The Ultra-Wideband Software-Defined Microwave Radiometer for Ice Sheet Sensing: Instrument Status and Experiment Results

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Motivation

- Understanding dynamics of Earth’s ice sheets important for future prediction of ice coverage and sea level rise
- Extensive past studies have developed a variety of sensing techniques for ice sheet properties, e.g. thickness, topography, velocity, mass, accumulation rate,…
- Limited capabilities for determining ice sheet internal temperatures at present
  - Available from small number of bore holes
- Internal temperature influences stiffness, which influences stress-strain relationship and therefore ice deformation and motion
- Can ice sheet internal temperatures be determined using microwave radiometry?
- Can 0.5-2 GHz microwave radiometry be used for sensing other cryospheric information?
Ultra-wideband software defined radiometer (UWBRAD)

- **UWBRAD**=a radiometer operating 0.5 – 2 GHz for internal ice sheet temperature sensing

- Requires operating in unprotected bands, so interference a major concern

- Address by sampling entire bandwidth (in 100 MHz channels) and implement real-time detection/mitigation/use of unoccupied spectrum

- Supported under NASA 2013 Instrument Incubator Program

- Preparing to deploy in Greenland Sept 2016

- Retrieve internal ice sheet temperatures and compare with in-situ core sites

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq (GHz)</td>
<td>0.5-2, 12 x 100 MHz channels</td>
</tr>
<tr>
<td>Polarization</td>
<td>Single (Right-hand circular)</td>
</tr>
<tr>
<td>Observation angle</td>
<td>Nadir</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>1 km x 1 km (500 m platform altitude)</td>
</tr>
<tr>
<td>Integration time</td>
<td>100 msec</td>
</tr>
<tr>
<td>Ant Gain (dB) /Beamwidth</td>
<td>11 dB / 60°</td>
</tr>
<tr>
<td>Calibration (Internal)</td>
<td>Reference load and Noise diode sources</td>
</tr>
<tr>
<td>Calibration (External)</td>
<td>Sky and Ocean Measurements</td>
</tr>
<tr>
<td>Noise equiv dT</td>
<td>0.4 K in 100 msec (each 100 MHz channel)</td>
</tr>
<tr>
<td>Interference Management</td>
<td>Full sampling of 100 MHz bandwidth in 16 bits resolution each channel; real time “software defined” RFI detection and mitigation</td>
</tr>
<tr>
<td>Initial Data Rate</td>
<td>700 Megabytes per second (10% duty cycle)</td>
</tr>
<tr>
<td>Data Rate to Disk</td>
<td>&lt;1 Megabyte per second</td>
</tr>
</tbody>
</table>
UWBRAD Science Goals

• Ice sheet temperature at 10 m depth, 1 K accuracy
  – 10 m temperatures approximate the mean annual temperature, an
    important climate parameter

• Depth-averaged temperature from 200 m to 4 km (max) ice sheet thickness, 1 K accuracy
  – Spatial variations in average temperature can be used as a proxy for
    improving temperature dependent ice-flow models

• Temperature profile at 100 m depth intervals, 1 K accuracy
  – Remote sensing measurements of temperature-depth profiles can
    substantially improve ice flow models

• Measurements all at minimum 10 km resolution
  – Timestamped and geolocated by latitude and longitude
UWBRAD: Ultra-Wideband Software-Defined Microwave Radiometer for Ice Sheet Subsurface Temperature Sensing
PI: Joel T. Johnson, Ohio State University

Objective
- Design, develop, test and validate an ultra-wide band, 0.5-2.0 GHz software defined microwave radiometer for sensing ice sheet internal temperature at depths up to 4 km and address key NASA climate variability and change issues
  - Includes 12 x 100 MHz fully digitized channels for RFI detection and mitigation
  - Includes forward modeling and retrieval studies for retrieving ice sheet temperatures and understanding ice sheet brightness temperature signatures
- Assess adaptation of UWBRAD to air and space platforms
- Develop software defined algorithms for real time RFI mitigation enabling operation outside protected bands
- Conduct ground based and airborne demonstrations
- Conduct science demonstration/validation of UWBRAD results

Approach
- Design, construct and demonstrate four channel system
  - Design, construct, and test scale model of antenna
  - Expand radiometer to 12 channels and test radiometer performance, software defined algorithms, cognitive radiometry, and full scale antenna in lab environment
- Develop and apply multi-frequency, model based retrieval algorithms to determine internal ice sheet temperatures
- Conduct flight demonstration to validate technologies and science capabilities
- Assess science and technical data to develop a plan for integration of UWBRAD into other NASA ice measurements

Co-Is/Partners: K. Jezek, C. Chen, M. Durand, Ohio State University; L. Tsang, University of Michigan

