Signals of Opportunity Airborne Demonstrator (SoOp-AD)

Earth Science Technology Forum

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Purdue University

EXELIS

NASA
Outline

- Overview
- Project Team
- Science Background and Motivations
- P-Band Signal Details
- Instrument Architecture
- Measurement Simulation
- Next Steps
We propose to measure Root Zone Soil Moisture (RZSM) through cross-correlation of direct and reflected P-Band geosynchronous communication satellite signals.
Project Team

- Purdue University
  *Simulation, Retrieval Algorithms, Requirements Def.*
  - PI: Jim Garrison (Assoc. Prof)
  - Georges Stienne (Post-doc)
  - Yao-Cheng “Zenki” Lin (PhD candidate)
- NASA GSFC
  *Systems Engineering, RF Design, Aircraft Integration*
  - Co-I: Jeff Piepmeier (555)
  - Co-I: Joe Knuble (555)
  - Ken Hersey (AS&D)
  - Cornelus Du Toit (AS&D)
  - Co-I: Alicia Joseph (617)
- Exelis, Inc
  *Digital Receiver Design*
  - George Alikakos
  - Co-I: Steve O’Brien
- Langley Research Center
  *Aircraft Operations*
  - Bruce Fisher
- Dr. Stephen Katzberg – Consultant
  *Scattering Model, Signal Processing*
Scientific Motivation

• Root Zone Soil Moisture (RZSM):
  – Water in top ~meter of soil
  – Critical link between surface hydrology and deeper process
  – Drainage and absorption by plant roots
  – Connection between near-term precipitation and long-term availability of fresh water

• Biomass: a related measurement
  – Carbon storage in vegetation – key part of CO₂ balance
  – Raw material and source of 9-13% of World’s energy
Current Sensing Limitations

• L-Band
  – L-band (SMAP) penetrates only few cm of soil
  – Saturation at L-band limits the ability to sense soil moisture through vegetation
  – SMAP Level 4 data product to estimate RZSM

• P-band radar
  – Difficult to find allocation in heavily utilized spectrum
  – ESA-BIOMASS cannot operate in North America or Europe due to interference with Space Object Tracking Radar
  – 4G mobile network may also cause problems
  – Expensive from space
SoOp Solution

• We propose to use the principles of reflectometry and reflected SATCOM signals to measure RZSM.
  – Cross correlation of direct and reflected signals will be used to measure reflection coefficient.
  – SoOP-AD will first measure RZSM from an aircraft.

• SoOP-AD will use the geostationary P-band satcom systems
  – 225-420MHz allocation for government use, SoOP will focus on 240-270MHz band: 18 25KHz channels, 20 5KHz channels.
  – Continuous use by US since 1978
  – SoOP-AD method measures correlation of direct and reflected signals - does not require demod / decode of the transmission.
SoOp-AD Mission Highlights

• IIP Timeline
  – Awarded in April ’14.
  – Subsystem I&T at GSFC this summer.
  – Science flights in Fall of ‘16.

• Instrument
  – Antennas: Patch, Dual Linear Pol, Null Steering
  – Digital System: FPGA based. 7TB Storage: 1 hour of raw data or many days of processed data.

• Aircraft Campaign
  – Co-Flying with SLAP instrument (GSFC’s Active / Passive L-Band).
  – Science flights over the St. Joseph’s Watershed.
  – Two aircraft racks: 12U Total
Signal Bands and Coverage

- **5 kHz channels**
- **25 kHz channels**

Frequency (MHz)

- November
- Oscar
- Papa
- Quebec

(Satellite Names)
Waterfall spectrum measured at GSFC over 11 days. Note persistence of satcom signals and broad-band RFI.
## Direct Signal Link Budgets

<table>
<thead>
<tr>
<th></th>
<th>P-Band</th>
<th>S-Band</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EIRP (dBW)</strong></td>
<td>26</td>
<td>68</td>
</tr>
<tr>
<td><strong>Frequency (MHz)</strong></td>
<td>240-270</td>
<td>2332.5-2045.0</td>
</tr>
<tr>
<td><strong>Bandwidth</strong></td>
<td>25 kHz</td>
<td>1.886 MHz</td>
</tr>
<tr>
<td><strong>Longitude (deg)</strong></td>
<td>-99.2</td>
<td>-105.6</td>
</tr>
<tr>
<td><strong>Distance (km)</strong></td>
<td>38128</td>
<td>38512</td>
</tr>
<tr>
<td><strong>Path loss (dB)</strong></td>
<td>-172.44</td>
<td>-172.53</td>
</tr>
<tr>
<td><strong>Atmospheric loss (dB)</strong></td>
<td>-1 dB</td>
<td></td>
</tr>
<tr>
<td><strong>Sky-view antenna gain</strong></td>
<td>7 dB</td>
<td></td>
</tr>
<tr>
<td><strong>Sky-view antenna noise</strong></td>
<td>145.0 K</td>
<td></td>
</tr>
<tr>
<td><strong>Pre-switch noise</strong></td>
<td>212.2 K</td>
<td></td>
</tr>
<tr>
<td><strong>Post-switch noise</strong></td>
<td>350.0 K</td>
<td></td>
</tr>
<tr>
<td><strong>Total noise</strong></td>
<td>707.2 K / -156.12 dBW</td>
<td>707.2 K / -137.35 dBW</td>
</tr>
<tr>
<td><strong>SNR (dB)</strong></td>
<td>15.7</td>
<td>15.6</td>
</tr>
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Antenna System Considerations

