UWBRAD:
Ultra-Wideband Software-Defined Microwave Radiometer for Ice Sheet Subsurface Temperature Sensing


Kickoff Meeting
10th April 2014
Columbus, OH
1330-1350  Overview of project
1350-1400  Review comments intro
1400-1420  Modeling and retrieval studies
1420-1435  DOME-C experimental results
1435-1450  Radiometer design
1450-1500  Antenna design
1500-1515  Experiment planning
1515-1530  Discussion
UWBRAD: Ultra-Wideband Software-Defined Microwave Radiometer for Ice Sheet Subsurface Temperature Sensing

Objectives:
- Design, develop, test & validate an ultra-wide band, 0.5-2.0 GHz software defined microwave radiometer for sensing ice sheet internal temperature at depth
- Develop software defined algorithms for real time RFI mitigation enabling operation outside protected bands
- Design, develop, test & validate a new aircraft 0.5-2 GHz antenna
- Conduct ground based & airborne demonstrations of UWBRAD; flights on a Twin Otter in Greenland
- Conduct science demonstration/validation of UWBRAD results
- Develop an experiment plan for deployment of UWBRAD to support future science observations of ice sheet temperatures
- Assess adaptation of instrument to other air and space platforms
- Address key NASA climate variability and change issues

Approach:
- UWBRAD is a .5-2 GHz nadir observing radiometer having 15 x 100 MHz fully digitized channels for RFI detection and mitigation
- Design, construct and demonstrate two channel system in year 1
- Design, construct, and test scale model of antenna in year 1
- After initial tests, expand radiometer to 15 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 in 2016 to validate technologies and science capabilities
- Assess science and technical data to develop a plan for integration of UWBRAD into NASA science mission
- Co-Is/Partners: K. Jezek (OSU), C. Chen (OSU), M. Durand (OSU), L. Tsang (University of Washington)

Key Milestones:
- Complete Detailed System Design 10/2014
- Complete Dual Channel Implementation/Test 4/2015
- Complete Antenna Scale Model Fabrication/Test 4/2015
- Complete 15 Channel Implementation/Test 10/2015
- Complete Antenna Implementation/Test 10/2015
- Complete Laboratory Tests of Full System 4/2016
- Conduct Airborne Experiments 12/2016
- Complete Data Analysis 4/2017

\[ TRL_{in} = 3 \quad TRL_{out} = 5 \]
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)
  - **Research Scientist:**  Dr. Brian Dupaix (Digital subsystem)
  - **Graduate Student:**  Mustafa Aksoy (RFI algorithms)
  - **Graduate Student:**  Domenic Belgiovane (Antenna)
  - **Graduate Student:**  TBD (Radiometer build/test)
  - **Technician:**  Jim Moncrief (Radiometer build/test)

- **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:**  TBD (Retrieval algorithms/science)

- **University of Washington, Department of Electrical and Computer Eng.**
  - **Co-PI**  Prof. Leung Tsang (Advanced RT modeling)
  - **Graduate Student:**  TBD (Advanced RT modeling)
Independent Contractor: Dr. Vladimir Leuski (Radiometer Front end design/build)

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

Collaborator (not official): Dr. Mark Drinkwater, ESA

- **Status:**
  Still awaiting official award of project
  Provided cost/budget details as requested by NASA contracts office last week
  Expected start date April 1, 2014?
Timeline

- T1: Detailed Design
- T2: Retrieval/RFI Studies
- T3: Two Channel Build/Test
- T4: Antenna Scale Model Build/Test
- T5: Dual channel calibration studies
- T6: Fifteen channel build/test
- T7: Antenna Implement/Test
- T8: Ground-based sky/cal tests
- T9: Shake down flight: prepare/perform/analyze
- T10: Greenland flight: prepare/perform/analyze
- T11: Spaceborne Transition Analyses
- T12: Other/Science Application Analyses
- T13: System refinement/final report

8/15: Delivery to Italy needed for potential participation in FY16 ESA DOME-C Tower measurements
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?
Insight

- Ice sheet brightness temperatures influenced by a variety of physical effects

- Brightness temperatures at differing frequencies are sensitive to differing portions of the ice sheet and to differing physical effects (e.g. scattering)

- Separating internal temperature information from current radiometer (e.g. L band single frequency or higher single frequency) systems difficult

- Future measurements with multi-frequency radiometers offer potential to extract more information on subsurface temperatures
  - A “model-based” retrieval will be required
Ultra-wideband software defined radiometer (UWBRAD)

- We propose design of 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 (15x100 MHz channels) and implement real-time detection/mitigation/use of unoccupied spectrum
- Supported under NASA 2013 Instrument Incubator Program
- Goal: deploy in Greenland in 2016
- Retrieve internal ice sheet temperatures and compare with in-situ core sites

