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

J. T. Johnson[1], K. C. Jezek[2], M. Andrews[1],
C. C. Chen[1], M. Durand[2], A. Bringer[1], J. Miller [2], M. Aksoy[1], H. Li[1]
D. Belgiovane[1], C. Yardm[1], L. Tsang[3], T. Wang[3],
S. Tan [3], G. Macelloni[4], M. Brogioni[4], M. Drinkwater[5]

[1] ElectroScience Laboratory, The Ohio State University
[2] Byrd Polar Research Center, The Ohio State University
[3] University of Michigan, Dept. of Electrical and Computer Engineering
[4] CNR-IFAC Italy
[5] European Space Agency

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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?

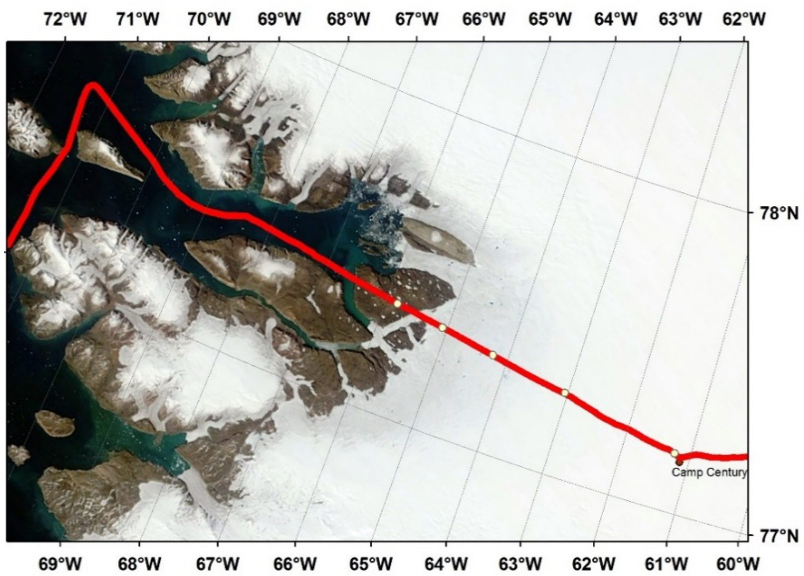
Ultra-wideband software defined radiometer (UWBRAD)

- 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

Freq (GHz)	0.5-2 , 12 x ~ 88 MHz channels
Polarization	Single (Right-hand circular)
Observation angle	Nadir
Spatial Resolution	1.2 km x 1.2 km (1 km platform altitude)
Integration time	100 msec
Ant Gain (dB) /Beamwidth	11 dB 60?
Calibration (Internal)	Reference load and Noise diode sources
Calibration (External)	Sky and Ocean Measurements
Noise equiv dT	0.4 K in 100 msec (each 88 MHz channel)
Interference Management	Full sampling of 88 MHz bandwidth in 16 bits resolution each channel; real time “software defined” RFI detection and mitigation
Initial Data Rate	700 Megabytes per second (10% duty cycle)
Data Rate to Disk	<1 Megabyte per second

Recent Experiments

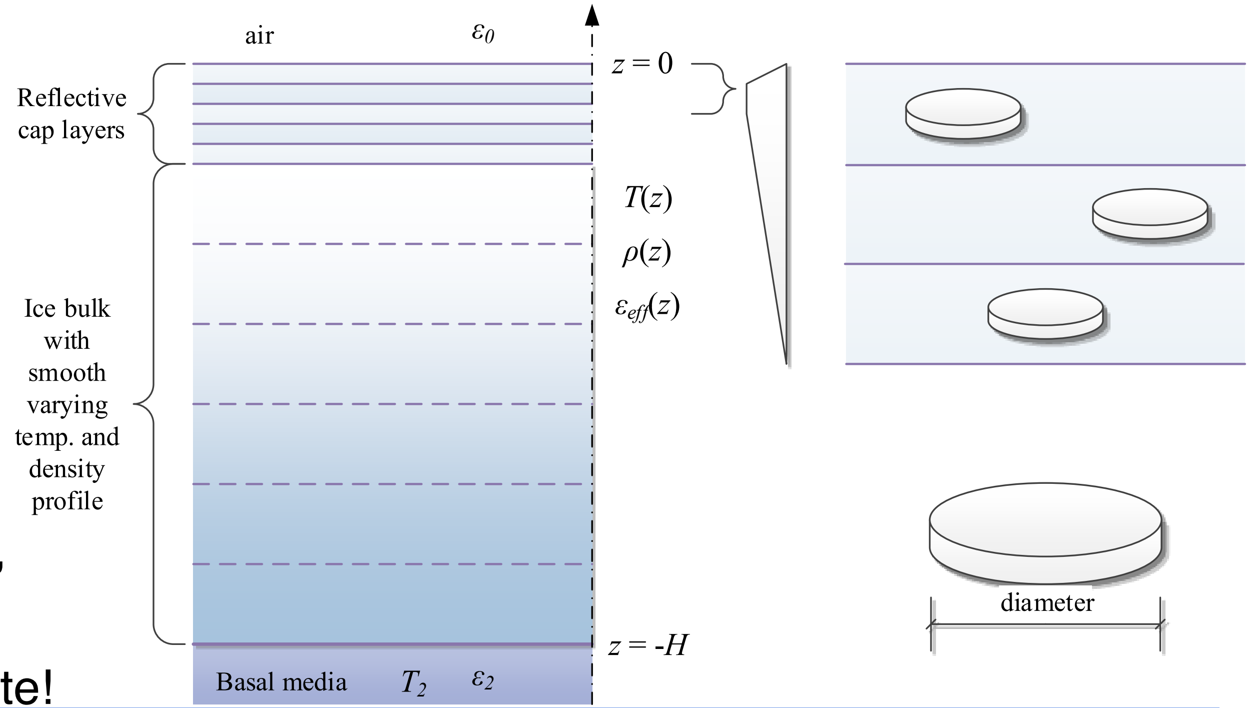
- First flight campaign conducted Sept 2016 aboard DC-3 aircraft from Ken Borek Airlines
- UWBRAD operated in test flight near Calgary, transit flight from Calgary to Thule AFB, and from Thule AFB to Camp Century
- Instrument experienced a failure after reaching Camp Century
- 0.5 – 2 GHz data acquired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



Installed Antenna

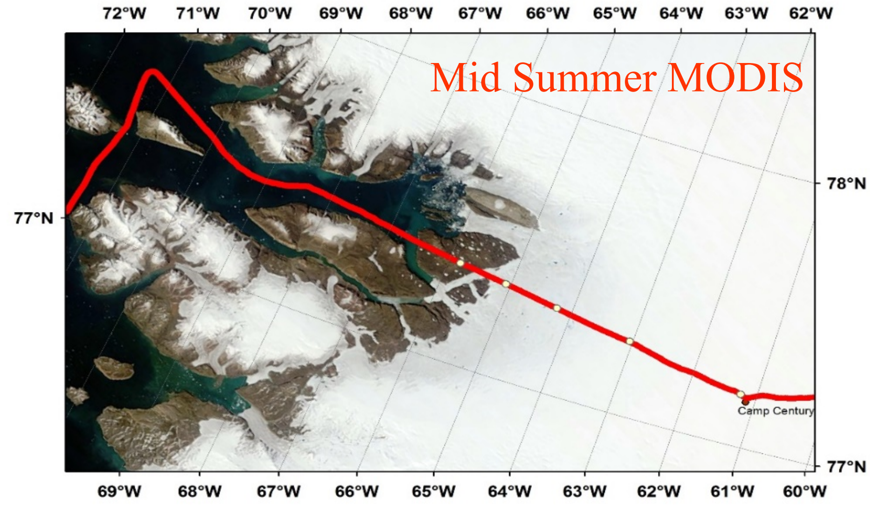
Physical Expectations

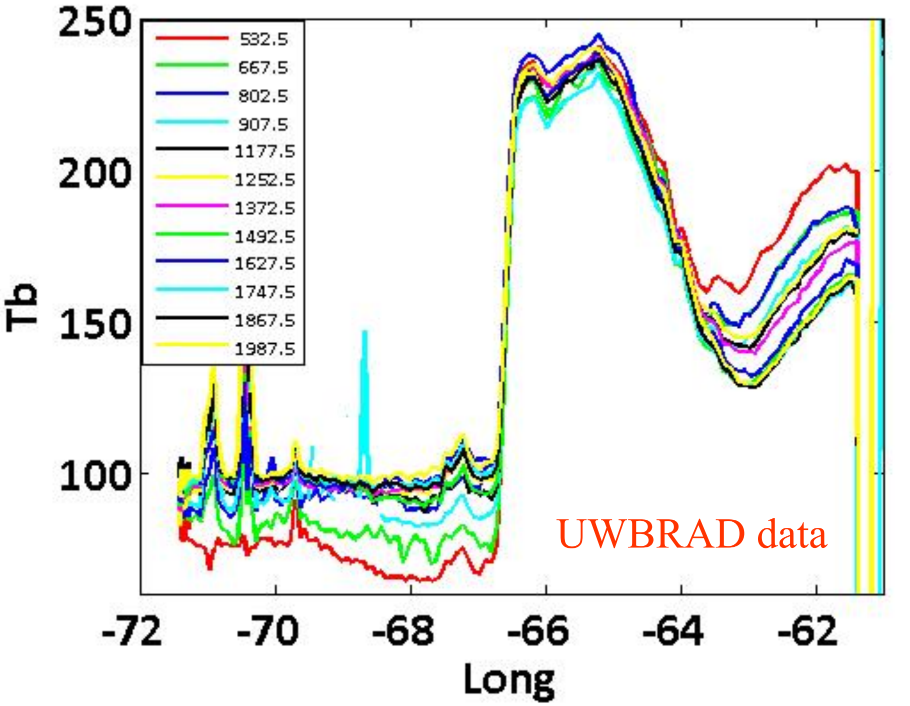
- Thermal emission from ice sheets influenced by:
  - Temperature profile of ice sheet
  - Density profile of ice sheet (both "large scale" behaviors and "small scale" fluctuations)
  - Presence of any large scatterers (more likely in melt than in dry snow zones)
- Project team has conducted extensive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





