Remote Optical Recession Measurement of Orion
Thermal Protection System

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Systems and Range Operations
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Gordon Scriven
Tait Pottebaum
Opto-Knowledge Systems, Inc. (OKSI)
19805 Hamilton Ave., Torrance, CA 90502

Michael Olson
NASA Ames Research Center
Moffett Field, CA 94035

Scott Splinter
NASA Langley Research Center
Hampton, VA 23681

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Motivation and Measurement Concept

• Motivation
  – Recession models for Orion ablator heatshield material (Avcoat) have large uncertainty, necessitating large safety factors
  – Current in situ diagnostics are not sufficiently accurate to reduce uncertainty
    ▪ Cannot simply improve as likely to be discontinued when Orion becomes operational
  – Need a non-invasive, time-resolved TPS recession diagnostic to support model validation and to enable lower safety factors and corresponding weight reduction

• Measurement Concept
  – Seed TPS close-out plugs with metals at known locations/depths
  – Metals released and vaporized during recession
  – Spectra measured by an off-board sensor
  – Detect tracer metal signatures using OKSI’s Spectral Processing for Optical Trace Element Detection (SPOTED) algorithm
    ▪ Developed for rocket health monitoring
    ▪ Detect and quantify weak metal signatures against complex background
    ▪ Exploits predicted spectral signatures generated by customized version of Optically Opaque Plasmas (OOPS) code from Spectral Sciences, Inc.
  – Spatial-temporal map of TPS recession
Development Path

• **Initial experiments**
  – Experiments conducted at HYMETS (NASA LaRC) in October 2015
    ▪ Hypersonic Materials Environmental Test System
    ▪ 400kW arc-jet facility, 1.5” diameter Avcoat test articles
    ▪ Relatively low cost, short time between tests
  – Objectives
    ▪ Proof-of-concept
    ▪ Verify “Do No Harm”
    ▪ Characterize various tracer metals
    ▪ Evaluate possible plug configurations
    ▪ Establish relationship amongst signal characteristics, tracer metal properties, and recession depth

• **Confirmation Experiments**
  – Experiments conducted at AHF (NASA Ames) in May 2017
    ▪ Aerodynamic Heating Facility
    ▪ More closely reproduces flight conditions than HYMETS does
      – Approximately the same heat flux, much higher dynamic pressure
      – 4” test articles → reduced edge effects
  – Objectives
    ▪ Verify indicator metal behavior in different facility and under more representative conditions
    ▪ Refine seeded plug design
    ▪ Identify limitations on depth resolution
HYMETS Seeded Plug Configurations