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
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<tbody>
<tr>
<td>Frequency Channels</td>
<td>0.5-2 GHz, 15 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 (1 km platform altitude)</td>
</tr>
<tr>
<td>Integration time</td>
<td>100 msec</td>
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<tr>
<td>Ant Gain (dB)</td>
<td>11 dB</td>
</tr>
<tr>
<td>/Beamwidth</td>
<td>30°</td>
</tr>
<tr>
<td>Calibration (Internal)</td>
<td>Reference load and Noise diode sources</td>
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<tr>
<td>Calibration (External)</td>
<td>Sky and Ocean Measurements</td>
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<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 in 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>
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<tr>
<td>Data Rate to Disk</td>
<td>&lt;1 Megabyte per second</td>
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</table>
UWBRAD Science Requirements

• Measurement of ice sheet physical temperature at 10 m depth to 1 K accuracy at minimum 10 km spatial resolution
  – 10 m temperatures approximate the mean annual temperature, an important climate parameter.

• Measurement of depth-averaged physical temperature from 200 m to maximum 4 km ice sheet thickness to 1 K accuracy at minimum 10 km spatial resolution
  – Spatial variations in average temperature can be used as a proxy for improving temperature dependent ice-flow models.

• Measurement of ice sheet physical temperature profile at 100 m depth intervals to 1 K accuracy at minimum 10 km spatial resolution
  – Remote sensing measurements of temperature-depth profiles can substantially improve ice flow models.

• Measurements time coded and geolocated by latitude and longitude.
The frequency range of the proposed instrument is 0.5-2GHz, which is a horrible RFI environment. The authors mention that their system will have the ability to detect and excise RFI contaminated samples, but do little to explain how they will do this. RFI at these frequencies is quite strong, ever changing and ever present. Their target locations will provide some relief, but it will still be a major challenge to do the types of model-based retrievals in presence of RFI and other error sources found in non-homogenous media. The authors mention the use of techniques, such as sampling at high-rates and applying methods such as kurtosis, but the description is quite vague and does not give the impression that the authors are aware of how difficult this aspect of the task will actually be.

Also, methods to detect and eliminate RFI using a wide band digitizer, but with a significant chain of RF amplifiers, as shown in Figure 5, are still prone to errors due to small signal suppression. Errors of up to 1dB are rare, but for systems hoping to make very precise measurements, small signal suppression can show up in spectrum that is clean due to strong RFI affecting the amplifiers. So even a perfect removal of RFI contaminated spectra may not yield correct measurements. The noise diode calibration may be effective in detecting and correcting this, but it depends on the implementation.
Initial Look at Reviewer Comments (Hardware Related)

• The team appears less experienced in instrument development. The RF hardware development appears to be outsourced to a subcontractor (Dr. V. Leuski of CIRES/NOAA/CET). The remaining instrument development proposed by the team appears to be limited to the "software radio" aspects, which are described only cursorily, and the antenna. The data system is the most expensive hardware component.

• The antenna development appears adequate for the airborne platform, though unknown whether such would translate to space. It is not clear whether the antenna will require a fairing, or how it may interact with the aircraft fuselage, avionics, etc. Given the low frequencies involved, this could be a challenge.

• Integration into space may be challenging for several reasons that are pointed out in the proposal, including RFI mitigation in space, and requirements of increased antenna directivity. The measurement concept is not clearly addressed in the proposal.
• There is no mention of how data will be averaged, smoothed, etc., after portions are found contaminated with RFI. How will their models handle gaps in time and/or frequency? Are the algorithms robust in the presence of gaps? How much data loss can be tolerated? How much impact on retrieval accuracy will the RFI mitigation have?

• The proposed retrieval techniques have shown "some success" but are “limited by the accuracy of the forward model." Thus, even with a perfectly functioning instrument, the likelihood of success appears questionable. This activity, and perhaps the antenna, appear to be the highest risk activities…. How will results of this effort be degraded if accuracy of less than 1K is achieved?

• In regards to calibration/validation in the Antarctic, is the distance from the flight lines to ice free water a concern? Since it is unlikely that there are few bore hole in Antarctica in the vicinity of the over-flights, will 10 m pits be excavated to evaluate the performance of the radiometer?

• The proposers mention the exciting aspect of the discovery of water within the accumulation region of central east Greenland by Foster et al, without discussing the potential problems with extensive water content in many areas of Greenland for estimating brightness temperature as a function of depth.
• There is little margin in the hardware budget for mistakes or failures. There is an explicit 10% shown, but this could easily be eaten up by mistakes or unexpected expenses, especially in the packaging area.

• The development of the RFI mitigation techniques does not appear to be funded or have personnel with expertise called out to perform the work. Knowing that RFI issue is complex and will require significant resources (mainly time).

