A New, Non-Intrusive Ultrasonic TPS Recession Measurement Needed to Determine the Thermal Structure of the Upper Atmosphere of Venus, Saturn, Uranus or Neptune

A NEW, NON-INTRUSIVE, ULTRASONIC TPS RECESSION MEASUREMENT NEEDED TO DETERMINE THE THERMAL STRUCTURE OF THE UPPER ATMOSPHERE OF VENUS, SATURN, URANUS OR NEPTUNE. J. A. Lloyd[1], M. Stackpoole[2], E. Venkatapathy[3], and D. E. Yuhas[1], [1]Industrial Measurement Systems, Inc. (jlloyd@imsysinc.com), (dyuhas@imsysinc.com), [2]NASA Ames Research Center (margaret.m.stackpoole@nasa.gov), [3]Entry Systems and Technology Division, NASA Ames Research Center (ethiraj.venkatapathy-1@nasa.gov)

Summary: This paper describes new, innovative, non-intrusive ultrasonic instrumentation under development for measuring recession of ablative TPS during atmospheric entry. In addition to recession measurements, the ultrasonic technique provides in-depth temperature profiles. This paper describes the principle behind the ultrasonic method, progress made to-date in designing and testing the instrument with ablative TPS and the challenges in maturing the system to a TRL 5/6 by 2016/2017. In a companion paper, we review the state-of-the art in recession sensors from Galileo to MSL.

Introduction: Saturn and Uranus Probe missions were identified as high priority missions by the NRC Decadal Survey Committee in its report "Visions and Voyages for Planetary Science in the Decade 2013-2022".[1] The NRC Committee report not only identifies the important science goals for the study of the giant planets, it provides detailed objectives associated with the goals, important questions to be answered, and a road map of recommended future directions for investigation and measurements over the decade**.** Mission studies performed in support of the NRC Decadal Committee identified the determination of atmospheric structure as a high priority objective. A number of scientific questions focus on understanding the atmospheric dynamical processes, heat flow and radiation balance, in general for all the outer planets. Saturn is of particular value, especially its thermal structure. Some of the relevant questions identified are: 1) What are the current pressure-temperature profiles? 2) Why and how does the atmospheric temperature and cloud composition vary with depth and location on the planet? 3) Which processes influence the atmospheric thermal profile, and how do these vary with location? And 4) What mechanism has prolonged Saturn's thermal evolution?

Mass loss measurement during entry can determine the thermal profile of an atmosphere, especially in the upper regions. This method has been applied to Jupiter's upper atmosphere from the mass loss of the Galileo probe's heatshield as a result of extreme heating during entry.[2] TPS mass loss in the heatshield occurs due to ablative processes at work in the extreme environment.

Future outer planet probes may use alternate highly reliable and robust ablative TPS under development. Heritage TPS, namely heritage carbon phenolic, has critical performance and manufacturability issues. The 2-D nature of the heritage material has inherent failure modes that are not desirable and the material cannot currently be manufactured to original specifications. Unlike heritage carbon phenolic, Woven TPS is more mass efficient and its performance can be tailored to withstand higher heat loads without significant mass penalties. Woven TPS can facilitate the use of shallower entry trajectories that reduce g-loads, which is a science mission enabler for g-limited instruments and protecting sensitive samples.

As part of the ablative TPS development, it is important to assess recession sensor compatibility with the TPS under development and if needed, co-develop the recession measurement system so that outer planet mission proposals can be assured of not only an engineering solution for the probe entry but also the ability to perform important science during the entry phase.

Woven TPS is a new, sustainable, weavable and tailorable ablative thermal protection material system known using textile manufacturing processes.[3] This development is time critical due to the fact that heritage carbon phenolic can no longer be manufactured to original specifications. An alternate TPS developed to TRL 5/6 by 2016/2017 is critical for any probe mission to Saturn or Uranus to be proposed with confidence. In addition to maturing TPS to high TRL level, development and integration of compatible instruments within the same time frame is also necessary to enable the achievement of scientific goals identified by the NRC Committee. While conventional TPS instruments such as thermocouple plugs and recession sensors could be adapted in some cases, ultrasonic methods developed by IMS, Inc. are very attractive. These methods are non-intrusive and can be readily integrated with Woven TPS. IMS Inc. and NASA Ames have partnered under a non-reimbursable space act agreement and are developing non-intrusive TPS instrumentation. Preliminary experiments have been conducted in a small scale arc jet at NASA Ames evaluating the recession of Woven TPS using IMS instrumentation compared to traditional approaches to recession evaluation. IMS Inc. has already applied ultrasonic thermometry to aeroshells, combustion chambers, regenerative cooling channels and other high temperature aerospace applications.

