A New, Non-Intrusive, Ultrasonic TPS Recession Measurement

Needed to Determine the Thermal Structure of the Upper Atmosphere of Venus, Saturn, Uranus or Neptune

Abstract

Real-time, non-intrusive ultrasonic recession measurement methods for ablative TPS can be used to characterize atmosphere during entry. The ultrasonic technique is capable of not only measuring recession, but of also independently determining in-depth temperature profiles. 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 technology to a flight ready system are shown. In a companion paper & presentation, we review the state-of-the art in recession sensors from Galileo to MSL.

Objectives

Woven TPS is a new, sustainable, weavable and tailorable ablative thermal protection material system using known textile manufacturing processes.[3] The development of this material is *time critical* for any probe mission to Saturn or Uranus due to the fact that heritage carbon phenolic can no longer be manufactured to original specifications. Sensors for this material can be developed in parallel to meet *both* scientific and engineering goals:

- **Parallel sensor and TPS development: development and integration of instruments while increasing TRL of TPS**
- **Engineering solution: spacecraft entry**
- **Science solution: atmospheric measurement**
- **Non-intrusive sensor placement**
- **Decreased cost compared to TPS plugs**
- **Temperature distribution and recession measurement**

Recession measurement supports both the science goal of determining the atmospheric structure and is also an engineering instrument that can help determine TPS risk. While conventional TPS instruments such as thermocouple plugs and recession sensors could be adapted in some cases to Woven TPS, they require coring and installing sensor plugs in the TPS. The potential risk of plugs allowing thermal breach is a concern. In contrast, ultrasonic methods are non-intrusive, have high temporal and spatial resolution, and can be readily integrated with Woven TPS.

IMS Inc. and NASA Ames have partnered to develop 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 of recession evaluation.

Approach

Ultrasonic Concept:

$$G = 2\int_0^L \frac{1}{V(T(x))}\,dx \approx \frac{2}{V_0}\int_0^L [1+\xi\theta(x)]\,dx$$

G = Ultrasonic Time-of-Flight (ToF)

L = Length of Propagation

ξ = Velocity-Expansion coefficient

V_0 = Velocity of Sound at reference temperature T_0

$\theta(x) = T(x) - T_0$

Under isothermal thermal conditions, $\frac{\Delta G}{G} = \xi(T - T_0)$

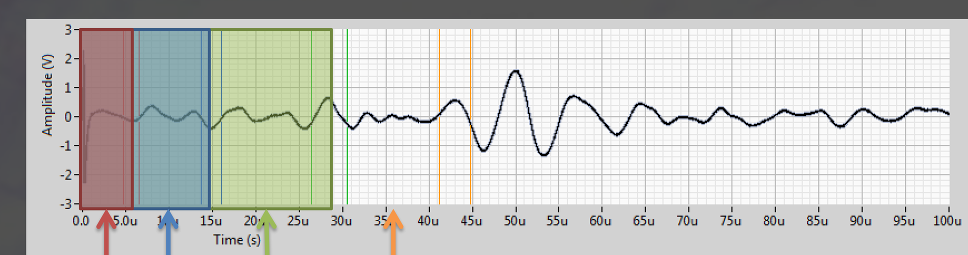
Combining Ultrasonic Thermometry and Thickness Gauging

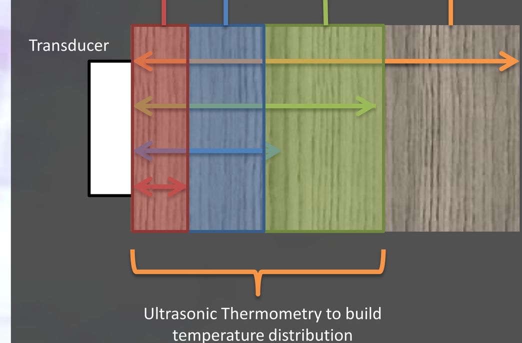
- Ultrasonic thickness gauging using receding echo (early in flight tests 1975)
- Internal Echoes to estimate internal temperature distribution.

