# 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

| | |
|---|---|
| Freq (GHz) | 0.5-2 , 12 x 100 MHz channels |
| Polarization | Single (Right-hand circular) |
| Observation angle | Nadir |
| Spatial Resolution | 1 km x 1 km (500 m platform altitude) |
| Integration time | 100 msec |
| Ant Gain (dB) /Beamwidth | 11 dB<br>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 100 MHz channel) |
| Interference Management | Full sampling of 100 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 |

# UWBRAD Science Goals

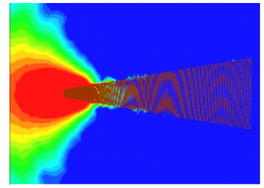
- Ice sheet temperature at 10 m depth, 1 K accuracy
  - 10 m temperatures approximate the mean annual temperature, an important climate parameter
- Depth-averaged temperature from 200 m to 4 km (max) ice sheet thickness, 1 K accuracy
  - Spatial variations in average temperature can be used as a proxy 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

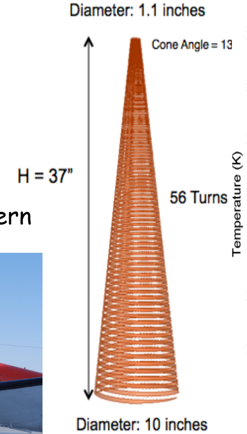
## Objective

- 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

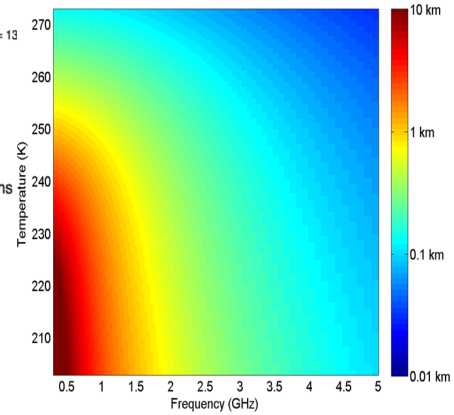


Near-field antenna pattern

DC-3T (Basler)




Antenna spiral arm profile




Pure ice penetration depth vs. frequency and temperature

## 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 $TRL_{current}$ = 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) |

# Project Team (cont'd)

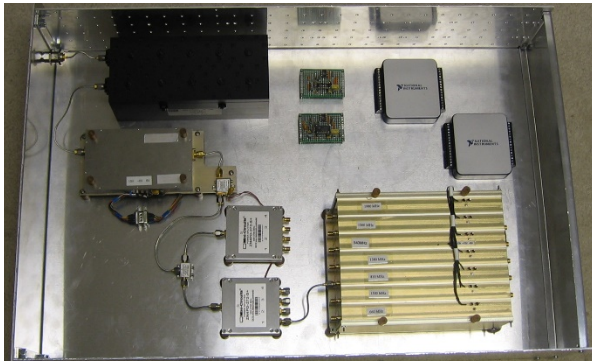
Independent Contractor: Dr. Vladimir Leuski (Radiometer Front end design/build)

