A Ka-band to baseband RF Testbed for the SWOT mission

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SWOT RF Testbed

• Based on ESTO funded downconverter development to explore receiver topologies and to characterize/compensate for thermal effects

• Additional testbed parts constructed from available test equipment and RF parts

• Ability to perform tests over temperature

• High-speed (2x3GSamp/sec ADC/FPGA Board) for capturing and processing data in real time

• TRL Advancement
Spacecraft block diagram

- **Control, timing and waveform generation**
- **RF upconversion and power amplification**
- **RF down-conversion**
- **Downconverter, A/D conversion and filtering**
- **Processing and data storage**
- **RF Electronics**
- **T/R switch**
- **Antenna subsystem**
- **Low frequency electronics**

- **KA-band**
  - Transmit
  - Receive
  - Receive

**ESTO ACT Project**
Block Diagram of RF Testbed

* Shaded regions indicate ESTO funded development components.
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- **T/R switch**
- **Ka-band transmit**
- **Ka-band receive**
- **ESTO ACT Project**
- **Antenna subsystem**

**Active RF Testbed for the SWOT Mission**

**2011 ESTF**

**UMass Amherst Microwave Remote Sensing Laboratory**

**JPL**
Ka-band downconverter development

SWOT prototype receiver

• To improve isolation and thermal management, DC electronics were moved into a secondary cavity
  • drop-down walls isolate filter cavities
  • between-board connections made with Tusonix through-connectors.
• L-band signal amplified to be directly sampled by A/D converter
Exposed RF subsection undergoing testing
Cross-Track Interferometry

\[ \theta = \sin^{-1}\left( \frac{\lambda \phi}{a 2 \pi B} \right) \]

\[ z = H - \rho \cos\left( \xi - \sin^{-1}\left( \frac{\lambda \phi}{a 2 \pi B} \right) \right) \]
Engineering Challenge

Topographic Measurement
Vertical height error

Baseline length
Affects instrument size and weight

Topographic induced phase
Inter-channel phase error
Baseline length error
Baseline angle error

- Temperature changes
- Nonlinear operations during downconversion
- Mechanical vibrations
- External interference
Temperature dependence of differential phase

- Concurrent measurements of temperature and differential phase showed a strong dependence of phase on temperature.
- Temperature fluctuations due to the ambient environment. Measurements in a closed environment were much more stable.
- Solid lines in the plot indicate a 3rd order polynomial fit to the data.
Thermal Analysis

- 35 GHz signals have a wavelength of 8.4 mm.
- Changes in the physical path length due to thermal expansion/contraction, will cause changes in the signal phase as will temperature imbalances in active components.
- A one degree phase change is equivalent to 23 μm of electrical path length change. Integrated over 5 cm of total path length, this is equivalent to a 0.05% expansion coefficient, or 5 parts in 10,000.
- Thermal imbalances between the two interferometric paths will thus induce a temperature dependent phase error.
- We are measuring temperature “on-board” so that this phase error may be monitored and corrected in the digital stage.
- Point measures of temperature are unlikely to be sufficient to characterize the phase error, as they do not take into account temperature distributions or the thermal inertia of the chassis.
- Thermal modeling will help understand the source of thermal imbalance as it is distributed throughout the system.
Measurements of Differential Phase

Two-Channel Downconverter

SiO2 Cables (5 inches)

Signal source

Power splitter

LNA HMC263 → RF BPF 35.6 GHZ → IR Mixer HMC555

Low Frequency Electronics

LO BPF 33.2 GHZ

LO Power Splitter

LO Amp XP1003

Differential Phase Measurement

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Thermal Testing and Characterization is a tricky affair

- Spikes due to active temperature control

0.25°C/second, 15°C/min; -100°C to 300°C temperature range

Remote operation via serial port or IEEE-488 bus

![Graph showing temperature changes over time with spikes due to active temperature control.]

downconverter
“Passive” thermal testing
A 3D-relief of previous Ka-band board

- On-board temperature sensors
- Telemetry and regulated power
- 35.75 GHz science data channel #1 in
- 34.55 GHz LO in
- 35.75 GHz science data channel #2 in
- 1.2 GHz science data channel #2 out

Used for COMSOL FEM modeling

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Modeled Thermal Imbalance

- COMSOL used to solve the heat equation and estimate board temperature and thermal imbalances.

