The Ultra-Wideband Software-Defined Radiometer (UWBRAD) for Ice Sheet Internal Temperature Sensing: Results from 2016 Flights in Greenland

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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?
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 12 x ~ 88 MHz channels) and implement real-time detection/mitigation/use of unoccupied spectrum
- Supported under NASA 2013 Instrument Incubator Program
- Deployed in first test flights Sep 2016
- Goal: 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>Freq (GHz)</td>
<td>0.5-2, 12 x ~ 88 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>1.2 km x 1.2 km (1 km 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>
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<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 88 MHz channel)</td>
</tr>
<tr>
<td>Interference Management</td>
<td>Full sampling of 88 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>
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<tr>
<td>Data Rate to Disk</td>
<td>&lt;1 Megabyte per second</td>
</tr>
</tbody>
</table>
Recent Experiments

- First flight campaign conducted Sept 2016 aboard DC-3 aircraft from Ken Borek Airlines
- UWBRAD operated in test flight near Calgary, transit flight from Calgary to Thule AFB, and from Thule AFB to Camp Century
- Instrument experienced a failure after reaching Camp Century
- 0.5 – 2 GHz data acquired for
  - Ice free ocean
  - Snow covered land
  - Melt zones characteristic of the Greenland Ice Sheet
Physical Expectations

- Thermal emission from ice sheets influenced by:
  - Temperature profile of ice sheet
  - Density profile of ice sheet (both “large scale” behaviors and “small scale” fluctuations)
  - Presence of any large scatterers (more likely in melt than in dry snow zones)

- Project team has conducted extensive forward modeling studies

- Some models predict only weak trends in TB vs. frequency on the order of 2-3 K

- Other models predict that small scale density fluctuations can make frequency variations much larger, up to 20-40 K

- Need data to investigate!
Data Analysis

- Data collected over 3 different media of interest
- TB’s calibrated using internal calibration sources and modeled brightness temperature of rough sea surface
- Extensive RFI processing to filter RFI contributions in vicinity to Thule AFB
- TB’s plotted are the averages of the individual 88 MHz subbands
Data Analysis

- Data collected over 3 different media of interest:
  - Ice free ocean
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“Spikes” correspond to isolated icebergs identified in thermal IR data also collected during the flight
Data Analysis

- Data collected over 3 different media of interest:
  - Ice free ocean
  - Snow covered land

- Tb increases once the flight path intercepts land just east of -67 degrees longitude
Data Analysis

- Data collected over 3 different media of interest:
  - Ice free ocean
  - Snow covered land
  - Melt zones characteristic of the Greenland Ice Sheet

- Tb decreases rapidly as the flight proceeds onto the ice sheet before increasing as Camp Century is approached.
Full UWBRAD Spectra/RFI Processing

- Extensive RFI across spectrum, even in Greenland
Full UWBRAD Spectra/RFI Processing

- Extensive RFI across spectrum, even in Greenland
- Pulse, Cross-frequency, and kurtosis detectors flag try to flag out corrupted parts of spectrum
- Appear to eliminate much RFI
- Large swaths of bandwidth lost in some cases
- Some evidence of RFI remaining
Correlation with Melt Facies

- No apparent correlation of Tb with surface topography
- Strong correlation of Tb with snow facies
- Tb increases from bare rock to the ablation zones (surface scattering at C-band is minimal)
**Correlation with Melt Facies**

- No apparent correlation of Tb with surface topography
- Strong correlation of Tb with snow facies
- Tb decreases as the line enters the wet snow zone
- Some small variations in Tb may be associated with refrozen surface lakes
Correlation with Melt Facies

- No apparent correlation of Tb with surface topography
- Strong correlation of Tb with snow facies
- Tb is minimum in the strongly scattering percolation facies
- Note that the minimum in Tb shifts eastward as the frequency increases
Correlation with Melt Facies

- No apparent correlation of Tb with surface topography
- Strong correlation of Tb with snow facies
- Tb increases as the surface transitions towards dry snow facies
Spectra of Facies

- Rock and ablation facies spectra appear flat across the band
- 20 K-40K changes for percolation facies and also at the site near Camp Century
- Wet snow facies have a range of about 10 K
- Some systematic calibration effects apparent but signatures seem reasonable
Comparison with SMOS