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

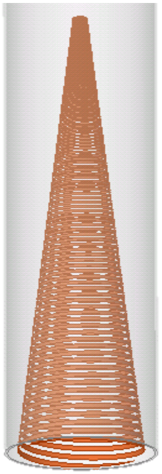
# UWBRAD System

- The radiometer is composed of three subsystems:
  - Front End/Downconversion

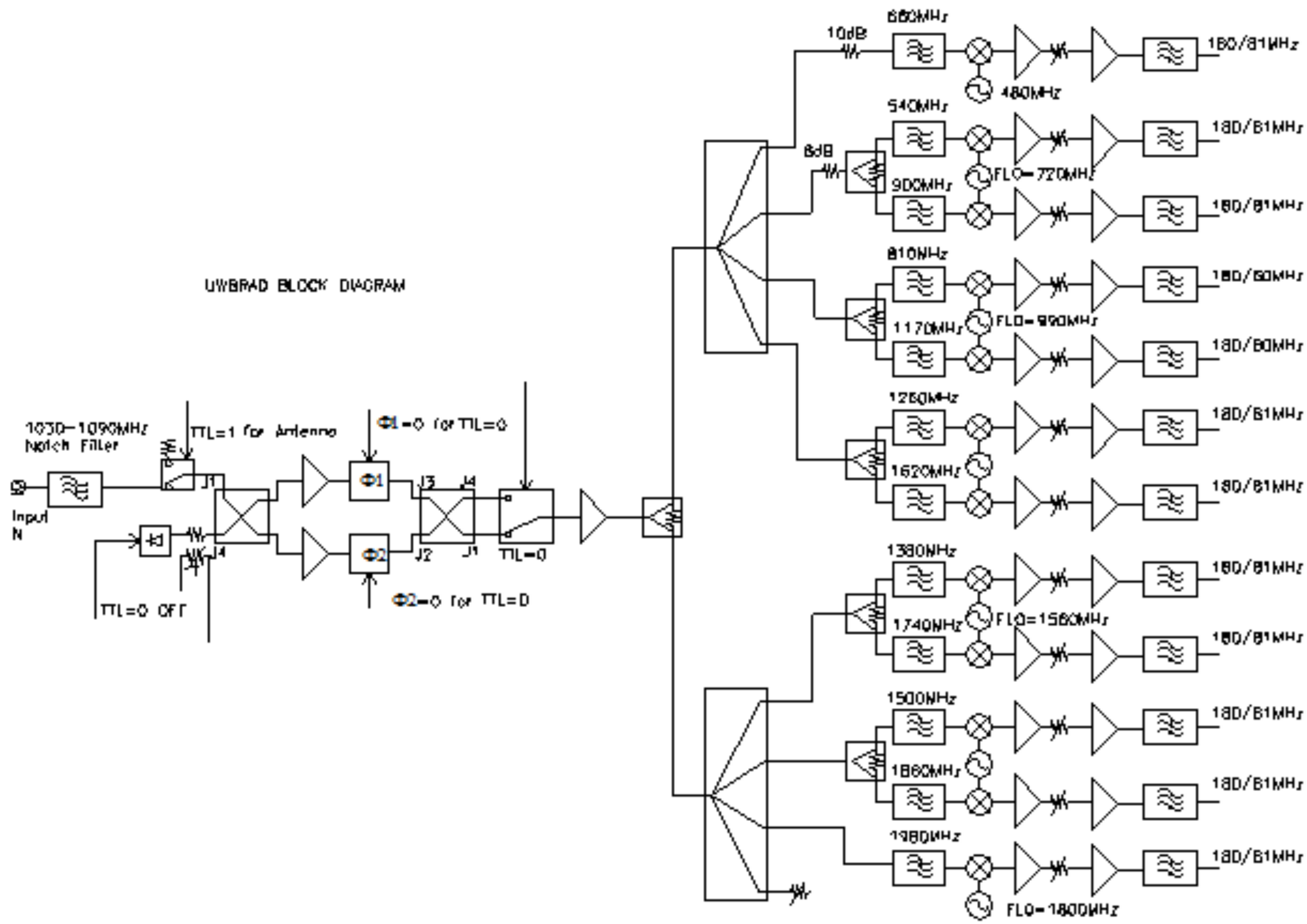


  - Digital Backend

  - Antenna

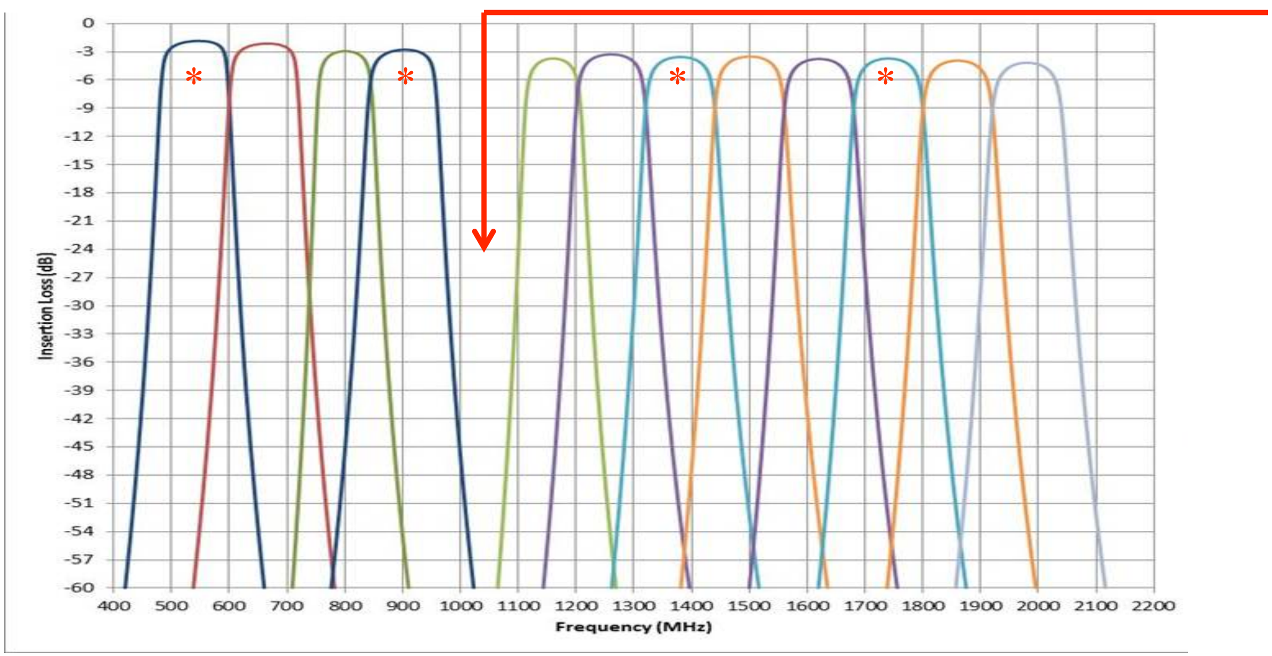