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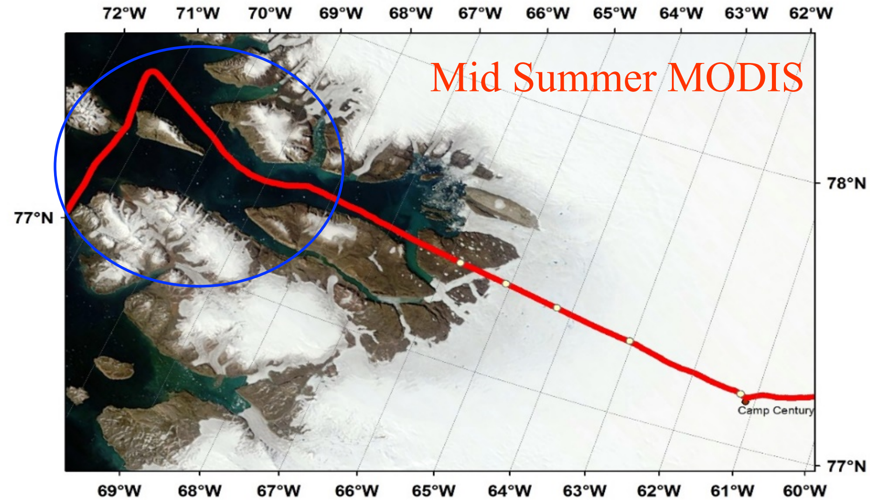
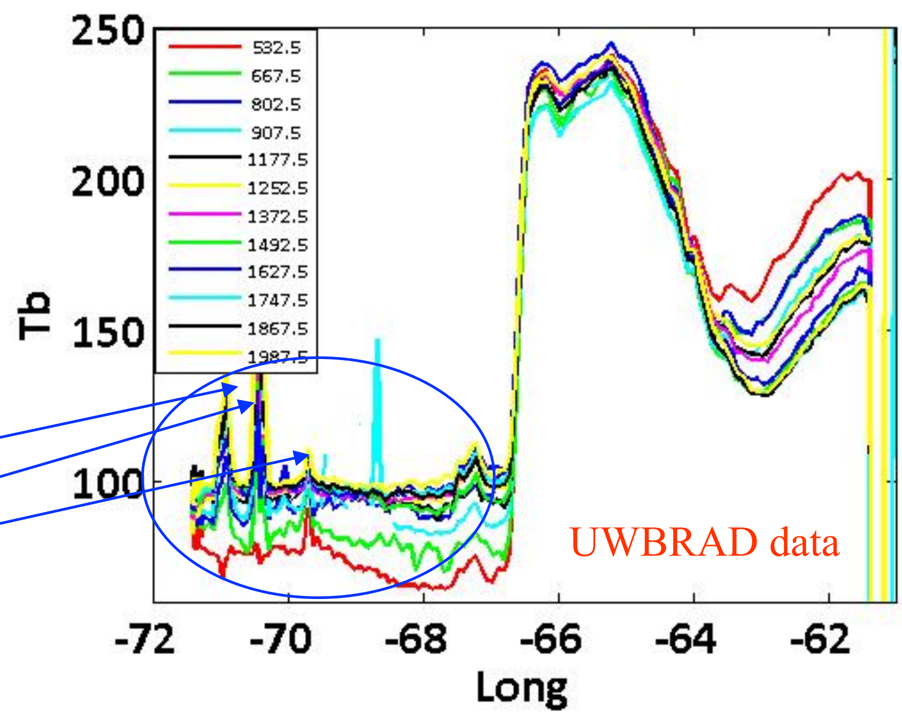
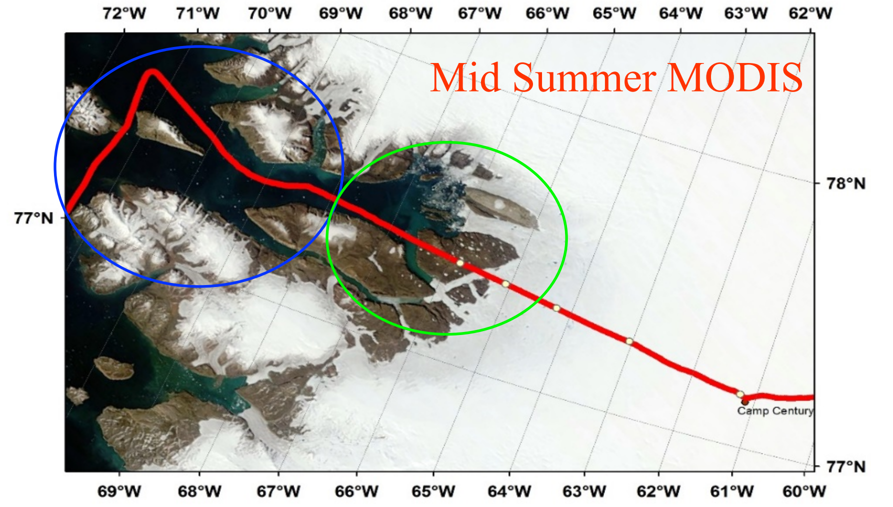


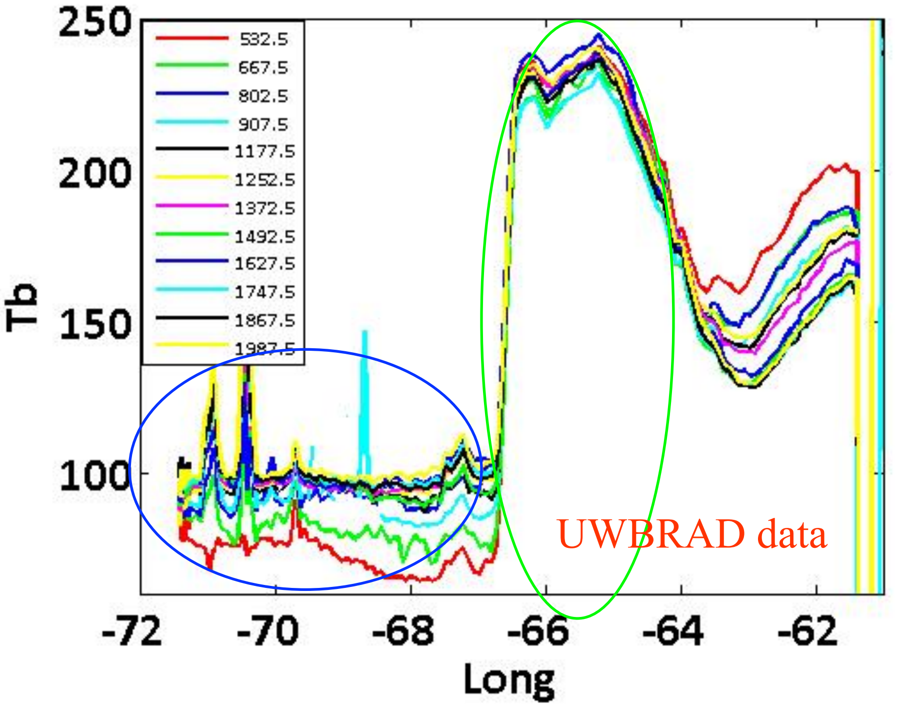


"Spikes" correspond to isolated icebergs identified in thermal IR data also collected during the flight

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

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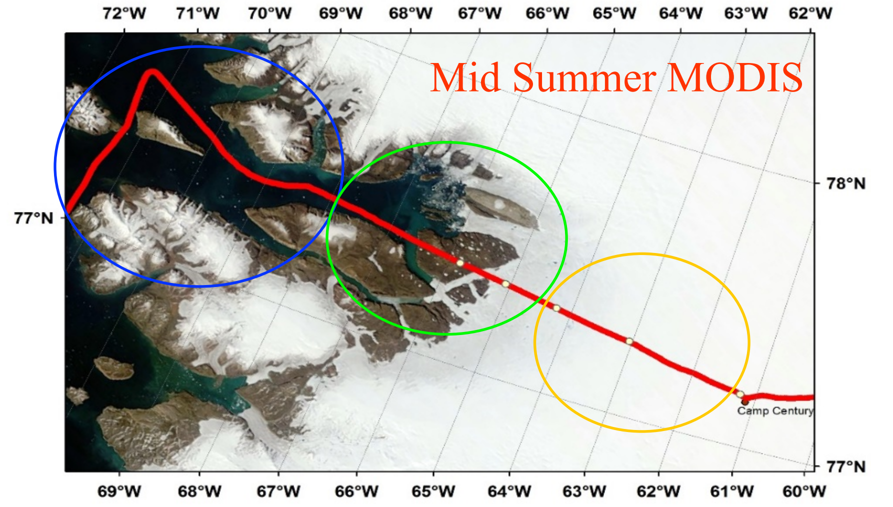
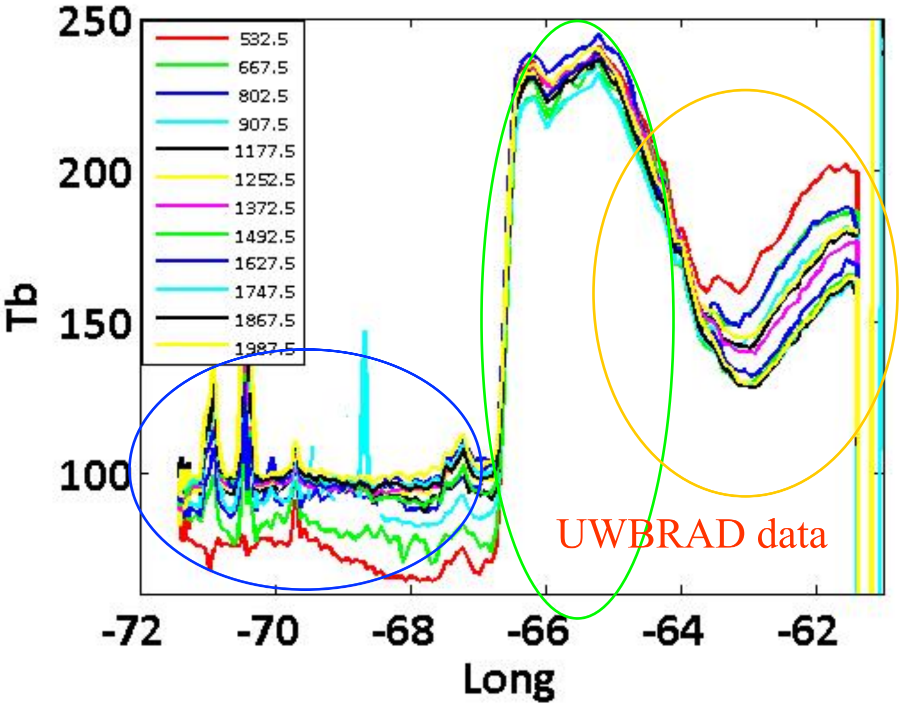
  - Ice free ocean
  - Snow covered land
  - Melt zones characteristic of the Greenland Ice Sheet

