Signals of Opportunity Airborne Demonstrator (SoOp-AD)

Earth Science Technology Forum

2014 ESTO Instrument Incubator Program (IIP)

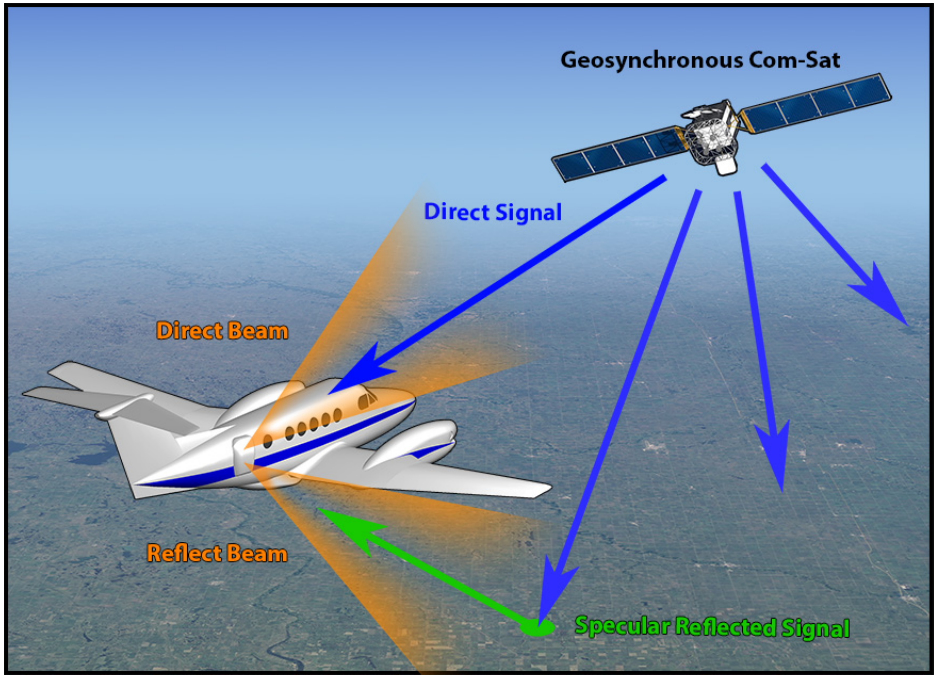
June 25th, 2015

Outline

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

Measurement Overview

P-Band Reflectometry



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

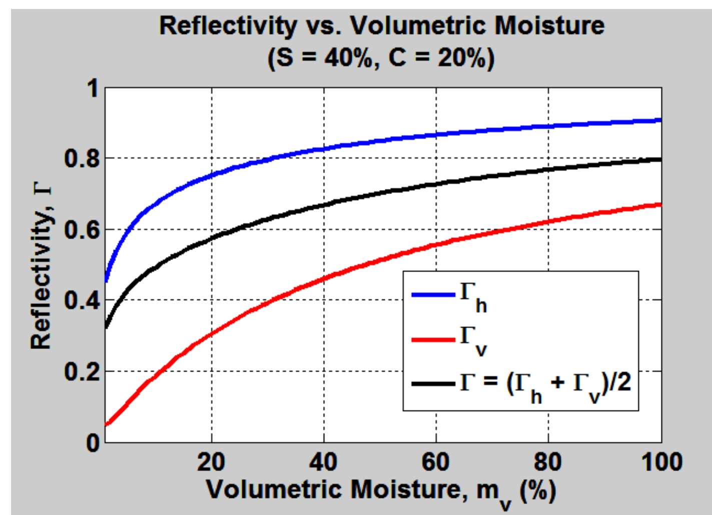
Expected Performance

Parameter	SoOP Airborne	SoOP Spaceborne
Resolution*	100m	870m
Sensing Depth	0-30cm	0-30cm
Sensing Precision**	$0.04 m^3/m^3$	$0.04 m^3/m^3$
Biomass Saturation	> 350 t/ha	> 350 t/ha
Antenna Size	75 x 75 cm	75 x 75 cm

*Specular Reflection Assumed

**SMAP Requirement

Basis of Measurement



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

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.