# Front End Design



# Front End

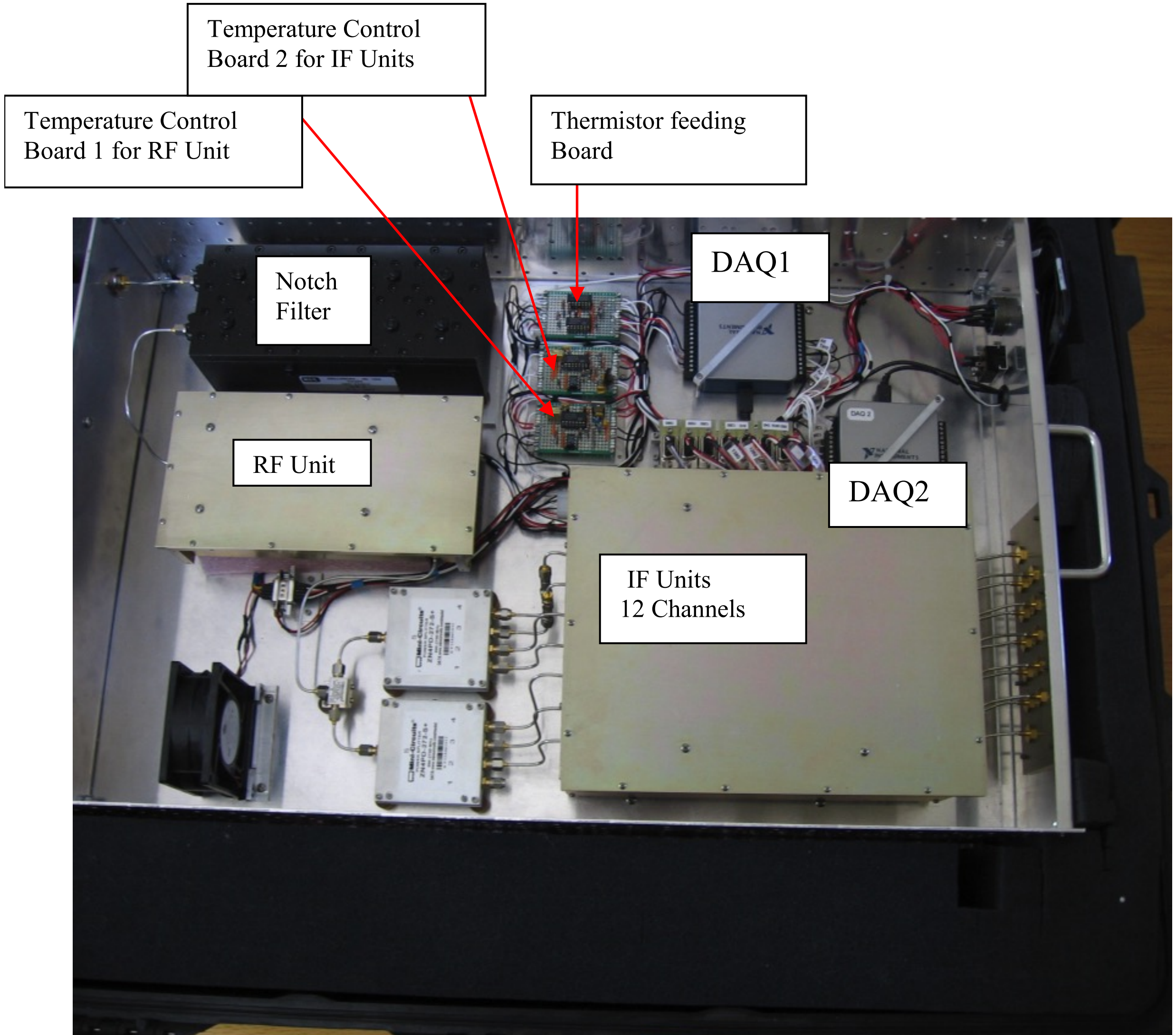
- 0.5-2 GHz divided into 12 separated channels in 2nd Nyquist of ADC




Avoiding DME equipment aboard aircraft

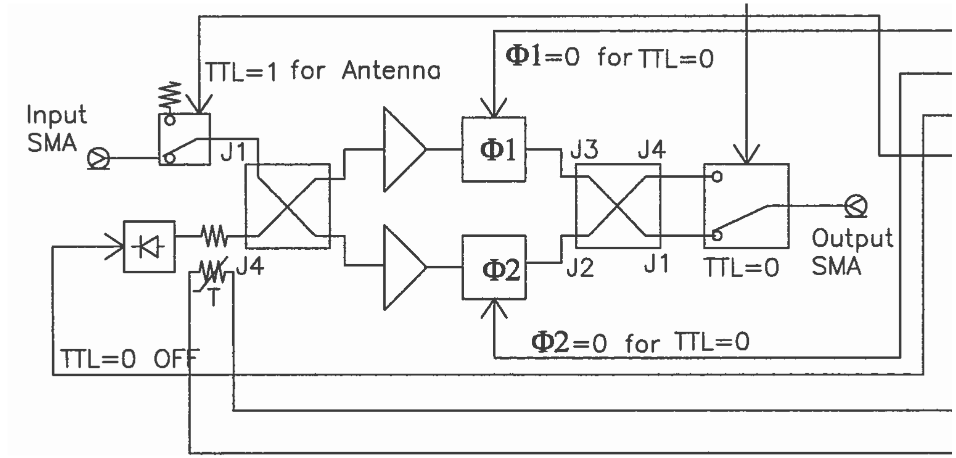
Channels marked with * included in 4 channel prototype