Key Milestones
- Complete detailed system design 10/14
- Complete four channel implementation and test 04/15
- Complete antenna scale model fabrication and test 04/15
- Complete 12 channel implementation and test 06/16
- Complete antenna implementation and test 05/16
- Complete laboratory tests of full system 08/16
- Conduct airborne experiments on DC-3T over Greenland 09/16
- Complete data analysis 04/17

TRL_{in} = 3  \quad \text{TRL}_{current} = 3
Project Team

- **OSU ElectroScience Laboratory, Department of Electrical and Computer Eng.**
  - PI: Prof. Joel T. Johnson
  - Co-PI: Prof. Chi-Chih Chen (Antenna)
  - Research Associate: Mark Andrews (Radiometer Hardware/Software)
  - Postdoctoral Researchers: Alexandra Bringer, Hongkun Li (Modeling/Calibration)
  - Research Scientists: Dr. Caglar Yardim (Modeling/Retrieval)
  - Graduate Student: Mustafa Aksoy (RFI algorithms, Graduated December 2015)
  - Graduate Student: Domenic Belgiovane (Antenna)

- **OSU Byrd Polar Research Center, School of Earth Sciences**
  - Science PI: Prof. Ken C. Jezek (RT modeling/science/campaign planning)
  - Co-PI: Prof. Michael C. Durand (Retrieval algorithms/science)
  - Graduate Student: Yuna Duan (Retrieval algorithms/science)
  - Post-doctoral Fellow: Dr. Julie Miller (supported by BRPC)

- **University of Michigan, Department of Electrical and Computer Eng.**
  - Co-PI: Prof. Leung Tsang (Advanced RT modeling)
  - Graduate Students: Shurun Tan, Tian-Lin Wang (Advanced RT modeling)
Independent Contractor: Dr. Vladimir Leuski (Radiometer Front end design/build)

Collaborators: Drs. Giovanni Macelloni and Marco Brogioni (CNR-IFAC, Italy) (Science/RT modeling/campaign planning)

Collaborators (not official): Drs. Mark Drinkwater, ESA, Ludovic Brucker, GSFC, Willie Thompson, Morgan State
The radiometer is composed of three subsystems:

- Front End/Downconversion
- Digital Backend
- Antenna
Front End Design
Front End

- 0.5-2 GHz divided into 12 separated channels in 2\textsuperscript{nd} Nyquist of ADC

Avoiding DME equipment aboard aircraft

Channels marked with * included in 4 channel prototype
Front End Implementation

- Temperature Control Board 1 for RF Unit
- Temperature Control Board 2 for IF Units
- Thermistor feeding Board
- Notch Filter
- RF Unit
- DAQ1
- DAQ2
- IF Units 12 Channels
Front End

• Based on ‘hybrid’ radiometer design to avoid need for wideband isolators

• Common 0.5-2 GHz RF stage
  – Calibration process considers multiple front end states

• Subsequent IF stage uses image reject mixers to obtain channels for both upper and lower sidebands

• RF channel definition filters for each channel to reduce out-of-band RFI impact
Back End

- Digital Subsystem based around the ATS9625 card from AlazarTech, Inc:
  - 2 channel, 250 MSPS, 16 bit/sample data acquisition card
  - Achieves high throughput to host PC
  - RFI processing performed on host PC

- Each board can handle 2 100 MHz channels

- 6 boards used for 12 channels

- One host PC can accommodate 2 ATS9625 boards
  - Need 3 PC’s to host boards
  - 4th PC to control system, handle data, etc.
Back End for Greenland Deployment

- Four PC system hosting ADC boards
- Rack mounted system
  - Aircraft approved rack will be used for flight deployment
- Interface between PC’s to provide for synchronization among channels and data sharing
- Host PC runs control and display software
Software Status

• Two main functions: Acquire and Process

• Acquire focuses on interacting with the ADC boards and recording the data to hard disk and memory

• Process focuses on RFI detection and mitigation and extracting brightness temperature information from the data
  – Currently calculates first 4 signal moments, signal power, kurtosis, and 1024 point spectrogram
  – 3 RFI detection algorithms used: pulse detection, cross frequency detection, kurtosis detection

• USB interface from computer to front end for radiometer state control

• Matlab based real-time display software for system monitoring and data visualization
Output Data Formats

- **“High rate”**: Raw ADC samples (16 bits) in all channels recorded every 10 minutes
  - “Burst” operations, 100 msec of data sampled at 250 MSPS (i.e. ~ 50 MB per channel)

- **“Medium rate”**: Software processing of data to perform 1024 point FFT, detection, and integration in each channel
  - Output resolution is 512 frequencies (~0.25MHz) @ 1 msec
  - Kurtosis of each frequency bin also computed (@100ms), as well as fullband kurtosis (@1ms)