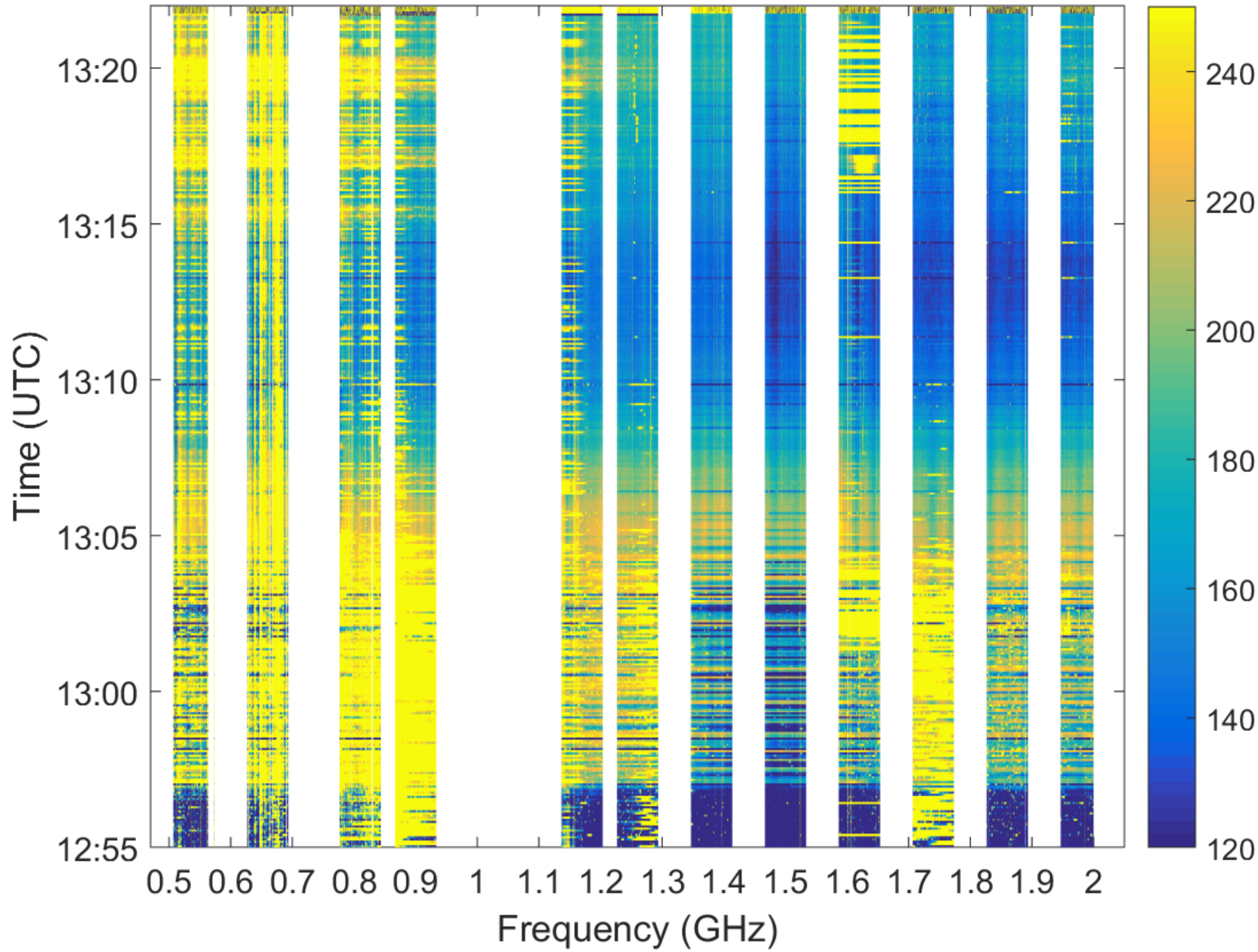




- Tb decreases rapidly as the flight proceeds onto the ice sheet before increasing as Camp Century is approached

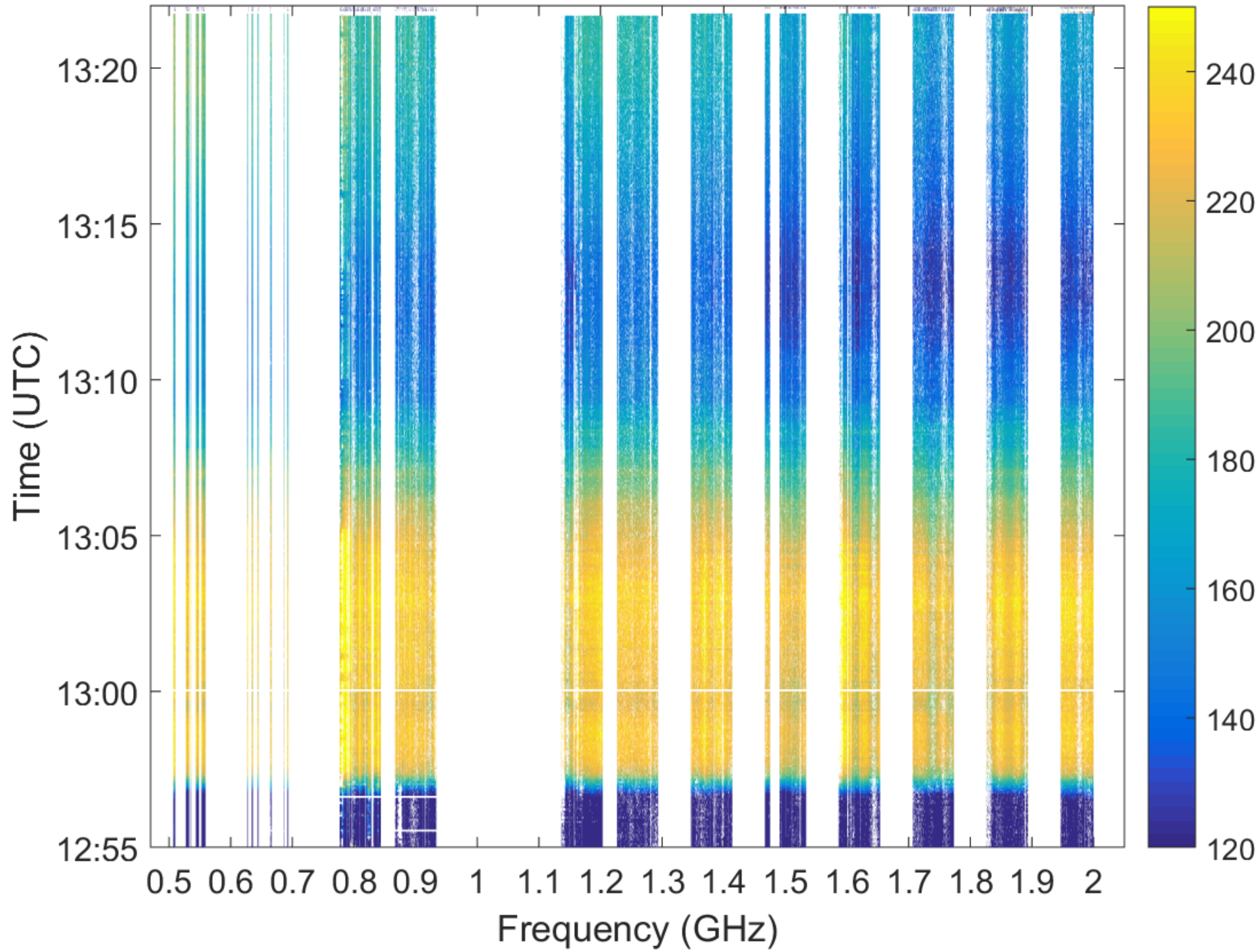
Full UWBRAD Spectra/RFI Processing

- Extensive RFI across spectrum, even in Greenland



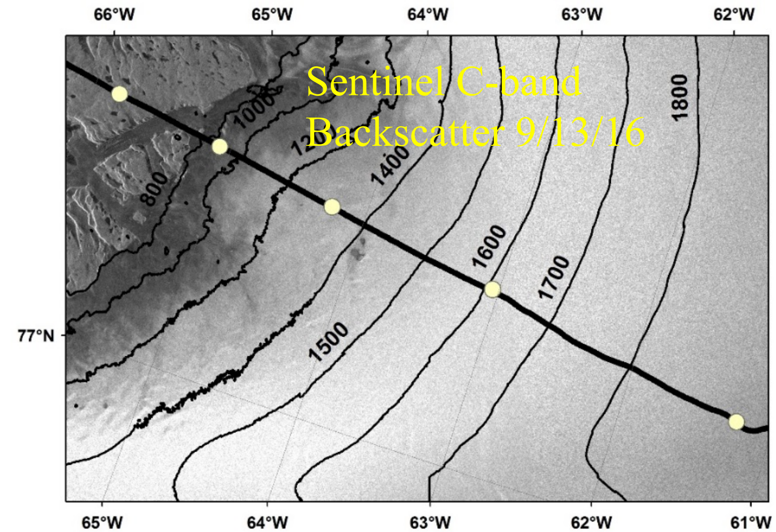
Full UWBRAD Spectra/RFI Processing

- 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



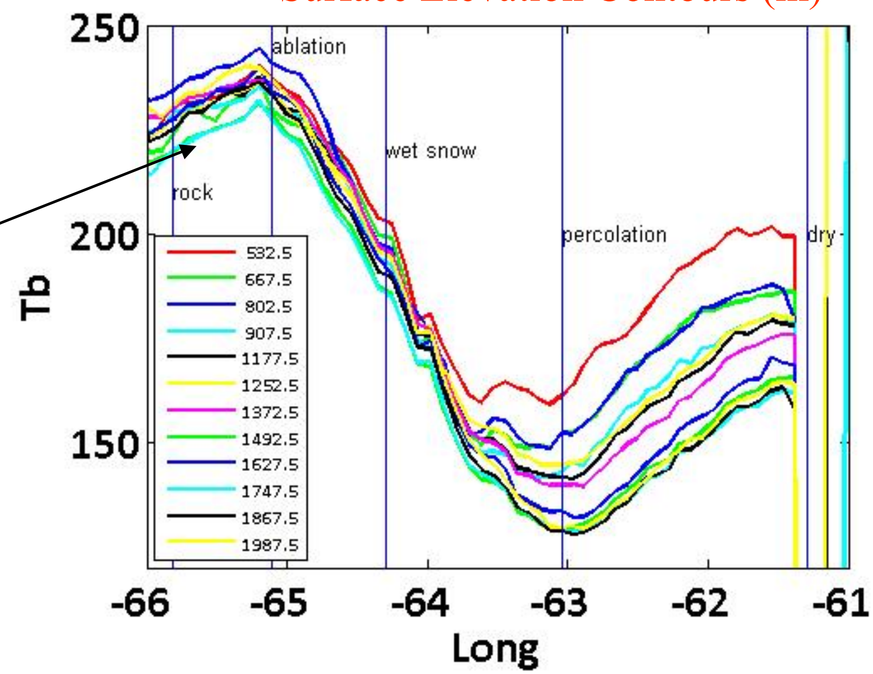
Correlation with Melt Facies

- No apparent correlation of Tb with surface topography
- Strong correlation of Tb with snow facies



