness from the Sun (10AU) that makes the nuclear (radioisotopic) energy the only practical source of power. A third challenge is remoteness from the Earth (~10 A.U., two-way light-time ~160 min) which imposes restrictions on data rates and makes impractical any meaningful real-time control. A small-size airship (~25 m^3) can carry a payload ~100 kg. A Stirling engine coupled to a radioisotope heat source would be the prime choice for producing both mechanical and electrical power for sensing, control and communications. The cold atmospheric temperature makes Stirling machines especially effective. With the radioisotope power source the airship may fly with speed ~ 5 m/s for year or more providing an excellent platform for *in situ* atmosphere measurements and a high-resolution remote sensing with unlimited access on a global scale. In a station-keeping mode the airship can be used for in situ studies on the surface by winching down an instrument package. Floating above the surface allows relatively simple means for flight control. Mission requirements and possible methods of navigation, control, data acquisition and communications are discussed. The presentation describes also the state-of-the art and current progress in aerially deployed aerobots.

SOUNDING OF ICY GALILEAN SATELLITES BY SURFACE OBSERVATORIES. K.K. Khurana[1], W.B. Banerdt[2], T.V. Johnson[2], C.T. Russell[1], M.G. Kivelson[1], P.M. Davis[1], J.E. Vidale[1], [1]Institute of Geophysics and Planetary Physics, UCLA, Los Angles, CA 90095-1567, kkhurana@igpp.ucla.edu, [2]Jet Propulsion Lab., 4800, Oak Grove Dr. Pasadena, CA, 91109-8099.

Introduction: Several independent geological and geophysical investigations suggest that Europa [1] and Ganymede [2, 3] contain subsurface oceans. Using Jupiter's rotating magnetic field as a primary signal, the magnetometer experiment onboard Galileo has measured secondary induction signals emanating from Europa [4], Ganymede [2] and *surprisingly* Callisto [4, 5]. The strong electromagnetic induction from these moons suggests that large global electrical conductors are located just below their icy crusts. A detailed analysis reveals that global salty oceans with salinity similar to the Earth's ocean and thicknesses in the range of ~ 6 -100 kms can explain the induction observed by the Galileo magnetometer [5].

Limitations of Galileo's Observations: Although Galileo's geological and geophysical observations have provided vital clues to the interior structure, dynamics and the presence of liquid water in the icy satellites, none of the inferences is unambiguous because of the limited nature of the observations. Alternate models that do not postulate liquid oceans can explain many of the observations [1, 3]. These observations also constrain the internal structures rather poorly. For example, the permissible range of sizes for the postulated metallic core of Ganymede are anywhere between 0.15 and 0.5 R_G [6]. Future orbiter missions with systems like ice penetrating radars will undoubtedly improve our knowledge of the upper icy crusts and the locations of the oceans. However, ambiguities about the thicknesses of the oceans and deeper structures are likely to persist.

A Future Observation Strategy: We contend that observations made from as few as two surface observatories comprising a magnetometer and a seismometer offer the best hope of unambiguous characterization of the 3-dimensional structure of the oceans and the deeper interiors of the icy moons. The observatories could also help us infer the composition of the icy crust and the ocean water. On the Earth, magnetic measurements are used routinely to probe the upper and lower mantle and seismic observations have located and characterized the liquid outer core and the solid inner core. In a similar way, normal mode seismic observations of background noise may reveal the gross radial structure of the moon. Satellite-quakes, interesting in their own right, are likely to provide signals for the seismic measurements on Europa and Ganymede. Asteroid impacts would also contribute to the background signals. Seismic technique are especially suited for locating liquids like subsurface oceans because the S waves are unable to propagate through liquids and a liquid/solid interface tends to be a strong reflector of both the P and S waves.

Magnetic sounding is also extremely well suited for the Galilean satellites because Jupiter provides a natural strong primary signal. From continuous observations from just two magnetic observatories over a few weeks, both the internal (the response of the moon) and the external (Jupiter's primary signal) harmonics can be uniquely determined over a range of frequencies. Electromagnetic sounding at multiple frequencies from fixed locations has the potential of providing unique estimates of both the conductivity and the thickness of the ocean. If periods longer than two weeks can be measured in the induction signal, invaluable information on the locations and conductivities of the cores can be obtained.

SOUNDERs: To probe the Galilean satellites interiors, we introduce the concept of SOUNDERs, Surface Observatories for UNDErground Remote-sensing. Extremely lightweight (< 5 kg total mass) and autonomous, these observatories could be deployed as penetrators from an orbiting spacecraft. A typical SOUNDER would comprise a fluxgate vector magnetometer, a three-axis seismometer, a data processing unit and a transmission unit. Because modern miniaturization techniques allow the observatories to be extremely lightweight, several of them could be carried on a single spacecraft and deployed to multiple sites on multiple satellites. By design, the penetrator-borne observatories would be buried under tens of centimeters of ice, so that the high radiation in the environment can be overcome. The SOUNDERs can also complement other instruments on the proposed future Europa lander mission to study Europa's pre-biotic chemistry. We will discuss issues relating to thermal control, power source and communication.

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A Combined Gamma-Ray and Neutron Detector for Measuring the Chemical Composition of Comets and other Planetary Bodies. D. J. Lawrence, B. L. Barraclough, W. C. Feldman, T. H. Prettyman, and R. C. Wiens; Los Alamos National Laboratory, Group NIS-1, Mail Stop D466 (djlawrence@lanl.gov).

Introduction: Galactic cosmic rays (GCR) constantly impinge all planetary bodies and produce characteristic γ-ray lines and leakage neutrons as reaction products. Together with γ-ray lines produced by radioactive decay, these nuclear emissions provide a powerful technique for remotely measuring the chemical composition of airless planetary surfaces. While lunar γ-ray spectroscopy was first demonstrated with Apollo Gamma-Ray (AGR) measurements [1], the full value of combined γ-ray and neutron spectroscopy was shown for the first time with the Lunar Prospector Gamma-Ray (LP-GRS) and Neutron Spectrometers (LP-NS) [2]. Table 1 shows the wide variety of lunar composition measurements that have been made to date using LP γ-ray, thermal, epithermal and fast neutron data.

Table 1

Measured quantity (abundances)	Technique	Instrument	References
K, Th, Fe, and Ti	γ-rays	LP-GRS	3, 4, 5, 6, 7
Enhanced polar H	epi. neutrons	LP-NS	8, 9, 10
Global H	epi. neutrons	LP-NS	11, 12
Gd and Sm	therm and epi. neutrons	LP-NS	13, 14
Mafic content	therm, epi. neutrons; γ-rays	LP-NS/LP-GRS	15, 16
Average soil mass	fast neutrons	LP-GRS	17, 18

Analysis of other elements such as Ca, Mg, O, Al and U should soon be completed using LP-GRS data. Furthermore, it has been shown that measurements of thermal neutrons provide an important correction (up to a factor of 3) to measurements of neutron-capture γ-ray lines such as those from Fe and Ti [6, 7]. With the inclusion of a γ-ray instrument on the NEAR mission [19], and γ-ray and neutron instruments on missions to Mars [20] and Mercury [21], it is clear that γ-ray and neutron spectroscopy (GR/NS) is becoming a standard technique for planetary science missions. While we are focusing here on using GR/NS for future cometary missions, these techniques will also provide powerful ways of measuring the surface composition on rocky and icy moons and asteroids.

GR/NS related to comets: Comets are thought to be primitive solar system bodies [22] and possibly precursors to the development of life on Earth. In order to understand how comets relate to the formation of the solar system, it is important that we understand their surface composition (which in turn reveals information about the bulk composition of comets). However, aside from suspecting that most cometary crusts are dominated by refractory elements, very little is directly known about the surface composition of comets. In the context of a comet sample analysis and/or sample return mission, a GR/NS would yield breakthrough science as well as provide critical input to a comet nucleus sample site selection by directly mapping the surface composition of a cometary nucleus. Specific measurement objectives of a GR/NS would include the following: 1) Measure the average surface composition of the nucleus; 2) Map compositional variations and assess the extent of heterogeneity on the surface of the nucleus; 3) Search for near-surface ices to depths of 100 g/cm^2; 4) Use all of the above measurements to support site selection for a landed *in situ* analysis and/or sample return acquisition.

Instrument Description: Any new Outer Planetary mission will likely have the requirement that instrument mass and power be kept to a minimum. To satisfy such requirements, we have been designing a GR/NS instrument which combines all the functionality of the LP-GRS and LP-NS for a fraction of the mass and power. Specifically, our design uses a BGO scintillator crystal to measure γ-rays from 0.5 – 10 MeV. A borated plastic scintillator and a lithium glass scintillator are used to separately measure thermal, epithermal, and fast neutrons as well as serve as an anticoincidence shield for the BGO. All three scintillators are packaged together in a compact phoswich design. Modifications to this design could include a CdZnTe γ-ray detector for enhanced energy resolution at low energies (0.5 – 3 MeV). While care needs to be taken to ensure that an adequate count rate is achieved for specific mission designs (e.g. r_{orbit}/R_{body} is a critical parameter), previous mission successes, particularly for $r_{orbit}/R_{body}<2$, demonstrate that a combined GR/NS provides essential information about planetary surfaces.

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ULTRA LOW POWER, RADIATION TOLERANT UHF RADIO TECHNOLOGIES FOR IN SITU COMMUNICATION APPLICATIONS. N. E. Lay, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, e-mail: norman.e.lay@jpl.nasa.gov.

Introduction: For future deep space missions, significant reductions in the mass and power requirements for short-range telecommunication systems will be critical in enabling a wide variety of new mission concepts. These possibilities include penetrators, gliders, miniature rovers and sensor networks. Under joint funding from NASA's Cross Enterprise and JPL's Telecommunications and Mission technology programs, recent development activity has focused on the design of ultra low mass and power transceiver systems and subsystems suitable for operation in a flight environment. For these efforts, the functionality of the transceiver has been targeted towards a specific Mars communications scenario. However, as depicted in Figure 1, the overall architecture is well suited to any short or medium range application where a remote probe will aperiodically communicate with a base station, possibly an orbiter, for the eventual purpose of relaying science information back to Earth. In 2001, these sponsors have been augmented with collaborative expertise and funding from JPL's Center for Integrated Space Microsystems in order to migrate existing concepts and designs to a System on a Chip (SOAC) solution.

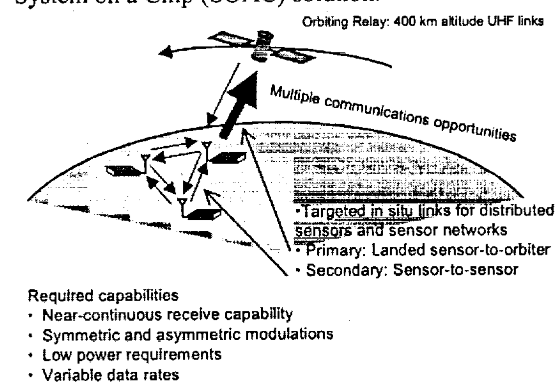

Figure 1. In Situ Communications Scenario

Communications Link, Functionality and Design Goals: As previously mentioned, the nominal communications link is based on Martian surface-to-orbiter communications for 400 and 800 km altitude orbits. Link analyses indicate that even at slant ranges amounting to nearly twice the orbit altitude (low horizon), substantial margins exist for low data rate (less than 1000 bps) command downlinks utilizing simple uncoded modulations. This in turn can reduce the complexity of the surface probe's receiver and allow for design approaches that tradeoff communications performance against power consumption to aid in mission longevity. The higher rate uplink, used for science data return, will employ a different, power efficient modulation and coding scheme and it is expected that the transmitter power consumption will be dominated by the power amplifier requirements. This results in a basic functionality consisting of a commandable, uplink communications transmitter. In terms of design goals, this transceiver development is aimed at achieving a better than ten times improvement in receiver power consumption as compared to other recent, short-range communications subsystems.

Current Status and Future Activity: To date, systems analysis has been performed to drive baseline functional specifications for the transceiver. Receiver and transmitter developments have proceeded in parallel with the low power receiver representing the greater developmental challenge. A multi-rate FSK baseband receiver ASIC (Figure 2) has been designed and fabricated by UCLA on a commercial CMOS process [1]. A prototype RF front end has also been developed utilizing discrete components to test the receiver performance. While the ASIC requires less than 2 mW for operation, the discrete front end consumes far more than the design goal. Consequently, the next stage of development will be directed towards RF integrated circuit (RFIC) design targeting a radiation tolerant or hardened process, such as Honeywell's Silicon-on-Insulator CMOS (SOIC). These designs will be captured both as prototype ASICs and as IP (intellectual property – reusable IC designs) for ultimate integration within any SOAC applications requiring telecom. Further evolution of this work will gradually integrate RF and digital IC designs onto a single ASIC and also merge transmitter and receiver functions. The development of these designs will be performed in a modular fashion to ultimately provide a reservoir of rapidly infusible functions tailored to future short-range communications needs.

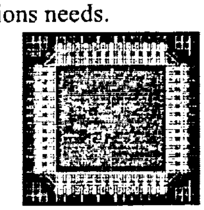

Figure 2. UCLA Ultra Low Power, Digital Baseband, FSK Receiver ASIC (0.25 μm CMOS)

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ReMaSp: a Reflectron time-of-flight Mass Spectrometer. S. A. Livi[1], D. L. Domingue[1], W. B. Brinkerhoff[1], and P. Wurz[2], [1]Johns Hopkins University Applied Physics Laboratory, [2]Physikalisches Institut, University of Bern.

Introduction: The ReMaSp (Reflectron Mass Spectrometer) is designed to analyze in situ the chemical and isotopic composition of the gaseous environment of planets and small bodies. Analysis of the local gas composition establish ground truth for remote observations, and can determine parameters that are otherwise difficult, if not impossible to obtain, like isotope ratios or abundance of noble gases and organic compounds.

The intrinsic high mass resolution ($\Delta m/m > 1000$), high sensitivity (10^{-3} A/torr), working pressure range (10^{-15} to 10^{-4} Torr), and radiation resistance (> 100 krad) of the proposed sensor are well suited to address several key questions regarding outer solar system bodies, from comets to planetary satellites.

This instrument placed on a cometary mission can address such issues as the presence of organics, the implied chemical composition of the solar protonebula, and the chemical mechanisms that contribute to the loss of materials from comets. This addresses our understanding of the origin and evolution of the early solar system and the transport of volatiles and pre-biotic material throughout the solar system.

The ability to measure the chemical composition of tenuous atmospheres allows for interesting studies of such planetary satellites as Europa and Triton. Measurements taken by this instrument can address such issues as the molecular composition of Europa's atmosphere (Is there water in the atmosphere? What radiation products from the interaction of the Jovian magnetosphere with the water ice surface are present in the atmosphere? Are pre-biotic materials present and being sputtered off the surface?), the chemical composition of the Triton plumes, the production rate of Europa and Triton's atmosphere (for Europa: how much surface material is loss at what rate due to magnetospheric interactions), and the spacial variability of the Europa's atmospheric composition and its relationship to the ion distribution relative to possible variations in surface composition. Such an instrument also has intrinsic applications for any probe of Titan's thick atmosphere and the measure of any organic materials.

Instrumental technique: Time of flight (ToF) instruments have the inherent advantage that the entire mass spectrum is recorded at once, without the need of scanning the masses through slits. With a storage ion source - a source that stores the continuously produced ions until their extraction into the ToF section -, with high transmission in the ToF section, and with a sensitive detector, it is possible to record a very large fraction (greater than 60%) of all ions produced. These factors contribute to the overwhelming sensitivity of ToF instruments. Another reason to use ToF instruments in space science is their simple mechanical design and easy operation. Their performance depends on fast electronics rather than on mechanical tolerances.

ReMaSp operates by simultaneous extraction of all ions from the ionization region into a drift space such that ions of a given m/q are time-focused at the first time focus plane. The very short m/q ion bunches are then imaged onto the detector by the isochronous drift section. Because different m/q bunches drift with different velocities, the drift length determines the separation of the bunches. The reflector incorporates the isochronity in the drift section. Mass resolution is determined by the drift time and the temporal spread of the ion packets.

ReMaSp will include two similar and independent source-detector systems, one optimized for ions and one for neutrals, using the same reflector. This configuration guarantees high reliability by almost complete redundancy.

Instrument heritage and future development: A reflectron-type instrument was successfully flown on the GIOTTO mission (COSIMA) to measure atoms and molecules ejected from a surface during impact of fast cometary dust particles. One explicitly design to measure gas and ions outgassing from the comet Wirtaanen (ROSINA) [1] is currently being built for the ROSETTA orbiter spacecraft. A miniaturized version of the same instrument (COSAC) is currently being tested for the lander of the same mission.

State of the art, flight-ready ToF spectrometers weight around 5 kilograms and use an average of 5 Watts of power. Development at various institutions aim at reducing those values while at the same time conserving the mass resolving capabilities, to enable flying this type of sensor in space mission. A prototype that uses the same detection technique [2] for analysis of surface and subsurface rock, ice, and fine samples is currently been developed at APL, and needs resources about a factor of two lower then today's state of the art. It is expected that further reduction, especially in weight and power of the associated electronics, will allow in near future to build a flight-unit ToF mass spectrometer that weights 1-2 kilograms and uses 1-2 watts of power.

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PETIT GRAND TOUR: MISSION CONCEPTS TO OUTER PLANET SATELLITES USING NON-CONIC LOW ENERGY TRAJECTORIES. M. W. Lo[1], [1]JPL 301-140L, 4800 Oak Grove Dr., Pasadena, CA 91109, Martin.Lo@jpl.nasa.gov

Interplanetary Superhighway System: Our Solar System is connected by a vast Interplanetary Superhighway System (ISSys) providing low energy transport throughout (see [1], [2]). The Outer Planets with their satellites and rings are smaller replicas of the Solar System with their own ISSys, also providing low energy transport within their own satellite systems. This low energy transport system is generated by all of the Lagrange points of the planets and satellites within the Solar System. Figure 1 shows the tubular passageways near L1 of Jupiter. Figure 2 shows the ISSys of Jupiter schematically. These delicate and resilient dynamics may be used to great effect to produce free temporary captures of a spacecraft by a planet or satellite, low energy interplanetary and inter-satellite transfers, as well as precision impact orbits onto the surface of the satellites.

Petit Grand Tour: Using modern dynamical systems methods, we have developed the theory and algorithms to compute global families of solutions with a near-arbitrary itinerary to serially tour the satellite system of any planet, to capture into orbit (temporary capture), depart, or land/impact the various satellites. This is the concept that we call "The Petit Grand Tour" (see [3], [4]). We present an example of such a transfer from Ganymede to capture into Europa orbit as well as a free transport (no propulsion needed, see Figure 3) between the Kuiper Belt and the Asteroid Belt computed using JPL's LTool. This spiral orbit flies by each of the Outer Planets starting at the Kuiper Belt before ending in the Asteroid Belt. A similar tour for the Jovian or Saturn system could be devised. This dynamics was used to designed the Genesis Mission soon to launch in the summer of 2001. We will also illustrate the use of this dynamics in an innovative concept for human servicing of observatory missions at the Sun-Earth L2.

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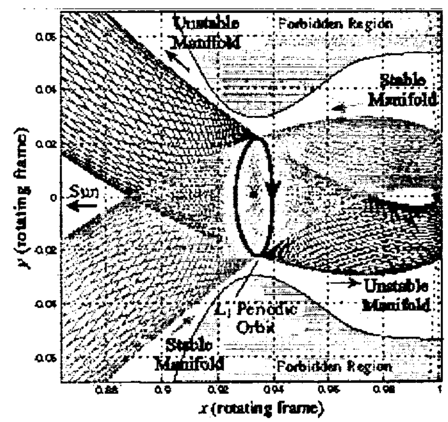
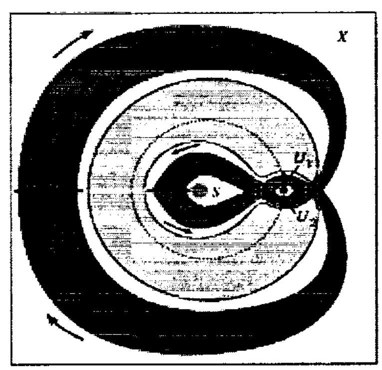
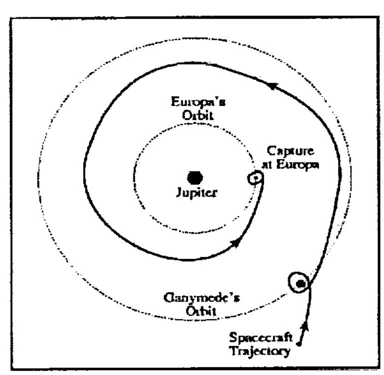






FLEXIBILITY FOR TITAN EXPLORATION : THE TITAN HELICOPTER. R. D. Lorenz[1], [1]Lunar and Planetary Lab, University of Arizona, Tucson, AZ 85721-0092 (rlorenz@lpl.arizona.edu).

Introduction: Future Titan exploration [1] should focus on what Cassini will not be able to provide: detailed chemical analysis of surface materials (especially where abundant organics have interacted with transient exposures of liquid water), subsurface mapping including the benthic topography of hydrocarbon lakes, high-resolution (m-scale) optical images of the spectacular landscape taken from beneath the blurring haze layers, and meteorological and geophysical monitoring. Neither an orbiter nor a single lander can adequately meet all these objectives. A rover is an uncertain prospect for Titan's environment, so some kind of aerial platform is required.

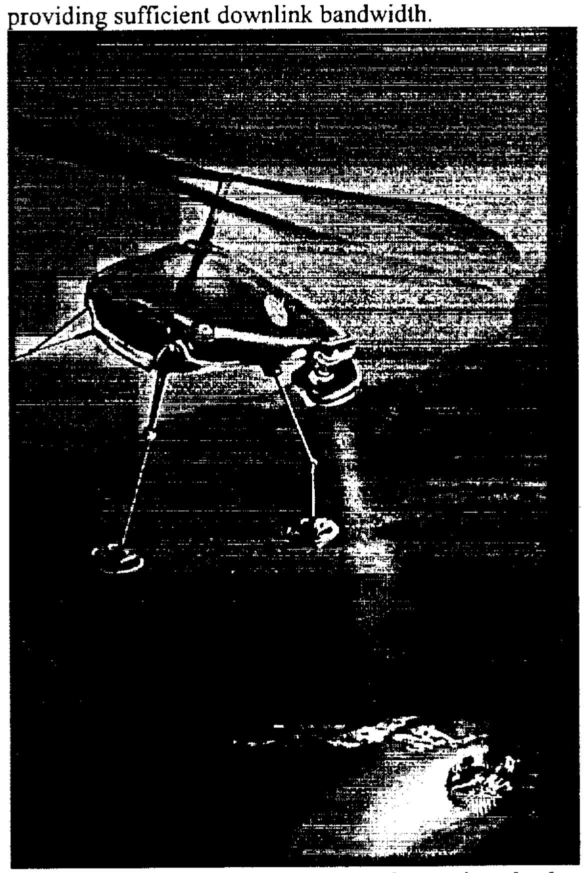
Platform Tradeoff: A case can be made for a modest balloon platform, e.g. [2], but to meet the highest-priority goals [3] as defined by the NASA Prebiotic Material CSWG, a platform that is both mobile (and thus able to access the most geologically and chemically/exobiologically interesting sites, as identified by Cassini and the platform's own airborne data) and able to safely access surface material at fixed sites in the presence of uncertain meteorological conditions, would be required. In this regard a helicopter excels.