• The proposal seems loaded with effort not directly associated with the instrument development but rather on the retrieval, modeling, and data analysis. That is, along with the Co-Investigator efforts, the complexity of the proposed instrument does not appear to warrant four graduate students, a postdoc, and a technician, in addition to the outsourced construction of the radiometer electronics.
MODELING/ RETRIEVAL STUDIES
A simple model of ice sheet internal temperatures is

\[ T(z) = T_s - \frac{G\sqrt{\pi}}{2k_c\sqrt{2k_dH}} \left( \text{erf} \left( z \frac{M}{\sqrt{2k_dH}} \right) - \text{erf} \left( H \frac{M}{\sqrt{2k_dH}} \right) \right) \]

(assumes homogeneous ice driven by geothermal heat flux, no lateral advection)

Temperature increases with depth; more rapid increase for lower M

Can reach melting point in some cases

Surface temperature \( T_s \) (K)
Surface accumulation rate \( M \) (cm/yr)
Ice temperature \( T(z) \)
Thermal conductivity \( k_c \)
Thermal diffusivity \( k_d \)
Geothermal Heat Flux \( G \) (mW/m²)
Ice Sheet Properties

- Upper layer of ice sheet comprised of snow: high volume fraction of ice crystals in air
  - “Dense medium” from electromagnetic point of view
  - Mass density of snow determines volume fraction of ice
  - Medium typically represented as air containing spherical ice particles
  - Particle radius typically characterized by the “grain size” parameter

- Density on average increases with depth
  - Volume fraction of ice increases and passes 50% at ~ several m depth
    - Medium is now air inhomogeneities in ice background
    - Inhomogeneity volume fraction on average decreases with depth past this point
  - Grain size increases with depth

- Medium on average approaches homogeneous ice at depths ~ 100 m

- “Random” variations in density and composition with depth on top of the average trends can appear as “layering” effects
Pure Ice Dielectric Properties

- Ice sheet is not pure ice but examination of penetration in pure ice informative.

- Matzler, 2006 model for pure ice dielectric properties enables computation of penetration depth as function of ice temperature and observing frequency.

- Penetration depth larger for lower frequencies and colder ice.

- Penetration depth > 1 km common for frequencies < 2 GHz.

- Can approach 10 km at lower frequencies.
Emission Physics

• In absence of scattering, thermal emission from ice sheet could be treated as a 0th order radiative transfer process

\[ T_B(z_s = 0) = \left(1 - R_{\text{air/snow}}\right) \left(\int_0^{z_s} (\kappa_a + \kappa_s) e^{-\int_0^z (\kappa_a + \kappa_s) dz} \, dz + T_B(z = H) e^{-\int_0^{z_s} (\kappa_a + \kappa_s) dz}\right) \]

• Similar to emission from the atmosphere: temperature profiling possible if strong variations in extinction with frequency (i.e. absorption line resonance)

• Ice sheet has no absorption line but extinction does vary with frequency
  – Motivates investigating brightness temperatures as function of frequency

• Inhomogeneities causing scattering or other layering effects are additional complication

• Need models that can capture effect of scatterers

Upwelling brightness temperature \( T_B(z_s=0) \)

\( R_{\text{air/snow}} \) reflection coefficient

Temperature \( T(z) \)

Absorption coefficient \( \kappa_a \)

Scattering coefficient \( \kappa_s \)

Upwelling brightness from subsurface \( T_B(z_s=H) \)
Cumulative brightness temperature found by summing emissions from the surface to each depth for 5 temperature profiles. Reflection loss at the surface is not included.

Estimated surface Tb versus average physical temperature for 5 loss models. Ice sheet base is wet for average temperatures above 240 K. The gray line accounts for reflection-coefficient driven emission-reduction from the beneath the ice for subglacial water at 273 K. The black line assumes the same physical temperature in the ice, but uses the same reflection coefficient for the rock and water case. Changing temperature profiles and changing bottom boundary conditions can modify the curves at the lowest frequency.
DMRT-ML Model

- DMRT-ML model (Picard et al, 2012) widely used to model emission from ice sheets (Brucker et al, 2011a) and snowpacks (Brucker et al, 2011b)
  - Uses QCA/Percus-Yevick pair distribution for sticky or non-sticky spheres
  - RT equation solved using discrete ordinate method
  - Need layer thickness, temperature, density, and grain size for multiple layers
  - Recommended grain size is 3 X in-situ measured grain sizes

- DMRT-ML computed results for DOME-C density/grain size profiles vs. frequency

  ![Graph showing brightness temperature vs. frequency for different grain sizes and layer thicknesses.](image)

  Lower frequencies “see” warmer ice at greater depths
  Scatterers less important at lower frequencies

  \[ T_B \text{ varies with internal } T(z) \]
SMOS Data Example

• ESA’s Soil Moisture and Ocean Salinity (SMOS) mission has operated an L-band (1400-1427 MHz) interferometric radiometer in space since Nov 2009
  – Provides multi-angular observations for each pixel