Background: Recession measurements from the Galileo probe entry and how the data was used to determine the temperature profile of Jupiter's upper atmosphere, is well detailed[2]. A short summary is provided below. During entry, the probe heat shield was ablated by radiative and convective heating from shock-layer plasma.

Figure 1. Galileo Atmospheric Entry produced entry heating that is considered one of the extreme environment ever encountered by any entry body ever designed by humans. The probe lost 25% of the total entry mass during entry

Sensors embedded in the heat shield measured the surface recession as a function of time, and were used to calculate changes in probe mass and frontal area as functions of time. The density of the atmosphere was derived from probe decelerations through Newton's second law and the defining equation for drag coefficient,

$$D = (1/2)(\rho V^2)C_D A = ma \qquad (1)$$

Here, D is the aerodynamic drag on the probe; ρ, the atmosphere density; V, the probe velocity; C_D, its drag coefficient; A, the frontal area, m, the probe mass; and a, the deceleration. Probe velocity was determined as a function of time by integrating the measured probe decelerations. Pressures are obtained from the density profile with the assumption of hydrostatic equilibrium. Temperatures were derived from these pressures and densities and the equation of state, $P = \rho RT$. The gas constant, R, varies with altitude according to a composition model, which defines atmospheric mean molecular weight as a function of altitude. At the start of descent, density calculated from pressure and temperature measurements agreed closely with the final density from the entry profile, demonstrating small density uncertainty.

On Recession Sensors: Science instruments are designed to obtain data to meet one or more science goals. Engineering instruments, on the other hand, are designed to measure hardware performance in order to assess the risk in the design so future designs can be improved. It is seldom that one sensor can serve both science and engineering goals, however – a recession sensor is the exception. Recession measurement supports both the science goal of determining the atmospheric structure and is also an engineering instrument that can help determine the TPS risk. For example, the Galileo recession sensor clearly pointed to the inadequacies of the original TPS thickness especially in the shoulder region. The recession sensor also allowed the construction of the upper atmospheric thermal profile. The recession sensor is an integral part of the heat shield design, hence designing the recession sensor with the fidelity needed to meet the science goal needs to be balanced by the risk to the heatshield as the recession sensors used in the Galileo probe or MSL require coring out holes in the TPS and installing the sensor plugs. The potential risk of plugs allowing thermal breach is a concern. Compared to standard techniques, a non-intrusive ultrasonic sensor does not require coring a hole or penetrating the TPS and hence if proven to work, this sensor will reduce the risk to the heat shield as well as lower heat shield certification costs.