- **“Low rate”**: Integration over spectrogram (100x1ms, 512 frequencies) to obtain final counts, both before and after RFI flagging by fullband kurtosis, fullband pulse, and sub-band kurtosis detection algorithms

- All processing performed on host computer in real-time

- Duty cycle for radiometer measurements currently ranges from ~3%-15% (final goal of 10%) for 100 ms integration times, depending on whether processing is performed or only raw data is collected
  - Still performing calibration analysis to optimize cal cycling
UWBRAD Antenna

Diameter: 1.1 inches

Cone Angle = 13.2°

Feed Board

H = 40”

Diameter: 10 inches

Realized Gain [dBi]

Simulation

Frequency [GHz]

Beamwidth [degrees]

Frequency [GHz]

Measured Gain and Matching Performance

Compact Range Measurements

Gain [dB] vs. Frequency [GHz]

• Greenland Antenna
• Antarctica Antenna
• Simulation

<table>
<thead>
<tr>
<th>S11 [dB]</th>
<th>Greenland Antenna</th>
<th>Antarctica Antenna</th>
<th>Simulation</th>
</tr>
</thead>
</table>

-40 -30 -20 -10 0

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2</td>
</tr>
</tbody>
</table>

-w/ Radome
Antenna Only
Measured Antenna Patterns

Outdoor Measurements

2000 MHz
Simulation
w/Radome
Antenna Only

1500 MHz
Simulation
w/Radome
Antenna Only

1000 MHz
Simulation
Antenna Only
w/Radome

500 MHz
Simulation
Antenna Only
w/Radome

Gain Pattern [dBi]
Theta [deg]
DOME-C Opportunity

- Opportunity to deploy at DOME-C obtained through collaboration with PNRA MAISARS project
- UWBRAD provided measurements potentially useful for Domex cal/val
  - Potentially useful ancillary data (retrieved snow temperature profile) to be used for modelling
- IFAC team: Marco Brogioni, Fabiano Monti (snow scientist), Vito Stanzione (technician, winterover)
- Instrument deployment and operation supported by IFAC team
DOME-C Prototype

- Four channels instead of 12: 540, 900, 1380, 1740 MHz
- Radiometer electronics packaged in insulated, temperature controlled enclosure
- Additional antenna support structure constructed for mounting on DOME-C tower
- Antenna included thermistor for monitoring temperature
- Enclosure found to overheat in room temperature environment, but no thermal issues when operated outside at Dome-C
- Required only power and Ethernet interface
UWBRAD Antenna on Antarctica Dome C Tower

IFAC scientist Dr. Marco Brogioni
Dome-C Campaign Events

- 11/17: UWBRAD assembly at Dome-C
- 11/19: UWBRAD turned on in lab, first data sent to OSU 11/24
- 11/24-12/15: Work to identify and mitigate self interference
- 12/15: UWBRAD repackaged; greatly reduced self interference
- 12/16-12/20: Sky observations on ground
- 12/21: UWBRAD deployed on tower in 45 deg position
- 12/26: UWBRAD on tower in 30 deg position
- 12/29: UWBRAD off tower, sky tests with extra attenuation
- 12/31: UWBRAD operations stopped, repackaged for shipment
- 2/4: UWBRAD data drives received at OSU
- Prototype return to OSU: May 2016
“Calibrated” TB spectrograms

- Example spectrogram from 1380 MHz channel for campaign (medium rate data)
- Evidence of narrow band RFI, some internally generated (but easily removed)
- Some evidence of apparent external RFI
- Clear differences between sky and ice sheet observed
- Real time RFI processing parameters not well set, but can reprocess using medium rate data
- 3 lower frequency channels similar; highest frequency channel problematic due to reduced gain and higher cable loss
Kurtosis and RFI Processing

- Fullband and sub-band kurtosis show evidence of RFI
- Narrowband CW type (likely internal) produces kurtosis <3
- Pulsed type RFI produces kurtosis > 3
- Evidence of both types
- Re-applying kurtosis detection to medium rate data in RFI reprocessing
Prep for Greenland Campaign

• Contracting Kenn Borek airlines for Basler BT-67 aircraft
• Campaign scheduled August 29th-Sept 16th, 2016

• 42 flight hours
  – 22 for transit
  – 20 hours for survey
  – 150 knots ground speed
• Check out flight to northern core sites
• Core Site flight modified for Aquifer sites
• Optional sea ice / ice cap flight
• Optional Dye 3/ western aquifer flight
• Optional flights also provide weather delay contingency for higher priority flights
• 1 circular flight with about 25 km radius about GISP/GRIP
Greenland Flight Paths