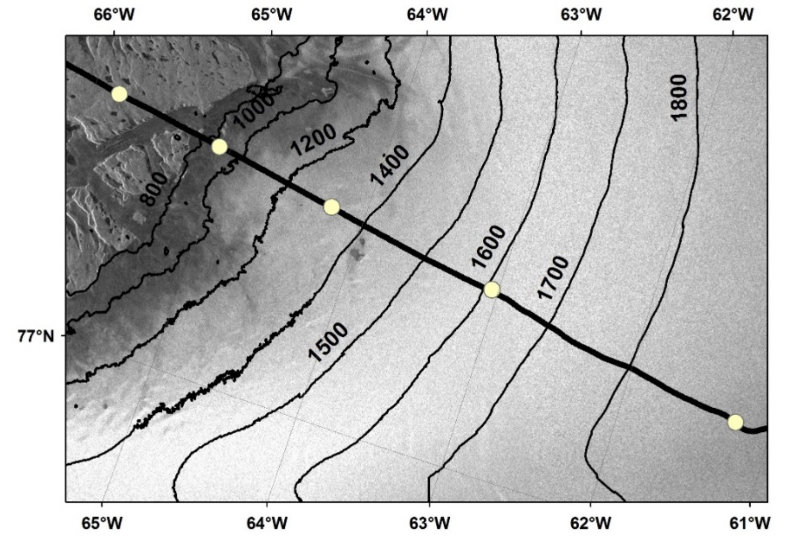
Surface Elevation Contours (m)

- Tb increases from bare rock to the ablation zones (surface scattering at C-band is minimal)

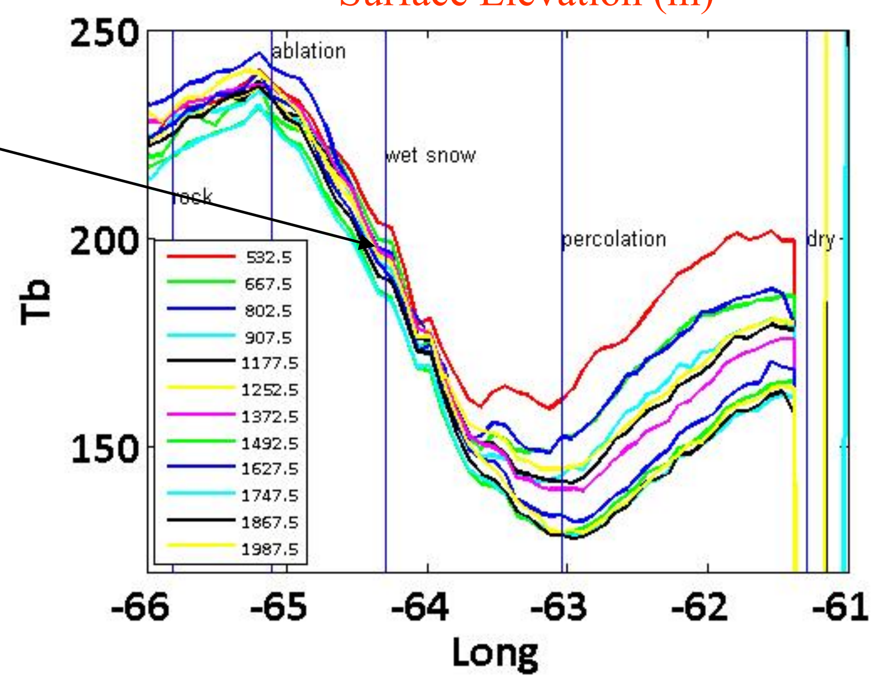


Correlation with Melt Facies

- 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



Surface Elevation (m)



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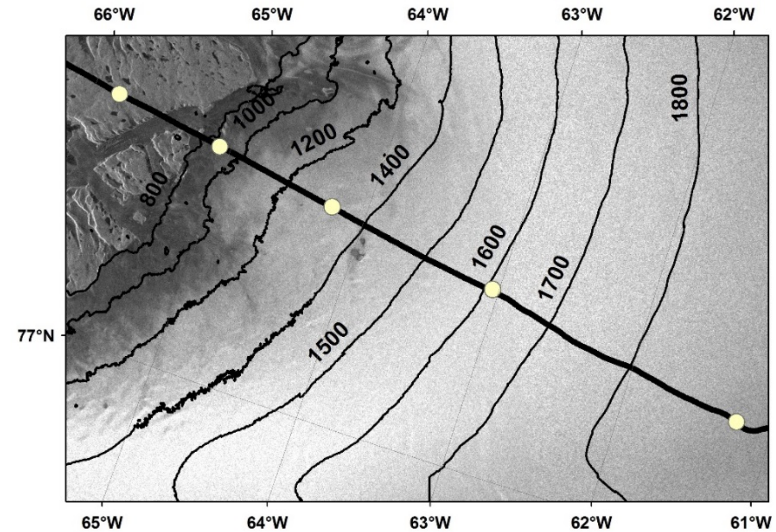
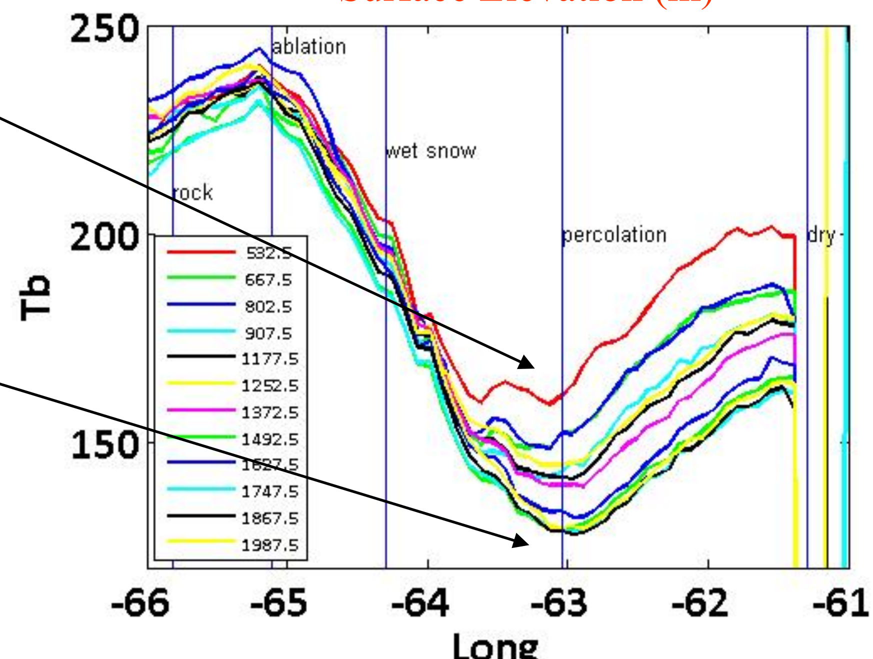


Surface Elevation (m)

- Tb is minimum in the strongly scattering percolation facies
- Note that the minimum in Tb shifts eastward as the frequency increases



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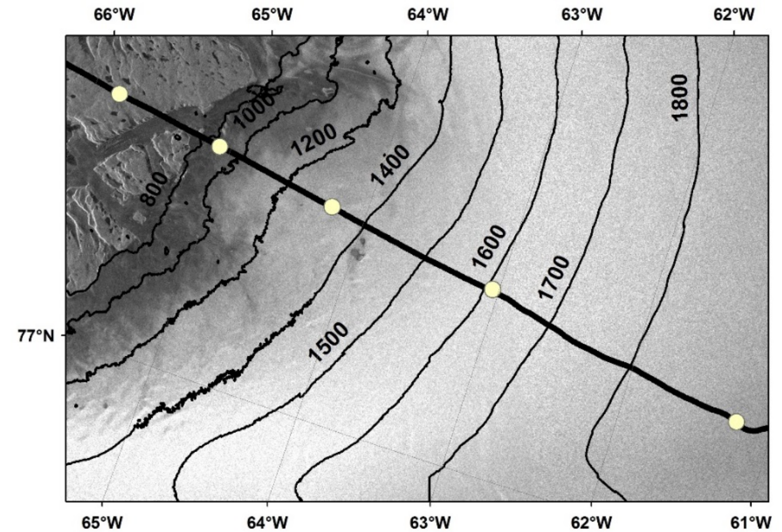
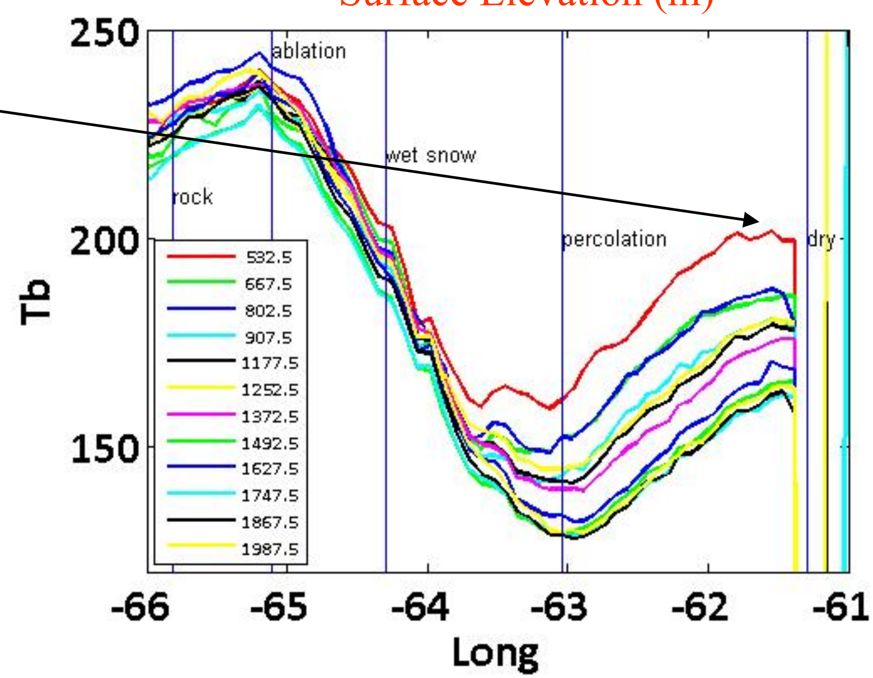