# Front End Implementation



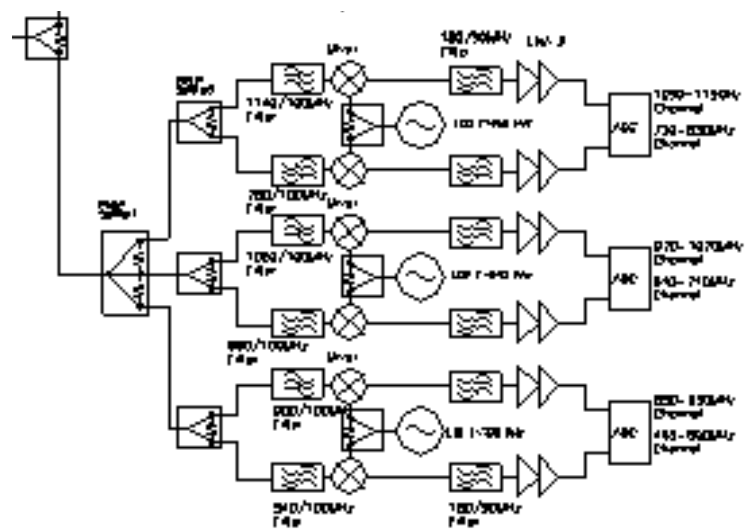
# Front End

- 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)

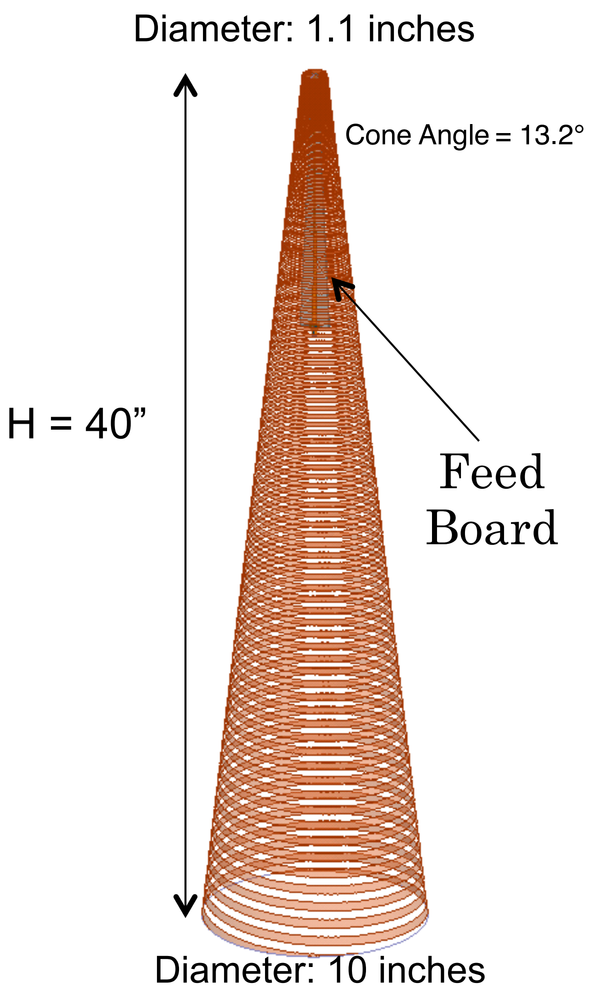
- "Medium rate": Software processing of data to perform 1024 point FFT, detection, and integration in each channel
  - Output resolution is 512 frequencies (~0.25MHz) @ 1 msec
  - Kurtosis of each frequency bin also computed (@100ms), as well as fullband kurtosis (@1ms)

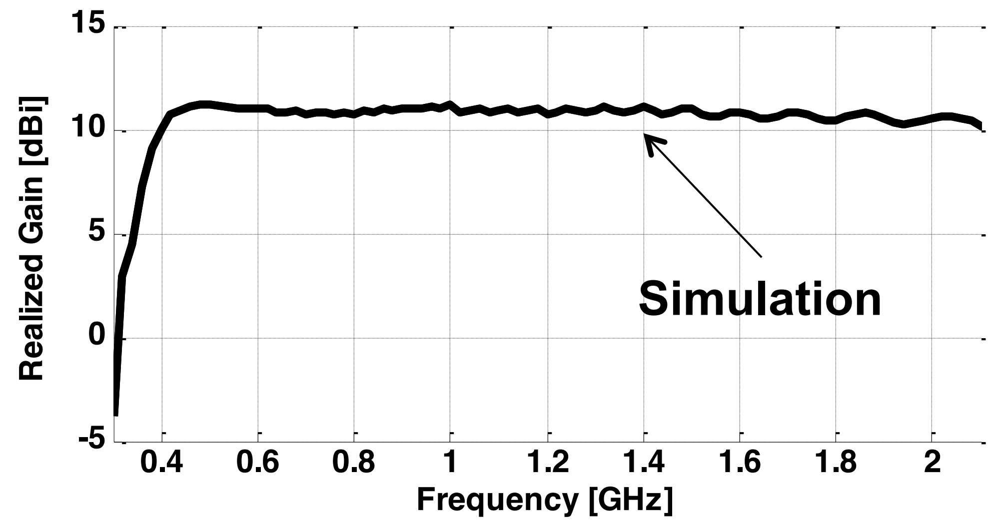
- "Low rate": Integration over spectrogram (100x1ms, 512 frequencies) to obtain final counts, both before and after RFI flagging by fullband kurtosis, fullband pulse, and sub-band kurtosis detection algorithms