Helicopter: Titan's unique environment lends itself to aviation of all kinds: while balloons and dirigibles benefit from its thick atmosphere (4x density of Earth), heavier-than-air vehicles benefit from both the thick air and the low gravity (1/7 of Earth). In particular, a helicopter of given mass and rotor diameter can hover with a power some 38 times less than on Earth.

A simple analysis [4] suggests that a ~100kg helicopter vehicle could fly on Titan with a power of 400-700W. Although too high for continuous flight, at a ~10% duty cycle, the vehicle could fly for a few hours every Titan day, covering ~200km with a reasonable-sized battery trickle-charged by a radioisotope power source. Such a vehicle could operate for years, and with a <200kg entry mass at Titan is compatible with a modest launch cost and short trip time.

Payload: A modest (<15kg) payload might include terrain cameras, a simple subsurface radar sounder, a surface prebiotic chemical analyzer, pressure and methane humidity sensors for meteorology, and a small magnetometer. An IR spectrometer might help identify chemically-interesting landing sites.

Challenges: In purely aeronautic terms, a Titan mission is trivial. However, safe operation of an aerial vehicle a billion miles from Earth requires sophisticated and robust on-board autonomy in a poorly-understood environment. Other challenges that require technology development include the power system (ensuring adequate cycle life for the battery – perhaps by keeping it warm with the primary power source) and providing sufficient downlink bandwidth.



Impression of Titan Helicopter inspecting the heroic corpse of the Huygens Probe on Titan's surface. (For change monitoring this would be an important scientific target) Entry shell packaging considerations advocate a contrarotating rotor design ; long legs minimize downwash perturbation to surface material. (c) James Garry – see www.fastlight.demon.co.uk

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A Nuclear Ramjet Flyer for Exploration of Jovian Atmosphere

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We investigated the design, operation, and data gathering possibilities of a nuclear-powered ramjet flyer in the Jovian atmosphere. The MITEE nuclear rocket engine can be modified to operate as a ramjet in planetary atmospheres. (Note: MITEE is a compact, ultra-light-weight thermal nuclear rocket which uses hydrogen as the propellant.) To operate as a ramjet, MITEE requires a suitable inlet and diffuser to substitute for the propellant that is pumped from the supply tanks in a nuclear rocket engine. Such a ramjet would fly in the upper Jovian atmosphere, mapping in detail temperatures, pressures, compositions, lightning activity, and wind speeds, e.g., in the highly turbulent equatorial zone and the Great Red Spot. The nuclear ramjet could operate for months because: 1) the Jovian atmosphere has unlimited propellant, 2) the MITEE nuclear reactor is a (nearly) unlimited power source, and 3) with few moving parts, mechanical wear should be minimal. This paper presents a conceptual design of a ramjet flyer and its nuclear engine. The flyer incorporates a swept-wing design with instruments located in the twin wing-tip pods (away from the radiation source and readily shielded, if necessary). The vehicle is 2 meters long with a 2 meter wingspan. Its mass is 220 kg, and its nominal flight Mach number is 1.5. Based on combined neutronic and thermal/hydraulic analyses, we calculated that the ambient pressure range over which the flyer can operate to be from about 0.04 to 4 (terrestrial) atmospheres. This altitude range encompasses the three uppermost cloud layers in the Jovian atmosphere: 1) the entire uppermost visible NH_3 ice cloud layer [where lightning has been observed], 3) the entire NH_4HS ice cloud layer, and 3) the upper portion of the H_2O ice cloud layer.

ELECTRICALLY ISOLATING THERMALLY COUPLED DEVICE FOR NOISE SUPPRESSION OF CIRCUITS IN DEEP SPACE. A. Mantooth[1], T. McNutt[1], M. Mojarradi[2], H. Li[3], B. Blalock[4], [1]University of Arkansas, BEC 3217, Fayetteville, AR 72701, mantooth@engr.uark.edu . [2] Jet Prolusion Laboratory, California Institute of Technology, 4800 Oak Grove, Pasadena, CA 91109. [3] University of Idaho, Elec. Engr., Moscow, ID 83844,. [4] Mississippi State University, Dept. of Elec. and Comp. Engr., Box 9571, Mississippi State, MS 39762 .

Introduction: Mixed mode rad hard avionics Systems on a Chip (SoC)designed for deep space applications such as Europa orbiters and Europa Landers will require data isolation circuits to block noise. This paper presents the simulation performance for a novel rad hard SOI CMOS compatible thermal transducer used for on-chip data isolation in SoC. The research presented involves the use of commercially available CAD tools to model the transient electrothermal behavior of the transducer. Both one- and two-dimensional analyses of a prototype thermal transducer were performed. Results indicate that thermal-based data isolator technology can pass a data bit in under a microsecond and, as a measurement of feasibility I^2C bus specifications can be met.

Definitions of Systems-on-a-Chip (SoC) vary from chips containing primarily complex digital circuitry to those comprised of mixed-signal and even mixed-technology subsystems. This latter definition includes analog/RF circuitry and MEMs devices. An important requirement of these mixed-signal or mixed-technology SoCs is on-chip electrical isolation. Isolation improves the noise performance of the overall system by reducing the coupling between the various technologies (e.g., power supply coupling).

SOI CMOS compatible solutions are an easy choice for low power SoC design, especially in avionics. Due to the properties associated with SOI technology, it performs much better in a radiation filled environment compared with bulk CMOS technology. Bulk processes are prone to single-event latchup (SEL), single-event upset (SEU), and other effects caused by particle bombardment. SOI technology is immune to SEL and has proven to be ten times less sensitive to SEU than bulk technology. Furthermore, SOI technology offers superior temperature performance over bulk, including functionality up to 800K [1].

With the goal being the high level integration of the aforementioned subsystems onto a single chip, obviously it becomes necessary to have a reliable form of on-chip electrical isolation to avoid noise propagation between different subsystems. One of the major hurdles in current SoC design is the ability to place inductors and transformers on-chip [2]. Usually, on-chip transformers take up a lot of space, on the order of 50,000 μm^2, and the circuits used to drive them consume a considerable amount of power.

One novel solution to a reliable source of data isolation is the use an electrothermal based data isolator. The advantage of using thermal media, as opposed to magnetic, as a means of isolation is the availability of on-chip devices that are able to transmit and receive thermal signals. Also, thermal based transducers are significantly smaller than their magnetic counterparts, usually around 1,600 μm^2 per transducer.

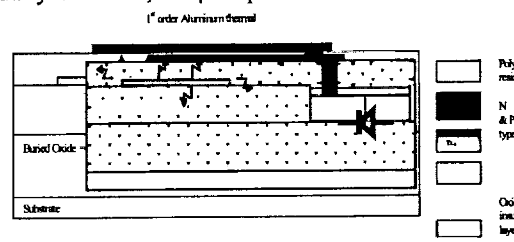

Figure 1. Cross Sectional View of Transducer

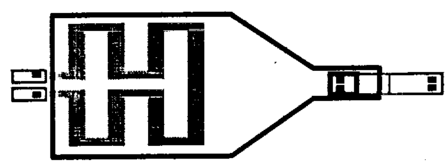

Figure 2. Top View of Transducer

Figure 1 and Figure 2 show a prototype thermal transducer structure that was fabricated in a 0.8 μm SOI CMOS compatible process. Figure 1 shows a cross sectional view of the transducer, where the solid white areas are silicon, the gray area is a poly-silicon resistor, the black area is the aluminum thermal lens, and the dotted area is silicon dioxide. The diode thermal detector is also illustrated.

Figure 2 is a top view of the transducer with the resistor input on the left and the diode output on the right. The thermal lens is outlined in solid black.

In the prototype structures, a poly-silicon resistor is used as a heater to produce a thermal signal from an incident electrical signal. The thermal lens is responsible for gathering the thermal signal and directing it toward the diode thermal detector. The electrically biased diode reproduces an electrical signal at the output as the temperature changes.

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A PROPOSED SEQUENCE OF EXPLORATION FOR EUROPA AND THE OTHER GALILEAN SATELLITES. William B. McKinnon, Dept. of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, Saint Louis, MO 63130, mckinnon@levee.wustl.edu.

Introduction: Europa, by virtue of its complex geology, geophysics, and exobiological potential has emerged as the prime planetary target in the Jupiter system, post Galileo. Here I discuss aspects of an exploration strategy for Europa as well as the rest of the Galilean satellites. The primary issue I address is the sequence of missions that leads to the most comprehensive exploration of Europa, and the answers to the most compelling scientific questions concerning that body, all subject to the manifest constraints of resources and mission duration. I also discuss possibilities that arise when resource constraints are modestly relaxed.

Europa: Evidence has steadily mounted for an ocean under Europa's ice shell [e.g., 1,2]. Various working groups and committees have examined the strategy for exploring Europa following the proposed Europa Orbiter [e.g., 3]. It is clear that future missions must go to the surface. Opinions differ as to how ambitious the first surface mission should be. The compelling nature of Europa science demands, in my view, an exploration *program* (i.e., think Mars exploration). The next logical step is to comprehensively analyze a surface sample (or samples) from an area that is as geologically fresh as possible, specifically, one that represents as recent a (frozen) sample of the ocean or crustal melt as possible. While it is possible to chose plausible landing sites based on Galileo images and data, it represents a substantial risk in terms of science return and technical feasibility. The highest resolution images of Europa show a very rough surface, and even if a sophisticated automated hazard avoidance system could be devised, without detailed foreknowledge of the landing site, such a landing would be foolhardy at best. On the other hand, the strawman complement of instruments for Europa Orbiter (visible and IR remote sensing, ice penetrating radar) would clearly allow the best landing sites to be selected as well as evaluate and mitigate landing risk (high-resolution imaging and laser altimetry). As a corollary, relatively uncontrolled landings and samplings run the risk of reaching geologically uninteresting and uninformative areas and/or sampling older, radiation processed (and hence science-depleted) surface materials.

In principle, a capable lander could be carried on the orbiter, and site selection carried out during the orbiter's primary mission phase. The radiation levels shorten the likely primary mission duration to the point (~1 month) that informed choice of the landing site is unlikely, and the landed mission, which may well need the orbiter as a relay, would have inadequate time to accomplish *its* primary mission. Hence, a staged approach is favored. The long flight-times from Earth to Europa orbit (~5 years) argue that the science and technical community should not simply wait for Europa Orbiter (EO) data to decide on the design and strategy for Europa Lander. Work should advance on the design and construction of the lander while EO is in flight. While it would be unacceptably risky to launch a lander mission before EO accomplishes its prime mission, I argue that it is acceptable to have the lander ready to be integrated, if not be "on the pad," when EO goes into Europa orbit. The success or failure of EO will be readily apparent at that time, and a launch/no launch decision can be made. Given that the arrival at Europa and launch from Earth will be dictated by celestial mechanics, there may be time to modify the spacecraft or payload to take advantage of initial EO results. A parallel set of arguments can be made with respect to the arrival of Europa lander and its follow-on, a Europa Sub-surface (ocean) Explorer. The goal is to telescope in time the sequence of Europa missions, but no shorter than can be justified. If we all do not live to see the more advanced missions return their data, then so be it; the price of failure is much longer delays and *no data*.

Other Satellites and the Case for Two Spacecraft: Failure is not an option, but it must be considered. If EO fails, then the logical step is not to fly the lander anyway (see above), but to re-fly an orbiter mission. It makes sense to build a flight spare, for modest cost, to guard against this eventuality. If the risk was perceived acceptable, two Europa Orbiters could be launched, perhaps staggered by a year or longer. Problems that arise with the first spacecraft could be better addressed in flight, before reaching Jupiter. A decision could be made, even if EO 1 was successful, to continue on to Europa, as one month (or less) may ultimately turn out to be too short a mission time, and EO 2 could serve as a valuable complement, further bolstering the chances of success of the follow-on lander mission. Alternatively, the second orbiter could be redirected to other high-priority science targets in the Jupiter system: Io and Ganymede. Both satellites, based on the latest Galileo data, are eminently worthy of orbiter missions and could take good advantage of the EO instrument group, and both are likely to be ignored under the present Outer Planets and Discovery Programs.

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A Library of Rad Hard Mixed-Voltage/Mixed-Signal Building Blocks for Integration of Avionics Systems for Deep Space., ,M. M. Mojarradi[1], B. Blaes[1], E. A. Kolawa[1],B.J. Blalock[2],H. W. Li[3], K. Buck[3] and David Houge[4], [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove, Pasadena, CA 91109,[2]Mississippi State University, Dept. of Electrical & Computer Engr., Box 9571, Mississippi State, MS 39762, [3]University of Idaho, Moscow, ID 83843, [4]Boeing Corporation Seattle WA.

Introduction: To build the sensor intensive system-on-a-chip for the next generation spacecrafts for deep space, Center for Integration of Space Microsystems at JPL (CISM) takes advantage of the lower power rating and inherent radiation resistance of Silicon on Insulator technology (SOI). We are developing a suite of mixed-voltage and mixed-signal building blocks in Honeywell's SOI process that can enable the rapid integration of the next generation avionics systems with lower power rating, higher reliability, longer life and enhanced radiation tolerance for spacecrafts such as the Europa Orbiter and Europa Lander.

The mixed-voltage building blocks are predominantly for design of adaptive power management systems. Their design centers around an LDMOS structure that is being developed by Honeywell, Boeing Corp, and the University of Idaho. The mixed-signal building blocks are designed to meet the low power, extreme radiation requirement of deep space applications. These building blocks are predominantly used to interface analog sensors to the digital CPU of the next generation avionics system on a chip.

LDMOS in Honeywell SOI Processes: Traditional SOI CMOS technologies only support low voltage transistors in their suite of devices. However, it is possible to create lateral high voltage transistors in the SOI CMOS process without any changes to the fabrication sequence. Fig. 1 shows a cross section of such a high voltage MOSFET in an SOI CMOS process. A drift region made of lightly doped material (already exists in the SOI CMOS process) is added to the drain terminal to sustain the high voltage. These transistors have several limitations. For on-chip integration of high voltage functions in radiation hard SOI CMOS technologies we have had to develop new non-traditional circuit topologies.

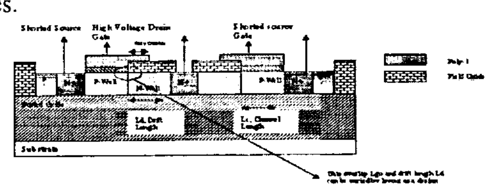

Fig. 1: A high voltage MOSFETs in SOI CMOS

A Space Rated Mixed-Voltage Mixed-Signal Library: Fig. 2 shows the block diagram for the next generation avionics system-on-a-chip for deep space applications. This SOAC requires a complex library of mixed-signal functions. Table-1 lists the typical cells that are part of this library. There are several limitations in the performance of SOI-based mixed-signal building blocks. For example, the input offset voltage in a single stage differential amplifier is much higher in

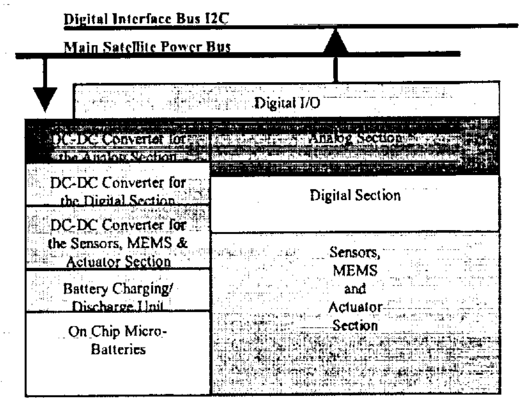

Fig. 2: Next Generation Avionic SOAC.

the SOI CMOS process due to mismatch of the input transistors. Current mirror circuits also suffer from transistor mismatch, in addition to thermal gradient induced offset. Finally, a traditionally designed band-gap reference generator primitive develops a large output offset due to mismatch between the bipolar elements. For certain applications, however, the unique isolation features of the SOI CMOS process allows circuits that are normally available only in discrete form and not easily realizable in bulk CMOS to be fabricated.

Table-1: Library integrated building blocks .

Cell Type	
Low Voltage	Precision References
Low Voltage	Analog to Digital Converter
Low Voltage	Digital to Analog Converter
Low Voltage	High-Speed Differential Amp
Low Voltage	Comparators
Low Voltage	Operational Amplifiers
Low Voltage	Analog Buffers
Low Voltage	Phase/Frequency Detectors
High Voltage	Rectifiers
High Voltage	Switching Inductor Drivers
High Voltage	Voltage Regulator
High Voltage	Analog Level Translator
High Voltage	Zero Crossing Detector
High Voltage	High Side Gate Pre-Driver

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NANOTUBE-BASED SENSORS AND SYSTEMS FOR OUTER PLANETARY EXPLORATION

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Introduction: Direct sensing and processing at the nanometer scale offer NASA the opportunity to expand its capabilities in deep space exploration, particularly for the search for signatures of life, the analysis of planetary oceans and atmospheres, and communications systems. Carbon nanotubes, with their unique mechanical, electrical, and radiation-tolerant properties, are a promising tool for this exploration. We are developing devices based on carbon nanotubes, including sensors, actuators, and oscillators.

Nanotube-based Sensors and Systems:

Artificial Stereocilia. We are developing unique nanotube-based sensor technology inspired by the widespread use of stereocilia in nature [1] to "listen to the sounds of life" generated by nanoscale activity (biochemical reactions, macromolecular transport, metabolic flows, micro-organisms). Nanoscale activity is a physical signature of pre-biotic and extant life, and is expected to be omnipresent and universal, as it is not dependent on any specific (Earth-centric) biochemical composition. In particular, a nanostethoscope (based on nanotube arrays [2]) and a nanoscale force sensor [3] are being investigated. The stereocilia arrays will also be used as very sensitive, miniature, and directional acoustic sensors and as a fish-like lateral line system for the autonomous exploration of planetary oceans and atmospheres.

Nanomechanical Actuators and Oscillators. Nanotube technology enables nanoscale mechanical actuators and oscillators, based on the concept drawn from nature that motion at molecular scales can be extremely efficient. Nano-actuators will allow controllable manipulation and characterization of individual molecules, and provide an essential interface between the macroscopic and nano-worlds [3]. Nanomechanical oscillators can exhibit far higher quality factors (Qs) than electronic resonators. Nanotube-based oscillators can be made with resonant frequencies from the kHz to the GHz range coupled with small force constants [4]. These properties provide the basis for ultra-stable, low-loss, low-noise resonators needed for miniaturizing a number of essential deep space exploration technologies, including communications, radar, and signal processors.

Molecular Sieves. Separation of molecules according to size, chirality, hydrophobicity, or other properties, is an essential technique in the analysis of extraterrestrial molecules. An array of carbon nanotubes used as an electrophoretic artificial gel or as a chromatographic resin [5] will enable rapid assay of molecular properties that may be a signature of biotic or pre-biotic life (such as enantiomeric ratios). This goal requires sieving pores on the scale of 10-50 nm, which is beyond the economic limits of lithography, but well within the parameter range of carbon nanotube arrays.

Nanofluidics and Nanotube Dynamics. A computational effort is in place to help guide the design of nanotube-based systems oscillating at high frequencies and interacting with fluids and molecules [6].

Relevance to NASA Deep Space Missions: The nanometer scale of nanotubes makes them perfectly suited for the search of biomolecular or microbiological signatures of life on outer planets. In addition, nanotube-based technology does satisfy the mass and power constraints for long-life deep space missions. Finally, nanotube-based mechanical devices are exceptionally radiation tolerant due to the strong C-C bonds and the relative insensitivity of mechanical systems to radiation damage. The combination of low power, low mass, high performance, and radiation hardness makes nanotube-based devices attractive candidates for deep space missions.

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NUCLEAR ELECTRIC PROPULSION FOR THE EXPLORATION OF THE OUTER PLANETS

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Introduction: New power and propulsion technology efforts such as the DS-1 ion propulsion system demonstration and renewed interest in space nuclear power sources call for a reassessment of the mission benefits of Nuclear Electric Propulsion (NEP) [1]. In this study, a large emphasis has been placed in defining the NEP vehicle configuration and corresponding subsystem elements in order to produce an estimate of the vehicle's payload delivery capability which is as credible as possible. Both a 100-kWe and a 1-MWe system are defined. Various Outer Planet missions are evaluated using NEP: a Pluto Orbiter, a Europa Lander and Sample Return, a Titan/Saturn Sample Return and a Neptune Orbiter.

Vehicle Configuration: The overall NEP vehicle configuration assumes the use of an ion propulsion system [2]. In this configuration, a long boom separates the power and propulsion systems from the other subsystems of the spacecraft. The boom also serves as a structural attachment for the deployable radiators. Every element of the vehicle other than the reactor is located in the reactor shield's shadow. The power conversion system, propulsion system fuel tanks, feed system, power processing and thrusters are mounted next to the shield. The very large deployed radiators are unfolded along each side of the main boom. In stowed configuration, the spacecraft fits within a Delta IV launch fairing (5-m diameter by about 14 m long).

Systems: A careful examination of all NEP vehicle subsystems was performed, leading to a 100-kWe and 1-MWe NEP vehicle dry mass respectively of about 3200 kg and 7500 kg.

Power. The 100-kWe system is the result of a detailed trade study in which a variety of reactor concepts and conversion systems were evaluated. The baseline system has a NASA/Marshall Space Flight Center (MSFC) SAFE-300 UO_2 fueled, heat-pipe-cooled reactor with a Brayton cycle power conversion system [3]. The 100-kWe system produces 102.4 kWe power and approximately 320 kWth power.

The 1-MWe power system is based on a direct gas-cooled concept, particularly attractive for its lighter weight at these thermal power levels. A Brayton power conversion cycle is also used for the 1-MWe system. The turbine speed and the size were increased over the 360-kWe design point of the study. This system has the potential to scale to at least the 10-MWe class of power.

Propulsion. The 100-kW ion propulsion system (IPS) is composed of 60-cm diameter ion engines that can process 25 kW of electric power and use krypton rather than xenon as propellant. The thruster has an estimated efficiency of 0.67 at a specific impulse (Isp) of 5000 s, and 0.77 at 15000 s. The propellant throughput capability of each engine was estimated to be 500 kg, by scaling the capability of the existing, flight qualified 2.3-kW engine.

