Implementation of Active Thermal Control (ATC) for the Soil Moisture Active and Passive (SMAP) Radiometer

Rebecca Mikhaylov, Eug Kwack, Richard French, Douglas Dawson, and Pamela Hoffman

Jet Propulsion Laboratory

California Institute of Technology

Marriott University Park, Tucson, AZ

July 13-17, 2014
SMAP Mission Objectives

- Direct observations of soil moisture and freeze/thaw states from space
- Improved estimates of water, energy and carbon transfers between land and atmosphere
- Enhanced weather and climate forecasts, improved flood prediction and drought monitoring

http://smap.jpl.nasa.gov/
SMAP Team Members and Responsibilities

- Radiometer and ground science data processing (GSFC)
- Radar, instrument integration, test and prelaunch mission management (JPL)
- Reflector boom assembly (Northrop Grumman)
- Spin mechanism assembly (Boeing)
### SMAP and Aquarius/SAC-D

Both fly a GSFC radiometer and JPL radar but:

<table>
<thead>
<tr>
<th>SMAP</th>
<th>Aquarius/SAC-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Measures soil moisture and freeze/thaw states</td>
<td>- Measures sea surface salinity</td>
</tr>
<tr>
<td>- Single feed horn exposed to the sun</td>
<td>- 3 feed horns permanently shadowed</td>
</tr>
<tr>
<td>- Spinning platform</td>
<td>- Non-spinning platform</td>
</tr>
<tr>
<td>- 6m deployable spinning antenna</td>
<td>- 2.5m fixed antenna</td>
</tr>
<tr>
<td>- 0.7°C/orbit thermal stability requirement</td>
<td>- 0.1°C/week thermal stability requirement</td>
</tr>
</tbody>
</table>
Instrument Configuration

- The L-band radar components are on the despun side of SMAP
- The L-band radiometer resides on the spun side of the observatory
  - Cylindrical core structure (CS) houses Spin Mechanism Assembly (SMA)
  - 4 major assemblies mounted on CS
    - Reflector Boom Assembly (RBA)
    - Integrated Feed Assembly (IFA)
    - Radiometer Back End Assembly (RBEA)
    - Instrument Control Electronics (ICE)
IFA and RBEA are the primary assemblies that make up the L-band radiometer
- RFEA contains the most thermally sensitive components
- RFE is the component with the tightest thermal stability requirement
- MLI cocoon is implemented around the RFEA
  - Isolates components from the environment
Derivation of Thermal Stability Requirements

- An acceptable error was allocated to four time periods
  - Instantaneous per minute rate
  - Change per orbit, month and mission life
Thermal Requirements

<table>
<thead>
<tr>
<th>Radiometer Component</th>
<th>Zone</th>
<th>Short Term</th>
<th>Long Term</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>dT/dt (^\circ C/\text{min})</td>
<td>dT/dt (^\circ C/\text{orbit})</td>
</tr>
<tr>
<td>RFE</td>
<td>1</td>
<td>0.05</td>
<td>0.7</td>
</tr>
<tr>
<td>Diplexers, Cal Noise Source, Couplers</td>
<td>2</td>
<td>N/A</td>
<td>2</td>
</tr>
<tr>
<td>OMT</td>
<td>3</td>
<td>N/A</td>
<td>3</td>
</tr>
<tr>
<td>Isolator &amp; Feedhorn</td>
<td>4</td>
<td>N/A</td>
<td>8</td>
</tr>
<tr>
<td>Radome</td>
<td>5</td>
<td>N/A</td>
<td>170</td>
</tr>
<tr>
<td>RBE</td>
<td>N/A</td>
<td>0.1</td>
<td>N/A</td>
</tr>
<tr>
<td>RDE</td>
<td>N/A</td>
<td>0.5</td>
<td>N/A</td>
</tr>
</tbody>
</table>

[Diagram of thermal requirements zones]
SMAP orbital parameters
- sun-synchronous 6PM AN orbit
- 685 km altitude
- orbital period is 98.5 minutes
- beta angles range from 58° to 88°
- eclipse when 58° ≤ β ≤ 65°
- max. eclipse time = 18.9 minutes
- no eclipse when 65° ≤ β ≤ 88°
- eclipse event lasts approximately 83 days from May 11 to August 2
ATC Implementation

- ATC implemented to adjust RFE temperature set point due to undetected gain glitches
  - Short term stabilities are met passively
- Instrument Thermal tasked with delivering the ATC algorithm to Boeing for implementation into ICE
- Peer Review held to confirm recommended algorithm was sufficient for delivery to Boeing
  - Effects of ATC implementation on stability performance
  - All sources of error addressed in modeling and resulting algorithm selection
Thermal Models

- ThermXL is an excel-based thermal model

- Used ThermXL to perform quick algorithm trade studies (10 minutes) compared to the detailed Thermal Desktop model (4 hours)
Algorithm Options

Proportional-Integral-Derivative Control

\[ Q \propto K_p \times (T_{set} - T) + K_i \times \int (T_{set} - T)dt + K_d \times \frac{d(T_{set} - T)}{dt} \]

Proportional Control

\[ Q = K_p \times (T_{set} - T) \]

Modified Proportional Control

\[ Q = K_p \times (T_{set} - T) + C_{offset} \]
Algorithm Selection

- Modified P-control is good enough to meet all stability requirements
- $Q_{\text{max}}$ (26W) not large enough to benefit from $K_i$ term for PI control
- Not dependent on time therefore no memory of previous temperature needed
- No reset problem
- Easy to change the set temperature
- Short term stabilities and temperature variations could be improved by tightening $T_{\text{band}}$
# Sources of Error