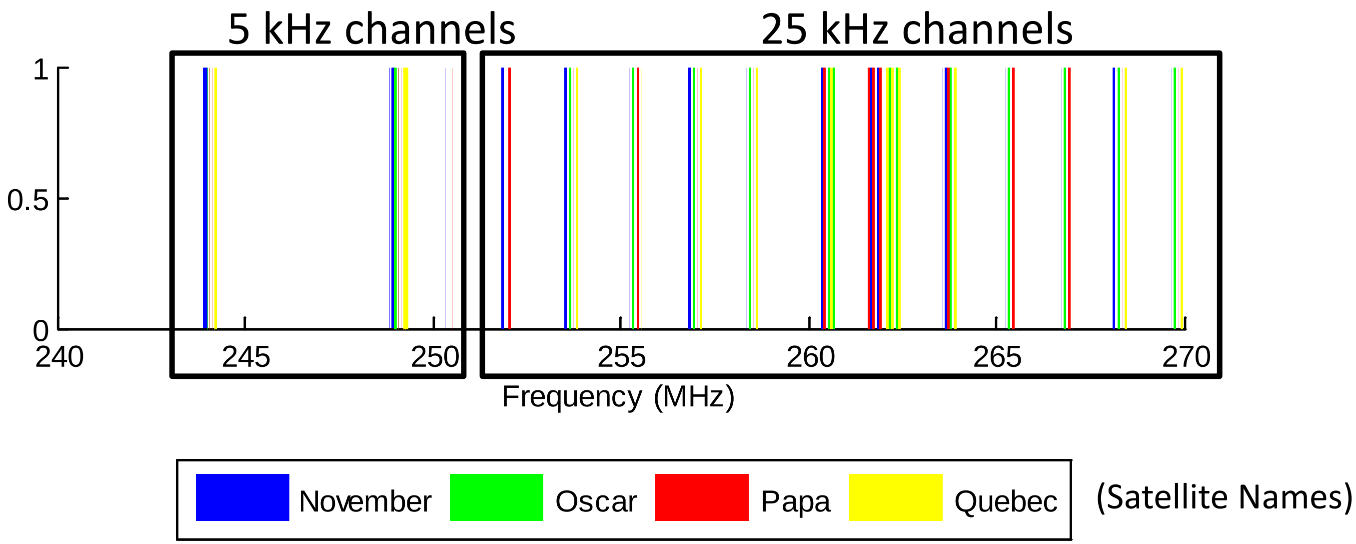
SoOp-AD Mission Highlights

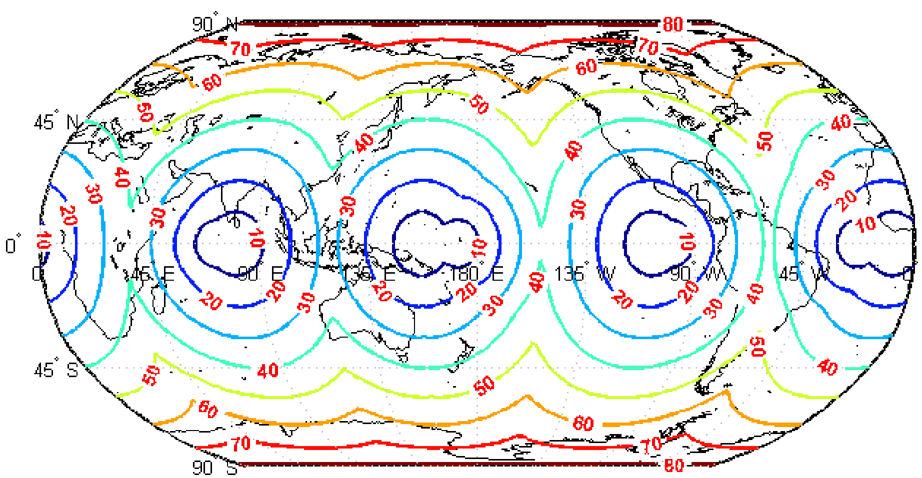
- IIP Timeline
  - Awarded in April ’14.
  - Subsystem I&T at GSFC this summer.
  - Science flights in Fall of ‘16.