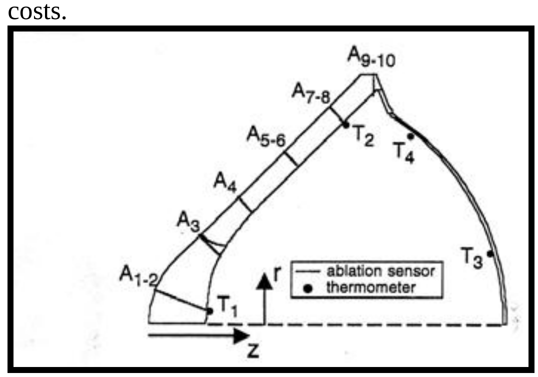

Figure 2. Location of 10 ablation sensors in the Galileo probe heatshield

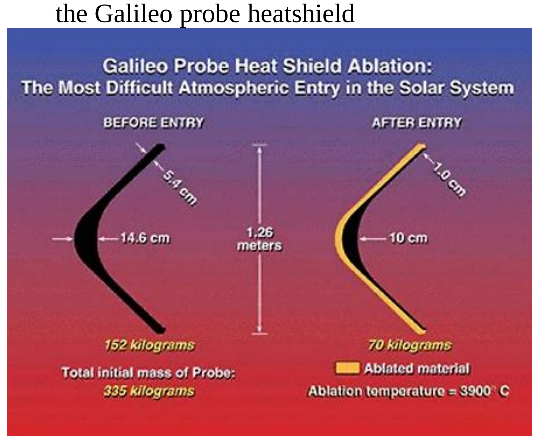

Figure 3. Heatshield TPS thickness prior to and post-entry

Ultrasonic Methods: Non-intrusive ultrasonic ablation and temperature distribution measurement offers the promise of real-time information. Ultrasound can transform a heat shield itself into a sensor while observing recession and recession rate, internal temperature distribution, and in some cases heat flux. While ultrasonic sensors have flown in heat shields in the past[3], modern signal processing and localization methods have been developed to combine the technologies of ultrasonic thickness gauging and ultrasonic thermometry into a method of temperature compensated recession measurement, with the side effect of temperature distribution measurement.

Ultrasonic sources embedded into or attached to the backside of a heat shield can be used to measure ablation. Thermal response times on the order of 100 microseconds (without thermal lag) can be attained [4]. Diffuse ultrasonic backscatter from a material's microstructure can be monitored at selected regions within a material and converted to temperature[5,6]. The data from regions that do not ablate can be used to directly compensate for temperature and material property changes at the surface without modeling.

Ultrasound provides one of the few approaches to measuring the recession rate without requiring any intrusive physical TPS modification. The method has the potential to provide real-time data using sensors located remotely from the ablating surface. The use of ultrasonic methods to monitor the ablators is not new. Around 1960, experimenters at AVCO began conducting experiments to measure the ablation of heat shields during re-entry. The method was found to be most successful for higher density heat shield materials where the ultrasonic attenuation is sufficiently low so that pulse-echo data could be obtained in the MHz frequency regime. In 1975, McGunigle and Jennings demonstrated an ultrasonic sensor in a number of flight tests.[3] In 1985, J.H. Gieske provided calibration data for an ultrasonic ablation detector (UAB) developed by Lockheed Missiles & Space Company. For this study, Gieske measured the ultrasonic longitudinal wave velocity from 70°F to 5400°F in carbon-carbon pitch and pitch/M2 shape stable nose tip material for the MK5 flight vehicle.[7] In a similar application, ultrasound has been used to measure recession (burning rates) in solid rocket propellants.[8] For recently, modern ultrasonic methods have been revisited to address the erosion and auto-ignition problems in large caliber guns[4].

Since the development of the initial ultrasonic ablation measurement systems of the 1970's, considerable advances have occurred in TPS materials as well as ultrasonic instrumentation, signal processing, and ultrasonic sensors. High temperature piezoelectric sensors are commercially available with some ceramics operating at temperatures as high as 600°C and single crystals operating in excess of 1400°C. High speed, inexpensive, analog to digital conversion hardware and signal processing methods have been developed which can achieve precision in time-of flight (ToF) measurements of better than 50 picoseconds in explosive environments12,13. Modern ultrasonic instrumentation is both small in size and has low power consumption. These advances have rekindled interest in ultrasound as a viable method for measuring temperature, heat flux, and ablation.

The ultrasonic method is illustrated in Figure 4. A sensor which is used to both generate and detect ultrasound is attached remotely from the heat shield surface, thus isolating the sensor from the harsh chemical and thermal environment. In some cases, a separate sensor to detect ultrasound is used for improved fidelity. The size of the measurement zone is determined by the ultrasonic sensor frequency and size, which in turn is ultimately controlled by the propagation characteristics of the TPS material and its thickness.

The basic equation relating the measured ultrasonic time-of-flight (ToF), G and the temperature, θ, and the sample thickness, *L*, is given by Equation 2 below:

$$G = 2\int_0^{L(\Theta(x))} \frac{1}{V(\theta(x))} dx \tag{2}$$

Where *L* is the length of the sample which in the most general case will be a function of the temperature distribution, *Θ(x)*, and *V* is the ultrasonic velocity which is also a function of the temperature. The basic measured parameter, *G*, is the ToF of the ultrasonic wave as it passes through the thickness of the component, reflects from the interface, and returns to the sensor. The ToF is influenced by temperature, changes in thickness and changes in material properties.