Configuration#1: **Spiral Wires**

Seeded plug inserted into test sample

Configuration#2: **Parallel Wires**

Seeded plug

Avcoat test sample
# Test Matrix

<table>
<thead>
<tr>
<th>Run</th>
<th>Sample ID</th>
<th>Config Type</th>
<th>Metals</th>
<th>Plug Adhesive</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Beta</td>
<td>blank plug</td>
<td>none</td>
<td>RTV-560</td>
<td>control sample</td>
</tr>
<tr>
<td>2</td>
<td>Gamma</td>
<td>blank plug</td>
<td>none</td>
<td>non-ferous epoxy</td>
<td>control sample</td>
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<tr>
<td>3</td>
<td>W</td>
<td>parallel wires</td>
<td>Cu, Chromel-C, W, Ti, Ag, Nb</td>
<td>non-ferous epoxy</td>
<td>low to high temp metals, staggered start</td>
</tr>
<tr>
<td>4</td>
<td>V</td>
<td>parallel wires</td>
<td>Fe, Mo, Ta, Re, V, Hf, Zr</td>
<td>non-ferous epoxy</td>
<td>mid &amp; high temp metals, staggered start</td>
</tr>
<tr>
<td>5</td>
<td>E</td>
<td>spiral</td>
<td>W, Ti, Chromel-C</td>
<td>non-ferous epoxy</td>
<td>mid &amp; high temp metals</td>
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<tr>
<td>6</td>
<td>G</td>
<td>spiral</td>
<td>In, Sb, Pb, Al, Cu</td>
<td>non-ferous epoxy</td>
<td>low temp metals only</td>
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<tr>
<td>7</td>
<td>A</td>
<td>double spiral</td>
<td>Ti, Nb, W, Ag, Cu, Ni</td>
<td>RTV-560</td>
<td>low and high temp metals at each depth</td>
</tr>
<tr>
<td>8</td>
<td>B</td>
<td>double spiral</td>
<td>V, Hf, Re, In, Sn, Pb</td>
<td>RTV-560</td>
<td>low and high temp metals at each depth</td>
</tr>
<tr>
<td>9</td>
<td>C</td>
<td>double spiral</td>
<td>V, Hf, Re, In, Sn, Pb</td>
<td>RTV-560</td>
<td>low and high temp metals at each depth</td>
</tr>
<tr>
<td>10</td>
<td>X</td>
<td>parallel wires</td>
<td>W, Ta, Re, Mo, Nb, Rh, V, Chromel-C, Cu, Fe, Zr, Ni, Ti</td>
<td>RTV-560</td>
<td>two layers: mid and high temp metals, then mid and low temp metals</td>
</tr>
<tr>
<td>11</td>
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<td>parallel wires</td>
<td>Ni, Hf, Mo, Ag, Cu, Fe, Nb, Ta, Re, Ti, V</td>
<td>RTV-560</td>
<td>two layers: mid and low temp metals, then mid and high temp metals</td>
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<tr>
<td>12</td>
<td>Z</td>
<td>parallel wires</td>
<td>Ag, Cu, V, Fe, Ti, Zr, Nb, Chromel-C, Ta, Hf, W, Mo</td>
<td>RTV-560</td>
<td>two layers: mid and low temp metals, then mid and high temp metals</td>
</tr>
<tr>
<td>13</td>
<td>D</td>
<td>spiral</td>
<td>Re, Ta, Mo, Nb, V, Hf, Zr</td>
<td>RTV-560</td>
<td>high temp metals only</td>
</tr>
<tr>
<td>14</td>
<td>U</td>
<td>parallel wires</td>
<td>In, Sn, Pb, Mg, Al</td>
<td>non-ferous epoxy</td>
<td>low temp metals, staggered start</td>
</tr>
</tbody>
</table>
HYMETS Setup

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Viewport</th>
<th>spectral band, nm</th>
<th>FWHM resolution, nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSS2-UV</td>
<td>Starboard side</td>
<td>320-450</td>
<td>0.08</td>
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<tr>
<td>OSS2-VNIR</td>
<td></td>
<td>450-1100</td>
<td>0.93</td>
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<td>UV Imager</td>
<td></td>
<td>390</td>
<td>10</td>
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<tr>
<td>pointing laser</td>
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<td>430</td>
<td>1</td>
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<tr>
<td>OSS1-UV</td>
<td>Starboard 4S</td>
<td>320-450</td>
<td>0.13</td>
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<tr>
<td>OSS1-VNIR</td>
<td></td>
<td>450-1100</td>
<td>1.3</td>
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<tr>
<td>Imaging Spectrometer</td>
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<td>380-1000</td>
<td>1.5</td>
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<tr>
<td>pointing laser</td>
<td></td>
<td>650</td>
<td>1</td>
</tr>
</tbody>
</table>

- UV Camera
- UV-NIR Spectrometer
- Blue Laser
- Imaging Spectrometer
- UV-NIR Spectrometer
- Red Laser
- ~3” shocklayer
- ~70Hz
- HD Camera
- pyrometer
- SWIR Camera
Example Spectral Data
(background removed, log radiance)

Sample U
(Parallel, Low- & Mid-temperature)

Sample G
(Spiral, Low- & Mid-temperature)
Spectral signal and recession (Sample G)

- Spiral plug yields clear ON/OFF signals
- Side view SWIR imagery used to measure recession
- Low-temperature metal signals detected before recession reaches location
- Mid-temperature metal signals consistent with recession