The 1-MW ion propulsion system is composed of two 480-kW ion engines. Each ion engine includes eight 60-cm diameter, 60-kW ion sources plus one redundant engine. This approach is called a "segmented ion engine" in which multiple discrete ion sources are integrated together to form a single large ion engine with a large effective total grid area. A significant advantage of such a design is in the ground testing and facilities (pumping requirements significantly relaxed). The 60-kW ion sources are essentially the same design as the previously described 25-kW engines.

Other subsystems. The Thermal, Attitude Control, Structures (long boom...), Mechanisms and Cabling subsystems are also defined.

Mission results and conclusion: It is found that the 100 kWe power and ion propulsion systems are applicable for a 9-12 year Pluto rendezvous, a 10-13 year Titan/Saturn Sample Return and a 3-4 year Europa Lander mission. Net delivered masses varies between 500 and 2000 kg. The 1-MWe class NEP vehicle also shows a Titan/Saturn Sample Return mission in 10-12 years on the Delta IV Heavy. This conclusion is an artifact of the constraint in Isp to 16000 s. A higher Isp (30,000 - 40,000 s) would increase the net delivered mass compared to the 100-kW vehicle. However, a 0.5-1-MWe class vehicle enabled a Europa Sample Return in 5-6 years. Since the total dry mass of both NEP vehicles is quite large, the benefit of NEP only shows for a Delta IV Heavy (or equivalent) launch vehicle. All robotic mission trajectories started from a slightly positive C3. The NEP vehicle specific mass (not including tank mass that varies with the trajectory) for the 100-kWe and 1-MWe vehicle is respectively 31.7 kg/kW and 7.5 kg/kW. This analysis shows that NEP is especially applicable for short trip time and very high-energy missions (40-60 km/s).

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APPLICATION OF SYNERGISTIC MULIPAYLOAD ASSISTANCE WITH ROTATING TETHERS (SMART) CONCEPT TO OUTER PLANET EXPLORATION. Gerald David Nordley[1], Robert L. Forward[2] and Robert P. Hoyt[2], [1]Consultant <GDNordley@aol.com>, [2]Tethers Unlimited, Inc., 19011 36th Ave. W, Suite F, Lynnwood, WA 98036 <TU@tethers.com> [www.tethers.com].

Introduction: We propose an innovative approach to outer planet exploration using the Synergistic Multipayload Assistance with Rotating Tethers (SMART) concept invented by Gerald David Nordley. The basic concept can be implemented in many different ways to accomplish many different types of planetary missions, especially missions to the outer planets.

SMART Concept: A pair of spacecraft are connected by a tether, set to rotating about their common center of mass, and injected into a hyperbolic orbit around a massive planet. The tether is caused to separate as the combined system approaches the periapsis of the hyperbolic orbit. The spacecraft which is rotating "backward" relative to the hyperbolic flight path receives a velocity decrease at separation which causes it to go into a lower energy orbit, typically an elliptical capture orbit about the planet. The spacecraft that is rotating "forward " with respect to the hyperbolic flight path gets a velocity increase which will cause it to exit the gravitational field of the planet with a higher velocity than it entered. In effect, each payload acts as the reaction mass for the other. Because the velocity increments obtained from the tip speed of the tether take place deep in the gravity well of the massive planetary body, they are "amplified" by the high periapsis velocity to produce significant changes in the final trajectories of the two separated bodies.

Combined Pluto/Europa Mission: Figure 1 illustrates the use of the SMART concept to carry out both the Pluto Flyby mission and the Europa Orbiter/Lander mission with one launch. The combined system arriving from Earth is moving 5.6 km/s slower than Jupiter. The velocity of the incoming system reaches 42.5 km/s at a periapsis of two Jupiter radii. With the tether giving the Pluto payload a 1 km/s increase in this velocity, the Pluto payload reaches a hyperbolic excess velocity with respect to Jupiter of 10.9 km/s, almost double what it had as it entered Jupiter's gravity field. Adding this velocity to Jupiter's orbital velocity gives a velocity of 23.9 km/s for the Pluto injection velocity. For the Europa payload, a ΔV of only 400 m/s from the tether is sufficient to provide capture into an elliptical orbit about Jupiter. Table I shows the results on the parameters of the two missions of using different tether tip speeds.

Table I - Post-Periapsis Payload Trajectories

Tether Tip Velocity (km/s)	Capture Orbit (days)	Pluto Inj. Velocity (km/s)	Pluto Trip Time (years)	Tether Mass Ratio
0.0	∞	18.7	11.6	-
0.4	1473	21.2	10.2	0.05
0.6	102	22.2	9.3	0.12
0.8	41	23.1	8.6	0.22
1.0	24	23.9	8.0	0.36

The tether mass ratio was determined using the well-known tether mass ratio formulas for fail-safe interconnected multistrand tethers [1] and assuming a 50% improvement in tether strength in the coming years.

Other Outer Planet Applications: The SMART concept can be used in many other ways than a dual mission. Either the Pluto mission or the Europa mission, or any other mission to any other planet could use the dead mass of the Earth escape injection stage as reaction mass. Any mission putting a payload into orbit around Jupiter could retain a conductive portion of the tether and use it to obtain both power and propulsion. With the tether available to provide the instantaneous thrust at periapsis, any mission could be redesigned to use efficient electric propulsion and completely eliminate the need for chemical propulsion.

Comparison With Rocket Assist: The mass of the tether necessary to obtain the necessary ΔV at periapsis in the SMART concept is typically comparable to the mass of the storable propellant and tanks needed to obtain a comparable ΔV. Detailed analyses will be required to determine the exact mass comparison numbers for each mission example. Rockets have more flight heritage, but one would think that the reliability and accuracy of a tether system that imparts all if its exactly known mechanical energy at a single point in time by the action of a simple mechanical separation system would be better than the release of an uncertain amount of chemical energy over a long burn time initiated by a complex ignition sequence.

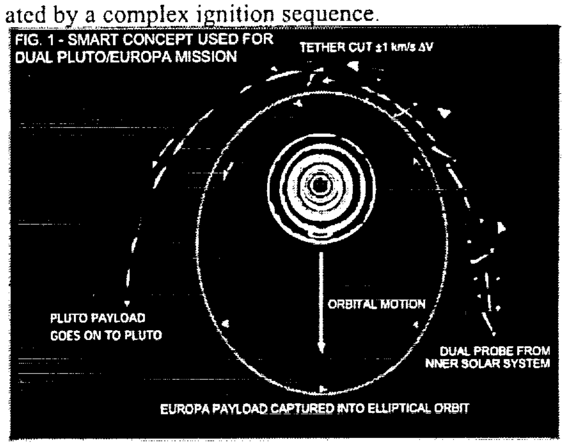

FIG. 1 - SMART CONCEPT USED FOR DUAL PLUTO/EUROPA MISSION

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Pluto/Kuiper Missions with Advanced Electric Propulsion and Power.

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Introduction: In response to a request by NASA Code SD Deep Space Exploration Technology Program, NASA Glenn Research center performed a study to identify advanced technology options to perform a Pluto/Kuiper mission without depending on a 2004 Jupiter Gravity Assist, but still arriving before 2020. A concept using a direct trajectory with small, sub-kilowatt ion thrusters and stirling radioisotope power system was shown to allow the same or smaller launch vehicle class (EELV) as the chemical 2004 baseline and allow launch in any year and arrival in the 2014 to 2020 timeframe. With the nearly constant power available from the radioisotope power source such small ion propelled spacecraft could explore many of the outer planetary targets. Such studies are already underway.

Advanced Technologies:
NASA Glenn Research Center is developing a lightweight (< 3.0 kg combined mass, representing a 5x reduction from state-of-the-art), sub-kilowatt thruster and power processor (fig. 1). Performance goals include 50% efficiency at 0.25 kW, representing a 2x increase over the state-of-the-art. The sub-kilowatt ion propulsion activity includes both an in-house hardware development element for the thruster and power processor, as well as a contracted system element.

The NASA Glenn Research Center (GRC) and the Department of Energy (DOE) are developing a free-piston Stirling convertor for a Stirling Radioisotope Power System (SRPS) to provide on-board electric power for future NASA deep space missions (fig. 2). The SRPS currently being developed provides about 100 watts and reduces the amount of radioisotope fuel by a factor of four over conventional Radioisotope Thermoelectric Generators (RTG). The present SRPS design has a specific power of approximately 4 W/kg which is comparable to an RTG.

Study Results: In an effort to show how advancing technology can improve Pluto-type missions technology "Launch Windows" were assumed using representative launches in '06,'09,'12 corresponding to available technology. A range of existing and projected ELV's was considered. Projections of 8cm ion propulsion and stirling converter programs, underway at the NASA Glenn Research Center, were made to create the '06,'09, and '12 baselines. Trajectories were designed which provided net spacedcraft masses (spacecraft less propulsion system) of 200 to 400 kg depending upon launch vehicle and launch date (fig 3).

Disclaimer:
This concept is presented as an example of how small ion thrusters and advanced radioisotope power systems can perform an outer planetary mission. This concept is not being submitted by NASA GRC for the Pluto AO.

Figure 1 8cm Ion Thruster

Figure 2 Stirling Radioisotope Power Concept

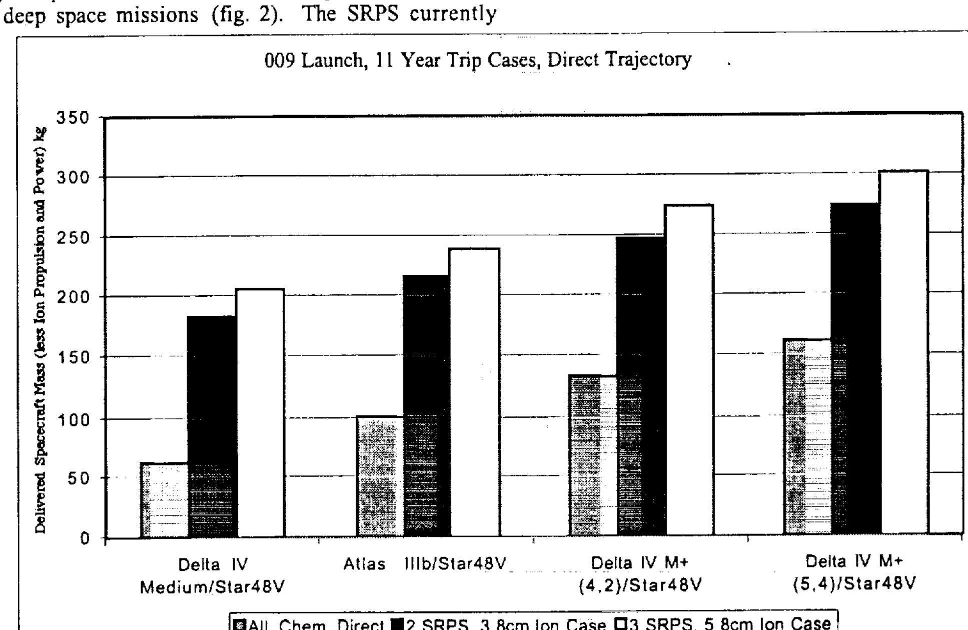

Figure 3 Sample Study Results

THE GRANDEUR OF GANYMEDE: SUGGESTED GOALS FOR AN ORBITER MISSION. R. T. Pappalardo[1], K. K. Khurana[2], and W. B. Moore[2] [1]Brown University (Dept. Geological Sciences, Providence RI 02912-1846; pappalardo@ brown.edu), [2]UCLA (Los Angeles, CA 90095-1567).

Introduction: Ganymede is an icy satellite of planetary grandeur, with alluring surface geology and chemistry, an internally generated magnetic field, a differentiated interior and hot iron core, and a tenuous but dynamic atmosphere. Its linked surface, interior, and orbital evolution recount the history of the jovian system. Moreover, an induced magnetic field component and warm interior imply a liquid water deep within the moon, and the potential for harboring primitive life. Broad goals of *surface*, *magnetosphere*, *interior*, and *atmosphere*--and overarching themes of *water* and *organics*--tie to high priority to NASA's exploration objectives. All can be thoroughly addressed by a dedicated Ganymede mission.

Surface: Ganymede has fascinating and diverse surface geology. Its relatively young bright "grooved terrain" is shaped by Earth-like tectonism [1], with faults and fractures that deform its surface ice. Icy volcanism may have paved its smoothest terrains [2]. Its ancient cratered "dark terrain" shows a complex geological history [3]. The dark terrain probably dates from the earliest days of the Galilean satellite system [4] and offers the best promise for unraveling its cratering history. Multi-ringed structures and palimpsests are impacts that probe to warm and perhaps liquid-rich layers [5]. Galileo succeeded in sampling Ganymede's surface features, but coverage is extremely limited, and regional relationships and distributions remain uncertain [6]. Topographic data has been extremely important to understanding Ganymede's surface geology, but is of relatively coarse resolution and very limited areal extent [7].

Ganymede's dark terrain material contains clays and organic materials [8] that may indicate the composition of the impactors from which jovian satellites accreted. Hydrated minerals may be salts similar to those inferred on Europa [9]. Ganymede is a significant dust source [10], implying that its surface composition could be sampled directly from orbit. Surface oxygen and ozone are probably the products of charged particles which tear the bonds of surface water-ice [11]. Many additional irradiation products, including simple organics, are predicted [12].

Magnetosphere: Ganymede is the only satellite known to have an internally generated magnetic field [13]. Its inferred equatorial surface field strength of ~750 nT is great enough to stave off Jupiter's field and carve out its own magnetospheric bubble. The interactions between Jupiter's and Ganymede's magnetic fields are analogous to those between the Earth and Sun, with the added advantage that the upstream field and plasma conditions are highly predictable. Equatorial latitudes are shielded from most charged particles, while polar latitudes are open to particles from the Jovian magnetosphere. Monitoring of the location and character of this boundary would provide a measure of the nature of both Jupiter's and Ganymede's fields. Galileo magnetometer measurements imply that Ganymede generates an induction response to Jupiter's rotating field, presumably from a subsurface salty water layer [14]. Continuous observations from orbit would measure the induction at multiple frequencies, constraining the conductivity and thickness of the water layer, and providing information on the solid metallic core where the magnetic field is thought to be generated. An orbiter would also measure higher order spherical harmonics of the internal field and determine secular changes in the field since the Galileo era measurements.

Interior: Galileo gravity data indicate that Ganymede is highly differentiated, with an ice-rich crust ~800 km thick above a rock mantle and iron core [15]; the magnetic field data imply that this iron core is hot and partially molten today. Its hot core and crustal water layer imply that Ganymede is cooling from a tumultuous heating event that may have occurred as recently as ~1 Gyr ago, plausibly from a huge pulse of tidal heat as Ganymede entered the Laplace resonance [16]. Measurements of Ganymede's gravitational field will refine models of its internal density and so its differentiation history. In combination with magnetometry, interior thermal profiles can be constrained. Detailed gravity data may determine if mass anomalies are associated with grooved terrain or impact palimpsests.

Atmosphere: Ganymede has a tenuous atmosphere driven by sublimation, sputtering, and dissociation of surface water-ice. The atmosphere is probably dynamic, sensitive to diurnal insolation, magnetospheric fluctuations, and geological terrain type [17]. Observed ultraviolet polar aurorae, equatorial visible airglow, and extended Lyman-α emission all attest to interactions between the magnetosphere and atmosphere [18, 19]. However, observational constraints are extremely limited regarding composition, density, transport, redeposition, loss, and magnetospheric interactions pertinent to Ganymede's atmosphere.

Suggested Objectives and Investigations: To address goals of *surface*, *magnetosphere*, *interior*, and *atmosphere* and tracking of the satellite's *water* and *organics*, we suggest the following science objectives (and measurement techniques) for a dedicated Ganymede mission:

- Characterize the global distribution, regional relationships, and detailed topography of geological features (global high-resolution imaging; laser altimetry).
- Determine the composition, distribution, and state of ice and non-ice surface components, notably organic materials and irradiation products (infrared spectroscopy; ultraviolet spectroscopy; orbiting mass spectroscopy).
- Measure and monitor magnetic field and plasma energy spectrum over time from a variety of altitudes (magnetometry; plasma measurement).
- Measure gravity field to high accuracy (radio science).
- Characterize the neutral atmosphere and ionosphere, including composition, source, and escape mechanisms (ultraviolet spectroscopy; radio science).
- Determine the characteristics, causes, and spatial/temporal variability of emissions (ultraviolet spectroscopy; imaging; plasma measurement; magnetometry).

Desirable Mission Characteristics: A Ganymede orbiter could perform the investigations outlined above. An initial highly elliptical orbit would allow for global reconnaissance, magnetopause studies, and atmospheric and auroral observations. A subsequent low-altitude, highly inclined, near-circular orbit would shield the spacecraft from damaging particle radiation during half of each orbit, and allows: uniform coverage for imaging, spectroscopy, altimetry, and magnetometry; ideal Doppler tracking data for gravity studies; repeated crossings of magnetospheric boundaries to understand interactions with Jupiter's field; and in situ compositional sampling of particles ejected from the surface. An orbiter would permit long-term, dedicated study of Ganymede as an integrated system, tracing its water and organics from interior to magnetosphere, to unlock secrets of this recently active world which holds the secrets to the evolution of the Galilean satellites.

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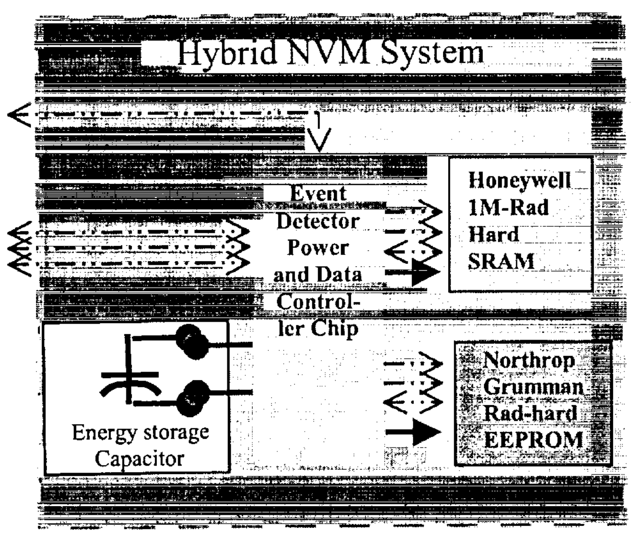
NONVOLATILE MEMORY SOLUTION FOR NEAR-TERM NASA MISSIONS: J.U. Patel, B. R. Blaes, M. M. Mojjaradi, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109 m/s 303-310 jupa-tel@jpl.nasa.gov

Introduction: Nonvolatile memory (NVM) system that could reliably function in extreme environments is one of the most critical components for many space-crafts being developed for NASA missions to be launched in next 4 to 7 years. NVM supports the computer system in saving and updating critical state data required for a warm restart after power cycling or in case of a power bus failure. It also provides a power independent mass storage capacity for the scientific data gathered by the instruments. In some cases window for gathering such data is very small and occurs only once in a given mission. Commercially popular and fully developed Flash NVM technology is inappropriate for many reasons such as the limited read write cycles with slower access speeds, radiation intolerance, higher Single Event Upsets (SEU) rates etc. It is desirable to have an NVM systems based upon a robust cell technology making it immune to the SEUs and with sufficient radiation hardness. Availability of such NVM system seems to be still 5 to 10 years in the future.

Meanwhile, it is possible to provide an interim hybrid solution by combining the existing rad-hard technologies as shown in the Figure below.



Hybrid Solution for NVM system: The main components of our system are 1. Honeywell's Rad-hard SRAM and 2. Northrop Grumman's Rad-hard EEPROM connected by a Rad-hard ASIC that detects an event of power failure and controls data transfer between the SRAM and the EEPROM. Emergency data transfer is powered by the energy stored in the super capacitor system. During the normal operation SRAM can take unlimited write cycles for the updating the data. Its only during an emergency event as detected by the system write operation is done on the EEPROM. Even though the EEPROM has a write cycle limitation of 10,000 to 100,000, the overall system offers an unlimited write cycle capacity with the data retention endurance of the EEPROM.

Proposed NVM solution seems even more attractive because the major components are already available except the Rad-hard ASIC which is very simple and could be fabricated within a year.

Characteristics and Reliability of Hybrid NVM Solution: As mentioned above, proposed NVM system offers unlimited write cycles with a reliable data retention endurance. It is also 300 Krad or better in radiation tolerance with extremely low SEU rates ($1x10^{-10}$ SEUs/bit-day) compared to the Flash technology. Thus, it will require less shielding compared to the Flash option in planned missions such as the Europa in extreme radiation and temperature environments.

Operating life and reliability of the proposed NVM system is also enhanced by the Evans super capacitors which are already being used by the DoD in F-15 avionics systems. These capacitors provide the highest energy density and about 10^6 charge-discharge cycles over 15-20 years. Advanced packaging will be one of the requirements for this system since, the EEPROM chips are only 256Kb at present. But the road map of Northrop Grumman indicates 1 Mb chips in next two years.

Mission insertion and benefits: Since the proposed solution is mostly based upon existing technologies and available parts it could be realized with adequate funding within next 2-3 years. This could benefit some key NASA missions that will be freezing technologies by 2004 –5 time frame. Prototypes could be ready by as early as 2004 and the Engineering models could be built by 2005. Proposed solution could also benefit subsequent missions till a permanent single technology Rad-hard NVM system becomes available.

Acknowledgement: The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

ELECTRONICS FOR EXTREME ENVIRONMENTS: J.U. Patel[1], John. Cressler[2], Ying Li[2] and G. Niu[2], [1]Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109 m/s 303-310 jupatel@jpl.nasa.gov, [2]The Electrical Engineering Department, Auburn University, Auburn, Alabama, 36849.

Introduction: Most of the NASA missions involve extreme environments comprising radiation and low or high temperatures. Current practice of providing friendly ambient operating environment to electronics costs considerable power and mass (for shielding). Immediate missions such as the Europa orbiter and lander and Mars landers require the electronics to perform reliably in extreme conditions during the most critical part of the mission. Some other missions planned in the future also involve substantial surface activity in terms of measurements, sample collection, penetration through ice and crust and the analysis of samples. Thus it is extremely critical to develop electronics that could reliably operate under extreme space environments.