• SMOS vertically polarized data at 55 degrees incidence acquired over Lake Vostok, Antarctica for Jan-Feb 2012
  – Gridded, averaged, and interpolated to create image
  – Results show a cold anomaly over the location of subsurface Lake Vostok (3.7 km below surface)
  – Other similar small variations in weekly averaged Antarctic SMOS TB’s observed by CNR

• Source of these effects still under investigation, but likely related to variations in internal temperature properties
Initial UWBRAD Retrieval Studies

• Initial retrieval studies have generated simulated UWBRAD observations of ice sheets for varying physical properties

• A database of 1600 ice sheet profiles created by changing variables in the temperature model and the grain size

\[ T(z) = T_s + C \times \text{erf}\left(\frac{H}{L}\right) - C \times \text{erf}\left(\frac{z}{L}\right) \]

- 4 Ice Thickness values: [1.5 2 2.5 3] km
- 4 L values: [1 2 3 4] km
- 5 C values: [24.7 27.8 30.9 33.9 37.0] °K
- 5 Ts Values: [214 215 216 217 218] °K
- 4 Grain size profiles:
  \[ [0 1 2 3] \times (0.25+0.75\times z/10)\text{mm} \quad 0<z<10\text{m} \]
  \[ 1\text{mm} \quad 10\text{m}<z<100\text{m} \]
  \[ 0 \quad z>100\text{m} \]
- Density: \[ \rho = 1000 \times (0.916 - 0.564 \times e^{-0.0165z}) \text{kg/m}^3 \]
  
  Snow in air when \( \rho < 458.5 \text{kg/m}^3 \), Air in ice when \( \rho > 458.5 \text{kg/m}^3 \)
- 10m layers
Initial UWBRAD Retrieval Studies

• “Database” of 1585 differing brightness temperatures vs. frequency created using DMRT-ML simulator

• A selected truth case perturbed with ~1 K NEDT noise on each frequency channel and “closest” profile from database selected
Initial UWBRAD Retrieval Studies

- 100 Monte Carlo trials for each truth case showed ~74% of correct

- Continuing to include “random” layering effects, expand range of cases simulated, and develop UWBRAD temperature retrieval algorithms
Current Model - DMRT-ML

- **volume scattering**
  - ice grains in air background
  - air bubbles in ice background
  - QCA-CP models scatterers with spheres
  - Rayleigh phase matrix and $\kappa_s \propto f^4 a^3$

- **reflections of layers**
  - Incoherent additions of reflections

Problem 1: Coherent approach

- Analyze density fluctuation using wave approach
  - Measurement reveals (5cm-10cm) density fluctuation
  - Each layer thickness smaller than wavelength
  - Coherent wave interaction between successive layers
  - Apply fluctuation dissipation theorem and dyadic Green’s function for stratified medium

Model density fluctuation with Gaussian noise and Monte Carlo simulation of brightness temperature.
Problem 2: Bicontinuous Medium combined with DMRT

- Snow/Ice modeling using bicontinuous medium (I)
  - Computer generated microstructure of snow/ice
  - Quantify microstructure between real snow/ice and computer generated snow/ice
  - Solve Maxwell’s Equation for each computer generated sample

DDA (Discrete Dipole approximation) simulation of bicontinuous medium to calculate phase matrix, scattering/absorption coefficient, and effective permittivity. These are then combined with DMRT to model Tb and backscattering.

Representative vertical cross section micro-CT images of firn column from Summit, Greenland. Ice is white and the pores are black. Image size 8mm x 8mm. Lomonaco et al, Journal of Glaciology, 57 (204), 755-762.

Bicontinuous medium cross sections. Ice is white and air pores are black. Image size 8mm x 8mm. Ice fractional volume varies from 0.2 to 0.9.
Brightness Temperature Modeling for layered ice sheet with internal temperature distribution

Problem 3: Bicontinuous Medium combined wave approach

- Snow/Ice modeling using bicontinuous medium (II)
  - Cascading of successive thin snow/ice layers above pure ice/water base
  - Full wave simulation of each layer using DDA with periodic boundary condition in the lateral direction and layered medium Green’s function
  - Add up scattering field coherently, Monte Carlo simulation
  - Calculate bi-static scattering coefficient and reflectivity

Cascading of bicontinuous medium layers.
Coupled models and uncertainty

\[ y = f(\alpha) \]
- \( y \): vector of physical states with depth: ice temperature, density, and grain size
- \( \alpha \): parameters (known to within some precision) such as ground heat flux, thermal conductivity, and the density-grain size relationship
- \( f() \) is the physical model of the vertical variability in physical states

\[ z = g(y, \beta) \]
- \( z \): vector of model-predicted \( T_b \) values at 15 UWBRAD channels
- \( \beta \): parameters within the radiative transfer model, such as the absorption coefficient parameterization
- \( g() \) is the radiative transfer model used to describe the functional relationships between physical and radiative states