- Yellow/Purple: core site plan modified to include aquifer (7.6 hrs)
- Gold: Check out flight (4.7 hrs)
- Red: Sea ice and Canadian Ice Caps (3.5 hrs)
- Green: Dye3 and coastal aquifer (4.3 hrs)
- Diamonds: subsurface aquifer locations
# Summary of Planned Greenland Flights

<table>
<thead>
<tr>
<th>Flight</th>
<th>Range (km)</th>
<th>Range (nm)</th>
<th>Duration (150 knots)</th>
<th>Priority and Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice Core/Aquifer</td>
<td>2108</td>
<td>1138</td>
<td>7.6</td>
<td>High – primary objective</td>
</tr>
<tr>
<td>Check out</td>
<td>1322</td>
<td>714</td>
<td>4.8</td>
<td>High – required to verify equipment</td>
</tr>
<tr>
<td>Sealice/IceCap</td>
<td>947</td>
<td>511</td>
<td>3.4</td>
<td>Med – Weather option for Thule. Could sub for check out flight</td>
</tr>
<tr>
<td>Dye3/Western Aquifer</td>
<td>1189</td>
<td>642</td>
<td>4.3</td>
<td>Low – Primary interest is western aquifer</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>5566</strong></td>
<td><strong>3005</strong></td>
<td><strong>20.0</strong></td>
<td></td>
</tr>
</tbody>
</table>
Experiment Overview

- Estimation framework uses a first guess temp. profile parameterized using the Robin model
- Demonstration using synthetic observations for 47 points (including Summit and Camp Century) along Greenland flight line
- Can UWBRAD improve poorly known prior parameter estimates?
- Unknown parameters: Surface temperature, geothermal heat flux, vertical density variations

Datasets

- Surface Temperature and accumulation rate from RACMO reanalysis
- Ice sheet thickness from Operation Ice Bridge
- Geothermal heat flux from Community Ice Sheet Model
- Mean density profile fit from Summit borehole data
- Density variations fit from Liz Morris’ neutron probe data
Estimation results: point 47

Experiment Plan
- Generate synthetic UWBRAD observations with Coherent model
- Estimate parameters from Markov Chain Monte Carlo (MCMC)

Results
- Estimated surface temperature to within 0.5 K
- Estimated geothermal heatflux to within 10%
Forward Models

• All the retrieval methods under investigation involve ‘tuning’ predictions of a forward model to match observations

• Need robust forward model for this to be successful!

• UWBRAD studies have investigated and compared
  – Standard incoherent models (DMRT-ML/MEMLS)
  – Coherent model
    – Both can capture inhomogeneous temperature and density profiles
    – Incoherent models include scattering, but not important at low frequencies
    – Coherent model captures coherent interactions; found potentially to be important at lower UWBRAD frequencies
    – Emphasizing use of coherent model in current retrieval analyses

• Neither model includes effects of surface roughness
  – DOME-C 1.4 GHz model/measurement comparisons suggest roughness may be an issue

• UM team members developing ‘partially coherent’ model to include and examine interface roughness contributions
Brightness temperature comparison between the incoherent and coherent models for different correlation lengths of density fluctuation. Cloud Model: grey dashed curve; DMRT-ML: grey dotted; MEMLS: black-dashed with red markers; Coherent: black solid.

- Model results are different for short correlation lengths of density fluctuation (less than half a wavelength)
- The coherent model is the baseline algorithm and gives correct prediction in the UWBRAD frequency range.
- The coherent model takes longer time to run due to the large number of realizations needed.
- The objective is to improve the efficiency of the coherent model.
- Partially coherent model gets the same physical results but runs much faster.

$\Delta = 0.040\, \text{g/cm}^3$; $\alpha = 30\, \text{m}$
Other Applications

• For smooth layered media, TB vs. frequency oscillates at rate that depends on layer thickness

• Indicates potential for multi-frequency radiometry in ice thickness sensing applications

• Ability to resolve finely in frequency a key aspect of system

• Fourier transform of TB vs. frequency is the temporal correlation function of the received noise: also can be used to determine thickness

• Other potential applications: root zone soil moisture, snow layer thickness, aquifer/wet zone applications
Publications


A. Bringer, et al, “An examination of models for predicting the 0.5-2 GHz brightness temperature of ice sheets,” IGARSS15.


Publications (cont’d)


• L. Tsang, T. Wang, J. T. Johnson, K. C. Jezek, S. Tan, “A partially coherent microwave emission model for polar ice sheets with density fluctuations and multilayer rough interfaces from 0.5-2 GHz,” IGARSS 2016.


Conclusions

• UWBRAD instrument nearing completion
• Laboratory calibration testing in process
• Prepping for September Greenland campaign
• Initiating studies for other applications and future transition