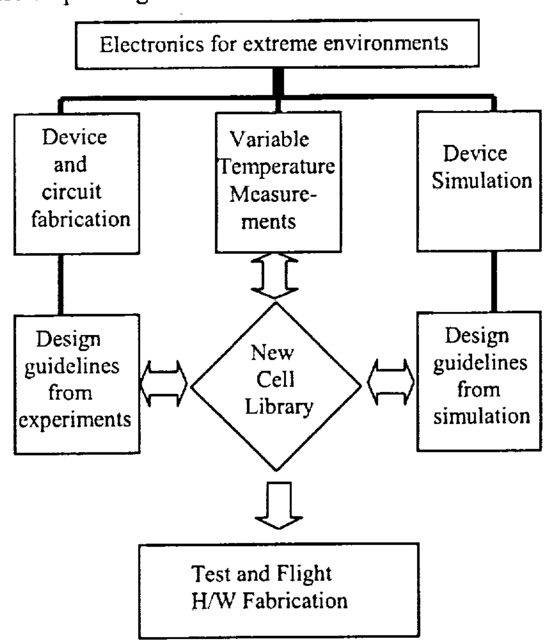
Silicon On Insulator (SOI) technology is an extremely attractive candidate for NASA's future low power and high speed electronic systems because it offers increased transconductance, decreased sub-threshold slope, reduced short channel effects, elimination of kink effect, enhanced low field mobility and immunity from radiation induced latch-up. A common belief that semiconductor devices function better at low temperatures is generally true for bulk devices but it does not hold true for deep sub-micron SOI CMOS devices with microscopic device features of 0.25 μm and smaller. Various temperature sensitive device parameters and device characteristics have recently been reported in the literature. Behavior of state of the art technology devices under such conditions needs to be evaluated in order to determine possible modifications in the device design for better performance and survivability under extreme environments.

Here, we present a unique approach of developing electronics for extreme environments to benefit future NASA missions as described above. This will also benefit other long transit/life time missions such as the solar sail and planetary outposts in which electronics is out open in the unshielded space at the ambient space temperatures and always exposed to radiation.

Technical approach: Developing electronics for extreme environments involve: 1. Characterization of current SOI technologies in extreme environments, 2. Determination of the device design modification for a better survivability and reliable operation in extreme environments. 3. Formulation of cell libraries with modified device designs and 4. Design, fabrication and testing of electronics using modified cell libraries. This will be accomplished with the following steps:

1. Experimental characterization of state-of-the-art SOI CMOS technologies (0.25 μm and smaller) in low temperature (77K to 300K) and radiation environments (300-1000 Krads protons and gamma).
2. Theoretical simulation of the same devices under similar conditions using the device simulator DESSIS to verify experimental results and determine the temperature and radiation sensitive device features. Critical features will include shapes of the source and drain structures, doping profiles, oxide thickness, channel length etc.
3. Determine necessary modifications in the device design and architecture using device simulator DESSIS in order to minimize sensitivity to the combined environment of low temperature and radiation. Formulate new device design guidelines and cell libraries based upon the modifications.

Fabricate basic electronics circuits such as op-amp and sense-amps using modified cell libraries.



Results from the initial characterization of current technologies are expected to be immediately useful in determining radiation and tolerance temperature of current electronics for designing the spacecraft shielding, temperature and in the planning of other mission activities.

Acknowledgement: The research described here was carried out by the JPL, California Institute of Technology, under a contract with the NASA.

Ion Propulsion Technology Programs at NASA Glenn Research Center

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Introduction As lead center for the agency in electric and ion propulsion, the NASA Glenn Research Center (GRC) is pursuing technology development in ion propulsion for a range of mission applications. The program goal is to develop key technologies for advanced NSTAR-derivative high-power ion propulsion, lightweight low power high-performance ion propulsion, "micro" ion propulsion, and engine and component technologies for high-power electric propulsion for very ambitious missions. Products include: a 5 kW, 400 kg-throughput ion thruster and power processing technology; extremely-lightweight high-efficiency sub-kilowatt ion thruster and power processor; a 1-25 W high-specific impulse ion engine; and engine and component technologies for high-power (30 kW class) ion and Hall engines. Identified applications include outer planetary science missions such as Europa orbiter/lander, Comet Nucleus Sample Return mission, Titan Explorer, Neptune/Triton, Pluto-Kuiper Belt Objects Mission, various second generation interplanetary Micro-spacecraft, and the Interstellar Probe Mission.

Program Overview: The in-house ion propulsion activity, which takes advantage of the NASA GRC resident expertise and unique electric propulsion infrastructure which has been established over the past 40 years, is maintained to address much of these development efforts. These include the development of a 5 kW prototype thruster, sub-kilowatt prototype and engineering model thrusters and breadboard power processor, prototype 1-25 W high-specific impulse ion engine, and prototype 30 kW engines and components. These activities establish design requirements and specifications which can then be transferred to U.S. industry for flight application.

Programs: A primary goal is to develop a high-performance 5 kW-class ion thruster with a 400 kg propellant throughput capability. This represents a 5x increase over the NSTAR thruster specification. Additionally, the development of a 15 kg mass power processor, a 2x reduction in specific mass compared to the NSTAR power processor, is being pursued. The 5-kW class ion propulsion technology is a key requirement and priority for technology development to support the SSE theme of the Space Science Enterprise. Identified applications include: Mars missions, Europa, Saturn Ring Observer, Neptune Orbiter, Comet Nucleus Sample Return, and Venus Surface Sample Return.

The sub-kilowatt activity goal is to develop a lightweight (< 3.0 kg combined mass, representing a 5x reduction from state-of-the-art), sub-kilowatt thruster and power processor. Performance goals include 50% efficiency at 0.25 kW, representing a 2x increase over the state-of-the-art. This sub-kilowatt system has recently been identified to be useful for outerplanetary class missions for small spacecraft powered by radioisotope sources. The sub-kilowatt ion propulsion activity includes both an in-house hardware development element for the thruster and power processor, as well as a contracted system element. In-house, the fabrication and performance assessment of a small (0.25 kW class) laboratory model thruster with an 8 cm beam diameter has been completed.[10-13] The fabrication of a second-generation light-weight engineering model thruster with a 100-500 W power throttling envelope is proceeding.

The goal of micro-ion propulsion technology activity to establish the feasibility of developing a "micro" ion thruster based on low-power hollow cathode technology. Overall performance objectives for this Hollow Cathode Micro Thruster (HCMT) are an efficiency exceeding 25% at > 1500 seconds specific impulse, operating over an input power range of about 1 to 25 Watts. A general need for high specific impulse (> 1000 sec), low-power (~10 W) propulsion has been identified for second generation Micro-spacecraft. This thruster fills the gap between micro Newton concepts and ~100W class electric propulsion

A program is underway to develop a 10-30 kW krypton ion engine technology in support of both high specific impulse (>10,000 seconds) applications such the Interstellar Probe Mission, as well as 30 kW-class xenon ion engine technology (sub-4000 second specific impulse) for Earth-space and planetary exploration missions.

MITEE: A Compact Ultralight Nuclear Thermal Propulsion Engine for Planetary Science Missions

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A new approach for a near-term compact, ultralight nuclear thermal propulsion engine, termed MITEE (**MI**niature ReacT**o**r **E**ngin**E**) is described. MITEE enables a wide range of new and unique planetary science missions that are not possible with chemical rockets. With U-235 nuclear fuel and hydrogen propellant the baseline MITEE engine achieves a specific impulse of ~1000 seconds, a thrust of 28,000 newtons, and a total mass of only 140 kilograms, including reactor, controls, and turbo-pump. Using higher performance nuclear fuels like U-233, engine mass can be reduced to as little as 80 kilograms. Using MITEE, V additions of 20 km/sec for missions to outer planets are possible compared to only 10 km/sec for H_2/O_2 engines.

The much greater V with MITEE enables much faster trips to the outer planets, e.g., 2 years to Jupiter, 3 years to Saturn, and 5 years to Pluto, without needing multiple planetary gravity assists. Moreover, MITEE can utilize in-situ resources to further extend mission V. One example of a very attractive, unique mission enabled by MITEE is the exploration of a possible subsurface ocean on Europa and the return of samples to Earth. Using MITEE, a spacecraft would land on Europa after a 2-year trip from Earth orbit and deploy a small nuclear heated probe that would melt down through its ice sheet. The probe would then convert to a submersible and travel through the ocean collecting samples. After a few months, the probe would melt its way back up to the MITEE lander, which would have replenished its hydrogen propellant by melting and electrolyzing Europa surface ice. The spacecraft would then return to Earth. Total mission time is only 5 years, starting from departure from Earth orbit. Other unique missions include Neptune and Pluto orbiter, and even a Pluto sample return.

MITEE uses the cermet Tungsten-UO_2 fuel developed in the 1960's for the 710 reactor program. The W-UO_2 fuel has demonstrated capability to operate in 3000 K hydrogen for many hours - a much longer period than the ~1 hour burn time for MITEE. Using this cermet fuel, and technology available from other nuclear propulsion programs, MITEE could be developed and ready for implementation in a relatively short time, i.e., approximately 7 years. An overview description of the MITEE engine and its performance capabilities is provided.

TOUCH AND GO SURFACE SAMPLER (TGSS). S. Rafeek, Honeybee Robotics, Inc., (204 Elizabeth Street, NY, NY 10012, rafeek@hbrobotics.com), S. P. Gorevan, Honeybee Robotics, Inc., (204 Elizabeth Street, NY, NY 10012, gorevan@hbrobotics.com).

Introduction: The Touch and Go Surface Sampler (TGSS) is a new class of planetary and small body sample acquisition tool that can be used for the surface exploration of Europa, Titan and Comets. TGSS in its basic configuration (Figure 1) consists of a high speed sampling head attached to the end of a flexible shaft. The sampling head consists of counter rotating cutters that rotates at speeds of 3000 to 15000 RPM. The attractive feature of this "touch and go" type sampler is that there are no requirements for a "lander" type spacecraft.

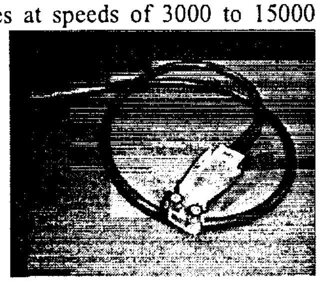


Fig 1-TGSS Sample Head Breadboard

Operation Sequence: Operationally, a hovering spacecraft with a TGSS attached will descend to a selected surface site in a controlled manner with a predetermined surface relative speed. A laser type altitude sensor will monitor surface distance and begins TGSS deployment. At a given height above the surface, the TGSS will be deployed and energized. The flex shaft (1.5 meters or longer) attached to the TGSS will provide the required preload (in the zero-g environment) for sampling as the spacecraft continues its descent for an additional 1 to 2 seconds after the contact sensor have been triggered. The samples can either be collected and captured at the tool head or directly ejected from the surface towards onboard sample analyzer apertures located at the bottom of the spacecraft payload/instrument bay.

The high cutting-bit speed ensures that the ejected samples have enough momentum to reach the sample analyzers. In a controlled capture, the samples are contained in the head of the TGSS and will be retracted into the payload/instrument bay of the spacecraft as the craft ascend back to a safe orbit.

Development Effort: A recently completed NASA SBIR Phase I effort to test the validity of TGSS as a surface sampler has yielded very positive results. In an open sample ejection mode, the TGSS has demonstrated that it can eject sample particles (in a 1 g environment) a height of 1 meter in a 2 second interval. It is expected that tests in a zero gravity environment (to be conducted in subsequent development efforts) will produce much higher dust plumes. Additional observation from the Phase I results show that TGSS can be used for more than just surface sampling. The results gave strong evidence to suggest that TGSS can be mechanically and functionally enhanced to penetrate the surface and obtain subsurface samples, possibly up to 1 meter in loose or low compressive strength material.

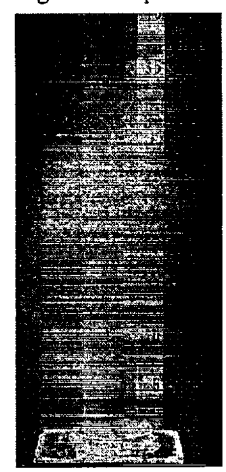


Fig 2 -TGSS Open Ejection

A TGSS class sampler can benefit OPP in a number of ways:

(1) In the "touch and go" mode, there are no requirements for a landing system. In past missions, the reliability of landing systems has resulted or contributed to failures resulting in the loss of entire payloads.

2) TGSS is better suited for unknown topography. The flexible shaft attached to the sampling head of TGSS allows it to conform to the various sloped, hill, and depression contours.

3) Samples can be obtained from multiple sites. A hovering spacecraft to a Comet can "hop" from site to site taking samples.

4) Reduced mission cost. With no requirements for a landing system or an orbiter, the cost of a TGSS mission to a Comet will be greatly reduced.

References: NASA SBIR Phase I – Contract No. NAS2 – 00019, Dec 9, 1999.

THE INCHWORM DEEP DRILLING SYSTEM FOR KILOMETER SCALE SUBSURFACE EXPLORATION OF EUROPA (IDDS). S. Rafeek[1,2], S. P. Gorevan[1], P. W. Bartlett[1,3], and K. Y. Kong[1], [1]Honeybee Robotics, 204 Elizabeth St.; NY, NY 10012; [2]rafeek@hbrobotics.com, [3]bartlett@hbrobotics.com.

Introduction: The Inchworm Deep Drilling System (IDDS) is a compact subsurface transport system capable of accessing regions of astrobiological interest deep below the surface of Jupiter's moon, Europa. The IDDS answers Focus Investigation Area 1 as an innovative concept for implementing subsurface exploration of Europa. The concept is being developed at Honeybee Robotics to reach depths on the order of one kilometer with no tether or umbilical of any kind. The device's unique, inchworm-burrowing method appears capable of achieving this near-term depth goal and it is foreseeable that the IDDS will be capable of autonomously drilling to tens of kilometers below the surface. Logical applications of the concept also include accessing the proposed subsurface oceans on Ganymede and Callisto, subsurface water ice on Mars, and Lake Vostok on Earth. The conference presentation will communicate the IDDS concept and how it can enable the search for prebiotic and biotic chemical processes on Europa by bringing proper instrumentation to the subsurface ocean for in-situ investigation and/or returning samples to the surface. Currently, a proposal for breadboarding the IDDS is pending for the Research Opportunities for Space Science's Astrobiology Science & Technology Instrument Development NRA.

The Basic IDDS Conceptual Framework: The IDDS is largely a convergence of concepts from two previous devices designed and produced by Honeybee Robotics. The planetary surface burrowing mole concept extends our work on a tethered subsurface sampler effort conducted in 1993 for Dr. Paul Mahaffy at NASA GSFC[1]. And the inchworm burrowing method is a direct application of our work on the Welding & Inspection Steam Operations Robot (WISOR), a steam tunnel-walking robot provided for the Consolidated Edison Corp. of New York. The IDDS robot is between 10 and 15 centimeters in diameter and 1 meter in length. Two symmetrical segments comprise the IDDS, each with a drill bit and a set of three shoes. Figure 1 below shows a rendering of the concept.

The IDDS gets around problems posed by tethers or umbilicals through the employment of drilling techniques developed by Honeybee Robotics for the Athena Mini-Corer that require no more power than that offered by a radioisotopic thermoelectric generator (RTG) or a successor technology. The high reliability, power density, and output duration of next generation power supplies such as the Sterling Power System (SPS) state a strong case for their use in a kilometer-deep burrowing device.

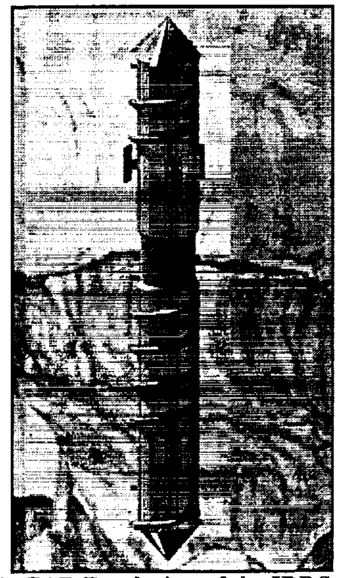


Figure 1: CAD Rendering of the IDDS concept

Burrowing Method: Once deployed by a lander on the surface, the IDDS autonomously drills into the ground under its own power. The inchworm motion of the device's two segments both walks it forward and provides the thrust necessary for drilling. Feet on each segment grip the walls of the hole. Flights along the body pass cuttings to the rear. Sampling and analysis take place once the proper depth is achieved, and since the burrowing method is independent of gravity, the IDDS can then return to the surface. The estimated burrowing rate projects a mission duration on the order of weeks.

Accommodating Scientific Functions: Once the IDDS burrows to the depth specified, it can perform in-situ analysis as well as sample acquisition. With data and samples stored on board, the IDDS can reverse its burrowing process and return to the surface. Various in-situ observations and tests such as imaging and spectroscopy can be facilitated by the IDDS. Once samples are brought into the IDDS by the sample acquisition hardware, treatment of the samples such as baking for a GCMS is feasible as well. As a novel access technology, the IDDS enables the direct search for Europa's possible past, present or future biotic activity.

References: [1] "A Tethered Subsurface Sample Acquisition System" performed for NASA Goddard Space Flight Center #NAS5-30894. Period of performance: April – November 1993.

SUBSURFACE SAMPLE ACQUISITION AND TRANSFER SYSTEMS (SSATS). S. Rafeek[1,2], S. P. Gorevan[1,3], and K. Y. Kong[1,4], [1]Honeybee Robotics, Inc., 204 Elizabeth Street, NY, NY 10012, [2]rafeek@hbrobotics.com, [3]gorevan@hbrobotics.com, [4]kykong@hbrobotics.com.

Introduction: In the exploration of planets and small bodies, scientists will need the services of a deep drilling and material handling system to not only obtain the samples necessary for analyses but also to precisely transfer and deposit those samples in in-situ instruments on board a landed craft or rover. The technology for such a deep sampling system as the SSATS is currently been developed by Honeybee Robotics through a PIDDP effort. The SSATS has its foundation in a one-meter prototype (SATM) drill that was developed under the New Millenium Program for ST4/Champollion. Additionally the SSATS includes relevant coring technology form a coring drill (Athena Mini-Corer) developed for the Mars Sample Return Mission. These highly developed technologies along with the current PIDDP effort, is combined to produce a sampling system that can acquire and transfer samples from various depths.

Key Features of the SSATS:

- Core through solid phase material with high compressive strength.
- Acquire stratigraphy maintained cores to depths of 1-10 meters and beyond.
- Selectively acquire cores of different length and at different depths below the surface without cross contamination.
- Allow samples to be viewed through a sapphire window located in the coring chamber.
- Positive sample ejection mechanism for micro gravity environment.
- Act as a tool to open and manipulate in-situ instruments and sample return containers during sample hand-off.
- Utilize passive brush station for internal (and external) chamber cleaning.
- Integrated core retainer and separator cutting tip.
- Dual operation as a drill or a coring device within the same borehole.

One meter SATM Drill: This drill was prototyped and demonstrated for the ST4/Champollion Program to acquire samples anywhere from the surface to one meter below the surface without cross contamination (see Figure 1). The captured samples were brought back to the surface and deposited to simulated in-situ instruments and sample return containers.

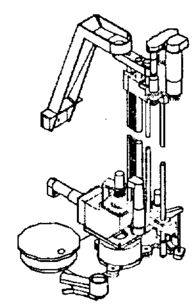


Figure 1- One meter SATM

Technical Advances: Current engineering development in the PIDDP effort seeks to advance the capabilities of the SSATS to make it more robust and scalable as a deep drilling system (DDS). The DDS will have the ability to access samples from 1-10 meters below the surface through the use of multiple drill strings that can be autonomously attached to each other during drilling. An alternative means of getting to 10 meters below the surface is through the use of a telescopic drill. This type of deep drilling system offers additional volume and mass savings while retaining the key features of the SSATS.

Sample Handling: A key part of the SSATS is its ability to combine drilling and sample handling in the same robotic platform. This feature minimizes transfer points and hence the chance of cross contamination. For example, a sapphire window on the drill tip will allow the core samples to be directly viewed by a microscope or the samples can be directly ejected to ovens or sample return canisters as in Fig 2.

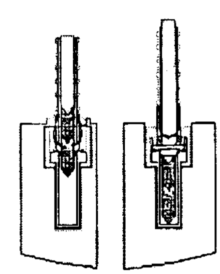


Figure 2 – Core Sample Transfer

References: 1) NASA SBIR Phase I – Contract No. NAS2 – 00019, Dec 9, 1999. 2) NASA PIDDP – Contract No. NASW-00024, Apr. 18, 2000.

A BALLOON-DELIVERED SUBSURFACE SAMPLE ACQUISITION & TRANSFER MECHANISM.

S. Rafeek[1,2], K. Y. Kong[1], S. P. Gorevan[1], and M. A. Ummy[1], [1]Honeybee Robotics, 204 Elizabeth St.; New York, NY 10012; [1]rafeek@hbrobotics.com.

Introduction: The scientific interest in studying the surfaces of both Titan and Triton is clear and strong, however as of yet the technologies that will enable such studies are not. Honeybee Robotics offers a novel access technology concept that could be realistically implemented in a landed mission in the coming decades. The concept is a balloon-delivered Sample Acquisition & Transfer Mechanism (SATM). The balloon-delivered SATM answers the solicitation of Focus Area 1 by providing both access to surfaces of planetary bodies with atmospheres such as Titan and Triton, and by extracting subsurface samples and transferring them to in-situ scientific instrumentation. Heritage exists at Honeybee Robotics for this concept in the form of a working SATM breadboard. The presentation will communicate more fully the concept's framework, it's heritage, and how it can enable successful sampling missions.

Concept Framework: The balloon-based SATM is delivered to a planetary body by an orbiter in an enclosed container. The enclosure opens in the upper atmosphere and utilizes a balloon to safely land on the surface. Once on the surface, the small lander opens, exposing the scientific instrumentation, other hardware, and the SATM. The SATM rights itself and commences drilling as mounted to the lander. One actuator turns the roughly meter length auger while another drives the auger down into the surface. Once at proper depth, by using counter-rotation in the auger, and auger tip opens to acquire a sample. The SATM then removes the sample from the hole and drops it off for in-situ analysis. Figure 1 below schematically shows the SATM prepared to sample.

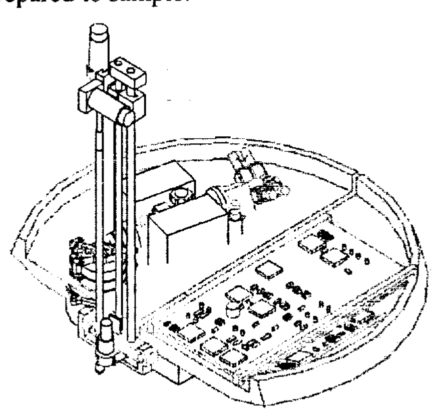


Figure 1: Schematic of the balloon-delivered SATM landed, deployed and ready for sampling.

Concept Heritage: Honeybee Robotics' extensive experience in planetary body sampling and sample transfer devices contributes substantially to the balloon-delivered SATM concept. The direct heritage began with a SATM prototype for the ST-4 / Champollion comet sampling mission. Development of the concept continued in the form of a feasibility study with Dr. Paul Mahaffy of the NASA Goddard Space Flight Center. The SATM prototype consists of a full-scale, computer controlled system capable of drilling to over 20 cm in depth, acquiring a sample at depth, and transferring the sample to a drop-off point. Figure 2 below shows a detail of the functioning prototype.

