Signals of Opportunity Airborne Demonstrator (SoOp-AD)

Earth Science Technology Forum

2014 ESTO Instrument Incubator Program (IIP)

June 25th, 2015
Outline

• Overview
• Project Team
• Science Background and Motivations
• P-Band Signal Details
• Instrument Architecture
• Measurement Simulation
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Measurement Overview

We propose to measure Root Zone Soil Moisture (RZSM) through cross-correlation of direct and reflected P-Band geosynchronous communication satellite signals.

Expected Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SoOP Airborne</th>
<th>SoOP Spaceborne</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution*</td>
<td>100m</td>
<td>870m</td>
</tr>
<tr>
<td>Sensing Depth</td>
<td>0-30cm</td>
<td>0-30cm</td>
</tr>
<tr>
<td>Sensing Precision**</td>
<td>0.04m$^3$/m$^3$</td>
<td>0.04m$^3$/m$^3$</td>
</tr>
<tr>
<td>Biomass Saturation</td>
<td>&gt; 350 t/ha</td>
<td>&gt; 350 t/ha</td>
</tr>
<tr>
<td>Antenna Size</td>
<td>75 x 75 cm</td>
<td>75 x 75 cm</td>
</tr>
</tbody>
</table>

*Specular Reflection Assumed

**SMAP Requirement

Basis of Measurement

Reflectivity vs. Volumetric Moisture (S = 40%, C = 20%)

Reflectivity, $\Gamma$

Volumetric Moisture, $m_v$ (%)
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 CO$_2$ 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
• **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)

0 0.5 1

240 245 250 255 260 265 270

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></td>
<td>-105.6</td>
<td>-85</td>
</tr>
<tr>
<td></td>
<td>-105</td>
<td></td>
</tr>
<tr>
<td><strong>Distance (km)</strong></td>
<td>38128</td>
<td>38512</td>
</tr>
<tr>
<td></td>
<td>37447</td>
<td>38474</td>
</tr>
<tr>
<td><strong>Path loss (dB)</strong></td>
<td>-172.44</td>
<td>-172.53</td>
</tr>
<tr>
<td></td>
<td>-191.31</td>
<td>-191.54</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>
<tr>
<td></td>
<td>20.1</td>
<td>19.8</td>
</tr>
</tbody>
</table>
SoOp-AD System Architecture

RF SYSTEM

- Direct-V
- Direct-H
- Reflect-H
- Reflect-V

RF Receiver

DIGITAL RECEIVER

- Correlator: \(<\text{Reflect-V}^*\text{Reflect-V}>*8\) Channels
- Correlator: \(<\text{Direct-H}^*\text{Reflect-V}>*8\) Channels

Channelizer

- Correlator: \(<\text{Direct-H}^*\text{Reflect-H}>*8\) Channels

- t_E, t_S, t_L, t_N
- Z(0), Z(t_s), Z(t_l), Z(t_n), Z(t_E)

Raw Data Mode

To Correlator

400 Complex Terms
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 0.04m^3/m^3 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

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:

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

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

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)

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

\[
Z_{1,1}(\tau) = \left\langle x_1(t)x_1^*(t-\tau) \right\rangle
\]

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

\[
Z_{2,2}(\tau) = \left\langle x_2(t)x_2^*(t-\tau) \right\rangle
\]

Extended Kalman Filter state vector

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

\[
g_{1D} = G_1 G_{SD}
\]

\[
g_{1R} = G_1 G_{SR} \sqrt{\Gamma}
\]

\[
g_{2D} = G_2 G_{ED}
\]

\[
g_{2R} = G_2 G_{ER} \sqrt{\Gamma}
\]

\[
\Gamma = \frac{g_{2R}^2}{g_{1D}^2} \times \frac{G_1^2}{G_2^2} \times \frac{G_{SD}^2}{G_{ER}^2}
\]

EKF estimates estimated using the transfer switch or noise source

antenna patterns (calibrated) + aircraft attitude (IMU)

5/15/2018 SoOP-AD 16
Modelling Results

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.**
Next Steps

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