Two independent ultrasonic measurements combined to compensate thickness for temperature yielding recession independent of temperature

Structural Localization & Temperature

- Only material property needed is velocity-expansion coefficient
- Thermal model **not required** to extract temperature information
- Any material feature that provides a secondary reflection is an opportunity for local temperature measurements between features
- Complex materials produce diffuse "backscatter", or semi-coherent reflections from material microstructure
- Relative changes in time of flight (ToF) are unaffected by what comes before or after



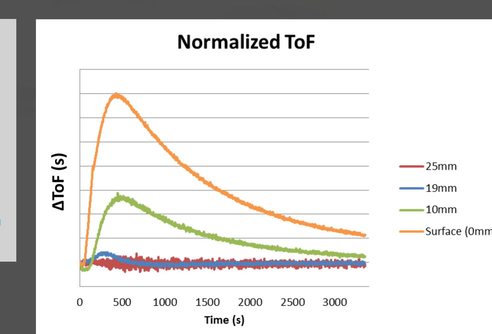


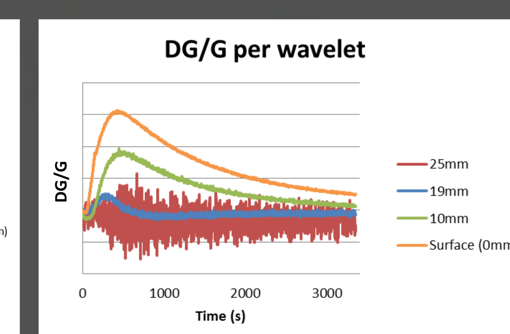
Localization separates regions of interest within a material to compensate for thickness measurements. Colored regions in a material are overlaid on an ultrasonic waveform to show where reflections originate.

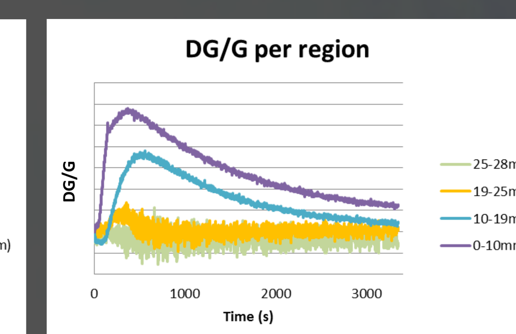
Ultrasonic Method In Practice

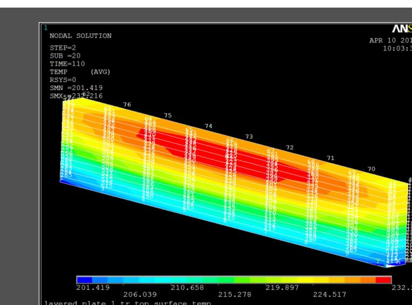
- Red, Blue and Green reflections within a waveform are tracked in time
- Time changes need to be related to temperature in each region
- Orange region contains temperature and recession information that need to be separated

This time of flight (ToF) tracking is performed in real-time at rates up to 70kHz. High speed digitization allows picosecond timing precision.

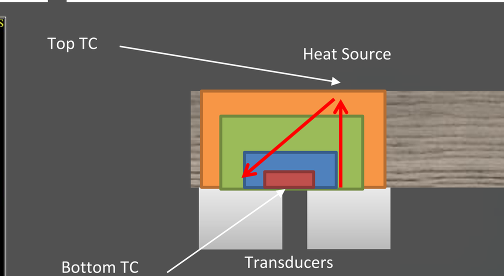




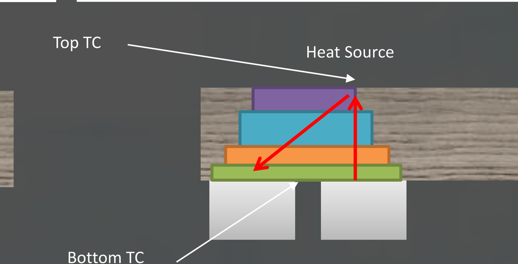




Raw measurements of ToF are shown with the same color-coding. ToF increases in this example with limited heating (no recession) to demonstrate localization.