Uncertainty in inversion of physical states from UWBRAD observations will depend upon 1) uncertainties in \( \alpha \) vector \( \beta \), and 2) sensitivity of \( T_b \) to those uncertainties [Durand et al. 2010]:
Estimation and uncertainty management

Goal is to derive the probability distribution of the temperature profile, given the observations: \( p(y|z) \)

This distribution can be calculated, as a function of the uncertainty in the parameters, using measurement uncertainty, and parameter uncertainty, using Bayes’ law, adapted for iterative simulation:

\[
p(y|z) \propto q(z|y, \beta) r(y|\alpha) s(\alpha, \beta)
\]

where \( q() \) represents measurement errors, and sensitivity due to the uncertainty in the radiative transfer model parameters, embedding the \( f() \) functional, \( r() \) represents sensitivity to the uncertainty in the physical model parameters embedding the \( g() \) functional, and \( s() \) is the first guess of the parameter values, and their uncertainty.

A nearly-identical approach was used by Durand and Liu [2012], and Durand et al. [2009] to handle a more-complex inversion, for mountain snow.
Synthetic test

Using this framework, but assuming no uncertainty in the parameters, temperatures and associated uncertainties were retrieved.

Next steps include expansion of the synthetic tests to include uncertainty using the framework of Jezek et al.
DOME-C EXPERIMENTAL RESULTS
The DOMEX Campaigns

DOMEX-1 : 2004 - 2005 – Pilot Experiment (1 month) included L and C –band
DOMEX-2 : 2009 - 2011 – 2 Years Experiment (3 Antarctic Campaigns)
DOMEX-3 : 2012 - 2015 – 3 Years Experiments (4 Antarctic Campaigns)

Air temperature
Mean: - 53 degs
Max: - 23 degs
Min: - 84 degs
DOMEX - Set Up

45 m tower

15 m height

DomeX-1

DomeX-2/3

L- C-Band
1 month

L-Band
2 + 3 years
Model analysis: angular trends

- L-band data were obtained from the Domex-2 dataset
- C-band data were obtained from the Domex-1 dataset
DMRT-ML Model results: continuous profile

L-band

C-band

Dots = measured data at V and H polarization

- the model overestimates the experimental measurements
- the difference between V and H polarizations is not reproduced at all
- the trend of the V pol is not reproduced at all
For \( \sigma_p = 60 \text{ Kg/m}^3 \) and \( \alpha = 30 \text{ m} \) we obtain

The introduction of fluctuations in the snowpack density profile makes possible:

- to fit quite well the experimental measurements
- to reproduce the difference between V and H polarizations
- to reproduce the trend of the V pol

<table>
<thead>
<tr>
<th>L-band</th>
<th>C-band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle (deg)</td>
<td>Angle (deg)</td>
</tr>
<tr>
<td>Tb (K)</td>
<td>Tb (K)</td>
</tr>
</tbody>
</table>

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The introduction of fluctuations in the snowpack density profile makes possible:
SMOS in EAST Antarctica

MEAN TbV
1.5 year average

Sdev TbV
Weekly averaged
Tb features in the EAP: Dome A – Dome F

SMOS

- 800 Km
Tb features in the EAP: Lake Vostok

SMOS

Lake Vostok

~500 Km
Ancillary data: Surf. Temperature & Bedrock

Mean Surface Temperature (2007-2013)

Ice Thickness

Modis data- MOD11C3V41

Bedmap-2 Project
Snow Temperature Profiles

Sensitivity to Ice thickness

\[ T_s = 217 \text{ K} \]

Sensitivity to Surface Temperature

Ice Thickness = 4000 m

\[ 217 \text{ – 220 K} \]
In order to investigate on ice sheet geophysical properties two transects were investigated:

- Transect 1: From DomeC to triangle (400 km)
- Transect 2: From DomeC to Lake Vostok (800 km)
Transect -1 : DomeC area

- Ice Thickness Increases
- Surf. Temp. Constant

- Surface Temperature Increases
- Ice Thickness constant
Transect -2 : DomeC - Vostok

Ice Thickness Increases
Surface Temperature Constant

Surface Temperature Increases
Ice Thickness Constant

Lake Vostok
Model and Data Comparison: Transect 1

Geophysical Parameters

- Ice Thickness Increases
- Surface Temperature Increases

L-Band Model & Data

- SMOS data
- Model

Surface Temperature Increases
Model and Data Comparison: Transect 2

Geophysical Parameters

L-Band Model & Data

SMOS data

Model

Ts

Ice Thick.
RADIOMETER DESIGN
Radiometer Design

• Three major subsystems: front end, digital backend, antenna
• Front end:
  – Low frequencies of interest enable board-level implementation
  – Traditional Dicke-switch design requires isolators to stabilize amp input impedance
  – Not easily available for 2:1 or more bandwidth
  – Recent “pseudo-correlation” designs eliminate need for isolator

15 channel “pseudo-correlation” design from proposal
Radiometer Operation Basics

- The pseudo-correlation radiometer proposed for UWBRAD operates by adjusting the phase of the reference and antenna signals and summing them in such a manner as to cancel the contributions from one of the input signals at a time.