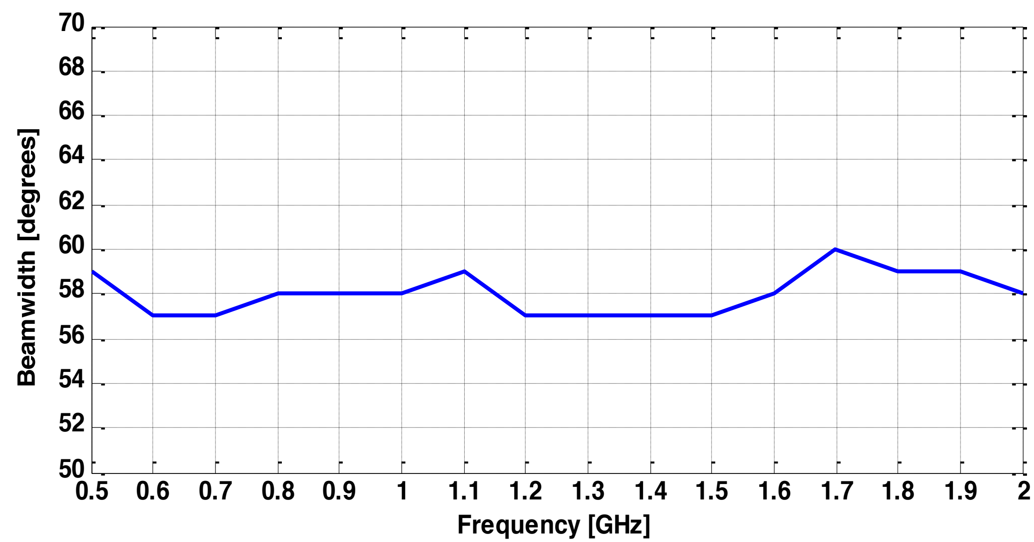
- All processing performed on host computer in real-time

- 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



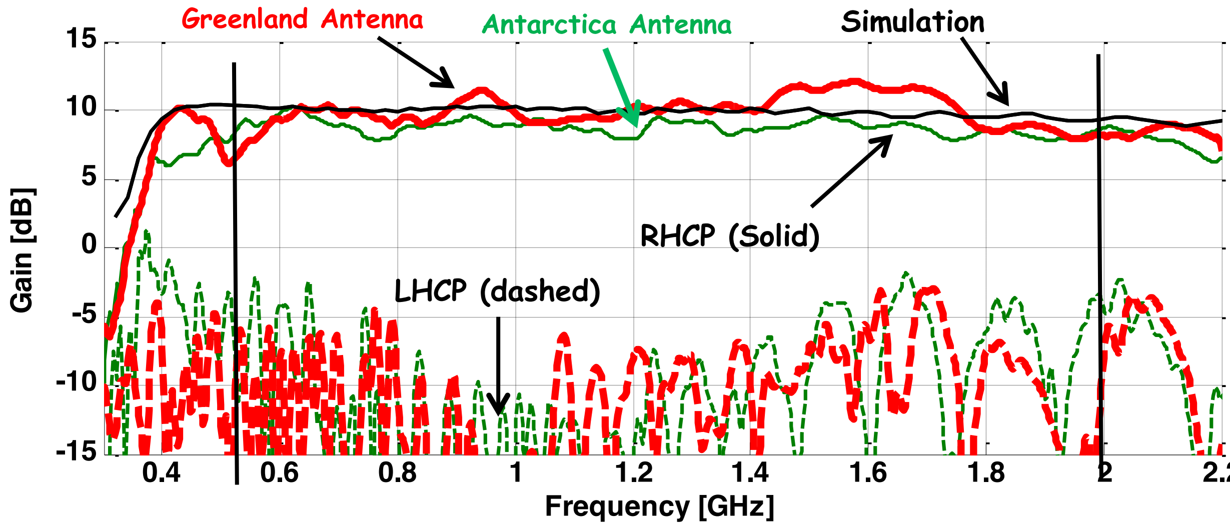
# Measured Gain and Matching Performance