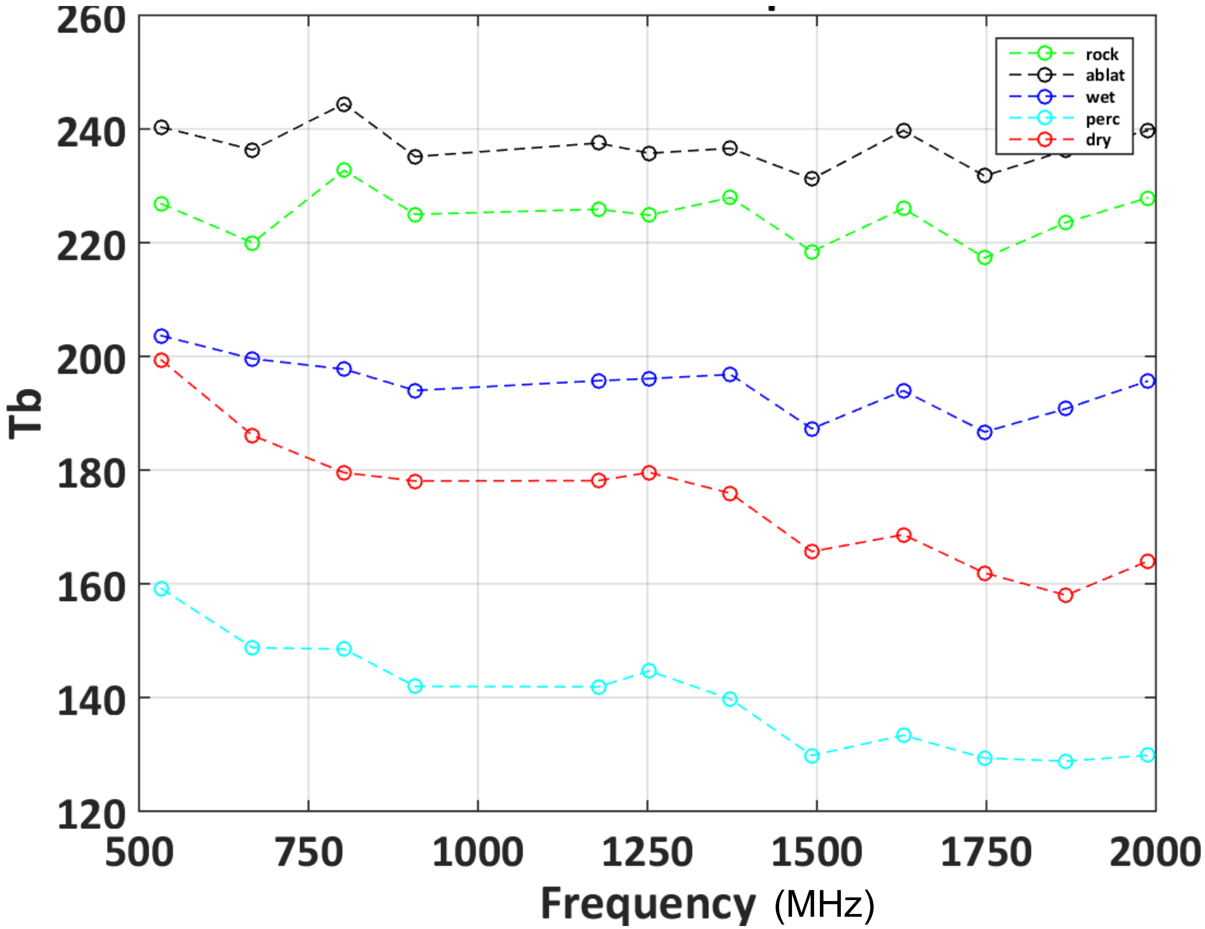
Surface Elevation (m)

- Tb increases as the surface transitions towards dry snow facies



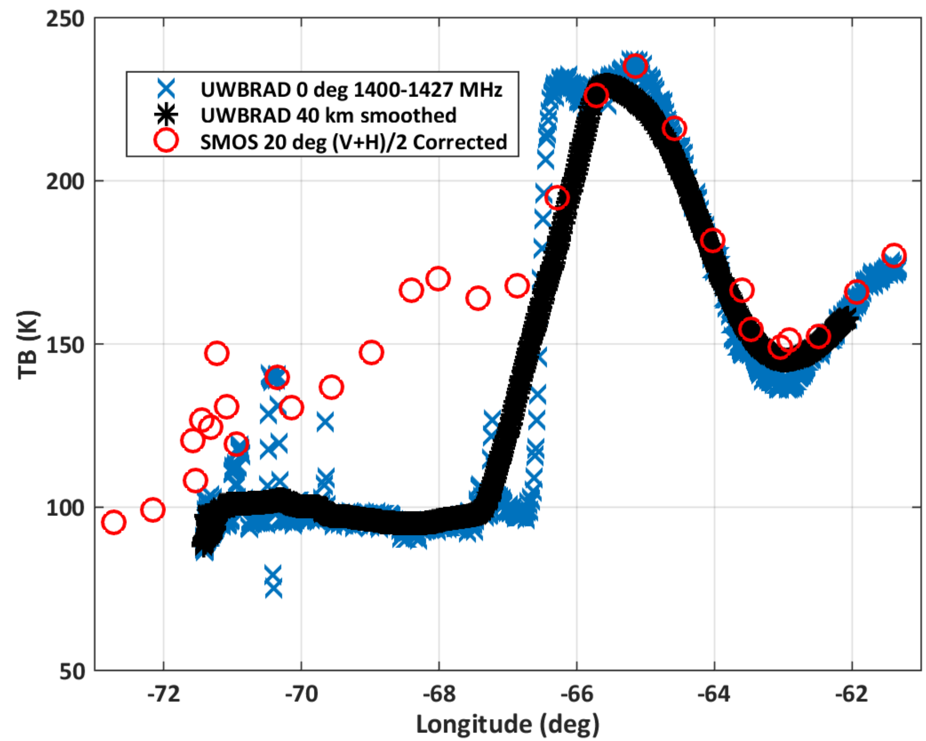
Spectra of Facies

- 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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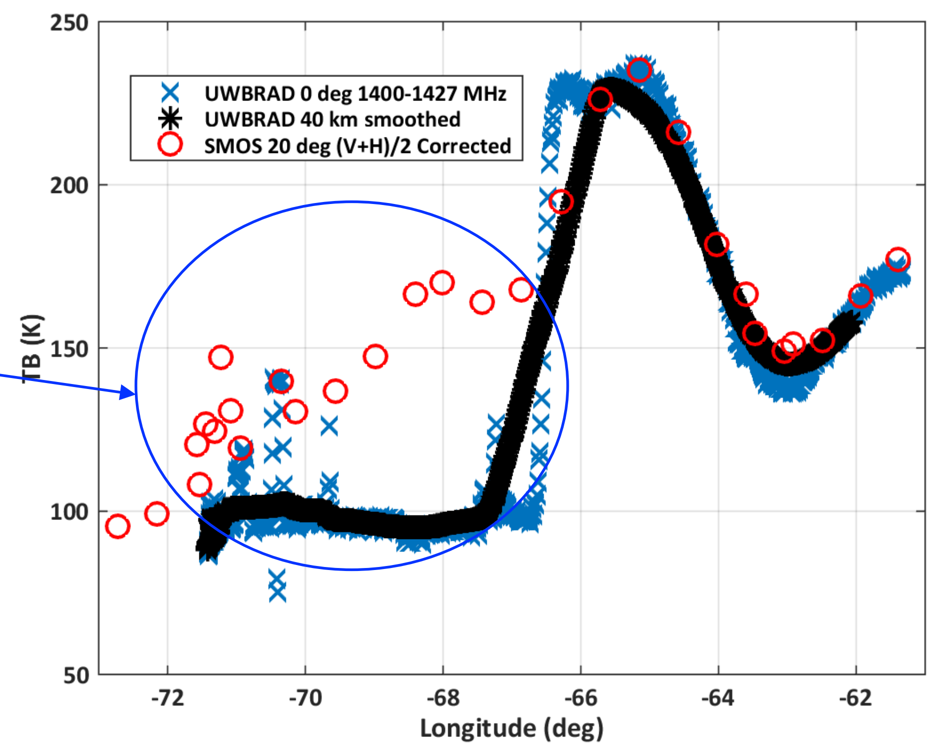
- Significant difference in footprint (UWBRAD ~ 1.2km, SMOS ~40 km)
  - UWBRAD smoothed with a 40 km long running filter
- Mixed land/sea scene in SMOS footprint causes SMOS TB's to exceed UWBRAD in the open ocean part of the flight