Low-temperature

Mid-temperature

*Al is in honeycomb, Cu is in arc-jet nozzle
HYMETS Testing – Conclusions

• Clear connection between melting / vaporization phenomenology and observed signals
  – Mid-temperature metals generate the most clear and easy to interpret signals
    ▪ Vaporize at or below the surface temperature
    ▪ Signal timing consistent with recession to tracer location
  – Low-temperature metals not of interest for recession indicator
    ▪ Melt and vaporize before recession reaches tracer depth
    ▪ May be useful to indicate heat soak or pyrolysis
  – High-temperature metals not of interest for recession indicator
    ▪ Surface temperature below the vaporization temperature
    ▪ Persist on surface and slowly vaporize
    ▪ Low signal level for extended period of time
  – Phenomenology verified using RGB video
    ▪ See paper for details

• Spiral configuration preferred
  – Clear start/end of signal as recession passes tracer location; signal in between more complicated
  – Multiple measurements possible per tracer metal
AHF test articles and setup

- Focus on spiral configuration
- Attempt resolution down to $\frac{1}{2}$ wire diameter
- Determine if higher dynamic pressure alters performance for high-temperature metals

Mid-temperature metals
TA #1 & #2
Ag, Ni, Cu, Fe, Al, Chromel-C

High-temperature metals
TA #3 & #4
Nb, V, Zr, Hf, Mo, Ti

Seeded plug (centered in test article)
1” diameter, 1.5” depth

Test article (thru hole in center)
4” diameter, 1.5” depth

Mirror (front spectrometer)
Side RGB Camera
IR Camera
B&W Camera

Mirror (front RGB camera)
Side spectrometer collection optics
Test Article 2 – Mid-temperature metals data summary
AHF Testing – Conclusions

• Verified that tracer metals behave consistently across facilities and conditions
  – Phenomenology and spectral signals are consistent with interpretation developed based on HYMETS data

• Mid-temperature metals remain the best candidates for use as tracers
  – Focus further efforts on detailed characterizing of specific metals, including expanded set of metals, specifically in this temperature range

• Identified local recession variation as potential limiting factor on spatial resolution and depth resolution
  – Require input from models or experiments on typical degree of local recession variation

• Plug configuration that produces short, distinct detection pulses
  – Spiral
  – Thinner wires
Next steps: Plug design and validation, observation platforms

- **Additional parametric testing at HYMETS**
  - Expanded set of mid-temperature metals
  - Spiral plug detailed design (wire diameters, spacing, etc.)
  - Repeated tests to quantify accuracy and precision

- **Further modeling**
  - Expected absolute radiance of spectral features
  - Minimum detectable signal above expected background

- **Final plug design and tracer metal selections**

- **Verification testing at AHF or similar facility**

- **Targeting integration into EM-2 test flight**

- **Observation platforms and instruments**
  - SCIFLI Airborne Multispectral Imager (SAMI)
  - High-fidelity Automated Airborne Reconfigurable Tracking System (HAARTS)
  - Imaging spectrometer
Possible Platforms and Instruments

• **SCIFLI Airborne Multispectral Imager (SAMI)**
  – OKSI is building a telescope and airborne tracking system for NASA Scientifically Calibrated Inflight Imagery program
  – Designed for NASA-owned HU-25 or Gulfstream III
  – Performance capabilities
    - Better than 5 urad (1 arc sec) pointing stability
    - Reconfigurable (swap-out filters, cameras, spectrometers, optics)
    - Planned configuration: 10” aperture telescope, 2m focal length (f/8), UV-VIS spectrometer, NIR, SWIR, MWIR cameras, Field-of-Regard +/-17°

• **High-fidelity Automated Airborne Reconfigurable Tracking System (HAARTS)**
  – OKSI is the prime contractor building a telescope and stabilized tracking system for the Air Force
  – Designed for a high-altitude, long endurance UAV
  – Part of the UAV-Based Range presented in the previous talk by Thomas Horvath

• **Imaging spectrometer**
  – Spatial resolution of recession provided by using different tracer metals at different locations
    - Do not need spatially resolved spectrometer data
  – For some observations (i.e., daytime), signal to background ratio must be considered
    - Large FOV = high background
    - Small FOV = challenge for tracking
  – Solution: use an imaging spectrometer
    - OKSI has built >10 custom 4DIS (4-Dimensional Imaging Spectrometer) for various customers/applications