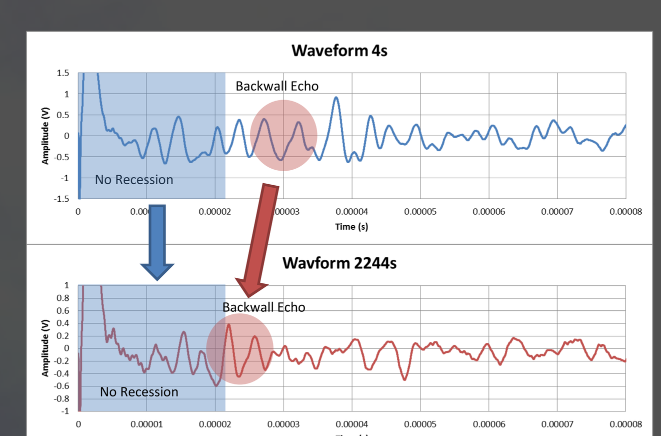


The fractional change in ToF (DG/G) is plotted for each reflection which results in integral data related to the entire volume sampled per color-coded wavelet.



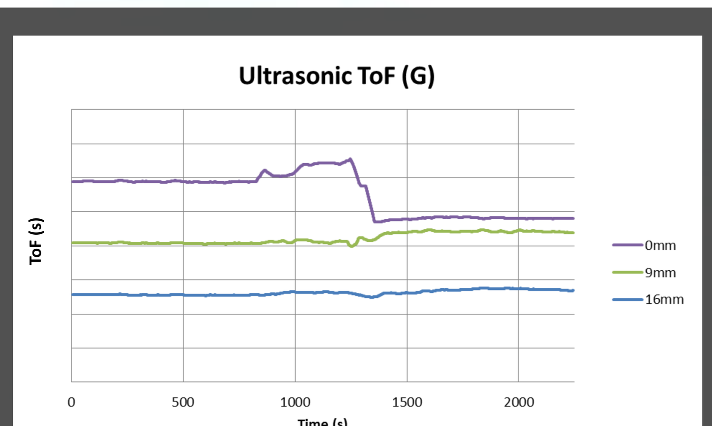
Subtracting regions allows the DG/G to be related to thin regions within the material regardless of recession, temperature or property changes in any other region.

Results



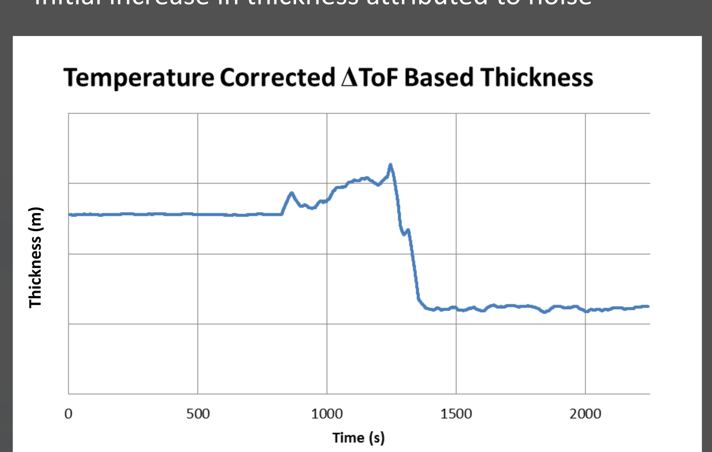
Time-domain analysis of ultrasound through Woven TPS before and after ablation shows signs of recession. During the recession event, ultrasonic signals are monitored and fractional changes in ToF (G) are measured. The ToF of the ablating surface reflection, (backwall echo), decreases due to thickness reduction and increases with temperature and material property changes. The ToF from internal (non-receding) echoes from microstructure will depend only on temperature and material property changes.