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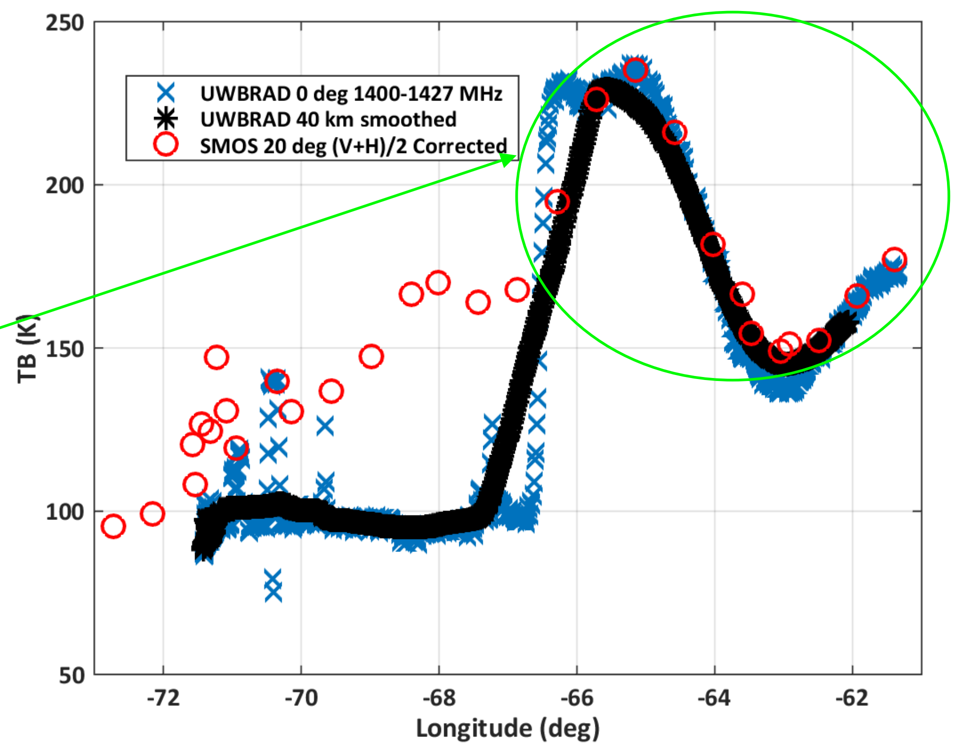
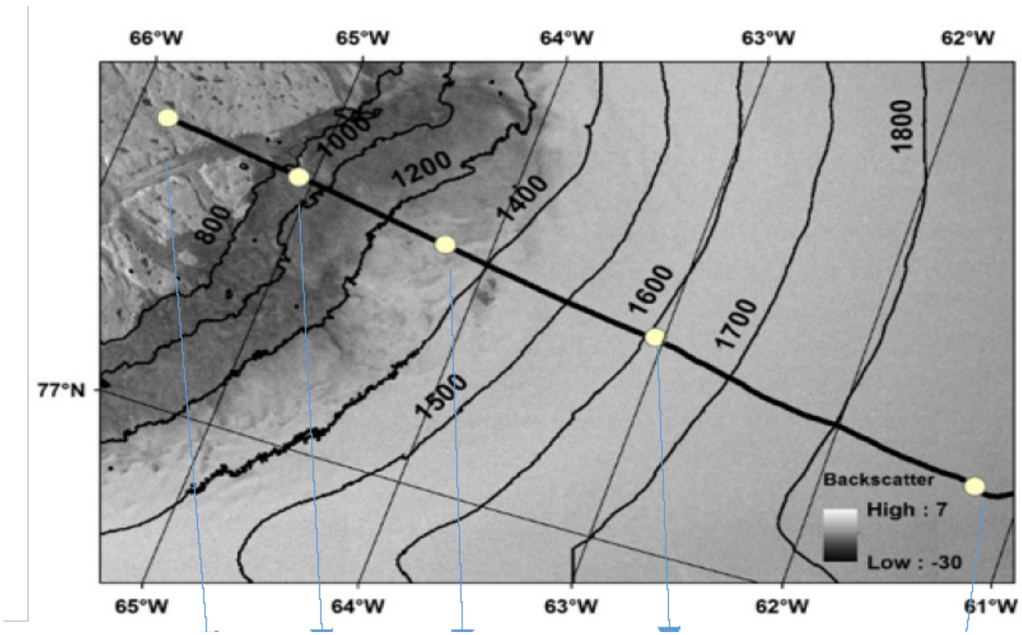
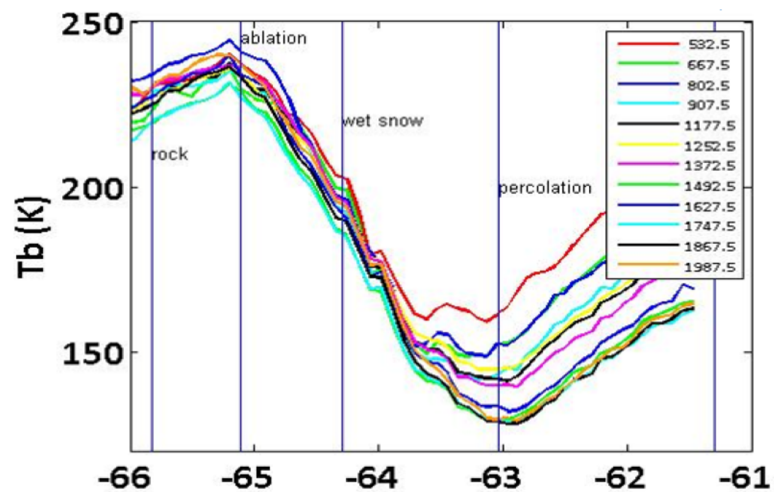
- Note UWBRAD observes in circularly polarization at 0 degrees
- SMOS 20 degrees data (average of H and V) used for comparison
- Significant difference in footprint (UWBRAD ~ 1.2km, SMOS ~40 km)
  - Smoothed with a 40 km long running filter
- Better match over the ice sheet
- SMOS remains somewhat warmer at TB minimum
  - Possibly due to remaining footprint differences

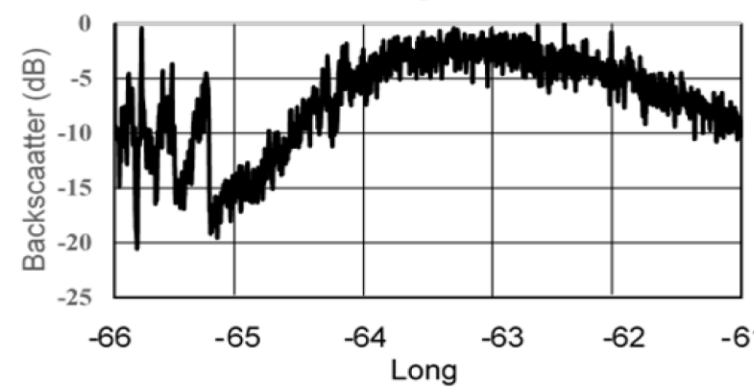


Comparison with PALSAR-2

- 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

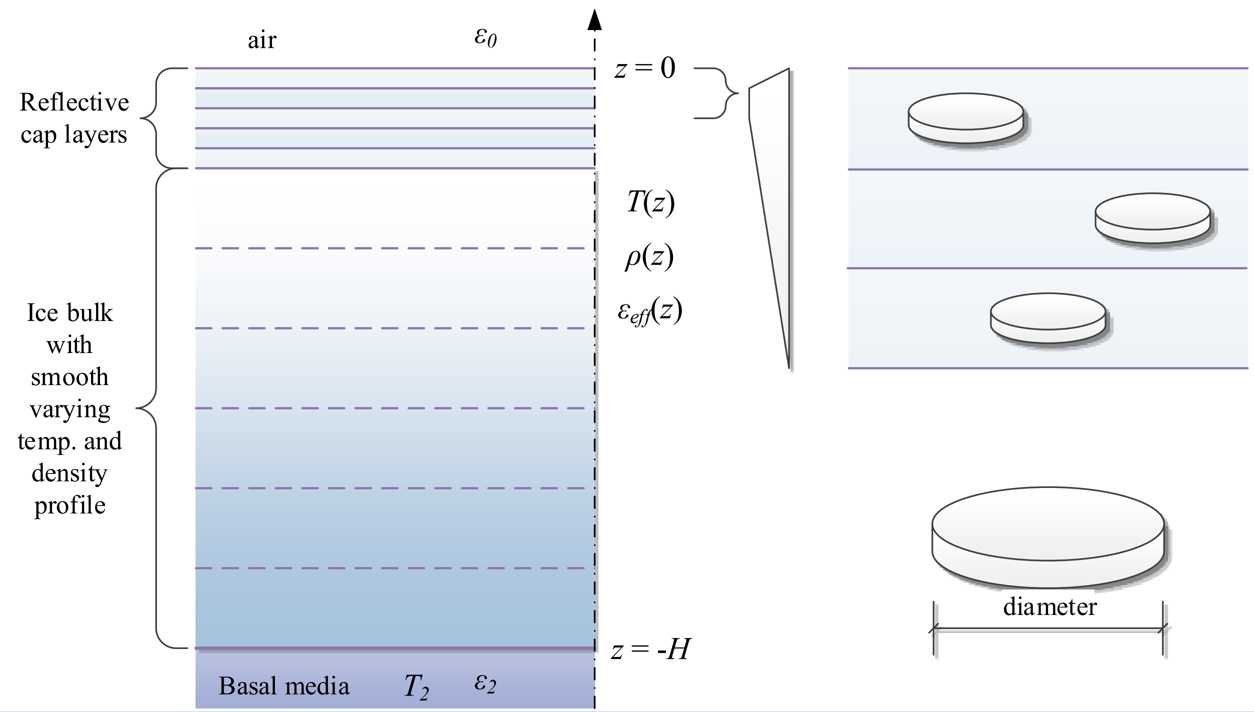




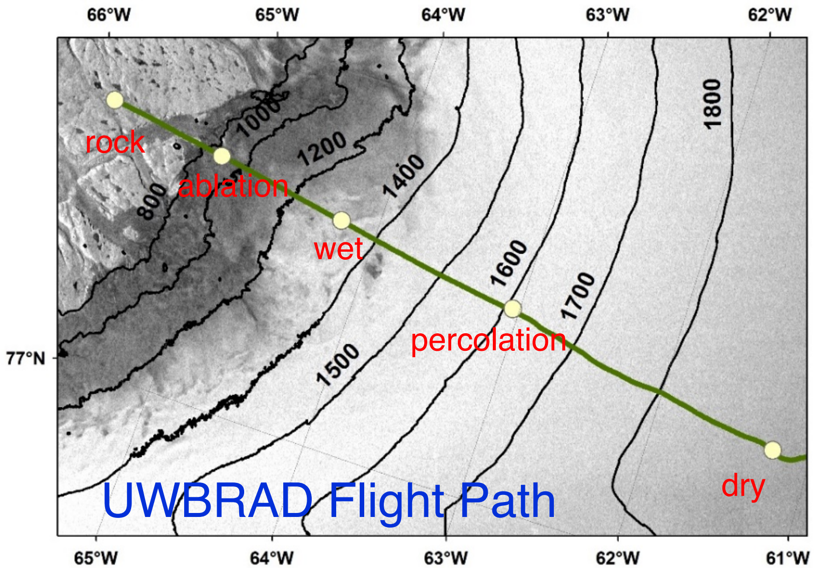


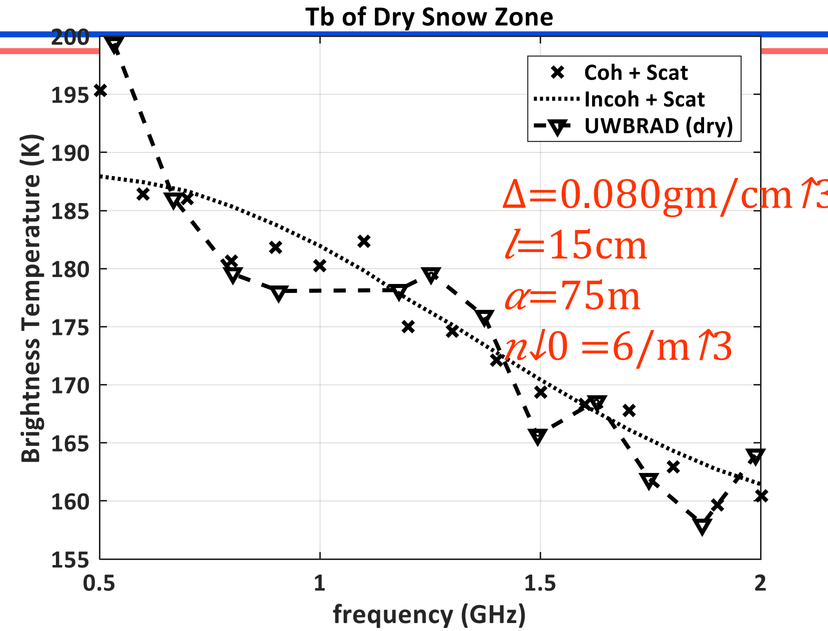
Forward Modeling of UWBRAD Data

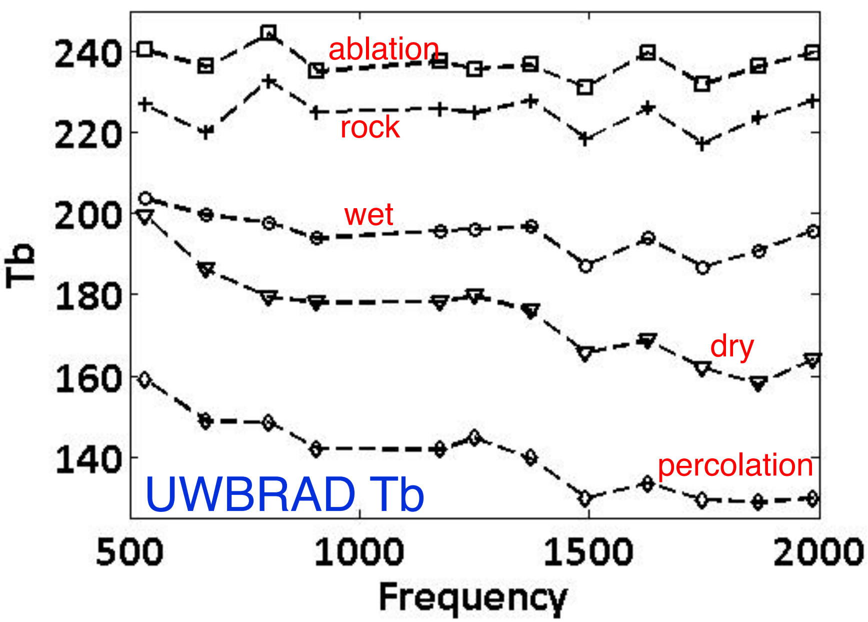
- Used the “partially coherent” forward model modified to include attenuation due to scattering by ice lenses (disks)
- Camp Century borehole information used for density and temperature profiles (assumed to apply over other portions of the nearby ice sheet)
- Correlation length of density fluctuations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