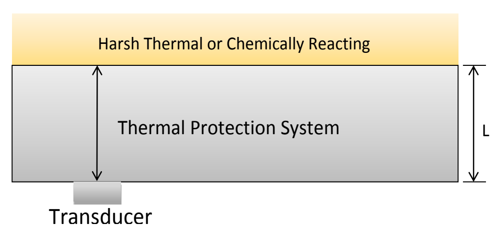

Figure 4. Illustration of ultrasonic methods

Ultrasonic thermometry uses small variations in ToF to measure changes in material temperature. Harvesting ultrasonic echoes from any material structure or microstructure that may reflect sound, as shown in Figure 5, enables the localization of temperature measurements to specific regions of a material. This localization is independent of conditions outside of the region of interest, whether there are material property changes, temperature gradients or ablation occurring.

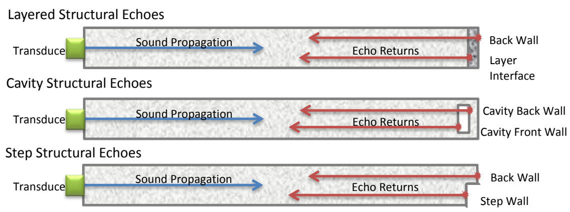

Figure 5. Methods of localization for ultrasonic thermometry

Ultrasonic ablation measurement combines ultrasonic thermometry with ultrasonic thickness gauging. The ToF of the receding surface is compensated by thermometry derived from the analysis of diffuse backscatter and converted to thickness. This can be accomplished without relying on any thermal models. The accuracy of this conversion depends on the quality and location of diffuse backscatter echoes. Non-recessed diffuse backscatter from regions close to the final ablated surface offer the best correction.

Diffuse backscatter from internal material microstructure is quite prevalent in many ablator materials. This backscatter can be used to localize measurements of temperature through a material as it ablates. Since these sound reflections are from internal microstructure, they are received in time before the receding surface echo and contain temperature and material property information for regions of a material that are not actively receding.

For an ablation event, the thickness L has both a reversible and irreversible component. The reversible component is the thermal expansion coefficient, α, while the irreversible component arises from the removal of material as well as permanent changes in the material properties (including char and pyrolysis). Similarly, the ultrasonic velocity will have reversible and irreversible changes with temperature. In this case, the reversible changes result in the variation of elastic modulus with temperature. These variations are reversible as long as the temperature is below the material's melting point. Irreversible changes can occur if the material undergoes a permanent phase change or is chemically altered. In theory it is necessary to know the temperature profile, the thermal expansion and the ultrasonic velocity of both the virgin material and the char zone over the entire ablation temperature regime. All of these factors contribute to the variation of the ToF, G shown in Equation 2. In practice, it is possible to obtain estimates of the recession rate without this extensive characterization data. In many cases, the variation in thickness is the dominant parameter responsible for ToF changes. In some cases, echoes from the backscatter in non-recessed zones can provide direct compensation for these reversible and irreversible changes without quantifying the magnitude of these changes.

Ultrasound in a Woven TPS is shown in Figure 6. In this case, strong internal microstructure is visible with simple broad regions encased by cursors to designate where ToF tracking took place. This time-domain tracking method can be applied in real-time and produces a limited temperature profile. To compensate for material property and temperature gradient changes, the ΔG of the internal microstructure closest to the backwall echo of the receding surface is simply subtracted from the ToF of the receding surface.

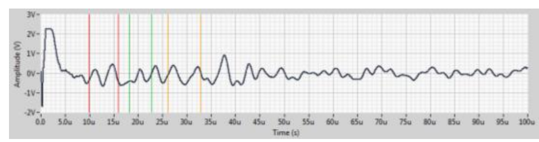

Figure 6. Ultrasound in Woven TPS with thickness gauging applied to the orange window after temperature and material property changes measured in the green window are filtered out

Raw data from a simple carbon phenolic is shown as measured in Figure 7 for a 20 second duration ablation event. In this case, the recession echo (red) decreases in ToF drastically and then increases later throughout the measurement. This shows the material receding while a torch is applied while after the ablation event, the ToF slowly increases as the result of temperature rise through the volume of material sampled. In blue, a microstructural echo is shown in this same data. The absolute ToF is lower because this data is from an internal region in the material beneath the receeding echo. This region increases in ToF which is consistant with heat propagation due to a torch being applied at the surface.