- Alternating the polarity of one of the 0°/180° phase switches alternates which signal will be observed on the hybrid outputs.
Radiometer Operation Basics

- Below are simplified equivalent block diagrams of the front end of the UWBRAD radiometer with the phase switch in each position.
Radiometer Operation Basics

- The output signals of the hybrid for the two phase states are: For 0° position
  - \( O_1 = (G_1 - G_2)R + (G_1 + G_2) \hat{H}(A) + N \)
  - \( O_2 = (G_1 - G_2)A + (G_1 + G_2) \hat{H}(R) + N \)
  - For 180° position
    - \( O_1 = (G_1 + G_2)R + (G_1 - G_2) \hat{H}(A) + N \)
    - \( O_2 = (G_1 + G_2)A + (G_1 - G_2) \hat{H}(R) + N \)
- (\( R=\)reference signal, \( A=\)antenna signal, \( N=\)noise added by LNAs, \( \hat{H} \) denotes a Hilbert transform)
- With a carefully balanced and calibrated system, the gain terms \( G_1 \) and \( G_2 \) will be nearly equal, leaving only one amplified input signal on the output (plus noise)
- Subtracting subsequent power measurements on a single output will negate the added noise power and leave only the difference in power between the reference signal and the antenna signal
Impacts of RFI

- Techniques for mitigating effects of in band and out of band interference are currently planned for use on UWBRAD (Guner et al 2007)

- Although the techniques used should neutralize the impact from most expected sources of RFI, additional analysis is planned to examine the effect of complete loss of data due to RFI corruption and what impact this has on obtaining an accurate temperature retrieval

- A hardware design trade is also being conducted to add additional filtering to the radiometer design to limit the corruption caused by RFI
Hardware Design Trades

- Each 100 MHz channel analyzed by the radiometer is currently filtered only at the IF band, subjecting the second stage LNA input to the full observed bandwidth of 500-1000 MHz or 1000-2000 MHz
- To prevent out of band or adjacent channel interference from overdriving and distorting the LNAs, two options are being considered:
  - Option 1: Adding 200 MHz bandpass filters prior to each second stage LNA
  - Option 2: Adding additional mixers and LNAs such that 100 MHz bandpass filters can be used
Hardware Design Trades

- Current Design

- Option 1

- Option 2
Digital Subsystem

- Digital Subsystem based around the ATS9625 card from AlazarTech, Inc.
  - 2 channel, 250 MSPS by 16 bit data acquisition card
  - Achieves high throughput to host PC
  - Team has past experience with similar AlazarTech board and software interface
  - RFI processing to be performed on host PC

- Each board can handle 2 100 MHz channels; 8 boards used for 15 channels

- One host PC can accommodate 2 ATS9625 boards
  - Need 4 PC’s

- Early acquisition of 2 boards and host PC will be used for throughput and software studies
Log Periodic Dipole Arrays (LPDA)

E-Plane Patterns

H-Plane Patterns

- Asymmetric Antenna Pattern
- Linear Polarization means Polarization Blind Spots
- Not Easy to Collapse Structure
Planar Spiral Antennas

- Bidirectional Radiation Patterns
- Ground Plane Backing (GPB) Reduce Bandwidth
- Maximum Gain Around 5 dBic even with GPB
Conical Spiral Antenna Operations

Base =7.2”
Length=30”
20 turns
GND=12” Dia.

Constant Symmetric Gain Patterns

0.6-2.0 GHz@0.1 GHz Steps

0.5-2.0 GHz@0.1 GHz Steps
Adjustable Gain and Beamwidth vs. Turns

Base = 7.2”
Height = 30”
20 turns
GND = 12” Dia.

30 turns
GND = 12” Dia.
Adjustable Gain and Beamwidth vs. Height

Base = 7.2”
Height = 36”
30 turns
GND = 12” Dia.

Base = 7.2”
Height = 30”
30 turns
GND = 12” Dia.