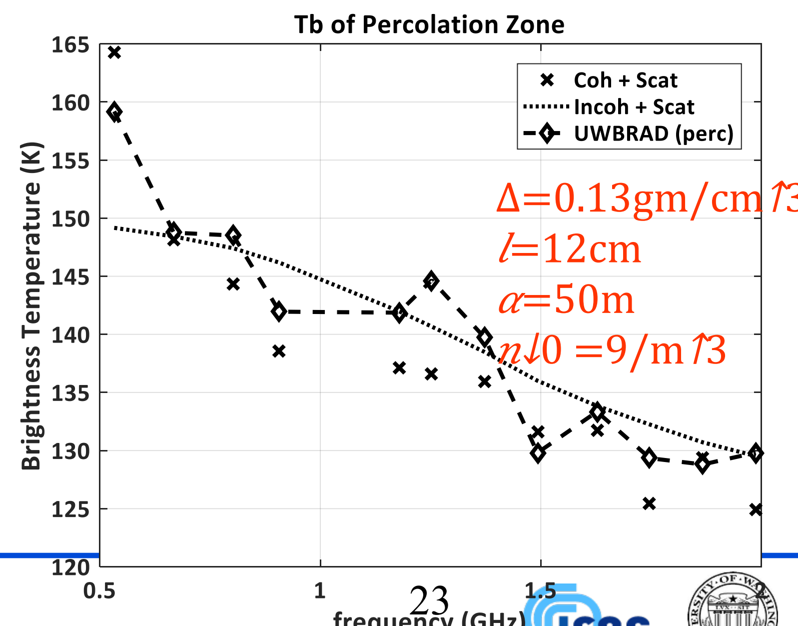


Tb Spectra in Various Facies: Model vs. Data

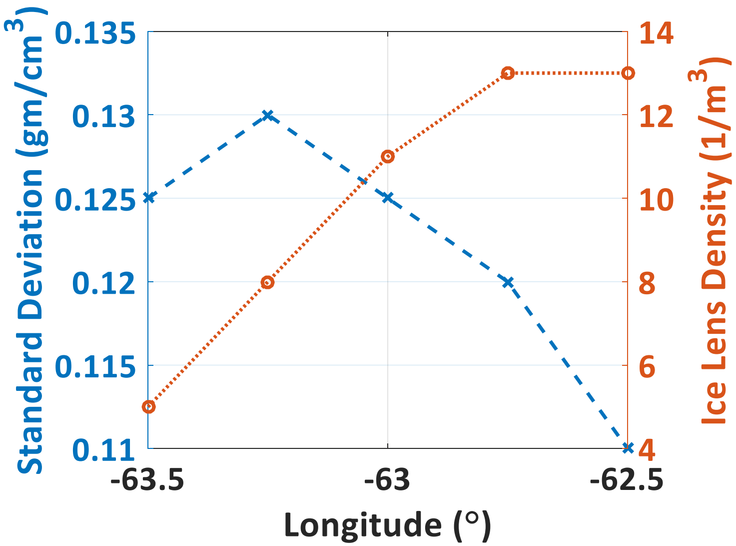






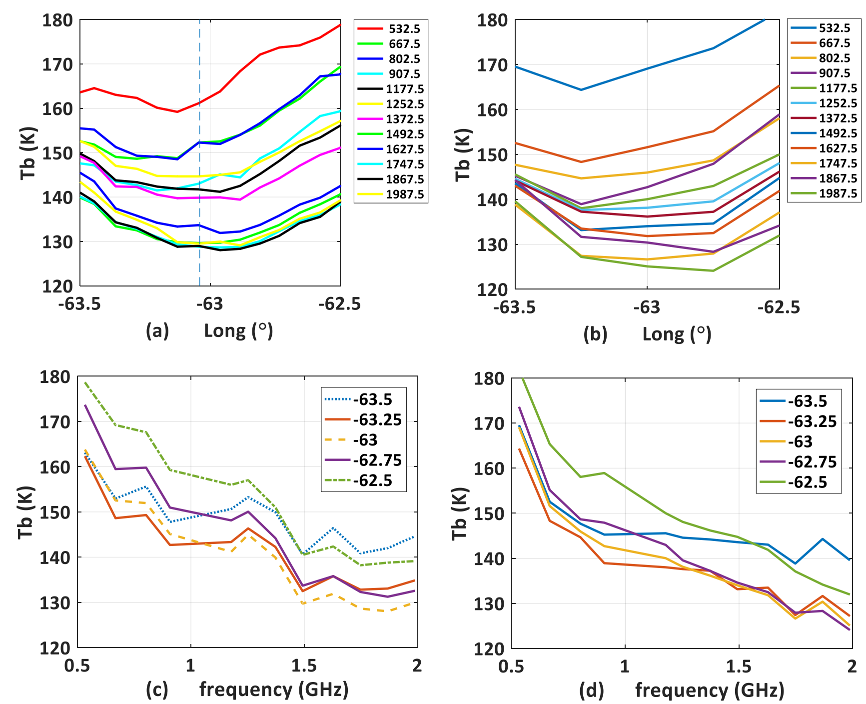


Tb Spatial and Spectral Patterns: Model vs. Data



Left: UWBRAD measurements

Right: Model Predictions



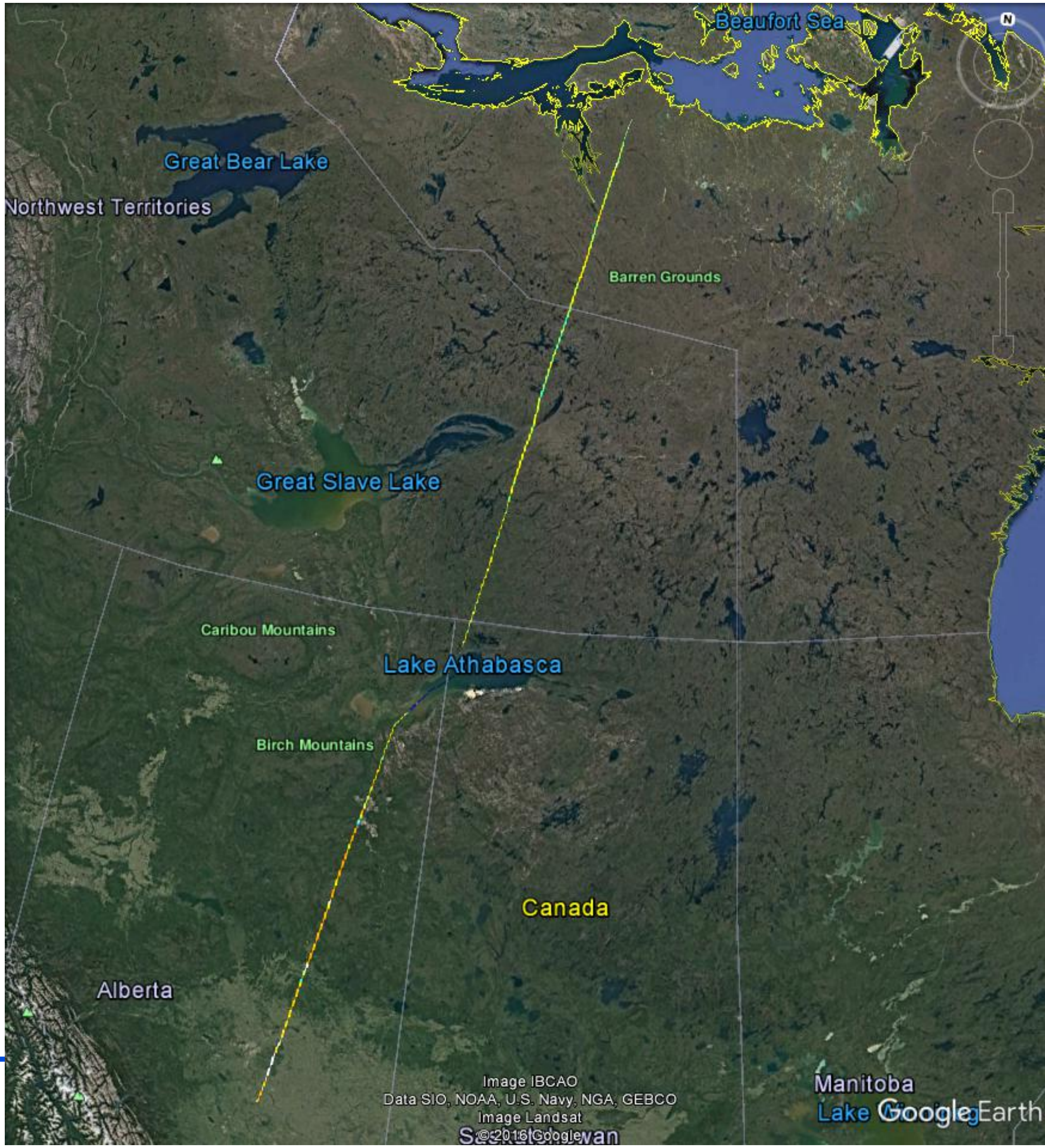
Δ: Tb level at low frequency

n_0 : spectral differences

n_0 estimated from T_b^{cloud} / T_b

- Good agreement in Tb spatial and spectral patterns

Transit Flight



Calgary to Cambridge Bay Refueling Stop

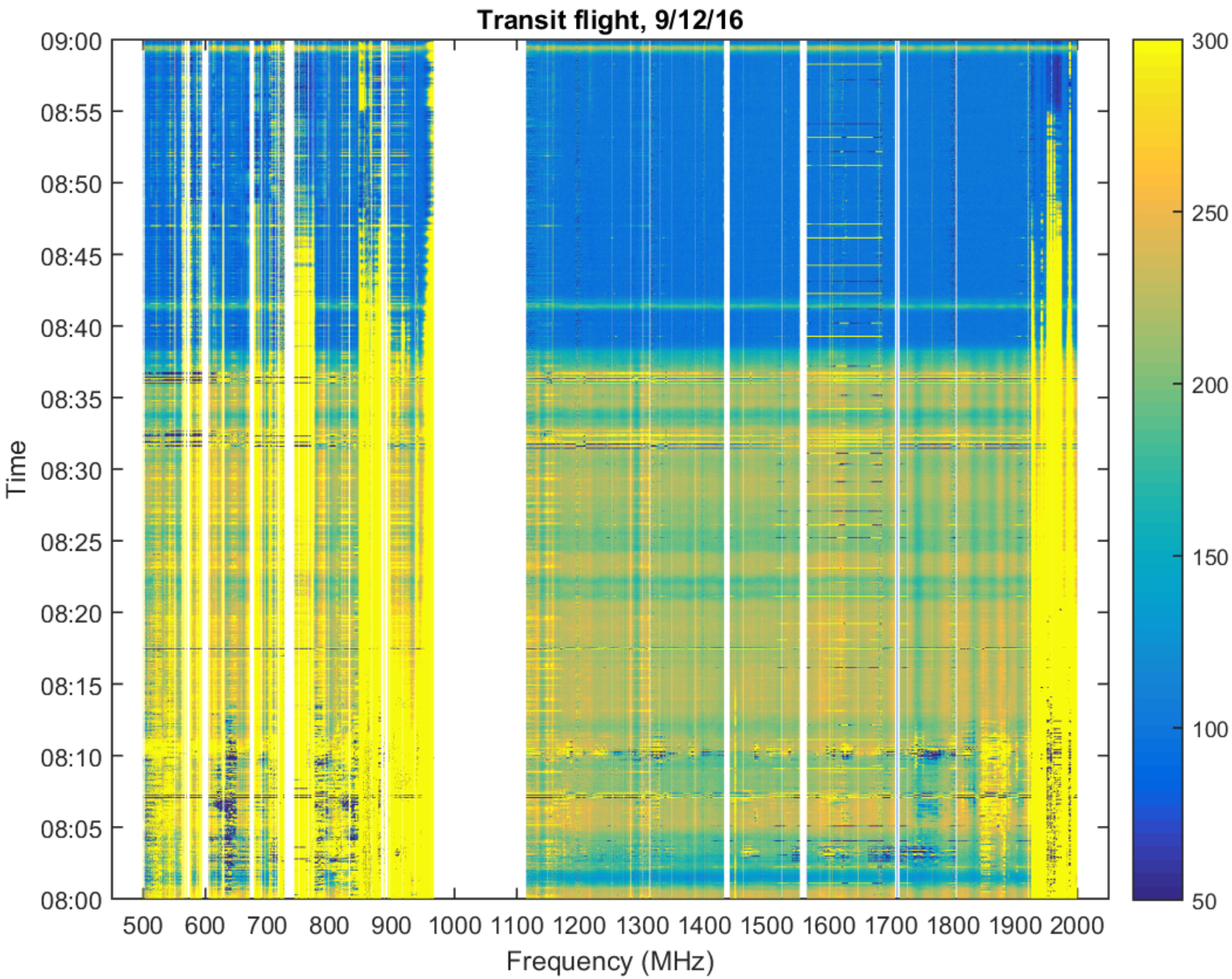
9/12/16