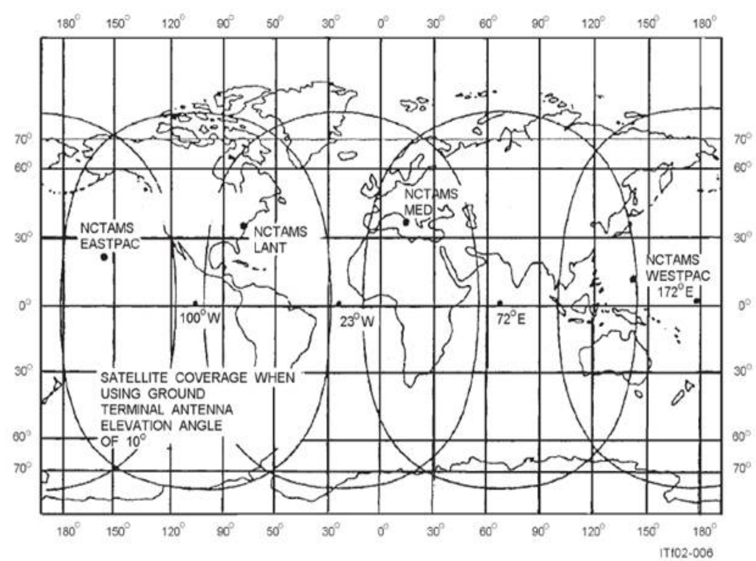
- Instrument
  - Antennas: Patch, Dual Linear Pol, Null Steering
  - Receivers: Standard P-Band Receivers w/ internal calibration. S-Band receiver for XM Radio included. Brassboard and compact card.
  - Digital System: FPGA based. 7TB Storage: 1 hour of raw data or many days of processed data.

- Aircraft Campaign
  - Flying on NASA Langley B200.
  - Co-Flying with SLAP instrument (GSFC’s Active / Passive L-Band).
  - Science flights over the St. Joseph’s Watershed.
  - Two aircraft racks: 12U Total