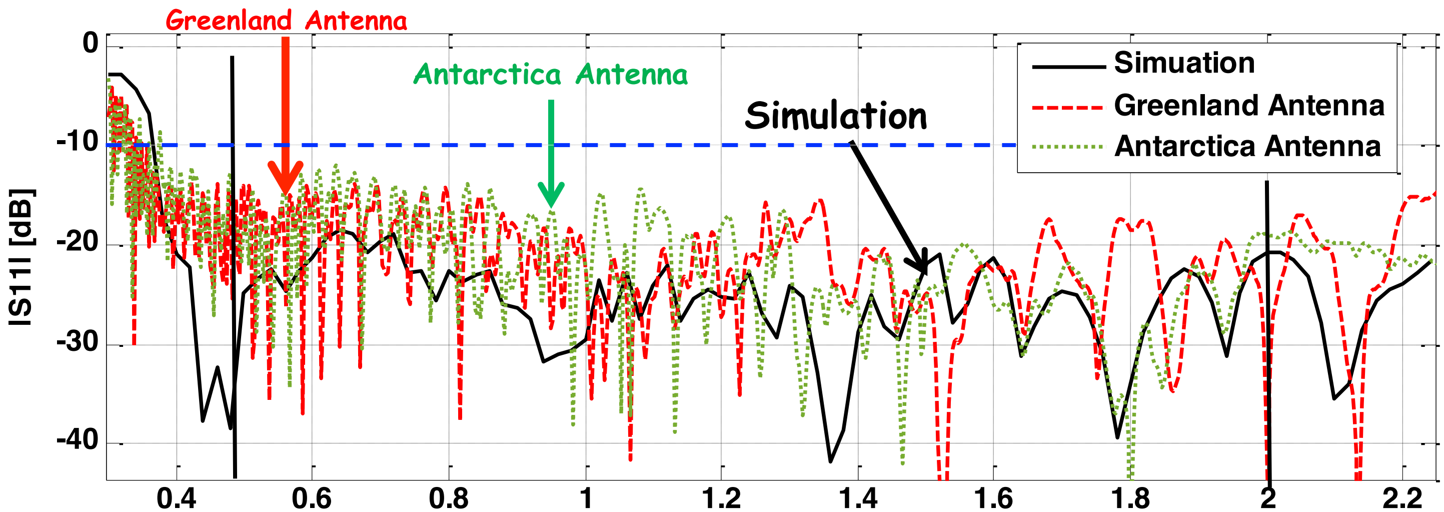
Earth Science Technology Office

Antenna Only

w/Radome

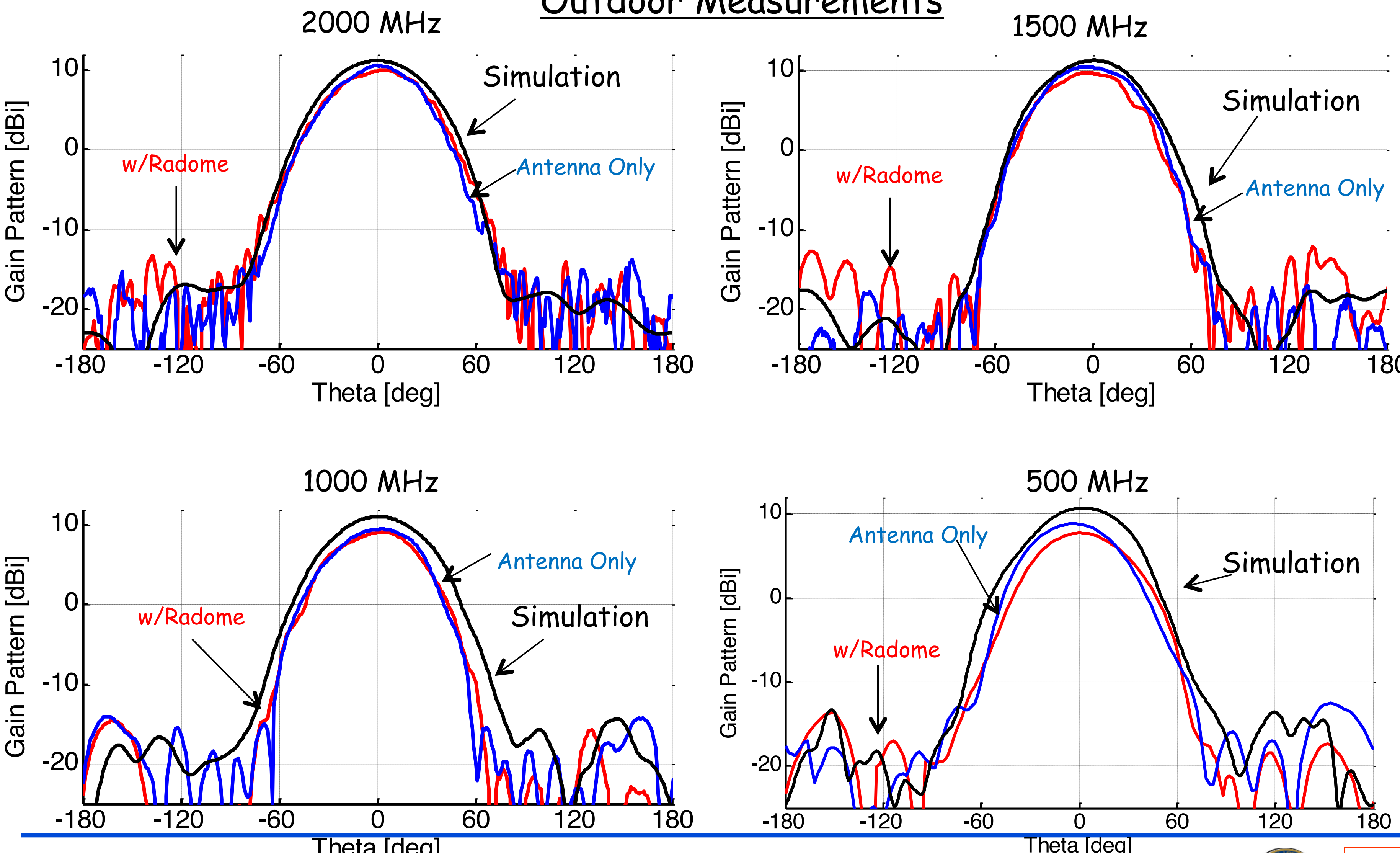
Compact Range Measurements



# Measured Antenna Patterns

## Outdoor Measurements



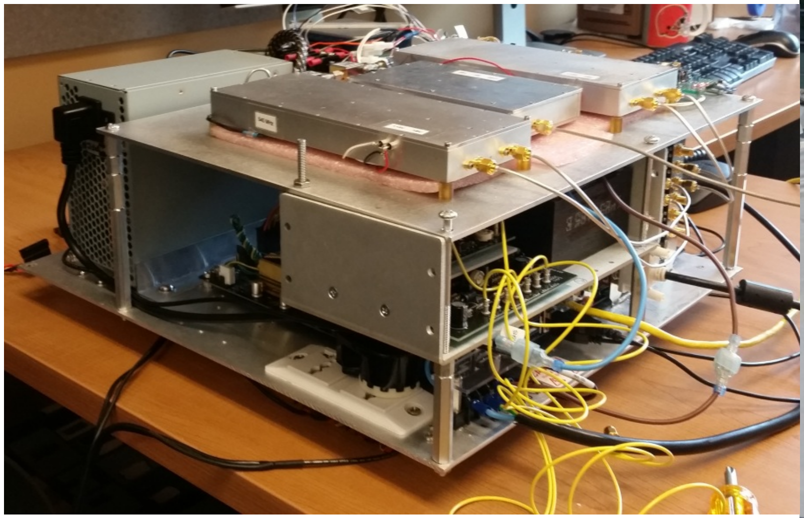