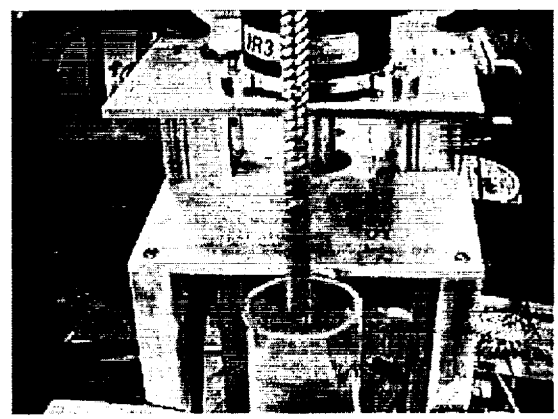


Figure 2: The SATM breadboard auger drilling into a 25cm tall column of Palogonite.

Conclusion: The balloon-delivered SATM concept incorporates many of the necessary capabilities to enable a surface sampling mission to Titan or to Triton, and does so with low mass, low power, and high reliability.

Ion Mass Spectroscopy for the Outer Solar System. D. B. Reisenfeld[1], R. C. Elphic[1], D. J. McComas[2], J. E. Nordholt[1], J. T. Steinberg[1], R.C. Wiens[1], [1]Los Alamos National Laboratory, Space and Atmospheric Sciences, NIS-1, MS-D466, Los Alamos, NM 87545, [2]Southwest Research Institute, P.O. Drawer 28510, San Antonio, TX 78228-0510

A proven method for determination of the exospheric and surface composition of moons and comets is ion mass spectroscopy. Ions are produced via sputtering of surface constituents by the ambient plasma (solar wind or planetary magnetospheres), and via photo- and electron impact ionization of neutral exospheric/atmospheric constituents.

A promising emergent technology in the field of space-based ion mass spectrometry is the low-cost, miniaturized but high-performance ion mass spectrometer (IMS) as exhibited by the Plasma Experiment for Planetary Exploration (PEPE) on Deep Space 1 (DS-1) [1]. A technology demonstration instrument, the PEPE IMS realized a mass resolution ($M/\Delta M$) of ~10. Its energy range extends from 5 eV to 9 keV at this mass resolution, and up to 33.5 keV in a lower mass resolution mode (see Figure).

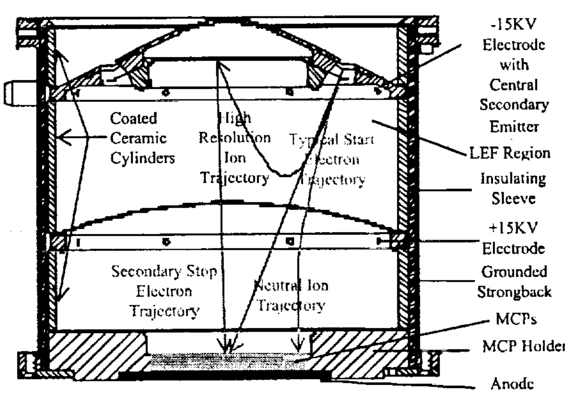
With minimal development, these capabilities can be greatly extended. Already, we have produced a fully functional engineering model having a $M/\Delta M$ = 20 and an energy range extending to 18 keV in the high-mass resolution mode. Further design modifications anticipate extending the mass resolution to 30-40 while still maintaining a miniaturized design. This makes possible many more isotopic and molecular differentiations than achievable with the original PEPE design.

A PEPE-class spectrometer can address a significant number of the OPP key strategic objectives (Focus 1). In particular, *in situ* cometary nucleus analysis, studies of Triton's atmospheric and surface composition, and Europa surface composition analysis, can all be performed through IMS measurements.

Cometary Nuclei: A cometary coma is composed of material outgassed and sputtered from the nucleus. Photoionization, charge exchange, and direct surface sputtering all generate a substantial ion population. A PEPE-class instrument can efficiently sample and analyze the ion population. Example targeted measurements are the cometary $^{13}C/^{12}C$ ratio (a possible test of solar vs. extra-solar system origins), the $^{18}O/^{16}O$ ratio (Halley is the only outer solar system object for which this is known), trace molecular abundances including the CO/N_2 ratio which a PEPE-class instrument is uniquely capable of measuring [2], and heavier organic molecules up to 135 amu. PEPE possesses a ***unique*** advantage over mass spectrometers flown on Giotto and those on known future comet missions: the carbon foil used to generate timing signals breaks up molecules, allowing isotopic ratios of volatile species such as H, C, N, O to be analyzed without interferences from hydride molecular ions (H_2, CH, NH, OH, H_2O, etc.) [2].

Outer Planet Moons: Our IMS design is ideally suited for magnetospheric studies of the Neptune-Triton or Jovian environments (Focus 2) where it could build on the high-mass-resolution studies of the Saturnian system planned with Cassini IMS [2]. Because our IMS/PEPE designs measure composition, they are also invaluable for the study of the ionospheres of outer planet moons, and indirectly, their atmospheric and surface chemistries (Focus 1). For the Neptune-Triton system, a PEPE-class instrument could give a first in-situ glimpse of the magnetosphere and help determine key processes in Triton's atmosphere, as well as yielding some key isotope ratios. Galileo's IMS mass resolution of only 2 did not allow Na to be distinguished from O, an important goal for the understanding of Io's ionospheric and exospheric processes. Key isotopic measurements, e.g. $^{34}S/^{32}S$, at Io are also crucial to understanding that body's evolution. Similarly, a high-mass-resolution instrument in low Europa orbit may give a better understanding not only of its tenuous atmosphere, but also of key isotopic and elemental surface compositions in lieu of a lander.

References: [1] Young, D. T. et al. (2000) Proceedings of the DS-1 Technology Validation Workshop, LA-UR-00-0602. [2] Nordholt et al. (1998) in *Measurement Techniques for Space Plasmas, AGU monograph series.*



Detail of PEPE time-of-flight spectrometer. A linear electric field (LEF) exists between the −15 kV and +15 kV electrodes. This field turns positive ions, causing them to describe a trajectory whose timing only depends on the ion mass, but not energy, resulting in a greatly enhanced mass resolution. The spectrometer is ~11 cm across and has cylindrical symmetry, thus capable of simultaneously detecting particles through 360°.

Significant Science at Jupiter Using Solar Power. Harold J. Reitsema [1], Edward J. Smith[2], Thomas Spilker[2], and Richard Reinert[1]. [1]Ball Aerospace & Technologies Corp., 1600 Commerce St., Boulder, CO 80301 , hreitsema@ball.com, [2]Jet Propulsion Laboratory, Pasadena, CA.

Introduction: Missions to the Outer Planets are challenging for a number of reasons, primary of which is the low output of solar arrays at large heliocentric distances. The INSIDE Jupiter mission is a Discovery concept for a science investigation at Jupiter that is capable of producing major studies of the Jovian internal structure and ionospheric-magnetospheric coupling.

Science Objectives: Jupiter's interior is inaccessible to electromagnetic remote sensing, so our current understanding of its structure and process is limited to theoretical models only loosely constrained by such gross characteristics as total mass, volume, magnetic dipole movement and energy production rate. A spacecraft in close orbit of Jupiter will measure the magnetic and gravity fields, the internal structure and processes that generate them, and their direct effects on Jupiter's atmosphere, ionosphere, and magnetosphere.

Mission Concept: The INSIDE Jupiter mission is highly focussed on making high accuracy gravity and magnetic field measurements. The spacecraft is a simple spin-stabilized vehicle with an Earth-pointed high gain antenna. It spends 15 months in an elliptical Jupiter orbit designed to avoid the areas of highest trapped radiation and to reach to within 4500km of the atmosphere to provide very high accuracy in the gravity field measurements.

Power is provided entirely by 2 lightweight deployed GaAs solar arrays with combined output at end of life of 90W. Spacecraft and instrument designs have emphasized low power consumption. Power is stored in spacecraft batteries to meet peak power demands and during eclipses. Specific issues that have been addressed in establishing the feasibility of solar power in the Jovian environment are low solar intensity, low temperature and the high radiation environment. Tests of GaAs cells in these environments have demonstrated the feasibility of this approach.

USE OF HIBERNATION MODES FOR DEEP SPACE MISSIONS AS A METHOD TO LOWER MISSION OPERATIONS COSTS. E. L. Reynolds[1], [1]Applied Physics Laboratory , The Johns Hopkins University, Laurel, Maryland 20723. Email address: ed.reynolds@jhuapl.edu.

Introduction: Deep space missions are dominated by long periods of low activity cruise before arrival at their main objective. The traditional technique of maintaining regular contact with a spacecraft as it cruises to a distant objective is expensive: a mission operations team must be staffed and DSN antenna time costs thousands of dollars per hour. As more missions are launched, each with longer cruise durations, the strain on resources will become unacceptable.

Placing spacecraft in an unattended hibernation state is a practical solution for drastically reducing mission operations costs and deep space network usage costs. Such a technique was used successfully on GIOTTO's extended mission and a new version of hibernation mode is baselined for NASA's CONTOUR spacecraft. CONTOUR is a Discovery class mission that cruises to different comet nucleii over several years.

Ultimately, hibernation mode enables more resources to be dedicated toward science operations and analysis by reducing infrastructure costs associated with mission cruise.

A white paper on CONTOUR's hibernation mode has been developed that covers different aspects of long term unattended operation including: spacecraft configuration and operation, autonomy requirements, navigation requirements, go-no go criteria, failure modes and response, spacecraft recovery strategy, historical precedent, etc.

The presentation will present details of the CONTOUR white paper along with discussions regarding the implications of hibernation for outer planets missions. Also discussed will be possible use of a beacon mode assisted hibernation for outer planet missions.

MINIATURE NEUTRON-ALPHA ACTIVATION SPECTROMETER. E. Rhodes[1] and J. Goldsten[2], [1]Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD 20723-6099, ed.rhodes@jhuapl.edu, [2]Johns Hopkins University Applied Physics Laboratory, john.goldsten@jhuapl.edu.

Introduction: We are developing a miniature neutron-alpha activation spectrometer for in-situ analysis of samples including rocks, fines, ices, and drill cores, suitable for a lander or Rover platform, that would meet the severe mass, power, and environmental constraints of missions to the outer planets. In the neutron-activation mode, a gamma-ray spectrometer will first perform a penetrating scan of soil, ice, and loose material underfoot (depths to 10 cm or more) to identify appropriate samples. Chosen samples will be analyzed in bulk in neutron-activation mode, and then the sample surfaces will be analyzed in alpha-activation mode using Rutherford backscatter and x-ray spectrometers. The instrument will provide sample composition over a wide range of elements, including rock-forming elements (such as Na, Mg, Si, Fe, and Ca), rare earths (Sm and Eu for example), radioactive elements (K, Th, and U), and light elements present in water, ices, and biological materials (mainly H, C, O, and N). The instrument is expected to have a mass of about 1 kg and to require less than 1 W power.

Focus Area: By selection of construction materials and detectors and design modifications, this instrument can be adapted to a number of mission requirements and space environments, including surface exploration of comets and moons, such as Titan and Triton. Data from this instrument can provide some inferences into prebiotic conditions, petrology, planetary differentiation, igneous evolution, and weathering history. But also, because of its penetrating scanning capability over the body's surface in neutron activation mode, this instrument can select promising samples as the front end of a landed instrument suite including possibly a core driller and specialized mass and infrared spectrometers, that together can provide more definitive information and support the decision to cache appropriate samples for return to earth. Otherwise precious resources can be wasted collecting and measuring uninteresting samples from the vast array of candidates available on the body's surface.

Key Technologies: Novel to our approach are two enabling technologies, a switchable radioactive neutron source (SRNS) and a small high-resolution gamma-ray detector (SHGD). The SRNS is based on the separation of alpha-emitting radioisotope material and light-element material such as Be, B, or Li, that have a large alpha cross section for generating neutrons. When the alpha emitter material is placed in close proximity to the light element material, the neutron source is switched on. When the materials are separated, the neutron source is switched off, preventing unwanted activation and radiation damage to space craft and instrument components when measurements are not being made, without any massive shield. The only other available switchable neutron source is accelerator-based and requires power for bulky ancillary equipment not needed by the SRNS, such as an ultra-high voltage supply (which tends to be relatively unreliable). The SRNS yields a reasonably high neutron flux but is small and requires very little power.

The SHGD consists of a small high-purity Ge (HPGe) or Cd-Zn-Te (CZT) gamma detector inside a bismuth germanate anticoincidence cup, along with low-power digital signal processing electronics. HPGe provides the best energy resolution and efficiency and is the material of choice, but requires low temperature operation. In warm environments, CZT would be used. The cup provides suppression of cosmic rays and detector gamma scattering, along with an escape coincidence mode that further suppresses background at energies above 1 MeV. This detector will yield adequate energy resolution and efficiency for analysis of all gamma lines up to 3.5 MeV (above the C/O double-escape peak), which covers all elements of interest.

Development Base: The SRNS has been patented by one of the authors and it has been demonstrated that a stable SRNS can be made that acts as a strong neutron source [1] (10^6 - 10^8 n/s). The technologies for deployment of HPGe detectors in space are well known. CZT detectors are beginning to be considered for space missions and questions concerning radiation damage, operating temperature range, and other environmental concerns are not yet answered, but the necessary technologies will develop rapidly and APL has a collaboration with a primary CZT developer [2]. The authors have experience developing nuclear spectrometers, analyzing their spectra, and their deployment in space. APL has a long history of successful development and deployment of space craft, including suites of highly sophisticated state-of-the-art instrumentation and involving adaptations to a wide variety of mission requirements and space environments.

References: [1] D. L. Bowers, E. A. Rhodes, and C. E. Dickerman (1998), "A switchable radioactive neutron source: Proof-of-principle", *J. Radioanalytical and Nuclear Chemistry, 131,* 315-321. [2] Z. He, G. F. Knoll, D. K. Wehe, and J. Miyamoto (1997), "Position Sensitive Single Carrier CdZnTe Detectors", *Nuclear Instruments and Methods A, 388,* 180-185.

PLUTO AND TRITON: INTERACTIONS BETWEEN VOLATILES AND DYNAMICS. D. P. Rubincam, Geodynamics Branch, Code 921, Laboratory for Terrestrial Physics, NASA Goddard Space Flight Center, Greenbelt, MD 20771. email: rubincam@core2.gsfc.nasa.gov.

Volatiles moving across the surfaces of Pluto and Triton can give rise to interesting dynamical consequences. Conversely, measurement of dynamical states can help constrain the movement of volatiles and interior structure of both bodies.

Polar wander may theoretically occur on both Triton and Pluto. Triton's obliquity is low, so that the equatorial regions receive more insolation than the poles. Hence there is a tendency for nitrogen ice to sublime at the equator and condense at the poles, creating polar caps [1]. If the nitrogen supply is large enough, then these caps could move in $\sim 10^5$ years the global equivalent of ~200 m of ice to the poles.

At this point the equatorial moment of inertia becomes larger than the moment of inertia measured about the rotation axis, so that Triton overbalances and becomes dynamically unstable. The satellite then undergoes polar wander, restoring stability when the new equator contains the excess matter. Hence the pole may be continually wandering. Neptune raises a permanent tidal bulge on Triton, so that the satellite's surface is elongated like a football, with the long axis pointing at Neptune. This is expected to be the axis about which the pole wanders. Volatile migration would resurface the satellite to some depth and wandering would disturb leading side/trailing side crater statistics.

Triton appears to have more impact craters on the leading side (apex of motion). This could indicate that the supply of volatiles is not large enough to make the pole wander, or that the effective viscosity of Triton's mantle is low enough that the satellite isostatically compensates the caps quickly enough to prevent wander, or some combination of the two. The effective viscosity is not well constrained, but for comparison, Earth-like mantle viscosities of 10^{21} or 10^{22} Pa s give Darwinian relaxation times of $\sim 10^5$ to 10^6 years.

Pluto too may undergo polar wander due to the movement of volatiles. However, Pluto's obliquity is such that the long-term insolation on the equator and pole are roughly equal, so that volatile migration may be controlled by the obliquity oscillations and perihelion geometry as well as viscosity. Charon also raises a tidal bulge on Pluto.

For both Triton and Pluto the tidal bulge is of comparable size to the rotational flattening, so that both objects may be distinctly triaxial. And as pointed out above, volatile migration may be large enough to overcome the flattening. Hence a measurement of the C22 and S22 components of the gravitational field as well as the J2 component would be desirable and possibly constrain the movement of volatiles. An anomalously low value for Triton's flattening, for instance, could indicate matter is piling up at the poles. On the other hand, Pluto's obliquity has been such that matter may have been piling up at the equator, giving an anomalously large flattening.

Pluto may also be the only known case of precession-orbit resonance in the solar system [2]. The Pluto-Charon system orbits the Sun with a period of 1 Plutonian year, which is 250.8 Earth years. The observed parameters of the system are such that Charon may cause Pluto to precess with a period near 250.8 Earth years. This gives rise to two possible resonances, heretofore unrecognized. The first is due to Pluto's orbit being highly eccentric, giving solar torques on Charon with a period of 1 Plutonian year. Charon in turn drives Pluto near its precession period. Volatiles, which are expected to shuttle across Pluto's surface between equator and pole as the insolation varies, might change the planet's dynamical flattening enough and the planet may be stiff enough so that Pluto crosses the nearby resonance, forcing the planet's equatorial plane to depart from Charon's orbital plane. The mutual tilt can reach as much as 3° after integrating over 8.4×10^6 years, depending upon how close Pluto is to the resonance and the supply of volatiles. The second resonance is due to the Sun's traveling above and below Charon's orbital plane; it has a period half that of the eccentricity resonance. Reaching this half-Plutonian year resonance requires a much larger but still theoretically possible amount of volatiles. In this case the departure of Charon from an equatorial orbit is about 1° after integrating for 5.6×10^6 years. The calculations ignore libration and tidal friction. It is not presently known how large the mutual tilt can grow over the age of the solar system, but is probably less than about 4°. If so, then observing such small angles from a Pluto flyby mission would be difficult.

References [1] Brown, R. H., and R. L. Kirk (1994) *J. Geophys. Res. 99*, 1965. [2] Rubincam, D. P. (2000) *J. Geophys. Res. 105*, 26,745.

STIRLING RADIOISOTOPE POWER SYSTEM AS AN ALTERNATIVE FOR NASA'S DEEP SPACE MISSIONS. R. K. Shaltens[1], L. S. Mason[1] and J. G. Schreiber[1], [1]NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135 (Richard.Shaltens@grc.nasa.gov, Lee.Mason@grc.nasa.gov, Jeffrey.Schreiber@grc.nasa.gov)

Introduction: The NASA Glenn Research Center (GRC) and the Department of Energy (DOE) are developing a free-piston Stirling convertor for a Stirling Radioisotope Power System (SRPS) to provide on-board electric power for future NASA deep space missions. The SRPS currently being developed provides about 100 watts and reduces the amount of radioisotope fuel by a factor of four over conventional Radioisotope Thermoelectric Generators (RTG). The present SRPS design has a specific power of approximately 4 W/kg which is comparable to an RTG. GRC estimates for advanced versions of the SRPS with improved heat source integration, lightweight Stirling convertors, composite radiators, and chip-packaged controllers improves the specific mass to about 8 W/kg.

Present SRPS Design: The present SRPS design is referred to as Version 1.0 and is shown conceptually in Figure 1. It consists of 1) two General Purpose Heat Source (GPHS) modules, 2) two opposed piston Stirling convertors, 3) a waste heat radiator, and 4) an electrical controller. The controller maintains proper operation of the Stirling convertors and converts the AC alternator output into DC for the spacecraft bus. The Version 1.0 SRPS produces 112 watts DC at Beginning-of-Mission (BOM) with a Stirling hot-end temperature of 650°C and a cold-end temperature of 120°C. The convertors are based on Stirling Technology Company's 55 watt Technology Demonstration Convertor (TDC). Convertor efficiency is approximately 28%. Accounting for heat source thermal losses and controller electrical losses, the total system efficiency for the SRPS is 23%. Total system mass is estimated at 27 kg which includes 15% margin on the non-heat source masses, and shielding on the controller to survive the Europa radiation environment. For comparison, a scaled version of the Cassini RTG design, which uses 9 GPHS to produce 139 watts BOM, has an estimated mass of 31 kg.

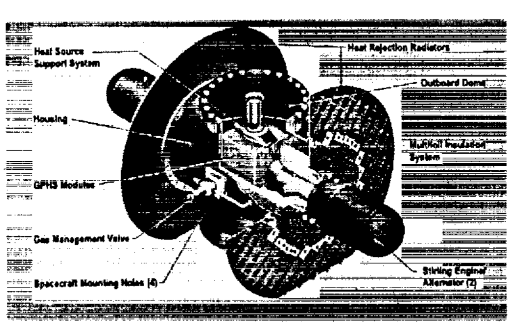


Figure 1. SRPS Conceptual Design

Future SRPS: Figure 2 provides a comparison of the small RTG, SRPS Version 1.0, and two advanced SRPS designs. Several minor modifications are incorporated into Version 1.1 which results in a specific power of about 6 W/kg. These changes include a smaller alternator and Stirling pressure vessel (while maintaining the TDC design configuration), a capacitor-free controller, and elimination of the Europa radiation shielding. The modified convertor would weigh 42% less than the TDC and would provide 30% conversion efficiency. The Version 1.1 system would produce 120 watts BOM and have a total mass of 20 kg while maintaining the hot-end temperature at 650°C and the cold-end temperature at 120°C. The mass includes 25% margin on the non-heat source components.

A complete redesign of the SRPS in Version 2.0 results in a specific power of about 7.8 W/kg. This system includes an improved GPHS integration, two ultra-lightweight Stirling convertors, an advanced composite radiator utilizing carbon-carbon or thermo-pyrolytic graphite (TPG), and a high efficiency controller-on-a-chip. Convertor mass is reduced by 42%, radiator mass is reduced by 33%, and controller mass is reduced by 17% as compared to Version 1.1. Total system mass for Version 2.0 is estimated at 16 kg with 25% margin on the non-heat source components. BOM power output is improved slightly to 124 watts while maintaining the 650°C hot-end and 120°C cold-end temperatures.