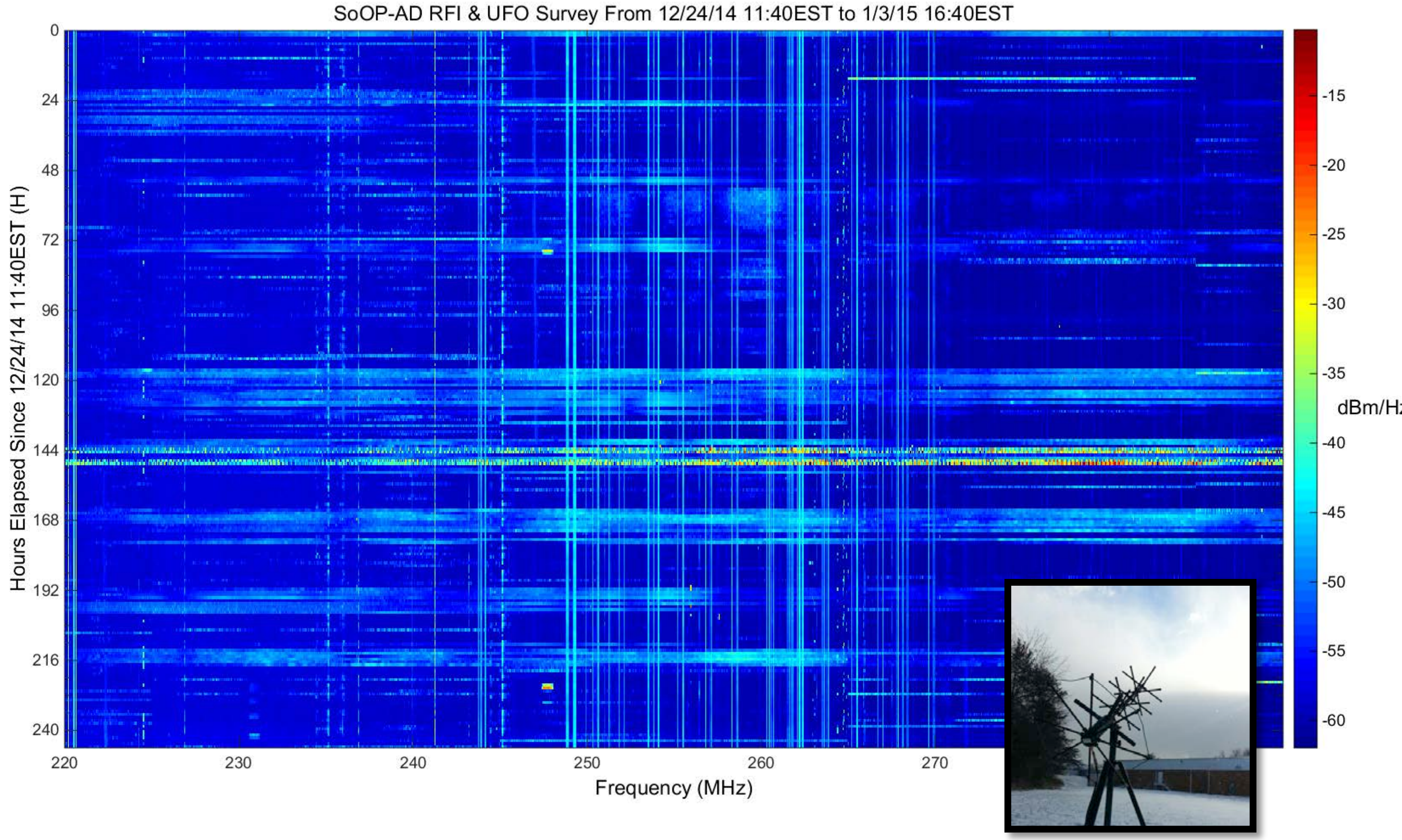
Signal Bands and Coverage







Measured Signal Details & RFI

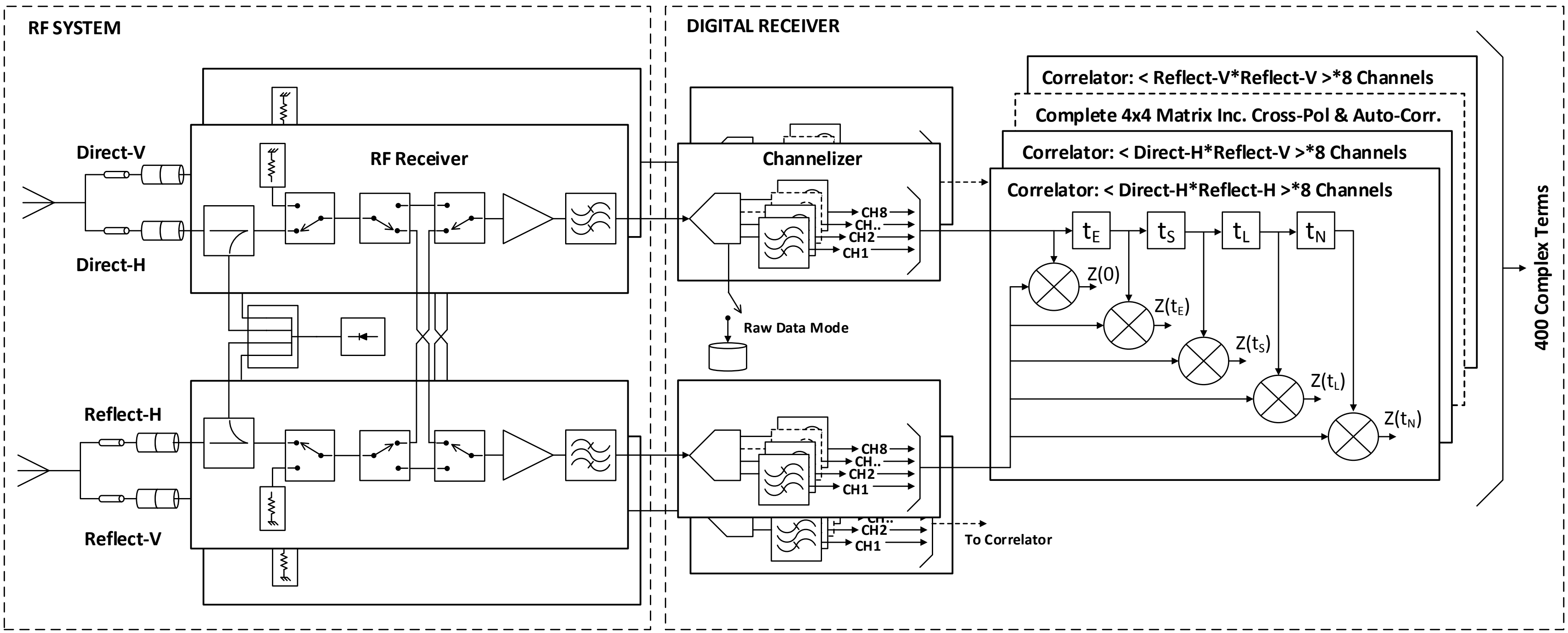


Waterfall spectrum measured at GSFC over 11 days. Note persistence of satcom signals and broad-band RFI.

Direct Signal Link Budgets

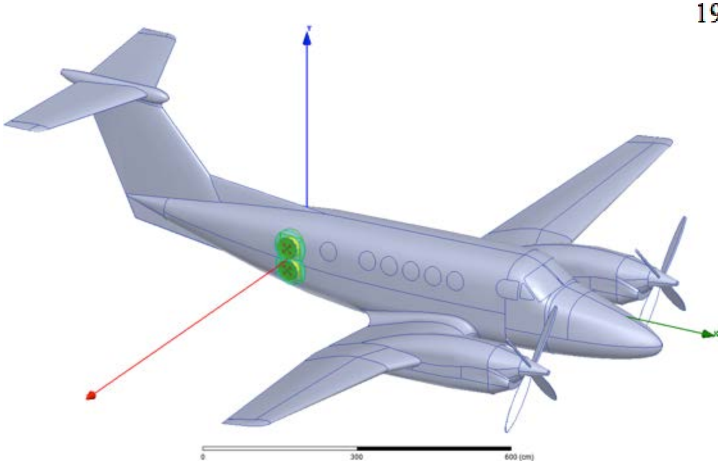
	P-Band		S-Band	
EIRP (dBW)	26		68	
Frequency (MHz)	240-270		2332.5-2045.0	
Bandwidth	25 kHz		1.886 MHz	
Longitude (deg)	-99.2	-105.6	-85	-105
Distance (km)	38128	38512	37447	38474
Path loss (dB)	-172.44	-172.53	-191.31	-191.54
Atmospheric loss (dB)	-1 dB			
Sky-view antenna gain	7 dB			
Sky-view antenna noise	145.0 K			
Pre-switch noise	212.2 K			
Post-switch noise	350.0 K			
Total noise	707.2 K / -156.12 dBW		707.2 K / -137.35 dBW	
SNR (dB)	**15.7**	**15.6**	**20.1**	**19.8**