# DOME-C Opportunity

- 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

Alessandro Conidi ©PNRA

# 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

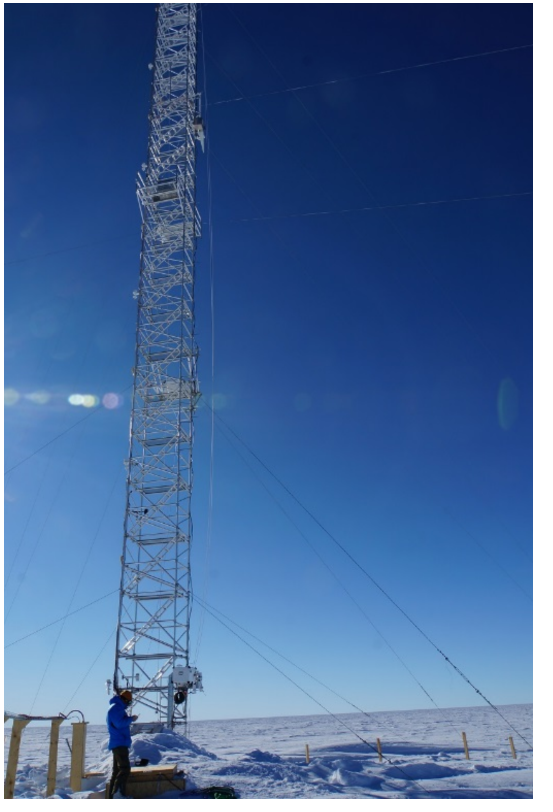



# UWBRAD Antenna on Antarctica Dome C Tower


IFAC scientist Dr. Marco Brogioni