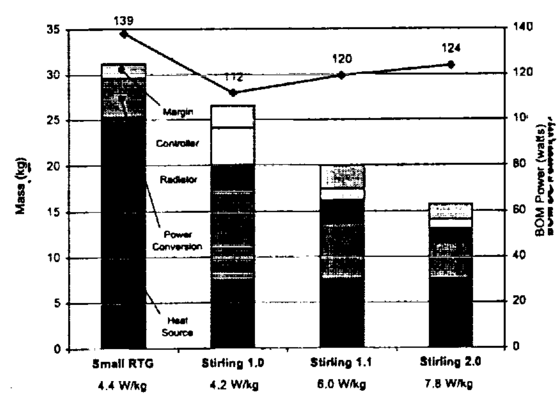


Figure 2. Power System Mass Comparison

Titan Orbiter Aerorover Mission. E. C. Sittler Jr.[1], M. Acuna[1], M. J. Burchell[6], A. Coates[7], W. Farrell[1], M. Flasar[1], B. E. Goldstein[3], S. Gorevan[4], R. E. Hartle[1], W.T.K. Johnson[3], D. R. Kojiro[2], H. Niemann[1], E. N. Nilsen[3], J. Nuth[1], D. Smith[1], and J. C. Zarnecki[5]. [1]NASA Goddard Space Flight Center (Greenbelt, MD, 20771), [2]NASA Ames Research Center (Moffett Field, CA, 94035), . [3]Jet Propulsion Laboratory (4800 Oak Grove Dr., Pasadena, CA, 91109), [4]Honeybee Robotics Inc. (204 Elizabeth St., NY, NY, 10012), [5]Open University (Walton Hall, Milton Keynes, MK7 6AA, UK), [6]University at Kent (Canterbury, CT2 7NR, UK), and [7]Mullard Space Science Laboratory (Holmbury St. Mary, Dorking, Surrey RH5 6NT, UK)

Introduction: We propose a combined Titan orbiter and Titan Aerorover mission with an emphasis on both *in situ* and remote sensing measurements of Titan's surface, atmosphere, ionosphere and magneospheric interaction. The biological aspect of the Titan environment will be emphasized by the mission (i.e., search for organic materials which may include simple organics to 'amono' analogues of amino acids and possibly more complex, lightening detection and infrared, ultraviolet, and charged particle interactions with Titan's surface and atmosphere). An international mission is assumed to control costs. NASA will provide the orbiter, launch vehicle, DSN coverage and operations, while international partners will provide the Aerorover and up to 30% of the cost for the scientific instruments through collaborative efforts. To further reduce costs we propose a single PI for orbiter science instruments and a single PI for Aerorover science instruments. This approach will provide single command/data and power interface between spacecraft and orbiter instruments which will have redundant central DPU and power converter for their instruments. A similar approach could be used for the Aerorover. The mission profile will be constructed to minimize conflicts between Aerorover science, orbiter radar science, orbiter radio science, orbiter imaging science and orbiter fields and particles (FP) science. The mission entails a 3 year development phase starting in 2007, launch in 2010 with a 9 year cruise phase to Titan, and about 20 month Titan orbiter-Aerorover phase. The launch vehicle would be a Titan III with Solar Electric Propulsion (SEP) to bring a combined payload of orbiter and Aerorover to Titan with launch mass of 810 kg. The orbiter weight is 490 kg, orbiter science instruments 120 kg, and Aerorover with science instruments 200 kg. The cost to NASA is estimated to be $540M for development and launch phase and $140M for mission operations phase. Aerobraking in Titan's atmosphere is used for orbit capture with elliptical orbit (periapsis at 1000 km altitude, apoapsis at 5 Titan radii and 14 hour orbital period) the Aerorover is injected into Titan's atmosphere, a balloon is used below 10 km altitude. The Aerorover instrument package** may include NIR Camera, EXOBIOLAB (sample collection & distribution unit, chromatography-ion mobility spectrometer, differential thermal analysis, pyrolysis, X-ray florescence, and Neutron Spectrometer), GCMS, seismometer (3-axis accelerometers), pressure and temperature gauge, radar altimeter, Atmospheric Properties Unit (APU), Siphoning Properties Unit (SPU), Siphon Sampling Unit (SSU), Drill Hover Sampling Unit (DHSU), Drill Core Sampling Unit (DCSU), Homochirality Detector (HD) and Cosmic Ray Detector (CRD). The orbiter will be in a polar orbit and while the Aerorover is drifting in Titan's atmosphere (winds are expected to transport the Aerorover once around Titan in 2 to 4 weeks), the orbiter radar instrument will obtain a coarse surface map of Titan; the time to complete a map of Titan's surface is about 1 month (16 day Titan orbit around Saturn). This map will be used to identify continents and oceans on Titan's surface and used to identify landing sites for the Aerorover. The Aerorover will remain in Titan's atmosphere for about two months at various altitudes while potential landing sites are determined. The Aerorover will first sample the oceans using a flexible weighted siphoning hose or SSU and SPU where it will hover 1-2 meters over the ocean. A similar approach will be used for land sites while hovering using DHSU . Finally, Aerorover will land on the surface and detach the balloon for detailed surface analysis at this final site using DCSU. Here the accelerometers could be used to detect Titan quakes. The hovering and landing phase will last about 2 months. We will then obtain a detailed map of Titan's surface using the orbiter radar for about 6 months with 100 meter resolution. Then for 1 month period perform radio science (RS) occultations of Titan's atmosphere, perform gravity experiments and DSN bi-static scattering of radio waves off of Titan to probe Titan's surface scattering properties. We will then have 6 month period for remote sensing of Titan's atmosphere and surface using orbiter imaging instruments** (UV/IR Imaging Spectrometer and submm Hetrodyne Spectrometer for winds) and orbiter FP instruments** to provide *in situ* measurements of Titan's upper atmosphere, ionosphere and magnetospheric interaction (Plasma Spectrometer (PLS), Ion/Neutral MS (INMS), Magnetometer (MAG), Radio-Plasma Wave/ Langmuir Probe (RPWS/LP), and CRD). The PLS and INMS will be designed to optimize organic molecule detection. Combined with MAG they will give information about upper atmosphere winds and heating. The RPWS can be used to detect lightning. During this period we plan to rotate orbit* to provide optimal RS occultation geometry and provide different local times and scattering phase angles for imagers. At end of 6 month period begin 3 month period for RS occultations and decrease orbit inclination from 90° to 0°* for 360° coverage of RS occultations of Titan's atmosphere and ionosphere. Gravity experiments and DSN bi-static scattering of radio waves off of Titan will also be performed. This mission will provide a broad scientific emphasis for the biological aspects of Titan's environment in a cost effective way. (*To be confirmed) (**Options being considered and may change as study progresses regarding science, mass, power, telemetry rate and cost.).

A RETURN TO IO: SCIENCE GOALS AND IMPLEMENTATION: J. R. Spencer[1], W. D. Smythe[2], R. Lopes-Gautier[2], and A. S. McEwen[3], [1]Lowell Observatory, 1400 W. Mars Hill Rd., Flagstaff AZ 86001, spencer@lowell.edu, [2]JPL, 4800 Oak Grove Dr., Pasadena, CA 91109, [3]University of Arizona, Tucson, AZ 85721.

Science Goals: Io remains one of the most fascinating objects in the solar system: the only place beyond Earth where we can watch hard-rock geology in action. In its high heat flow Io resembles the early Earth, providing a present-day analog to some of the processes that dominated the Earth's geology at the time that life first appeared. Io's usefulness as an early-Earth analog has been underscored recently by the detection of very high eruption temperatures, hotter than terrestrial basaltic lavas [1]. These temperatures are most plausibly interpreted as resulting from ultramafic lava compositions, analagous to the komatiites that were common on Earth in the Precambrian but which have been virtually absent during the Phanerozoic. The large scale of many Io eruptions also provides useful analogs to Phanerozoic terrestrial eruptions, such as flood basalts, which are important for the Earth's geological and biological evolution but which occur too rarely to be witnessed by humans on our own planet. By providing living examples, Io can thus play the same role in understanding large-scale planetary volcanism that volcanically active terrestrial regions have played in understanding the results of smaller-scale volcanic processes seen in the geological record worldwide.

Despite the recent close flybys [2,3,4], Galileo, with its 1980-vintage instrumentation and very low data rate, has not been able to answer many fundamental questions about Io. These include the following:

1) What is the composition, and compositional range, of Io's lavas? Answering this question will give a critical window into Io's interior. High-resolution Galileo images have shown dark, fresh, lava surfaces but have not been able to obtain diagnostic spectra of these small but critical regions, though there are hints of diagnostic silicate absorption features in very low-resolution image-derived spectra.
2) What is the range of eruption mechanisms on Io? Galileo has made important contributions to this question, revealing both slowly inflating and rapidly emplaced lava flows, but its temporal and spatial coverage has been too intermittent for detailed studies.
3) What is the age of Io's surface? Galileo has been unable to obtain the wide-area, high-resolution coverage needed to detect the few small impact craters that could easily exist given current estimates of resurfacing rates.
4) What is the composition of Io's volcanic gases? These provide another important window on the interior. Progress has been made with Hubble UV spectroscopy [5], but spatial resolution is severely limited.
5) What is the magnitude, time evolution, and spatial distribution of Io's total heat flow? This provides an important constraint on models of the tidal heating that is the engine behind Io's volcanism, and provides insights into Europa's internal energy budget because of the coupled nature of the two satellites. Heat flow estimates require disentangling the volcanic and re-radiated solar components of Io's thermal emission [6], and are currently hampered by our limited understanding of Io's bolometric albedo distribution and limited maps of Io's thermal emission.

Implementation: To answer most of these questions, a return to Io is needed. To obtain good temporal coverage while minimizing radiation dose and delta-V, a Galileo-type Jovocentric eccentric orbit with perijove near 5.9 R_J may be preferred, allowing repeated Io flybys. Data return and distant monitoring would be carried out between Io flybys. Galileo has so far survived five passes within 5.9 R_J, and rad-hard technology developed for the Europa orbiter should allow an Io mission to survive many such passes.

Minimum instrumentation for such a mission would include a high-resolution imager, a visible/NIR spectrograph for compositional and volcanic emission studies, and a 10 - 20μm thermal mapper for heat flow and lava cooling studies. Atmospheric studies could be accomplished with an additional UV spectrometer and/or onboard mass spectrometer, and a magnetometer could provide additional insights into Io's internal structure at minimal extra cost. Further insights into Io's interior might be possible via studies of tidal deformation by laser altimeter. Large solar panels may prove feasible for use at Jupiter.

Such a mission would have less stringent delta-V and radiation dose constraints than the planned Europa orbiter, and could thus probably be carried out with significantly lower cost than EO.

References: [1] McEwen A. S. et al. (1998) *Science 281* 87. [2] McEwen A. S. et al. (2000) *Science 288* 1193. [3] Lopes-Gautier, R. et al. (2000) *Science 288* 1201. [4] Spencer, J. R. et al. (2000) *Science 288* 1198. [5] Spencer, J. R. et al. (2000) *Science 288,* 1208. [6] Veeder, G. J. et al. (1994) *J. Geophys. Res., 99,* 17095.

Saturn Deep Atmospheric Entry Probes Delivered by INSIDE Jupiter Derivative Spacecraft. T. R. Spilker, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109-8099, tspilker@mail1.jpl.nasa.gov.

Introduction: *In situ* probes are the most reliable means for sampling composition and conditions deep in giant planet atmospheres. Deep constituent abundances at the giant planets offer clues to conditions in the solar system's protoplanetary disk and variations with heliocentric distance. Currently *in situ* atmospheric data are available from only one giant planet, Jupiter, and probes that penetrate deeper than the *Galileo* probe are needed there to measure the deep abundances of such important species as H_2O and H_2S. Deep probes at Saturn would extend the sampled heliocentric range to Saturn, providing important constraints on the conditions and variability of the protoplanetary disk, and would provide significant new information about Saturn and its evolutionary processes. Such a probe mission could be implemented using a derivative of the INSIDE Jupiter mission's spacecraft [1] as the Carrier/Relay Spacecraft (CRSC), with probes per JPL/Team X [2] and other design studies.

Science Objectives: The primary science goals are to understand:

1. Bulk composition & its gradients, especially as related to solar system formation & planetary evolution
2. Atmospheric chemistry
3. Atmospheric structure & dynamics
4. Spatial variability in the troposphere & deeper

These are supported by the mission's measurement objectives, in rough priority order:

1. Mixing ratios of the primary C, O, N, & S bearers, as a function of depth
2. Cloud composition, density, & particle size
3. Atmospheric temperature, pressure, & density as a function of depth
4. Bulk flow (wind) as a function of depth
5. Vertical radiant energy flux as a function of depth
6. Ortho- to para-H_2 ratio
7. Noble gas & disequilibrium species mixing ratios; isotopic ratios for selected elements

The objectives address all three major topics of the SSE Roadmap Quest, "To Explain the Formation and Evolution of the Solar System and Earth."

Payload: Candidate instruments: GCMS; net flux radiometer; nephelometer; atmospheric structure package with thermometers, pressure transducers, and accelerometers; sound speed instrument, for ortho-/para-H_2 ratios; USO for Doppler wind experiments.

Mission Design: About six months before arrival via a "standard" transfer to Saturn, the spacecraft deploys one or two ~100-kg atmospheric entry probes. If one probe is delivered, the mission design could closely resemble that of the *Galileo* orbiter and probe at Jupiter. Deploying two probes would use a strategy similar to that of the Multiple Deep Jupiter Probes mission described in this forum [3]. In either case, Saturn orbit insertion is not necessary.

Spacecraft: Considerable mass and power savings are realized relative to the original INSIDE Jupiter spacecraft design by removing equipment specific to the Jupiter orbital mission, such as the MAG instrument boom, parts of the telecom subsystem, and notably the large (>500 kg) primary propulsion module, whose main function is JOI. The mass savings allow adding equipment needed for the Saturn probe(s) mission. Figure 1 illustrates some of the changes: with the mag boom gone, an additional set of two solar arrays adds to the power available and also to spin stability.

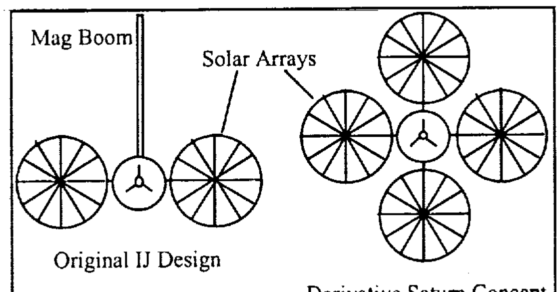


Figure 1

The Saturn mission benefits from avoiding Jupiter's radiation environment. The original IJ design had solar arrays sized for EOL power, significantly degraded from the BOL power by radiation. A Saturn mission suffers much less degradation, such that doubling the array area provides sufficient power to operate the spacecraft. This requires further study to verify that recent progress in LILT arrays are capable of attaining the requisite efficiency at Saturn distances.

Removing the JOI propulsion system provides multiple options for attaching and deploying probes, including options that permit attaching a SEP stage if the Earth-Saturn transfer should so require. The solar arrays produce enough power at 1 AU to operate up to three NSTAR engines. This would require adding a 3-axis-stabilized mode, which could be controlled from the SEP stage.

Data Relay. Data sent from the probes to the CRSC is stored for playback from heliocentric orbit.

References: [1] Jonaitis J. et al. (2000) *IAA Conf Low-Cost Plan Miss IV*, L-0601. [2] Oberto R. et al. (1997) JPL Team X report, *Outer Planet Probes.* [3] Spilker, T.R. et al. (2001), this forum.

Saturn Ring Observer. T. R. Spilker, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109-8099, tspilker@mail1.jpl.nasa.gov.

Introduction: Answering fundamental questions about ring particle characteristics, and individual and group behavior, appears to require close-proximity (a few km) observations. Saturn's magnificent example of a ring system offers a full range of particle sizes, densities, and behaviors for study, so it is a natural choice for such detailed investigation. Missions implementing these observations require post-approach ΔV of ~10 km/s or more, so past mission concepts called upon Nuclear Electric Propulsion [1], [2]. The concept described here (presented at the Intern'l Conf on Low-Cost Plan Missns, 2000; published in those proceedings [4]) reduces the propulsive ΔV requirement to as little as 3.5 km/s, difficult but not impossible for high-performance chemical propulsion systems.

Science Objectives: For this mission the Astrophysical Analogs CSWG provided a prioritized list of science objectives [3] grouped in three categories:

1.A (minimum mission, unique) Determine the physical nature and kinematics of ring particles and agglomerations of particles

1.B (mission enhancing, unique) Determine the mass distribution over a wide radial and azimuth range. Collect data to test models of wave production, shepherding, and ring confinement

2.A (mission enhancing, extension of Cassini) Determine the rings' electromagnetic environment, dust distribution, and neutral and ionized "atmosphere" distribution

Measurement objectives that support the 1.A science objectives include particles' physical nature (shape, roughness, etc.) and 3D random velocities and spin states, coefficients of restitution in collisions, agglomeration clumping/sliding/shearing behavior, and ring scale height. These objectives directly address many not-yet-understood phenomena in planetary ring systems, and find important applications in understanding astrophysical systems, such as protostellar and protoplanetary accretion disks, with direct bearing on the origins of our solar system and the planets within it.

Payload: The 1.A and 1.B objectives can be accomplished by narrow- and wide-angle imaging and a radar or lidar altimeter also needed for near-ring navigation and maneuvering. The 2.A objectives require additional instruments, such as a mass spectrometer, a dust detector, and electric and magnetic fields sensors.

Mission Design: Figure 1 illustrates the most important aspects of the initial orbit insertion at Saturn. After arrival via a "standard" transfer to a slightly inclined hyperbolic approach to Saturn, the spacecraft aerocaptures as it crosses the ring (equatorial) plane, net ΔV ~7 km/s. Immediately after atmosphere exit, the onboard autonomous system uses a chemical propulsion stage to perform a clean-up maneuver of <0.5 km/s to cancel residuals. The captured orbit has an equatorial line of apsides, with its apoapse radius at the initial target region of the rings. As it nears apoapse, the propulsion stage performs a final, 3 km/s maneuver to place the spacecraft in the initial "hover" orbit.

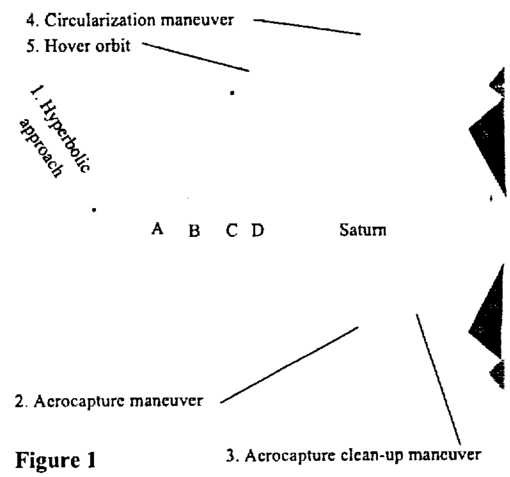


Figure 1

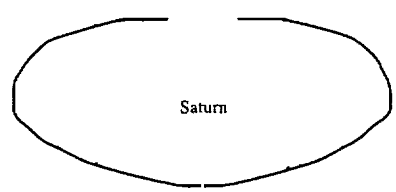


Figure 2 *Not to scale!*

From that point, small (<1 m/s) maneuvers every few hours maintain the hover orbit as shown in Figure 2, where the small open circles locate the maneuvers, and the light line on the ring plane is the hover orbit projected onto that plane. Using bipropellant thrusters with a propellant mass fraction of 10% maintains the orbit for nearly two months [4], [5]. Additional propellant permits changing the orbit radius to investigate various interesting regions of the rings.

Data Relay. The spacecraft is placed on the sunlit and Earth-facing side of the rings, allowing continuous data downlink except for brief Saturn-occulted periods.

References: [1] Wells W.C. and Price M.J. (1972) *A survey of candidate missions to explore Saturn's rings,* IIT Rsch Inst Rpt M-31. [2] Nock K.T. (1989) *Rendezvous with Saturn's rings,* JPL internal publication. [3] Porco C. et al. (1999) *Science Objectives for Saturn Ring Observer,* AACSWG communication to JPL's Team X. [4] Spilker T.R. (2000) *IAA Conf Low-Cost Plan Miss IV,* L-0604. [5] Oberto R. et al. (1999) JPL Team X report, *Saturn Ring Observer.*

FLYBY DELIVERS MULTIPLE DEEP JUPITER PROBES. T. R. Spilker[1], W. B. Hubbard[2], and A. P. Ingersoll[3], [1]Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109-8099, tspilker@mail1.jpl.nasa.gov, [2]Lunar & Planetary Laboratory, Univ. of Arizona, Tucson, AZ 85721, [3]California Inst. of Technology, Pasadena, CA 91125.

Introduction: *In situ* probes are the most reliable means for sampling composition and conditions deep in giant planet atmospheres. While exceeding its baseline mission, the *Galileo* probe entered a distinctly non-representative region of Jupiter (a "hot spot") and apparently did not measure the full deep abundances of such important species as H_2O and H_2S, whose measured abundances were still increasing at the deepest datum [1], [2]. Multiple deep (~100 bar) *in situ* probes minimize the hot spot risk, and address spatial variations and deep constituent abundances.

Science Objectives: The primary science goals are to understand:

1. Bulk composition & its gradients, especially as related to solar system formation & planetary evolution
2. Atmospheric chemistry
3. Atmospheric structure & dynamics
4. Spatial variability in the troposphere & deeper

These are supported by the mission's measurement objectives, in rough priority order:

1. Mixing ratios of the primary C, O, N, & S bearers, as a function of depth
2. Cloud composition, density, & particle size
3. Atmospheric temperature, pressure, & density as a function of depth
4. Bulk flow (wind) as a function of depth
5. Vertical radiant energy flux as a function of depth
6. Ortho- to para-H_2 ratio
7. Noble gas & disequilibrium species mixing ratios; isotopic ratios for selected elements

The objectives address all three major topics of the SSE Roadmap Quest, "To Explain the Formation and Evolution of the Solar System and Earth."

Payload: Candidate instruments: GCMS; net flux radiometer; nephelometer; atmospheric structure package with thermometers, pressure transducers, and accelerometers; sound speed instrument, for ortho-/para-H_2 ratios; USO for Doppler wind experiments.

Mission Design: Figure 1 illustrates the most important aspects of the mission design. About 6 months before arrival via a "standard" transfer to Jupiter the Carrier-Relay Spacecraft (CRSC), with up to 3 or 4 100-kg probes [3], is on the trajectory labeled "South Probe." The probe is released, and a maneuver of ~30-50 m/s places the CRSC and remaining probes on the "Equatorial Probe" trajectory, such that arrival is ~2-3 hours before the south probe arrives; that probe is then released. Another maneuver of 30-50 m/s places the CRSC and north probe on the "North Probe" trajectory such that arrival is 2-3 hours before the equatorial probe, and that probe is released. A final maneuver of ~70 m/s places the CRSC on the polar flyby trajectory indicated. Probes deployed in this manner can reach latitudes up to ~25° away from equatorial.

Data Relay. As the CRSC flies by Jupiter N-to-S, it receives the probes' transmissions in non-overlapping order, storing them for later playback from heliocentric orbit. Planetary rotation carries the probes toward the CRSC "ground track" for the deepest parts of their missions.