Conversion to thickness involves subtracting the ToF of internal microstructure from the ToF of a backwall echo.

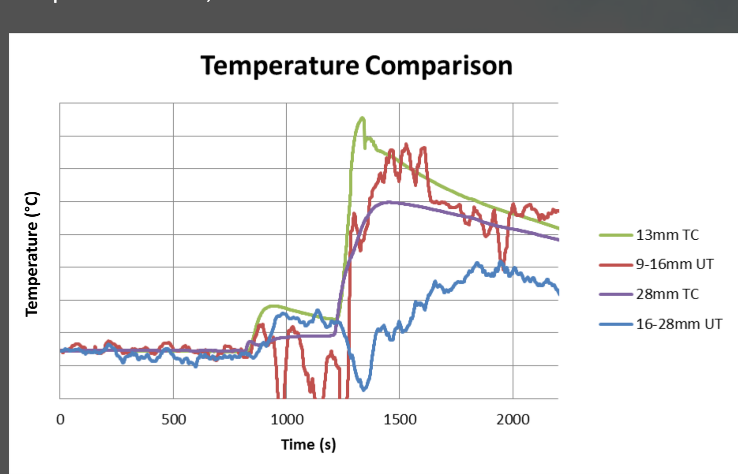


TOF variation of two internal microstructural reflections are shown along with the receding wall echo (0mm).

- Microstructural echoes slightly increase with temperature after ablation event
- Thickness measurement (once corrected) shows no increase after ablation event
- Initial increase in thickness attributed to noise



- Temperature conversion requires ξ value, expressed in ppm/°C
- ξ is the change in velocity of a material and includes both velocity change due to temperature and the velocity change due to thermal expansion
- For many materials this value is linear
- A calibrated temperature conversion can only be made for temperatures where ξ has been measured
- ξ will be different depending on the ultrasonic wave mode, and for anisotropic materials, the wave orientation



- Temperature from embedded thermocouples is compared to calibrated ultrasonic backscatter
- The ultrasonic data draws from thermal information through a volume sampled and is like an average through a large region, not just a point source
- This data demonstrates the high environmental noise present, but correlates with embedded thermocouples in shape and magnitude

Conclusions

Initial experiments on woven carbon phenolic TPS have demonstrated the feasibility of ultrasonic-based recession measurements. Continuous recording of echoes during a recession event has been used to obtain precise measurements of ToF variations from both the receding surface and internal echoes. Novel methods have been formulated which can be used to correct the receding echo ToF data for variations in temperature and thermally induced property variations in the intervening material. **The total recession measured by the real-time ultrasonic method compares favorably with that obtained from post analysis of the sample.**

Independent estimates of the internal temperature distribution within a TPS during a recession event have been more problematic. Key influencing factors in the success and precision of temperature distribution reconstruction include the ultrasonic frequency, sensor configuration and signal-to-noise. Although our test results based on monitoring non-receding internal echoes yield temperature data which is consistent with that derived from thermocouples, the sensitivity and spatial resolution are poor owing to the high ultrasonic loss and long ultrasonic wavelength at low frequency. Furthermore, better measurement of the ultrasonic velocity-expansion coefficient is needed for quantitative conversion of ToF data to temperature. **Enhanced sensors and analysis methods can be used to improve the internal temperature measurements.**

Future development will include tuning ultrasonic instrumentation for better lower frequency operation, multi-sensor operation with improved spatial resolution, and low power, compact instrumentation suitable for in-flight application. To date experiments have been conducted measuring recession on a single small spot, however, **plans include surface-area shape recession measurement using ultrasonic arrays; a capability no other measurement technology offers.**

References

Please see our companion paper:

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See also abstract paper for reference usage.

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