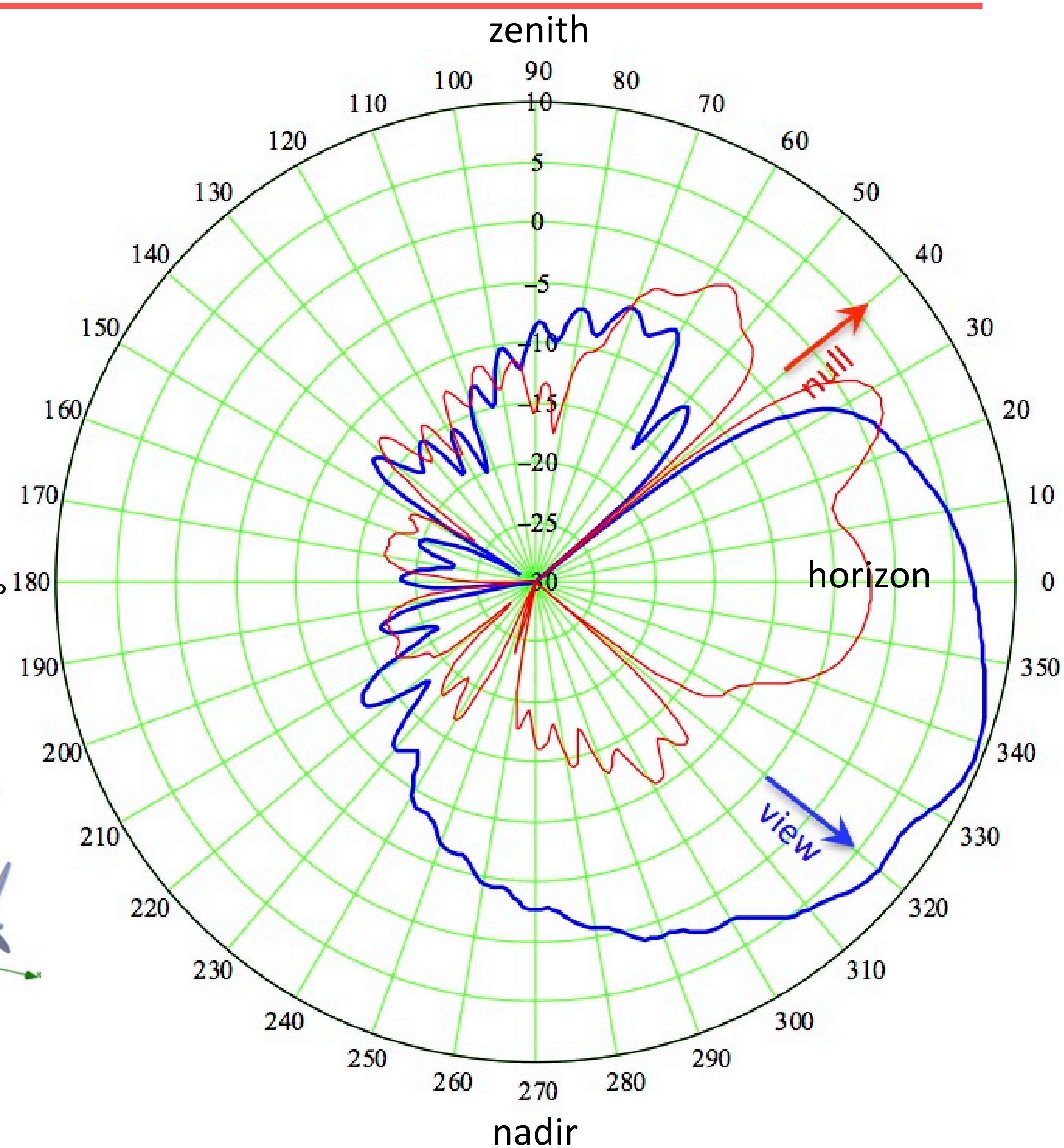
SoOp-AD System Architecture



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°

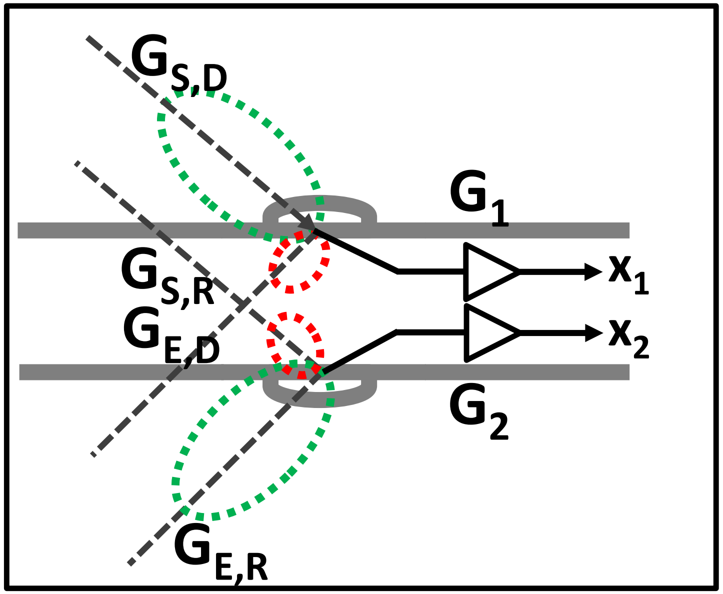




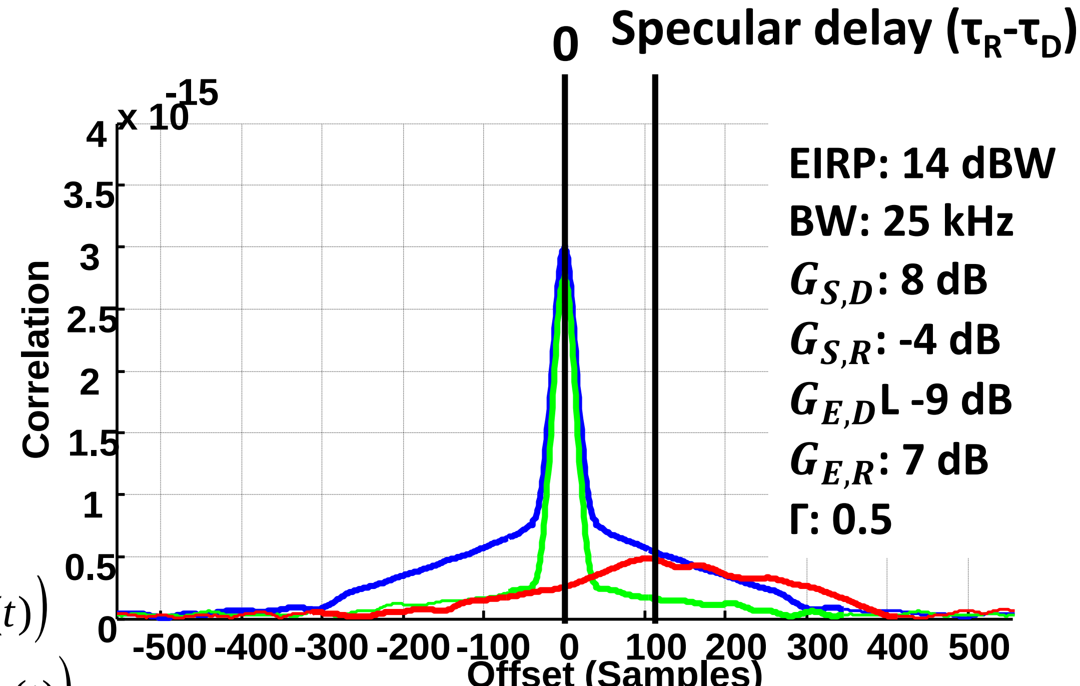
Measurement Simulation

- 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 $0.04 m^3/m^3$ 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



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
$G_{E,D}$L -9 dB
$G_{E,R}$: 7 dB
Γ: 0.5

Space signals models:

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

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

Receiver channels signals models:

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

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

Extended Kalman Filter Method

Measurements: signals auto- and cross- correlations

$$
\begin{aligned}
Z_{1,1}(\tau) &= \left\langle x_1(t) x_1^*(t-\tau) \right\rangle \\
Z_{1,2}(\tau) &= \left\langle x_1(t) x_2^*(t-\tau) \right\rangle \\
Z_{2,2}(\tau) &= \left\langle x_2(t) x_2^*(t-\tau) \right\rangle
\end{aligned}
\quad = \quad f(\underbrace{g_{1D}, g_{1R}, g_{2D}, g_{2R}, \sigma_1, \sigma_2}_{\text{Extended Kalman Filter state vector}}, \tau_{RD})
$$