0.5 GHz

0.5-2.0 GHz @ 0.1 GHz Steps
Field Program Planning

• Antarctica, Greenland, Russian/Canadian ice caps are desirable sites

• Antarctica pursued in proposal development via potential collaboration with Operation IceBridge
  – Uncertainties with Operation IceBridge McMurdo operations shifted focus instead to Greenland; still interested in Antarctica if possible

• Tentative priority of Greenland sites (based on known surface conditions and availability of ancillary data)
  1) GISP2/GRIP (dry snow zone and substantial ancillary data)
  2) NGRIP (dry snow zone, wet bed in area, some ancillary data)
  3) Camp Century (dry snow zone, some data available- 1966 borehole)
  4) NEEM (most recent site, dry snow zone but ancillary data are difficult to retrieve so far)
  5) Dye 3 (experiences surface melt but substantial ancillary data)

Canadian Ice Caps as contingency:
  1) Devon Island (ancillary data available, surface conditions need to be investigated, Canadian Cryovex validation site)
  2) Agassiz Ice Cap (ancillary data available, surface conditions need to be investigated)
Greenland Deep and Intermediate Drill Sites/
OIB Flight Trajectories

Deep and Intermediate Boreholes

OIB Trajectories
Devon and Aggasiz Ice Cap Secondary Sites/ OIB Trajectories
Aircraft

- Proposal costs quoted for Twin Otter operation (Twin Otter International)
  - 5 hr checkflight at contractor location + 24 science flight hrs in Greenland
- Subsequently in additional discussions with Ken Borek Air, Ltd. as well as Twin Otter International to obtain quotes for specific flight trajectories using either the Bassler or Twin Otter.
- Initial discussion with vendors indicates either aircraft is capable for our purpose.
  - Bassler is desired given the extended range and familiarity of Borek Ltd with conducting US science projects in Greenland.
Other Possibilities

• IFAC-CNR will deploy their radiometer from the tower at DOME-C again in November 2014-January 2015
  • This deployment will complete the current IFAC project with ESA
  • Too soon for UWBRAD

• IFAC planning to propose to ESA to deploy the system again November 2015-January 2016
  • Potential to include UWBRAD tower deployment at DOME-C as part of the proposal
  • ESA project could cover transport costs for UWBRAD to Antarctica if UWBRAD were to arrive at IFAC by August 2015
  • Would be desirable to include full 15 channel system, but even a 2 or 4 channel system could provide valuable information
  • Costs for project personnel support of this effort likely manageable within baseline budget since “ground based tests of 15 channel unit” are part of baseline project plan

• Team will continue to seek opportunities for work in the Antarctic with NSF and NASA
The frequency range of the proposed instrument is 0.5-2GHz, which is a horrible RFI environment. The authors mention that their system will have the ability to detect and excise RFI contaminated samples, but do little to explain how they will do this. RFI at these frequencies is quite strong, ever changing and ever present. Their target locations will provide some relief, but it will still be a major challenge to do the types of model-based retrievals in presence of RFI and other error sources found in non-homogenous media. The authors mention the use of techniques, such as sampling at high-rates and applying methods such as kurtosis, but the description is quite vague and does not give the impression that the authors are aware of how difficult this aspect of the task will actually be.

- The project team has extensive experience with RFI detection and mitigation approaches for microwave radiometry, including the use of time, frequency, and kurtosis based methods, and will use all of these approaches.
- The use of full spectrum sampling will enable high time and frequency resolution to retain available portions of the spectrum within a single 100 MHz channel.
- Even in non-polar environments, actual 0.5-2GHz spectrum occupancy (despite allocation) is moderate, enabling the potential for radiometry in the “white spaces”
- Current trade studies are being performed to reduce the susceptibility of the design to loss of a wide range of frequencies due to a single RFI source.
Also, methods to detect and eliminate RFI using a wide band digitizer, but with a significant chain of RF amplifiers, as shown in Figure 5, are still prone to errors due to small signal suppression. Errors of up to 1dB are rare, but for systems hoping to make very precise measurements, small signal suppression can show up in spectrum that is clean due to strong RFI affecting the amplifiers. So even a perfect removal of RFI contaminated spectra may not yield correct measurements. The noise diode calibration may be effective in detecting and correcting this, but it depends on the implementation.

- Design trade studies are being performed to reduce the susceptibility of the design to loss of a wide range of frequencies due to a single RFI source.
Response to Reviewer Comments (Hardware Related)

- The team appears less experienced in instrument development….The RF hardware development appears to be outsourced to a subcontractor (Dr. V. Leuski of CIRES/NOAA/CET). The remaining instrument development proposed by the team appears to be limited to the "software radio" aspects, which are described only cursorily, and the antenna…. The data system is the most expensive hardware component.

- Members of the project team have previously designed and operated multiple airborne radiometer systems, including RFI detecting and mitigation digital subsystems. The digital aspects of the proposed design are simpler than previous investigations because no FPGA components are used.