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

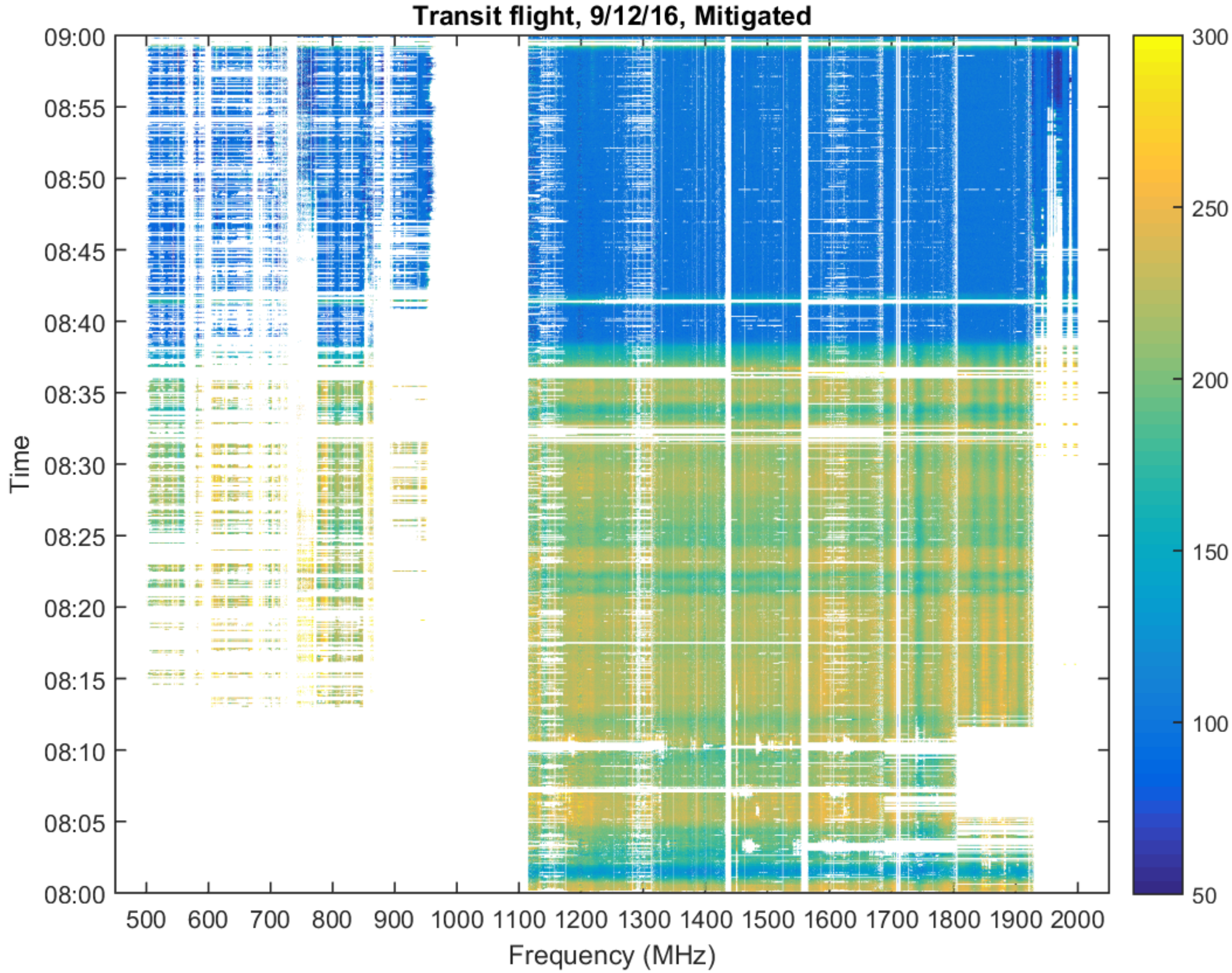
Includes variety of land cover types

Many small water bodies

Transit Flight Examples

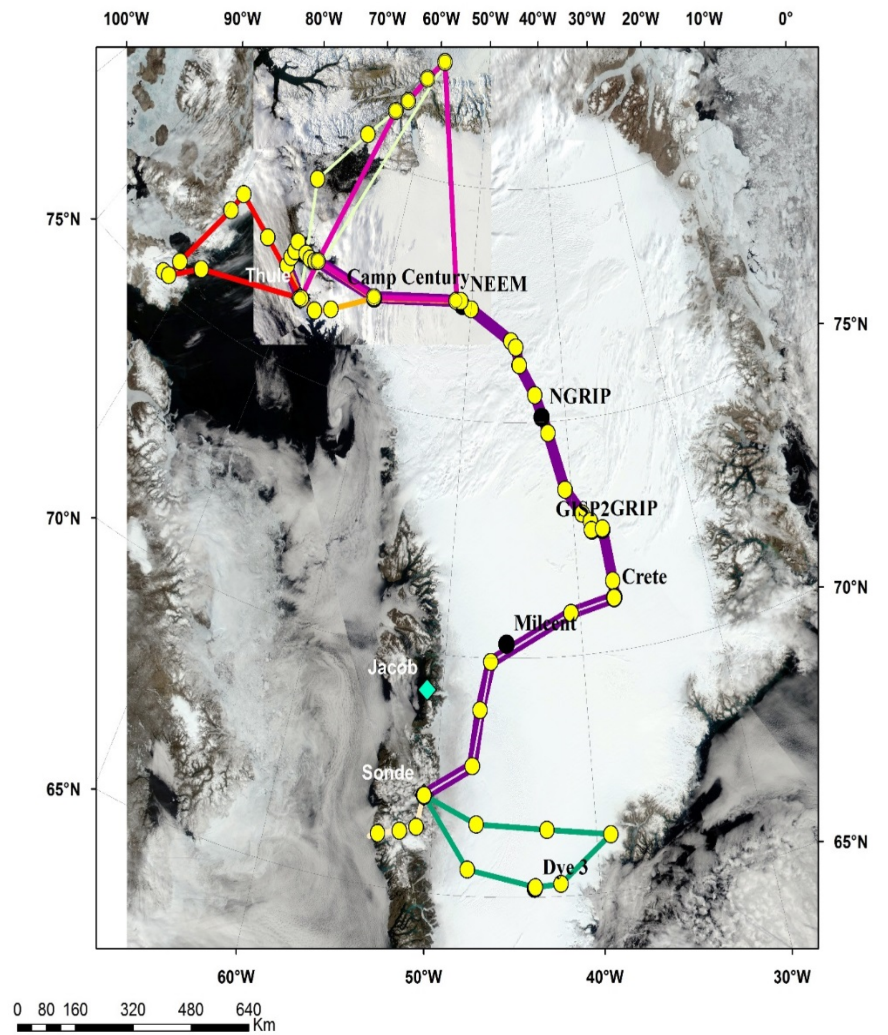


Transit Flight Examples



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

Jezek, K. C., J. T. Johnson, M. R. Drinkwater, G. Macelloni, L. Tsang, M. Aksoy, and M. Durand, “Radiometric approach for estimating relative change in intra-glacier average temperature,” **IEEE Trans. Geosc. Rem. Sens**., vol. 53, pp. 134-143, 2015.

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