- Thermal asymmetry in the downconverter design will lead to an asymmetry in the electrical path length.

- While this is not a bad thing in of itself, in a dynamic temperature environment, it will create a bias in the phase measurements, and hence the inferred height.
Dynamic Modeling of Temperature

- Dynamic modeling of temperature is challenging because of the complexity of the subject matter.
- Absolute accuracy is less important than the ability to capture the low order derivatives.
- As modeling improves, we will incorporate the results into the observed phase behavior between the two channels.
- Similar model results have been obtained using COMSOL. An empirical model is used currently for tuning the COMSOL model.
- Results will be used to better inform the microwave engineering.

\[
T(t) = T_{SS} - \left(T_{SS} - T_0\right)e^{-\alpha t}
\]
Thermal Telemetry combined with Science Data

Thermal telemetry

A/D
Chan 1

Demux

FPGA
filtering and
temperature
compensation

two channels
of digital
output

A/D
Chan 2

Demux

Active RF Testbed for the SWOT Mission
Spacecraft block diagram

1. **Control, Timing and Waveform Generation**
2. **Processing and Data Storage**
   - Low frequency electronics
   - Downconverter, A/D conversion and filtering
3. **RF Electronics**
   - RF upconversion and power amplification
   - RF down-conversion
4. **T/R Switch**
   - Ka-band transmit
   - Ka-band receive
5. **Antenna Subsystem**
6. **ESTO ACT Project**

Active RF Testbed for the SWOT Mission
ESTO funded Analog to Digital & FPGA board using all space qualifiable parts
Front Panel Connections

- ADC +Z Input
- ADC -Z Input
- Trigger Input
- External Clock
- 20 pin I/O header
- 9 pin serial input
- 9 pin I/O port
- SATA connector
- SFP connector
A/D performance validation

- Residual errors are less than 1/100\textsuperscript{th} of the input voltage (~40 dB in power)
- Dominated by quantization errors (7 bits ~ 44 dB QSNR)
- ENOB estimated to be 7 bits, close to the published ENOB of 7.2 bits
Error Spectra

- Error spectra used to determine periodic signals (e.g. clocks) which may be dominating the observed errors
- Dominant source at 110 MHz not yet identified, yet it is better than specification
FPGA and A/D board outreach

REAL TIME ESTIMATES OF DIFFERENTIAL SIGNAL PHASE FOR SPACEBORNE APPLICATIONS USING FPGAS

Vishwas Vijayendra, Paul Siqueira, Harikrishnan Chandrikakutty, Akilesh Krishnamurthy, Russell Tessier

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- **Basic form of algorithm**
  - Feed a single tone signal into ADC and compare the resultant waveform with reference waveform
  - Differences are used to characterize phase and gain characteristics of the observed waveform

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**Phase Accuracy vs. Number of Samples**

- $\sigma_\Phi$ (deg)
- $\log_2(N_{samp})$

- 5 dB
- 10 dB
- 20 dB
Supporting Test Equipment

- Arbitrary Waveform Generator (120 MHz BW); Agilent 1.25 GHz AWG also being used
- 40 GHz Spectrum Analyzer
- 40 GHz Signal Generator
- Digital Oscilloscope (1 GHz BW, 4 Gsamp/Sec)
- Trigger Generator
- Power Supply
- RF Electronics
- 2 GHz Signal Generator
Spacecraft block diagram

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Baseband to Ka-band Upconverter

- Ka-band LO out
- Ka-band LO in
- Modulation
- L-band LO
- modulated Ka-band transmit signal
Ka-band EIK (CPI) and HVPS (Pulse Systems)

• 1.5 kW 5% duty cycle extended interaction klystron (EIK) amplifier from CPI
• Modulator provided by Pulse Systems
• EIK Demand for large current from the HVPS at the PRF (4 kHz) causes an oscillation in the system phase performance
Advancing the TRL

Working interferometer used for TRL advancement, integrated system testing and as a potential SWOT ground validation and pre-flight target characterization.
System in working order, continues to be developed and improved
• We are continuing our expertise in Ka-band microwave technology development

• Integration of RF hardware with digital subsystems allows detailed analysis of error in components and across the system

• Measurement accuracy sufficient for measuring milligree variations in the propagation path

• Hardware components are valid across a variety of NASA mission types (e.g. GRACE II, SWOT)

Questions?