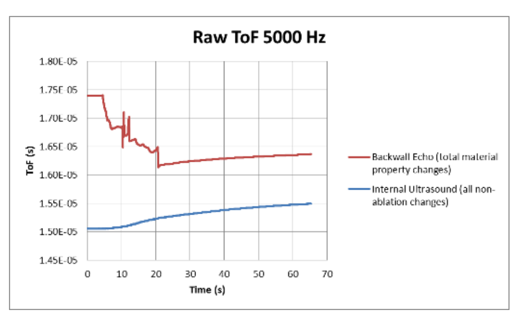

Figure 7. Raw data collected from ultrasound on a carbon phenolic (not Woven TPS) from the receding surface and internal microstructure

Subtracting the ToF variation (blue) in Figure 7 from the ToF in the receding wall (red) removes the vast majority of temperature and material property changes from the thickness measurement. The ToF of the receding echo can then be converted to thickness using standard ultrasonic thickness gauging techniques, as seen in Figure 8 which shows only a change in thickness in the sample tested.

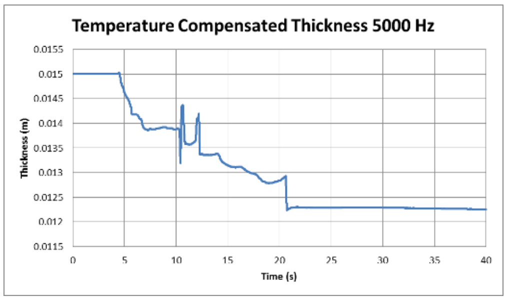

Figure 8. Data from Figure 4 converted directly to thickness without a model

To date, the ultrasonic method has been demonstrated on several carbon phenolic types from simple nozzle grade material to Woven TPS. Oxy-acetylene torches and NASA's small scale arc-jet have been used to produce recession which was monitored in real-time.

Calibrating the technique and verifying the recession rate and temperature distribution is a matter of ongoing development. Methods of ensuring quality test data, especially in arc-jet like high EMI environments are important. Currently a few embedded thermocouples have been the primary sources of real-time verification.

Temperature distribution reconstruction is a promise of the technology, however diffuse backscatter monitoring in real-time is a nontrivial task. As such, early investigation has focused on providing a few regions of interest that track well as opposed to pulling out a full temperature distribution. Key influencing factors in the success and precision of temperature distribution reconstruction include the ultrasonic frequency, sensor configuration and signal-to-noise. The current commercial laboratory equipment is generally best suited for slightly higher frequencies than are needed in materials like Woven TPS.

Future development will include tuning ultrasonic instrumentation for better lower frequency operation. Additionally, experiments have been conducted thus far on small spot sizes, however plans to mature the technology to include surface shape recession with ultrasonic arrays are an important part of development. While TPS plugs and other invasive recession monitors offer point-source measurements, ultrasound is often applied in arrays for area measurement. If this technology can be adapted to produce area surface measurements on ablators this would provide an additional engineering and scientific benefit.

This technology has been applied to several select materials including higher density carbon phenolics, with each class of material representing a unique set of challenges for calibration and characterization. Materials with high levels of porosity decrease the available operating frequency range, while materials with strong internal reflectors due to weave type or orientation offer unique microstructural analysis methods.

Overall, ultrasonic methods have been shown to have promise in measuring recession non-intrusively in real time. Development of the technologies to TRL 5/6 by 2016/2017 would provide a new enabling technology for scientific missions to outer planets with significant benefits to legacy techniques for recession measurement.

References: [1] Committee on the Planetary Science Decadal Survey, (2011) *National Academies Press*. [2] Seiff, A., et al. (1997) *Science* 276, 102. [3] McGunigle R. D. and Jennings M. (1975) *International Instrumentation Symposium Proceedings, 12,* 19–24. [4] Yuhas D. E. et al. (2009) *American Institute of Physics QNDE, 28B,* 1759-1766. [5] Simon C. et al. (1998) *IEEE Trans. on Ultrasonics, Ferroelectric and Frequency Control, 45(4).* [6] Amini A. N. (2005) *IEEE Trans. Biomed Eng., 52(2),* 221-228. [7]Gieske J. H. (1977) *SAND*, 76-0434 [8] Frederick R., Traineau J. C. (2000) *AIAA*, 2000-3801