## Temperature Sensor

<table>
<thead>
<tr>
<th>Description</th>
<th>Comments</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermistor Tolerance</td>
<td>Tolerance included in specification to vendor. Value will be known at installation since calibration curves provided.</td>
<td>N/A</td>
</tr>
<tr>
<td>Harness</td>
<td>Interested in relative temperature readings as opposed to absolute. Can be calibrated out.</td>
<td>N/A</td>
</tr>
<tr>
<td>mA current source</td>
<td>0.005mA value is assumed negligible.</td>
<td>N/A</td>
</tr>
<tr>
<td>12-bit ADC</td>
<td>Absorbed in sampling rate.</td>
<td>N/A</td>
</tr>
<tr>
<td>12-bit coefficients</td>
<td>Temperature sensor quantization error based on thermistor selected.</td>
<td>TS Quantization = 0.0335°C/count</td>
</tr>
<tr>
<td>Delays</td>
<td>Absorbed in sampling rate. Not concerned due to large thermal mass.</td>
<td>Sample Rate = 30 seconds</td>
</tr>
<tr>
<td>Noise</td>
<td>Not modeled.</td>
<td>N/A</td>
</tr>
</tbody>
</table>

## Heater

<table>
<thead>
<tr>
<th>Description</th>
<th>Comments</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heater Tolerance</td>
<td>Tolerance included in specification to vendor. Value will be known at installation.</td>
<td>N/A</td>
</tr>
<tr>
<td>Harness</td>
<td>Can be calibrated out.</td>
<td>N/A</td>
</tr>
</tbody>
</table>

## Controller

<table>
<thead>
<tr>
<th>Description</th>
<th>Comments</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>12-bit DAC Voltage</td>
<td>Heater quantization error. Voltage variation of 29.5V ± 6%.</td>
<td>Heater Quantization = 0.007326V/count</td>
</tr>
</tbody>
</table>
ThermXL Algorithm Trade Studies

- Simple model performs rapid studies to determine Modified P algorithm effects
  - Quantization of temperature reading and applied voltage for heater power
  - Gain margin
  - $T_{\text{band}}$ (error band)
  - Voltage variation

- Examined by comparing orbital stability of RFE (most sensitive component) for the worst case variation in environmental conditions ($58^\circ$ with hot conditions) with a temperature set point of $20^\circ$C (most likely initial set temperature)
Quantization Effects

- Digitization step value of operational heater depends on $Q_{\text{max}}$ and $T_{\text{band}}$
  - Heater size = 26W
  - 0.43W per step for $T_{\text{band}} = 1.0^\circ\text{C}$

- No significant impact of RFE orbital stability due to digitization of $Q$
Gain Margin and Error Band Effects

- For the Modified P algorithm, the gain is proportional to the heater power.

- To demonstrate gain margin and its effects on temperature stability, an increase in 26 W heater power was modeled, although not physically possible.

- No significant improvement in thermal stability (>0.03°C/orbit) until at least at least 4X 26 W for $T_{band}$ of 1.0°C and 2X 26 W for $T_{band}$ of 0.1°C.

<table>
<thead>
<tr>
<th>$Q_{htr}$ [W]</th>
<th>Predicted Stability [°C/orbit P-P]</th>
<th>±1°C $T_{band}$</th>
<th>±0.1°C $T_{band}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.160</td>
<td>0.160</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.166</td>
<td>0.135</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>0.175</td>
<td>0.079</td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>0.166</td>
<td>0.035</td>
<td></td>
</tr>
<tr>
<td>104</td>
<td>0.137</td>
<td>0.034</td>
<td></td>
</tr>
</tbody>
</table>
Voltage Variation Effects

- Voltage variation of 29V ±6% effects the stability by approximately 0.06°C/orbit with $T_{band}$ of 1.0°C, but it can easily be absorbed since the design includes large margins.

- One concern is the overshoot on nearby components due to the offset between the heater and temperature sensor locations.

<table>
<thead>
<tr>
<th>$Q_{max}$</th>
<th>$T_{band}$</th>
<th>$V_{var}$</th>
<th>Overshoot Temp, °C</th>
<th>$dT/dt$</th>
<th>$dT$</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>+/− °C</td>
<td>+/- %</td>
<td>Heater</td>
<td>Diplexer</td>
<td>RFE</td>
</tr>
<tr>
<td>26</td>
<td>0.1</td>
<td>0</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>26</td>
<td>0.1</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>26</td>
<td>1.0</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>26</td>
<td>1.0</td>
<td>6</td>
<td>5</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>
Conclusions

- 10-node ThermXL model allows a quick and detailed parametric study of ATC with Modified P-control
  - Over 200 ThermXL model scenarios were evaluated to demonstrate that the ATC implementation does not violate temperature stability requirements
  - ATC implemented to adjust RFE temperature set point due to undetected gain glitches

- Digitization errors in the temperature sensor reading and applied heater powers were shown to be insignificant

- Short term stabilities are effected using ATC with $T_{\text{band}}$ of 1.0°C but improved with $T_{\text{band}}$ of 0.1°C

- Voltage variation of 29V ±6% effects the short term stability by approximately 0.06°C/orbit with $T_{\text{band}}$ of 1.0°C, but it can easily be absorbed since the design includes large margins (0.32°C/orbit vs. 0.7°C/orbit for RFE)