- Integration into space may be challenging for several reasons that are pointed out in the proposal, including RFI mitigation in space, and requirements of increased antenna directivity.

- Future use of the technologies developed for space applications will be considered in year three of the project. The concerns raised are legitimate; however the project at a minimum will provide new insights into how to interpret and apply current 1.4 GHz spaceborne observations for ice sheet property sensing.
The antenna development appears adequate for the airborne platform, though unknown whether such would translate to space. It is not clear whether the antenna will require a fairing, or how it may interact with the aircraft fuselage, avionics, etc. Given the low frequencies involved, this could be a challenge.

- Studies of potential application in space will be considered in Year 3.
- Space applications may not include use of the full 0.5-2 GHz range, thereby resulting in a need for a modified antenna design from the current airborne investigation.
- Initial discussions with Twin Otter, International and Ken Borek Air Ltd. have raised no significant concerns about mounting and deploying the proposed antenna.
There is no mention of how data will be averaged, smoothed, etc., after portions are found contaminated with RFI. How will their models handle gaps in time and/or frequency? Are the algorithms robust in the presence of gaps? How much data loss can be tolerated? How much impact on retrieval accuracy will the RFI mitigation have?

• Because the full bandwidth of individual 100 MHz channels will be available at a high sample rate, narrowband RFI can be removed while still retaining much of a single channel. The resulting averaged brightness temperature will still be available (although at increased NEDT) for use in retrieval. Retrieval studies will be conducted in the next year to assess the impact of the unlikely loss of the entirety of one or more channels.

The proposed retrieval techniques have shown "some success" but are “limited by the accuracy of the forward model." Thus, even with a perfectly functioning instrument, the likelihood of success appears questionable. This activity, and perhaps the antenna, appear to be the highest risk activities.... How will results of this effort be degraded if accuracy of less than 1K is achieved?

• Addressing the challenge of achieving reliable temperature information retrieval is one of the highest project priorities, which will be investigated through extensive retrieval algorithm development efforts over the next year. These studies will include attempts to assess “model” errors as well.
In regards to calibration/validation in the Antarctic, is the distance from the flight lines to ice free water a concern? Since it is unlikely that there are few bore hole in Antarctica in the vicinity of the over-flights, will 10 m pits be excavated to evaluate the performance of the radiometer?

- The use of water bodies as an external validation target is common practice in radiometry and is proposed for UWBRAD as well. However our goal is to be required to use water body observations only as a check on calibration and not to perform calibration itself. The radiometer system design will be performed to seek system stability over long time intervals so that only infrequent external calibration will be necessary, and to characterize properties of the radiometer antenna losses so that they can be modeled as a function of physical temperature.

The proposers mention the exciting aspect of the discovery of water within the accumulation region of central east Greenland by Foster et al, without discussing the potential problems with extensive water content in many areas of Greenland for estimating brightness temperature as a function of depth.

- We do not propose to retrieve temperature information in the presence of shallow subsurface water bodies but rather can explore the UWBRAD potential to map such water bodies. Temperature retrieval studies will focus on the “dry snow” regions of Greenland.
There is little margin in the hardware budget for mistakes or failures. There is an explicit 10% shown, but this could easily be eaten up by mistakes or unexpected expenses, especially in the packaging area.

- We believe the 10% margin is adequate and do not anticipate budget overruns or challenges unless there are unexpected major problems.

The development of the RFI mitigation techniques does not appear to be funded or have personnel with expertise called out to perform the work. Knowing that RFI issue is complex and will require significant resources (mainly time).

- Project personnel are allocated to support the RFI mitigation effort; this will require less effort than previous RFI subsystem development projects because no firmware development is involved. The digital subsystem implementation primarily involves RFI software development.

- The proposal seems loaded with effort not directly associated with the instrument development but rather on the retrieval, modeling, and data analysis. That is, along with the Co-Investigator efforts, the complexity of the proposed instrument does not appear to warrant four graduate students, a postdoc, and a technician, in addition to the outsourced construction of the radiometer electronics.
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- The project team includes personnel for the radiometer front end development, digital subsystem/RFI software, antenna development, forward modeling, retrieval studies, science assessment, and campaign planning.

- A significant portion of personnel resources is allocated to the forward modeling/retrieval studies/science assessment portion due to the high risk of this portion of the project as commented previously by the reviewers.
Conclusions

- Multi-frequency brightness temperature measurements can provide additional information on internal ice sheet properties
  - Increased penetration depth in pure ice and reduced effect of scatterers as frequency decreases

- SMOS measurements show evidence of subsurface temperature contributions to observed 1.4 GHz measurements

- UWBRAD proposed to allow further investigations
  - Website at: http://bprc.osu.edu/rsl/UWBRAD

- UWBRAD development beginning April 2014, goal for deployment in 2016 to demonstrate performance