- Direct-to-Reflect Isolation is Driving Requirement
- Using “Smart Antenna” to steer a null as necessary in post-processing.
- Simulation: Earth View Beam
  - Co-pol (blue): LHCP
  - X-pol (red): RHCP
- Results simulate a post-processed pattern with a null steered to +40°
Measurement Simulation

• Purpose:
  – Science requirement flow-down to technology requirements
  – Error budget
  – First generation retrieval algorithms

• Two Methods: Synthetic (IF) Signal Generator (forward) and Extended Kalman Filter (inverse estimator)

• Evaluate Error Sources against 0.04m³/m³ Precision Req.
  – SNR
  – Direct signal leakage into reflect antenna (easier in orbit!)
  – Multiple Satellite Interference / Isolation
  – Antenna Pattern Knowledge
  – Aircraft Position & Attitude Knowledge
  – Number of correlation delays
  – Terrain Height Fluctuation
  – RFI
Modelling Details

Measurements are made on samples of $Z_{11}$ (autocorrelation of channel 1), $Z_{22}$ (autocorrelation of channel 2) and $Z_{12}$ (cross-correlation between channel 1 and channel 2).

Space signals models:

$$x_D(t) = \sqrt{C_D} a(t - \tau_D) e^{j\omega t} e^{-j\omega \tau_D}$$

$$x_R(t) = \sqrt{C_R} a(t - \tau_R) e^{j\omega t} e^{-j\omega \tau_R}$$

Receiver channels signals models:

$$x_1(t) = f_{RF} \left( \sqrt{G_1 G_{S,D}} x_D(t) + \sqrt{G_1 G_{S,R}} x_R(t) + n_1(t) \right)$$

$$x_2(t) = f_{RF} \left( \sqrt{G_2 G_{E,D}} x_D(t) + \sqrt{G_2 G_{E,R}} x_R(t) + n_2(t) \right)$$

EIRP: 14 dBW

BW: 25 kHz

$G_{S,D}$: 8 dB

$G_{S,R}$: -4 dB

$G_{E,D}$: -9 dB

$G_{E,R}$: 7 dB

$\Gamma$: 0.5

Specular delay ($\tau_R - \tau_D$)
Extended Kalman Filter Method

Measurements: signals auto- and cross- correlations

\[ Z_{1,1}(\tau) = \left\langle x_1(t)x_1^*(t - \tau) \right\rangle \]
\[ Z_{1,2}(\tau) = \left\langle x_1(t)x_2^*(t - \tau) \right\rangle \]
\[ Z_{2,2}(\tau) = \left\langle x_2(t)x_2^*(t - \tau) \right\rangle = f\left(g_{1D}, g_{1R}, g_{2D}, g_{2R}, \sigma_1, \sigma_2, \tau_{RD}\right) \]

Extended Kalman Filter state vector

Chosen delays: \( \tau = 0, \tau_{RD} - \Delta\tau, \tau_{RD}, \tau_{RD} + \Delta\tau \) \( \Rightarrow \) 12 complex measurements (22 real + imaginary parts)

\[
\begin{align*}
g_{1D} &= G_1 G_{SD} \\
g_{1R} &= G_1 G_{SR} \sqrt{\Gamma} \\
g_{2D} &= G_2 G_{ED} \\
g_{2R} &= G_2 G_{ER} \sqrt{\Gamma} \\
\Gamma &= \frac{g_{2R}^2}{g_{1D}^2} \times \frac{G_1^2}{G_2^2} \times \frac{G_{SD}^2}{G_{ER}^2}
\end{align*}
\]

EKF estimates estimated using the transfer switch or noise source antenna patterns (calibrated) + aircraft attitude (IMU)
Results including limited antennas directivities, interference from a second milsat satellite, uncertainty on aircraft position and attitude, 14dBW EIRP, and using 4 samples per correlation, 1s integration time. **Good margin on measurement requirements so far.**

**Monte Carlo Results**

**EKF Results**

\[ NRMSE_{dB} = 10\log_{10} \left( \frac{1}{n} \sqrt{\sum_{i=1}^{n} (\hat{\Gamma}_i - \Gamma_i)^2} \right) \]
Next Steps

• Continue Model Refinement
• Perform I&T at GSFC this Summer
• Field campaign using a tower
• Aircraft campaign