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

$$
\begin{aligned}
g_{1D} &= G_1\ G_{SD} \\
g_{1R} &= G_1\ G_{SR}\ \sqrt{\Gamma} \\
g_{2D} &= G_2\ G_{ED} \\
g_{2R} &= G_2\ G_{ER}\ \sqrt{\Gamma}
\end{aligned}
$$

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

EKF estimates

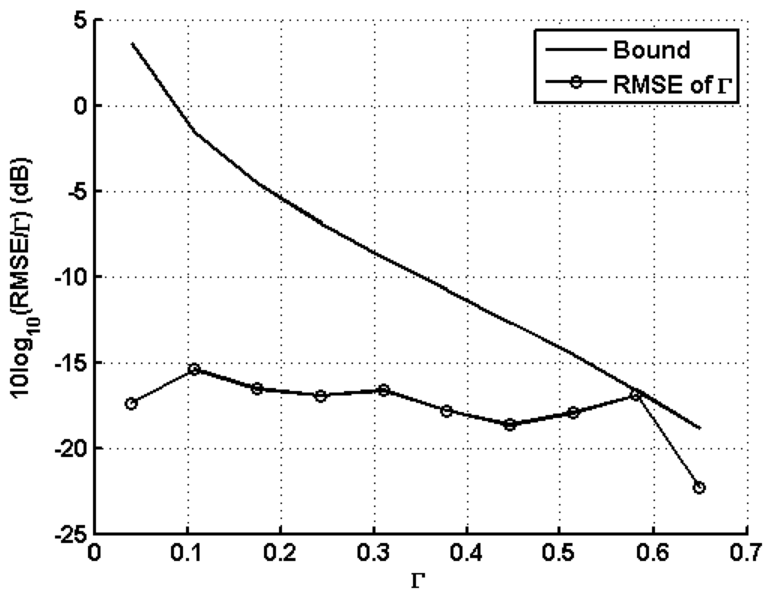
estimated using
the transfer switch or noise source

antenna patterns (calibrated)
+ aircraft attitude (IMU)

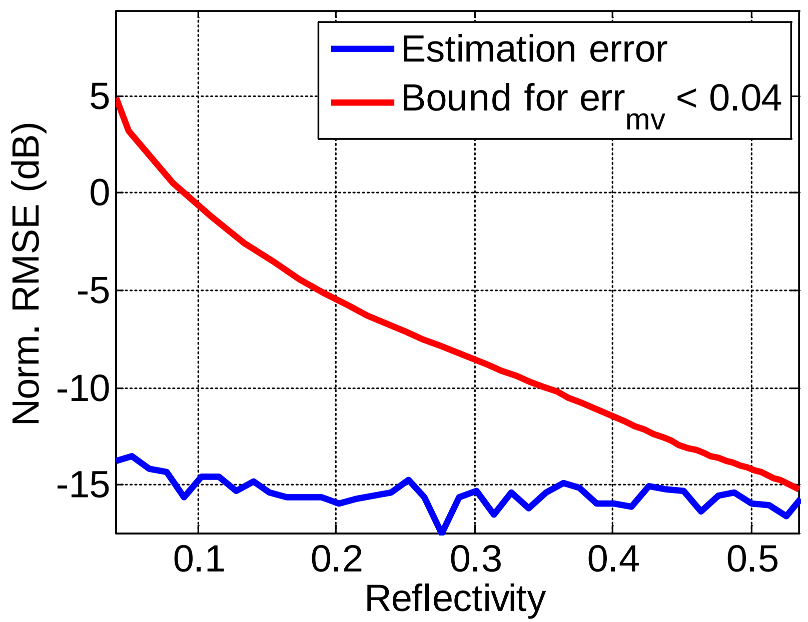
Modelling Results

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.**

Monte Carlo Results



EKF Results



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

Next Steps

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