Radiation: A polar flyby yields less than 1/3 the dose of the Galileo orbiter's first perijove pass, less than 30 krad. The equatorial probe's radiation environment is similar to the Galileo probe's, while the N and S probes experience less than that.

History & Status: In 1997 JPL's Team X, under guidance from SSES' Astrophysical Analogs CSWG, conducted preliminary studies of this new mission design. At that time the AACSWG made it their top near-term priority. Delivery by other spacecraft, such as Solar Probe and Pluto-Kuiper Express, was examined and rejected. No more detailed studies have been conducted since that time.

Cost: The *INSIDE Jupiter* spacecraft, modified to substitute the probes and their deployment mechanism for IJ's substantial (>500 kg wet) primary propulsion module, could function as the CRSC, so the CRSC and mission could be implemented within a Discovery Program budget plus the cost of the probes. Probe development would require ~\$15M for heat shield R&D before project start [3].

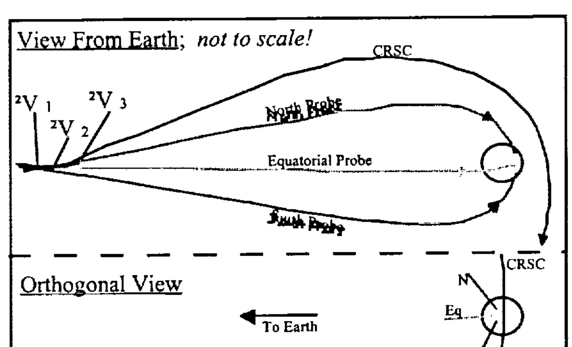


Figure 1

References: [1] Neimann H.B. et al. (1998) *JGR., 101,* E10, 22,857-89. [2] Hubbard W.B. et al. (1997) *Science Objectives For Jupiter Deep Probes,* AACSWG communication to JPL's Team X. [3] Rowley R. et al. (1997) Team X Study Report, *Jupiter Deep Multiprobes.*

EVOLVABLE HARDWARE FOR EXTREME ENVIRONMENTS: "HOT OR COLD, WE LIVE LONG"

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Introduction: Temperature tolerant electronics and long life survivability are key capabilities required for future NASA/JPL missions. Current approaches to electronics for extreme environments focus on component level robustness and hardening. Compensation techniques e.g. as offered by bias cancellation circuits have also been employed. This paper presents a novel approach, based on evolvable hardware technology (see Figure), which allows adaptive in-situ circuit redesign/reconfiguration during the operation in the environment. This technology would complement material/device advancements and bring closer the success of missions in harsh environments.

Relevance to Deep Space: Exploration of planets like Neptune requires electronics able to operate below –220 C, or even -235 C on the surface of Triton, as cold as Pluto. Electronics for Venus missions need to operate at above 470 C, and it appears that hot electronics technology for >400 C environments may not be ready in time for the 2006-2007 missions, except possibly for "grab-and-go" or "limited life" operations [1].

EHW Approach: Conventional, fixed circuit solutions satisfy operational requirements over a given temperature range. Once the limits of the range are exceeded the performance deteriorates and can not be recovered. With configurable chips, such as Field Programmable Transistor Arrays (FPTA), the interconnections between components can be changed, and new circuits can be configured, in an arrangement that may be able to use the devices at the new operational point on their characteristic.

In essence, a new design process takes place automatically, in-situ, under the control of a search algorithm. We demonstrated this technology with an experimental test chip, reconfigurable at transistor level, on which functional recovery was demonstrated through evolutionary self-configuration.

EHW Experiments: The evolutionary recovery of degraded functionality was demonstrated in experiments at –196 C, and +250 C for a variety of analog and digital circuits. In all cases evolution was able to recover functionality, by finding a new circuit solution (interconnection pattern). The experiments were performed on bulk CMOS because of the convenience and low cost of fabricating in this technology, yet the technology is portable and should be used as enhancing technique combined with materials/devices more appropriate for extreme temperatures, such as silicon carbide, etc.

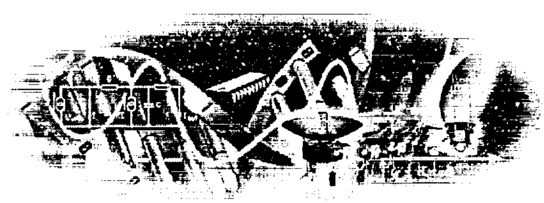

Figure: Evolvable hardware techniques enable self-reconfigurability and adaptability of programmable devices and thus have the potential to significantly increase the functionality of deployed hardware systems from electronics to antennas. Evolvable Hardware is expected to have major impact on deployable systems for space missions that need to survive and perform at optimal functionality during long duration in unknown, harsh and/or changing environments.

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IN SITU **CHRONOLOGY IN THE OUTER SOLAR SYSTEM.** T.D. Swindle, R. Brown, R. Greenberg, J. Lunine, A. McEwen. Lunar and Planetary Laboratory, University of Arizona, Tucson AZ 85721-0092.

Introduction: Determining the age of a feature on a solar system body is one of the most important tasks that can be done on a planetary sample, since almost any model has to include time as one of its parameters. Unfortunately, determining the age of a feature is also one of the most difficult things to do *in situ*. At the University of Arizona's Lunar and Planetary Laboratory, we have identified techniques that could provide essential age determinations, using *in situ* technologies suitable for spacecraft delivery.

We will adopt a 10% uncertainty as a target precision. For many planetary situations, an age with an uncertainty of 10% would be a huge improvement on current knowledge, and could resolve critical issues of origins and evolution. For example, there are major uncertainties about the size-frequency distribution and abundances of small bodies in the outer solar system [1], so a few *in situ* dates could go a long ways toward calibration of cratering statistics. Similarly, *in situ* ages would be useful for bodies on which cryovolcanism does, or might, occur, such as Europa and Titan. In addition, *in situ* dating could be used to determine the rates of surface processes such as sputtering on Europa [2].

We propose four basic techniques – potassium-argon (K-Ar) dating, cosmogenic noble gas exposure age dating, ^{14}C dating, and maturation of D/H in surface ices. K-Ar dating measures the time since formation (or perhaps significant reheating) of an ice, while the others measure surface exposure.

Noble gas dating (K-Ar and cosmogenic): The first two require the same measurements, abundances of major and minor elements and isotopic abundances of the light noble gases (He, Ne, and Ar). We have a PIDDP grant to develop such a system for Mars, and are also funded to study how it might be applied to the outer solar system. K-Ar dating requires the presence of K, but theoretical studies suggest that there should be K present at the surfaces of differentiated objects such as Europa and Titan [3,4], and Galileo NIMS data suggest that there is some non-ice (salt?) component on the surface of Europa [5], of which K is a plausible constituent [6]. Cosmogenic noble gases should be produced within a few meters of every solid surface in the outer solar system except for that of Titan, and can determine ages of 1-100 Ma. Even pure ice would produce abundant ^{3}He, while ^{21}Ne, ^{22}Ne and/or ^{38}Ar would be produced by many of the potential non-ice components.

^{14}C dating: On Titan, while the atmosphere prevents cosmic ray interactions at the surface, cosmic ray interactions in the atmosphere will produce ^{14}C, which will then become incorporated into any carbon-bearing species that form in equilibrium with the atmosphere. Since the production and processing of organic material is a key issue in discussions of Titan, ^{14}C is uniquely suited, although it addresses timescales of no more than 10-20ka. Instrumentation would need to be developed, but appears feasible.

D/H enrichment: Dating by measurement of D/H enrichment may be an effective technique on any icy surface except Titan. Sputtering of water ice by energetic particles will do at least two things to an icy surface: (1) kick molecules off the surface, sometimes to escape velocity; and (2) break chemical bonds. Both of these processes should enhance the D/H ratio, so an older piece of surface should have a higher D/H ratio. Unlike the previous methods, this technique has not been proven. It is not clear what timescales and fractionations are to be expected, and whether that would allow dating areas of the surface to a useful precision. We suspect that this might be useful on relatively short timescales, perhaps up to 1 Ma or so. However, detailed calculations and experiments are needed.

Hence, *in situ* chronology appears feasible and scientifically useful on every solid surface in the outer solar system. However, in no case is the technology fully developed at present. Chronology is an obvious goal for any landed mission in the outer solar system.

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SEISMOBALL: A SMALL EUROPA ORBITER DROP-OFF PROBE FOR EARLY EXPLORATION OF THE EUROPAN SURFACE. L. Tamppari, W. Zimmerman[1], and J. Green, [1]Jet Propulsion Laboratory, 4800 Oak Grove Drive, Mail Stop 198-219, Monrovia CA 91109, USA.

Recent magnetometry data received from Galileo indicate that the most likely explanation for the magnetic signature there is indeed a a global conducting layer below the surface (Kivelson, 2000). This conducting layer is well-matched by a salty, mineral rich strata beneath the Europan ice crust or a salt water ocean. Galileo imaging results show a variety of terrain types thought to contain young material; for example, lineaments, chaotic terrain, and eruption features. Additionally, Galileo images have shown indications of areas of up-welling where subsurface material periodically gets pushed to the surface due to the forces of fracturing, butting, and refreezing of the ice sheet. While Europa Orbiter will provide close-flyby high resolution images, as well as magnetometry, spectroscopy and other remote sensing data of the surface, it will not be able to provide essential engineering data like surface hardness and surface ice structure needed to support eventual landed missions. Additionally, ice chemical composition at microscopic scales can only be studied in detail through in-situ instrumentation.

Seismoball is a small probe designed to be injected into a surface intersect orbit around Europa. Using small reverser thrusters, the probe will be capable of nulling the high horizontal injection velocity as it approaches the 2km surface injection altitude, thus allowing it to fall to the surface at an impact velocity of <100m/sec (much less than the DS-2 impact velocities). The external breakaway thruster structure and crushable exterior shell absorb the impact energy while allowing the science instrument suite to remain intact. JPL has already started analyzing the entry dynamics and designing/building a small, low mass probe which will withstand the impact g-forces and fit as a "carry-on" onboard the Europa Orbiter. The probe will carry a suite of 5-6 micro-instruments for imaging the surface (both microscopic and far-field), surface and shallow subsurface ice temperatures, surface hardness, crustal dynamics and periodicity, and compositional chemistry. If selected, this flight development activity will provide a unique science opportunity and adjunct to the primary Orbiter science mission. The final flight system will be designed to accommodate orbiter mass, volume, and power interface constraints, as well as entry dynamics, g-load mitigation, and arbitrary landing orientation.

Concepts and Engineering Advances Required for Near-Term Solar Sail Propelled Outer Planet Probes. T.S. Taylor, Teledyne Brown Engineering, 300 Sparkman Drive, Huntsville, Al. 35805, phone: 256-726-2105, email: travis.taylor@tbe.com.

Introduction: The concept of using light pressure for propulsion is not a new one. In fact, Tsiolkovsky was writing about the possibility as early as 1921 [1]. Solar sailing has been the subject of many papers and has been discussed in at least four textbooks since that time [2,3,4,5]. However, most research in solar sails ordinarily focuses on specific aspects of the concept and goes into great detail about one subcomponent or is more general and discusses basic theories involved, without investigating finer details that may inhibit successful implementation of the concept.

Teledyne Brown Engineering (TBE) has developed an internal solar sail research concept that suggests that it is possible to use solar sails on the order of 200-500 meters in diameter to propel payloads up to 100 kg at speeds of nearly 10 Au/year. However, these spacecraft would be constructed of state-of-the-art and near-term available technologies, so there is some program risk involved.

This presentation discusses the concept and engineering advances required to make solar sail propulsion an enabling technology.

Engineering Advances:

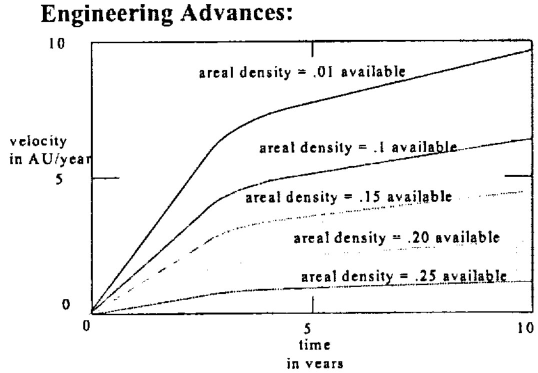

Figure 1 Velocity vs. time for various solar sail materials

Material Science. Advances in Materials Science are needed to bring the concept to fruition. State-of-the-art solar sail candidate materials have areal densities approximately one order of magnitude too large [6,7]. Figure 1 shows the velocity of a 500 m diameter solar sail with a 100 kg payload for various areal densities. The analysis shows that areal densities on the order of 10-15% of that currently available [6] are required to reach probe velocities of 5 AU/year.

Systems Engineering. Assuming that the material density needed is attained, developing, manufacturing, deploying, and controlling a large lightweight structure such as a solar sail probe is doable.

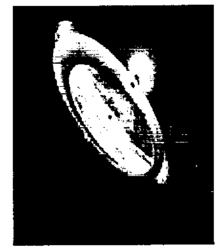

Figure 2 TBE solar sail baseline design

TBE is developing an integrated systems engineering (ISE) approach for solar sail spacecraft design. The approach utilizes a database of all spacecraft subcomponents and risks and benefits associated with each that allows for changes in one subcomponent in the spacecraft to propagate throughout the model. Using the ISE approach a baseline architecture for a solar sail spacecraft has been developed. Figure 2 shows the downselected spacecraft design. The spacecraft consists a preformed sail material supported by a preformed circumferential support structure. The support structure can be a torus or a stiffened annular disc. TBE favors the torus since microcircuitry can be deposited throughout the interior of it for self diagnostic as well as scientific instrumentation. TBE has proposed flight validation experiments to prove the viability of the spacecraft design [8].

Outer Planet Probe: The preliminary analyses given here suggest that an outer planet probe using solar sails is possible in the near future. TBE suggests a design as shown above deployed at 1 AU from SOL with a diameter of 500 m, an areal density of 0.0003 kg/m^2, a payload of 100 kg, and total spacecraft mass of about 160 kg. A spacecraft thus configured can achieve flyby mission times to the outer planets on the order of 10 years or less.

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[8] Taylor, T.S., et. al., (2000) *Light Sail Systems Technology and Integration,* response to NASA NRA 00-OSS-06.

NIAC Support to Innovation in Outer Planet Exploration

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Arlington, VA 22202

Abstract

Imagine:

A magnetized plasma bubble is riding the solar wind, delivering payloads to the outer planets in months instead of years. Swarms of thousands of thumb-nail sized "mesocopters" are measuring the outgasing of an awakening volcano on Titan. A long-duration, nuclear ramjet-powered unmanned aircraft is navigating the winds of Jupiter. A colony of robotic swimmers are exploring remote oceanic vents under the Europan ice.

This vision is derived from a sampling of the many studies in aerospace and aeronautics underway or completed through the auspices of the NASA Institute for Advanced Concepts (NIAC).

NIAC was established in 1998 for the explicit purpose of being an independent source of revolutionary aeronautical and space concepts that could dramatically impact how NASA develops and conducts its mission. The institute is to provide a highly visible, recognized and high-level entry point for outside thinkers and researchers. The purpose of the NIAC is to provide an independent, open forum for the external analysis and definition of space and aeronautics advanced concepts to complement the advanced concepts activities conducted within the NASA Enterprises. The NIAC has advanced concepts as its sole focus. It addresses revolutionary concepts - specifically systems and architectures -that can have a major impact on missions of the NASA Enterprises in the time frame of 10 to 40years in the future. It generates ideas for how the current NASA Agenda can be done better; it expands our vision of future possibilities.

NIAC's interest in participating in the Innovations in Outer Planet Exploration Workshop is three-fold:

- Ensure that NIAC is aware of the innovative research in Outer Planet exploration funded in NASA Centers
- Ensure that the appropriate individuals in NASA are aware of relevant NIAC studies
- Communicate to the broader research community that NIAC exists and is funded by NASA to pursue long range revolutionary research that could impact NASA missions

SMALL NUCLEAR-POWERED HOT AIR BALLOONS FOR THE EXPLORATION OF THE DEEP ATMOSPHERE OF URANUS AND NEPTUNE. Jeffrey E. Van Cleve[1] and Carl J. Grillmair[2], [1] Cornell University SIRTF/IRS Customer Office, 16321W FA-3, Ball Aerospace, Boulder CO 80301, vancleve@astrosun.tn.cornell.edu, [2] SIRTF Science Center, Mail Stop 314-6, California Institute of Technology, Pasadena, CA 91125, carl@ipac.caltech.edu

Introduction: The *Galileo* probe gathered data in the Jovian atmosphere for about one hour before its destruction[1]. For a wider perceptive on the atmospheres of the outer planets, multiple, long-lived observations platforms would be useful. In this paper we examine the basic physics of hot-air ballooning in a hydrogen atmosphere, using plutonium RTGs as a heat source. We find that such balloons are buoyant at a sufficiently great depth in these atmospheres, and derive equations for the balloon radius and mass of plutonium required as a function of atmospheric mass density and balloon material parameters. We solve for the buoyancy depth given the constraint that each probe may contain 1.0 kg of Pu, and find that the temperature at that depth is too great for conventional electronics (> 70 C) for Jupiter and Saturn. However, the Pu mass constraint and the operating temperature constraint are consistent for Uranus and Neptune, and this concept may be applicable to those planets.

Model: The balloon is a spherical shell of radius R_b, with an insulating layer of thermal conductivity K_i, mass density ρ_i, and thickness t_i. Inside the balloon is a PuO_2 source with a specific thermal output P_{Pu} W/kg and a mass m_{Pu}. The temperature of the ambient atmosphere is T_a and its pressure is p_a. The temperature of the gas inside the balloon is T_b. The mass density of the ambient atmosphere is $\rho_0 p_a/T_a$, and the ideal gas law is assumed for hydrogen mass densities <= 10 kg/m^3.

Derivation of Results: The two basic equations are the lift balance equation

$$(4/3)\pi R^3_b \rho_0 p_a(1/T_a - 1/T_b) = m_{Pu} + 4\pi R^2_b \rho_i t_i \quad (1)$$

and the heat balance equation, in which the heat from the Pu source is equal to the heat flowing through the insulating shell, assuming the gas inside the balloon is isothermal:

$$P_{Pu} m_{Pu} = 4\pi R^2_b K_i (T_b - T_a)/t_i \quad (2)$$

Eq. 1 and 2 may be combined to give an expression for R_b

$$R_b = (3T_a T_b/\rho_0 p_a)[K_i/t_i P_{Pu} + \rho_i t_i/(T_b - T_a)] \quad (3)$$

Since we are interested in the smallest buoyant balloon, we solve for t_i such that $\partial R_b/\partial t_i = 0$ and solve for T_b such that $\partial R_b/\partial T_b = 0$. Combining thise results, we find that the smallest balloon results when

$$t_i = (T_a K_i/\rho_i P_{Pu})^{1/2} \quad (4)$$

and

$$T_b = 2T_a \quad (5)$$

which gives

$$R_b = 12(T_a/\rho_0 p_a)(K_i \rho_i T_a/P_{Pu})^{1/2} \quad (6)$$

and a plutonium mass of

$$m_{Pu} = 576\pi(T_a/\rho_0 p_a)^2 (K_i T_a \rho_i/P_{Pu})^{3/2} \quad (7)$$

Numerical Results. An unclad PuO_2 source has $P_{Pu} \sim 10^3$ W/kg. For an insulator, we take an aerogel with $\rho_i = 5$ kg/m^3; since the mean free path of H_2 is smaller than the aerogel pore size of 20 nm, K_i is effectively that of H_2 near 300 K, or 0.10 W/mK. The temperature at the 100 bar level of Uranus is 300 K, and the mass density $T_a/\rho_0 p_a$ = 10 kg/m^3. Then R_b = 0.5 m, and m_{Pu} = 1.0 kg.

A comparable atmospheric mass density is achieved in the Jovian atmosphere at levels for which the temperature exceeds 500 K[1], which is not survivable for conventional electronics. Unacceptably large (> 1.0 kg) Pu loads are thus required to make the balloon float at cooler and less dense levels of the Jovian atmosphere.

References:

[1] A. Seiff *et al.* (1996) *Science*, 272 p. 844

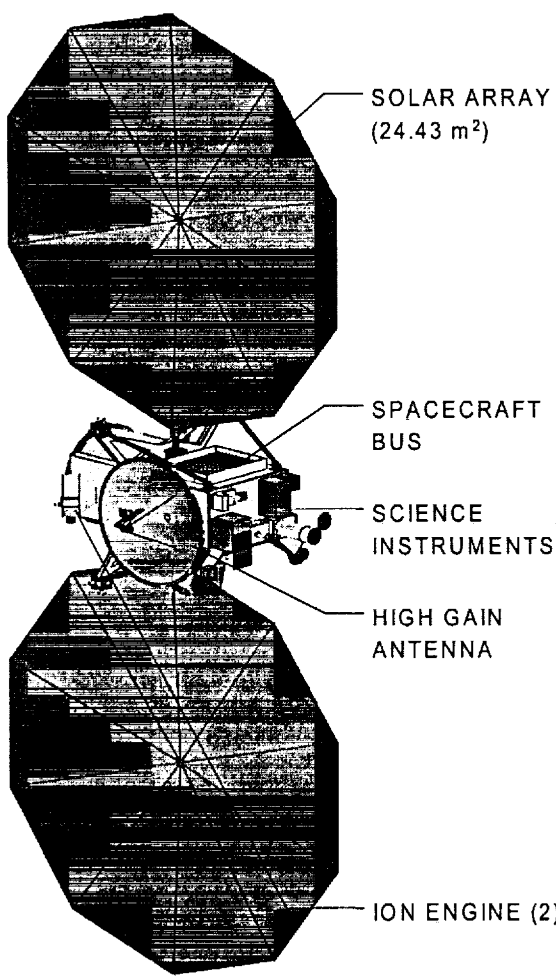
RADIOISOTOPE POWER SYSTEMS FOR OUTER PLANET MISSIONS. E. J. Wahlquist, Associate Director, Office of Space and Defense Power Systems, Office of Nuclear Energy, Science and Technology, U.S. Department of Energy, 19901 Germantown Road, Germantown, Maryland 20874-1290, email address: Earl.Wahlquist@hq.doe.gov

A summary of the Department of Energy's (DOE) capabilities and ongoing program efforts to develop and provide radioisotope power systems to support space exploration missions will be presented. The Office of Nuclear Energy, Science and Technology (DOE/NE) within DOE is responsible for the development, assembly, testing, acceptance, and delivery of radioisotope power systems to the National Aeronautics and Space Administration (NASA). To that end, DOE/NE is maintaining a program and facility infrastructure at various DOE laboratories and production sites ensuring the viability of future missions that will require radioisotope power systems. This infrastructure includes facilities to manufacture key components, process and encapsulate plutonium-238, and assemble, test, and accept the systems. DOE also pursues a low level technology program committed to the continued evolution of energy conversion technologies with applicability to radioisotope power systems. In addition, DOE recently made a decision to pursue re-establishing the domestic capability to produce plutonium-238 as part of DOE's commitment to maintaining the infrastructure necessary to produce and deliver radioisotope power systems. The currently available U.S. inventory of plutonium-238 is sufficient to provide one radioisotope power system of roughly the same power level as each of the three units used on the Cassini spacecraft. Until the domestic production is realized, plutonium-238 requirements can be met through an existing contract with Russia.