- UWBRAD measurements 1400-1427 MHz compared to SMOS spaceborne data over the flight path for partial validation
- Note UWBRAD observes in circularly polarization at 0 degrees
- SMOS 20 degrees data (average of H and V) used for comparison
- Significant difference in footprint (UWBRAD ~ 1.2km, SMOS ~40 km)
  - UWBRAD smoothed with a 40 km long running filter
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- Mixed land/sea scene in SMOS footprint causes SMOS TB’s to exceed UWBRAD in the open ocean part of the flight
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- Better match over the ice sheet
- SMOS remains somewhat warmer at TB minimum
  - Possibly due to remaining footprint differences
Comparison with PALSAR-2

- UWBRAD measurements also compared with PALSAR-2 L-band HH polarization backscatter collected on 8/27/16
- Generally inverse relationship with UWBRAD TB’s
- High backscatter levels indicative of strong volume scattering in this region
Forward Modeling of UWBRAD Data

- Used the “partially coherent” forward model modified to include attenuation due to scattering by ice lenses (disks)
- Camp Century borehole information used for density and temperature profiles (assumed to apply over other portions of the nearby ice sheet)
- Correlation length of density fluctuations and density of ice lenses used as fitting parameters in data matchup
Tb Spectra in Various Facies: Model vs. Data

\[ \Delta = 0.080 \text{gm/cm}^3 \]
\[ l = 15\text{cm} \]
\[ \alpha = 75\text{m} \]
\[ \eta_{0} = 6/\text{m}^3 \]

\[ \Delta = 0.13 \text{gm/cm}^3 \]
\[ l = 12\text{cm} \]
\[ \alpha = 50\text{m} \]
\[ \eta_{0} = 9/\text{m}^3 \]
\( \Delta \): Tb level at low frequency
\( n \downarrow 0 \): spectral differences

\( n \downarrow 0 \) estimated from 
\( T_{\downarrow b}^{\uparrow \text{cloud}} / T_{\downarrow b} \)

- Good agreement in Tb spatial and spectral patterns
Transit Flight

Calgary to Cambridge Bay Refueling Stop

9/12/16

Data available from: 6:34:25 UTC to 12:16:58

Includes variety of land cover types

Many small water bodies
Transit Flight Examples

Transit flight, 9/12/16
September 2017 Greenland Flight Paths

- Primary science core site flight (7.6 hrs)
- Check out flight (4.7 hrs)
- Red: Sea ice and Canadian Ice Caps (3.5 hrs)
- Light Yellow: Nares Straits sea ice flight (optional, ~ 5 hrs)
- Purple: Alternate combined sea ice/checkout flight
- Green: Dye3 and coastal aquifer (4.3 hrs)
Other Activities

• Investigating UWBRAD transition into science and space operations
  – Italian Space Agency project “CryoRad” at IFAC on spaceborne transition: includes extending analysis to sea ice and permafrost
  – Italian National Project “ISSIUMAX” funded to support flight hours for UWBRAD in Antarctica November-January 2018

• Other potential UWBRAD applications:
  – Firn aquifer monitoring
  – Lake ice/sea ice applications
  – Snow applications
  – Soil moisture applications
  – Sea salinity applications
  – White paper submitted to decadal survey and to ESTO technology review
Conclusions

• UWBRAD acquired 0.5-2 GHz TB’s of Greenland Ice sheet in September 2016
• Correlations between UWBRAD spectra and ice sheet melt facies observed
• Spectral behavior in this morphologically complex sector of the ice sheet can be plausibly explained by varying the distribution of horizontal density layers and isolated icy bodies in the upper portion of the firn
• Planning return flight to Greenland in September 2017 to observe dry snow portions of the ice sheet for temperature profile demonstration + sea ice and firn aquifer regions
• Also exploring application of UWBRAD data for sea ice, firn aquifer, land, and oceanographic applications
• “Software defined” aspect similar to technologies used in software defined radio
Publications


Publications (cont’d)


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


Jezek, K. 2015. Airborne and spaceborne remote sensing of Earth’s cryosphere. Invited lectures at Beijing Normal University (Beijing), Xi’An Technical University (Xi’ An), Guilin Technical University (Guilin), East China Normal University (Shanghai), Tongji University (Shanghai), China, June 2015.
Publications (cont’d)


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.


• A. Bringer, J. Johnson, K. Jezek, M. Durand, Y. Duan, "Observations of Snow Packs with an Ultra-Wide Band Radiometer", 73rd Eastern Snow Conference.