ODYSSEY COMET NUCLEUS ORBITER: THE NEXT STEP IN COMETARY EXPLORATION. P. R. Weissman,[1] E. N. Nilsen,[1] W. D. Smythe,[1] J. Marriott,[2] and R. Reinert[2] [1]Jet Propulsion Laboratory, MS 183-601, 4800 Oak Grove Drive, Pasadena, CA 91109, pweissman@lively.jpl.nasa.gov, [2]Ball Aerospace & Technologies Corp., 1600 Commerce Street, Boulder, CO 80301, rreinert@ball.com.

Introduction: Cometary nuclei are the most primitive bodies in the solar system, containing a cosmo-chemical record of the primordial solar nebula. Flyby missions to comets, such as those that encountered Comet Halley in 1986, provide a glimpse at this record. However, to study a cometary nucleus in detail requires a rendezvous mission, i.e., a nucleus orbiter. Only an orbiter provides the ability to map the entire nucleus surface at high resolution, to study the complex chemistry in the cometary coma and its variation with time, and to determine the mass and bulk density of the nucleus, key parameters in understanding how small bodies first formed in the solar nebula. A nucleus orbiter also provides the opportunity to sense the nucleus surface in preparation for more ambitious landing and sample return missions in the future

Odyssey Comet Nucleus Orbiter: Odyssey is a Discovery-class mission that would be NASA's first comet nucleus orbiter. Odyssey uses solar electric propulsion (SEP) to effect a rendezvous with a short-period comet in only 3.3 years, far less than possible using chemical propulsion.



Science Payload: Odyssey's scientific payload includes narrow and wide angle CCD cameras, an IR imaging radiometer, a gas chromatograph/mass spectrometer, an XRD/XRF dust compositional analyzer, a dust counter/momentum sensor, and dust accumulation sensors. All science instruments are body-fixed and boresighted so that they can observe the cometary nucleus simultaneously. Additional instruments that might be carried onboard Odyssey include a laser altimeter, and a gamma ray/neutron spectrometer. Also, the mission can carry an array of simple penetrators that would be fired into the nucleus surface to measure its strength, density, stratigraphy, and temperature, in preparation for future landed missions.

Spacecraft: The Odyssey spacecraft is a 3-axis stabilized spacecraft equipped with a two-engine, Deep Space 1 SEP system, and carrying up to 180 kg of xenon. Solar power is provided by 6 kW (@1 AU, EOL) deployable Ultraflex arrays. Attitude control is provided by momentum wheels and a monopropellant hydrazine system provides wheel unloading and small ΔV maneuvers, including all maneuvers during comet rendezvous. An X-band telecom system provides data rates at the comet of 6.3 to 113 kbps over a DSN 34m net.

Mission Scenario: A typical mission scenario has Odyssey launching in June 2006 on a Delta II 2925 vehicle, using SEP to rendezvous with periodic Comet Kopff in September 2009. Kopff is one of the most active short-period comets known, with a gas production near perihelion of $5 \cdot 10^{28}$ molecules/sec and an estimated nucleus diameter of ~3.6 km. En route to Kopff, Odyssey would fly by the C-type asteroid 24 Themis, the largest asteroid ever encountered by a planetary spacecraft ($d \approx 215$ km). Following rendezvous, the spacecraft will initially perform slow flybys of the active Kopff nucleus at distances between 500 and 100 km, and will then be placed in orbit around the nucleus at altitudes between 200 and 50 km. The *in situ* instruments will collect and analyze gas and dust in the cometary coma, providing elemental, molecular, isotopic, and mineralogic measurements of the cosmo-chemical record locked in comets of the origin of our solar system and the origin of life. The narrow angle camera will map the entire nucleus surface at a resolution of 1 m/pixel, providing detailed images of the nucleus topography and its change with time. The thermal imager will do the same at 21 m/pixel, providing unprecedented data on the energy balance at the surface of the cometary nucleus, key to understanding how the comet works. Odyssey will study Comet Kopff for 9 months, as the comet moves outward from 1.9 to 3.5 AU.

Extended mission: Extended mission options include: 1) higher resolution mapping at even lower altitudes, and 2) touch-down of the spacecraft on the nucleus surface.

Micro-Power Sources Enabling Robotic Outpost Based Deep Space Exploration : W. C. West[1], J. F. Whitacre[1], B. V. Ratnakumar[1], E. J Brandon[1], and G. Studor[2], [1]Jet Propulsion Laboratory, California Institute of Technology (4800 Oak Grove Drive, Pasadena, CA 91109), [2]Johnson Space Center, (2101 NASA Road 1 Houston, TX 77058).

Introduction: Robotic outpost based exploration represents a fundamental shift in mission design from conventional, single spacecraft missions towards a distributed risk approach with many miniaturized semi -autonomous robots and sensors. This approach can facilitate wide-area sampling and exploration, and may consist of a web of orbiters, landers, or penetrators. To meet the mass and volume constraints of deep space missions such as the Europa Ocean Science Station, the distributed units must be fully miniaturized to fully leverage the wide-area exploration approach. However, presently there is a dearth of available options for powering these miniaturized sensors and robots. This group is currently examining miniaturized, solid state batteries as candidates to meet the demand of applications requiring low power, mass, and volume micro-power sources. These applications may include powering microsensors, battery-backing rad-hard CMOS memory and providing momentary chip back-up power.

Technical Approach: The requirements of micro-power sources for robotic outpost applications are high specific energy, high energy density, robustness to temperature extremes and mechanical shock, long cycle life and long storage lifetime. Furthermore, the system should be capable of being integrated directly on an integrated circuit for low noise on-chip power, voltage leveling and voltage referencing. The solid state lithium battery system most fully meets these requirements. This battery design consists of thin films of a $LiCoO_2$ cathode, lithium phosphorous oxynitride (LIPON) solid electrolyte, and a lithium anode. The process of RF sputtering and thermally evaporating these layers to fabricate a thin film solid state battery was first developed at Oak Ridge National Laboratories.[1] However, the ORNL process requires the thin film battery cathode to be annealed at 700°C to achieve desired crystallinity and high capacity. This high temperature processing step precludes on-chip integration of the battery, or use of heat sensitive substrates. A process has been developed in our laboratories to achieve high capacity cathode performance with a 300°C anneal, which is much more compatible with back-end IC processing. [2]

Results: The thin film batteries have many attractive features such as high voltage (3.9V/cell), high capacity (65 μA-hr/μm-cm^2) and excellent cycle life (>7000 cycles) as shown in Fig. 1. As a means of comparison, thin film batteries with footprints of approximately 1 cm^2 can power devices such as electronic thermometers for several hours on a single discharge cycle.

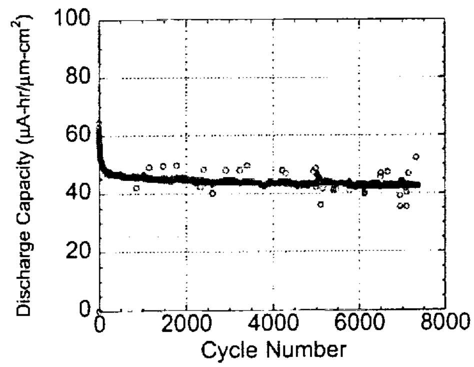


Fig. 1. Discharge capacity as a function of cycle number. This cell was cycled continuously for approximately three months.

The thin film battery fabrication process has recently been modified to yield cells with active area on the order of tens of microns on a side, as shown in Fig. 2. Using conventional microelectronic fabrication techniques such as photolithography, wet etching, and ion milling, the cells can be prepared in both parallel and serial arrangements, yielding a suite of available voltages and capacities.

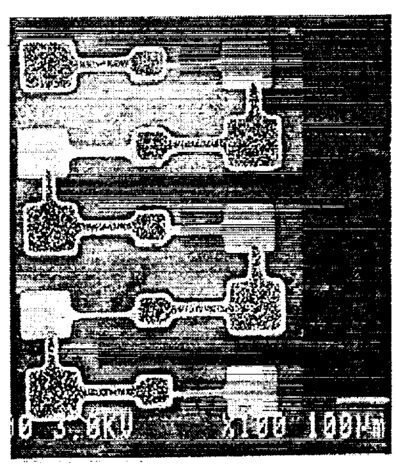


Fig. 2. Array of micro batteries fabricated on a Si substrate.

References: [1] See for example: B. Wang, J. B. Bates, F. X. Hart, B. C. Sales, R. A. Zuhr, and J. D. Robertson, *J. Electrochem. Soc.*, **143**, 3203 (1996). [2] J. F. Whitacre, W. C. West, B. V. Ratnakumar, and E. J. Brandon, submitted to *J. Electrochem. Soc.* (2001).

A Highly Miniaturized Inertial Grade Gyroscope for Space Applications. Dean Wiberg[1], Dorian Challoner[2], Kiril Shcheglov[1], Ken Hayworth[1], Sam Bae[1], Karl Yee[1], Brent Blaes[1], Saverio D'Agostino[1], Tim Stock[2], [1] California Institute of Technology, Jet Propulsion Laboratory, MS 302-231, 4800 Oak Grove Drive, Pasadena, CA 91109, Ph 818 354 5724, dean.v.wiberg@jpl.nasa.gov, [2]Boeing Space Systems, PH 310 416 5219, A.Dorian.Challoner@HSC.com

The evolution of inertial grade gyroscopes for space applications represents well over 50 years of technology development and an investment of hundreds of millions of dollars. The workhorse product which represents the current state-of-the art for commercially available high performance devices is the Litton-Hemishperical Resonator Gyro (HRG) Inertial Measurement Unit (IMU). This product has a performance figure of merit of 0.003 deg/hr bias drift, a volume of 567 in^3, weighs 19 pounds, draws about 30 watts and costs over $1 million each. Clearly devices of this magnitude are not conducive to the minimized mass, volume, power and cost constraints of outer planet missions. An approach to breaking these potential barriers is the use of Microelectromechanical Systems (MEMS) based inertial devices. Although substantially reduced in size, mass power and cost, this approach has produced devices in the tactical performance range of greater than 1 deg/hour bias drift. This level of performance satisfies the preponderance of high market volume requirements such as automotive and tactical munitions but does not meet the limited market quantity requirements for the high precision space based market. Because of the very limited size of the space based market, there is little economic incentive for commercial fabricators of tactical grade devices to address the necessary performance improvements. The Jet Propulsion Laboratory (JPL) in conjunction with Boeing Space Systems (BSS) is addressing this void to satisfy our mutual requirements in this area. The project objective to is to achieve 0.01 deg/hr performance in an IMU which is less than 10 in^3 in volume, weighs less than 0.5 pounds, draws less than 1 watt and is available in volume production for less than $2500. Reductions of this magnitude will be mission enabling capabilities for a variety of anticipated outer planet mission attributes such as autonomous control and docking, formation flying and robotic outposts. The improved performance will be realized using improved relative precision fabrication, enhanced vibratory drive and sense designs, and statistical data analysis.

TOWARD A MICRO GAS CHROMATOGRAPH/MASS SPECTROMETER (GC/MS) SYSTEM. Dean V. Wiberg, Beverley Eyre, Otto Orient, Ara Chutjian, Vachik Garkanian, California Institute of Technology, Jet Propulsion Laboratory, MS 302-231, 4800 Oak Grove Drive, Pasadena, CA 91109, Ph 818 354 5724, dean.v.wiberg@jpl.nasa.gov

Miniature mass filters (e.g. quadrupoles, ion traps) have been the subject of several miniaturization efforts. A project is currently in progress at JPL to develop a miniaturized Gas Chromatograph/Mass Spectrometer (GC/MS) system, incorporating and/or developing miniature system components including turbomolecular pumps, scroll type roughing pump, quadrupole mass filter, gas chromatograph, precision power supply and other electronic components. The preponderance of the system elements will be fabricated using microelectromechanical systems (MEMS) techniques. The quadrupole mass filter will be fabricated using an X-ray lithography technique producing high precision, 5X5 arrays of quadrupoles with pole lengths of about 3 mm and a total volume of 27 mm^3. The miniature scroll pump will also be fabricated using X-ray lithography producing arrays of scroll stages about 3 mm in diameter. The target detection range for the mass spectrometer is 1 to 300 atomic mass units (AMU) with a resolution of 0.5 AMU. This resolution will allow isotopic characterization for geochronology, atmospheric studies and other science efforts dependant on the understanding of isotope ratios of chemical species. This paper will discuss the design approach, the current state-of-the art regarding the system components and the progress toward development of key elements. The full system is anticipated to be small enough in mass, volume and power consumption to allow in-situ chemical analysis on highly miniaturized science craft for geochronology, atmospheric characterization and detection of life experiments applicable to outer planet roadmap missions.

ELEMENTAL COMPOSITION MEASUREMENTS USING LASER-INDUCED BREAKDOWN SPECTROSCOPY (LIBS). R. C. Wiens[1], D. A. Cremers[2], J. E. Nordholt[3], and J. D. Blacic[4] [1]Space and Atmospheric Sciences, Los Alamos National Laboratory (MS D466, Los Alamos, NM 87545; rwiens@lanl.gov), [2]Chemistry, [3]Physics, and [4]Earth & Env. Sci. Divisions, LANL.

Introduction: LIBS is an extremely versatile method of determining elemental compositions. It can be used in-situ or at distances to ~20 m in vacuum or in an atmosphere. It can be easily combined with other optical techniques such as Raman spectroscopy to deliver elemental, mineralogical, and biological information. It can also be used in LIDAR mode to yield information on atmospheric properties. We will present concepts for stand-off, in-situ, and combined instrumentation.

The LIBS Technique: In the LIBS method [1], powerful laser pulses are focused on the target sample to form a laser spark or plasma. Material within the spark is the result of vaporization and atomization of a small amount of target material. The spark contains the emission spectra of the elements within the plasma. Collection of the plasma light, followed by spectroscopic detection, permits identification of the elements via their unique spectral signatures. When calibrated, concentrations can be determined. At ~1 Å FWHM, LIBS emission peaks are narrow relative to passive emission or reflectance spectroscopy, yielding far more information. The spectral region of interest, from 180-850 nm, includes numerous peaks per element, allowing cross-checking for interferences. Advantages of the method compared to more conventional elemental analysis methods include:

- rapid analysis (one measurement/pulse),
- small analysis area of ~1 mm dia.,
- simultaneous multi-element detection,
- ability to detect all elements (high and low z),
- low detection limits in the range of 2-800 ppm,
- quantitative results (accuracy better than ±10-15%),
- ability to remove dust or weathering surfaces, and to provide depth-profiles into the sample at rates from 0.1 µm/shot (basalt) to 0.2 mm/shot (sand or dust) [2]; this is possible even at stand-off distances;
- stand-off analysis capability [3]. Stand-off analysis is possible because the laser pulses can be focused at a distance to generate the laser sparks on a solid.

Stand-off vs. In-Situ Analysis: The stand-off analysis capability is being developed for the Mars Instrument Development Program (MIDP). This capability allows numerous rapid analyses of the surrounding rocks without having to move the rover and position the sensor head for each analysis. For outer solar system landers, the stand-off capability allows analysis of a much greater area than is otherwise possible. This may be critical for analyzing a variety of terrains from a single lander. Distances to 20 m (e.g., ~1200 m^2 areal coverage) are feasible using a small laser generating 35 mJ pulses [2], consuming ~1 W power at a repetition rate of 0.1-0.5 Hz. A prototype stand-off instrument was developed and field tested under the MIDP program [4]. A flight stand-off LIBS instrument is expected to be <2 kg and consume <5 W. We will present details of the MIDP prototype development and testing.

In-situ LIBS may be of interest for micro-landers or penetrators. For example, LIBS is being considered for the Europa drop-off package advanced concept study. In this configuration, fiber optic cables carry the laser light and the return signal between a point close to the surface and the instrument. No aiming or focusing is required, and light collection is efficient because of the proximity to the spark. LIBS has been used in this configuration previously for harsh environments, such as inside a nuclear reactor [5], and underwater. Required mass and volume can be minimized, with a mass of ≤1.1 kg expected for a flight instrument.

Combination Instruments: Because Raman spectroscopy uses nearly all of the same components, it can be easily combined with LIBS, providing both molecular (mineralogical and/or biological) and elemental compositions. Raman spectroscopy has been demonstrated with the MIDP prototype LIBS instrument using the same pulsed laser [6]. The use of a pulsed laser allows Raman spectroscopy to take advantage of the same depth profiling capabilities as LIBS. Alternately, Raman can use a co-mounted CW laser and share the LIBS detection system. Field testing of a combined LIBS/Raman instrument in at least one of these configurations is planned for 2001.

Because of the evidence for aerosols in the Titan atmosphere, LIDAR measurements may be an extremely important part of any Titan instrument package. If outfitted with the appropriate timing electronics, a stand-off LIBS instrument is also capable of making LIDAR measurements when the laser beam is aimed through the atmosphere. Such an instrument could be used to detect airborne particle densities and spatial distributions.

References: [1] Cremers D. A. and Radziemski L. J. (1986) In *Laser Spectroscopy and Its Applications* (L.J. Radziemski, et al., eds.), Chapter 5, Marcel Dekker, New York. [2] Knight A.K. et al. (2000) *Appl. Spectrosc. 54,* 331. [3] Cremers D. A. (1987) *Appl. Spectrosc. 41,* 1042. [4] Wiens R. C., et al. (2001) Combined remote mineralogical and elemental measurements from rovers: Field and laboratory tests using reflectance and laser induced breakdown spectroscopy. Subm. To JGR-Planets. [5] Lawson S. et al. (2000) *Nucl. Eng. Int. 45,* 22-23. [6] Wiens R. C. et al. (2000) *Lunar Planet. Sci. XXXI*, 1468-1469.

EXPLORATION OF TITAN USING VERTICAL LIFT AERIAL VECHICLES.
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Introduction: Autonomous vertical lift aerial vehicles (such as rotorcraft or powered-lift vehicles) hold considerable potential for supporting planetary science and exploration missions. Vertical lift aerial vehicles would have the following advantages/attributes for planetary exploration: low-speed and low-altitude detailed aerial surveys; remote-site sample return to lander platforms; precision placement of scientific probes; soft landing capability for vehicle reuse (multiple flights) and remote-site monitoring; greater range, speed, and access to hazardous terrain than a surface rover; greater resolution of surface details than an orbiter or balloons. Exploration of Titan presents an excellent opportunity for the development and usage of such vehicles.

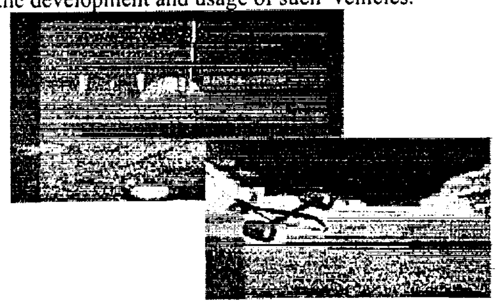

Fig.1-Titan Vertical Lift Aerial Vehicle

Current Work: Titan, Saturn's largest moon, is unique in the solar system in that it is the only moon that has a substantial atmosphere. Titan's atmosphere may even have properties similar to Earth's early atmosphere, before life began. The use of vertical lift aerial vehicles to explore Titan would be a tremendous enabler of scientific investigations of one of the solar system's more mysterious planetary bodies. References 2-3 provide some preliminary discussion of the potential for vertical lift aerial exploration of Titan.

Several types of rotorcraft (such as helicopters and tiltrotor aircraft) or powered lift vehicles could be developed for aerial exploration of Titan. Such vehicles by necessity will be highly autonomous and will likely have electric propulsion for their rotors or fans. In particular, ducted fan configurations such as tilt-nacelle aircraft are perhaps ideally suited for Titan (fig.1). Ducted fan aerial vehicles would inherently be more robust taking off or landing in an unknown, potentially hazardous, environment than conventional rotors. Nonetheless, detailed design studies will be required to identify the optimal design configuration for a specified planetary mission.

Initial mission concepts being studied at NASA Ames would employ a lander-based architecture where small ducted fan tilt-nacelle vertical take-off and landing (VTOL) aircraft could use the lander as a primary base site. The lander would service and support the vertical lift aerial vehicles, including: recharging their power supplies with radioisotope thermoelectric generators; download and transmit data acquired in-flight and at remote landing sites; act as a storage depot for science packages, drop probes, and other payload for the aerial vehicle; store spare aircraft; provide/erect temporary shelter for the aerial vehicles to protect them from severe weather conditions.

Figure 2 shows estimates of hover total shaft power for a notional Titan tilt-nacelle VTOL vehicle having two ducted fans that can pivot at the wing tips. A Titan VTOL's ducted fans will be very small and consume very little power as a result of the high atmospheric density near Titan's surface and it's low gravity field.

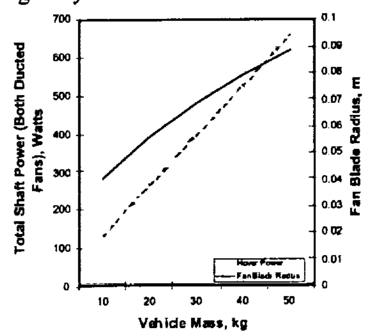

Fig.2-Ducted Fan Hover Performance

Figure 3 shows range estimates for a 50kg Titan twin tilt-nacelle/ducted-fan VTOL vehicle, assuming power matching between the hover and cruise design points.

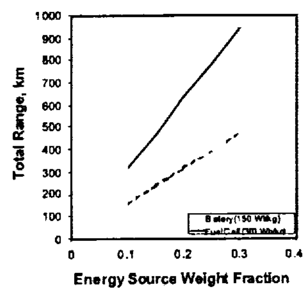

Fig.3-Vehicle Range

As can be seen from figures 2-3, a small aerial vehicle acting in concert with a lander (which would recharge and service the vehicle) could enable mapping and scientific investigations of an area of several thousand square-kilometers.

Future Work: Work continues at NASA Ames on design studies of vertical lift planetary aerial vehicles. The feasibility of NASA sponsoring a student design competition for Minority Universities and HBCUs for Titan vertical lift aerial vehicles is being explored. This would complement the American Helicopter Society Student Design Competition on Martian autonomous rotocraft [4,5].

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[5] Georgia Institute of Technology Design Proposal (http://www.ae.gatech.edu/research/controls/projects/mars/reports/index.html).