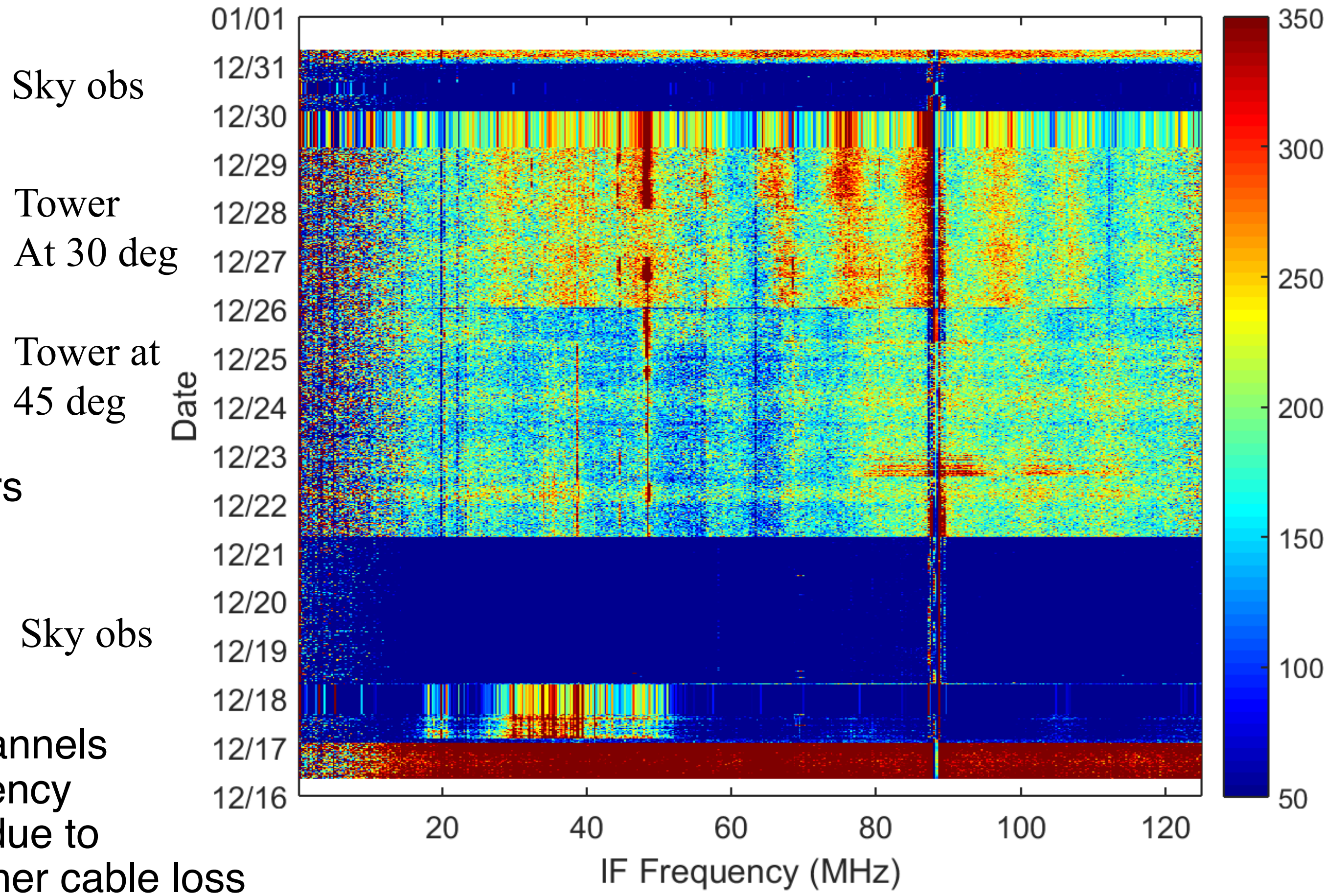
# Dome-C Campaign Events

- 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

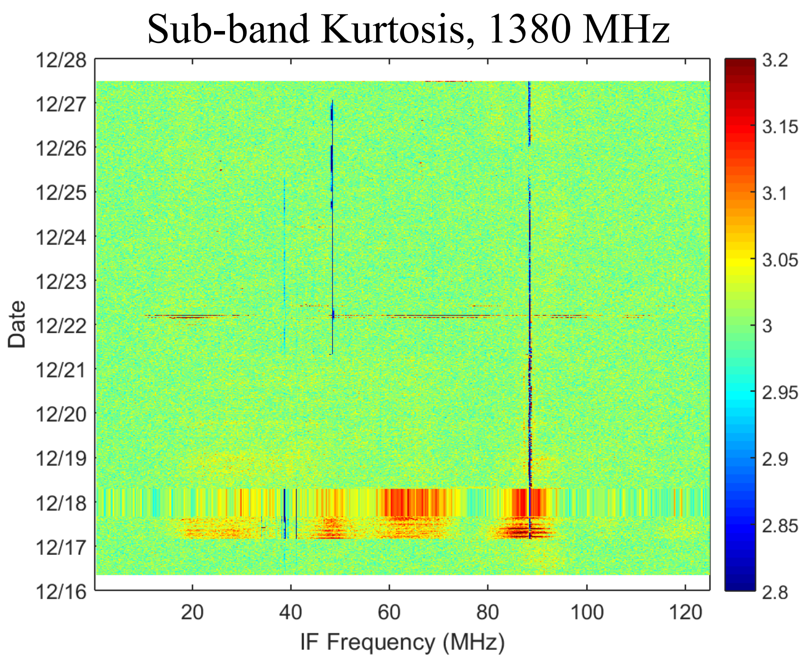


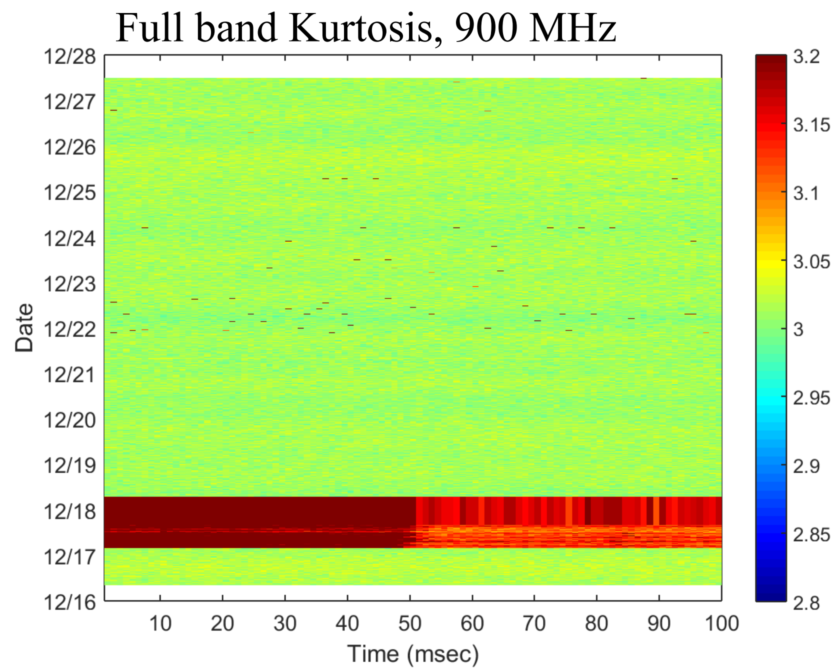
# “Calibrated” TB spectrograms

- 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

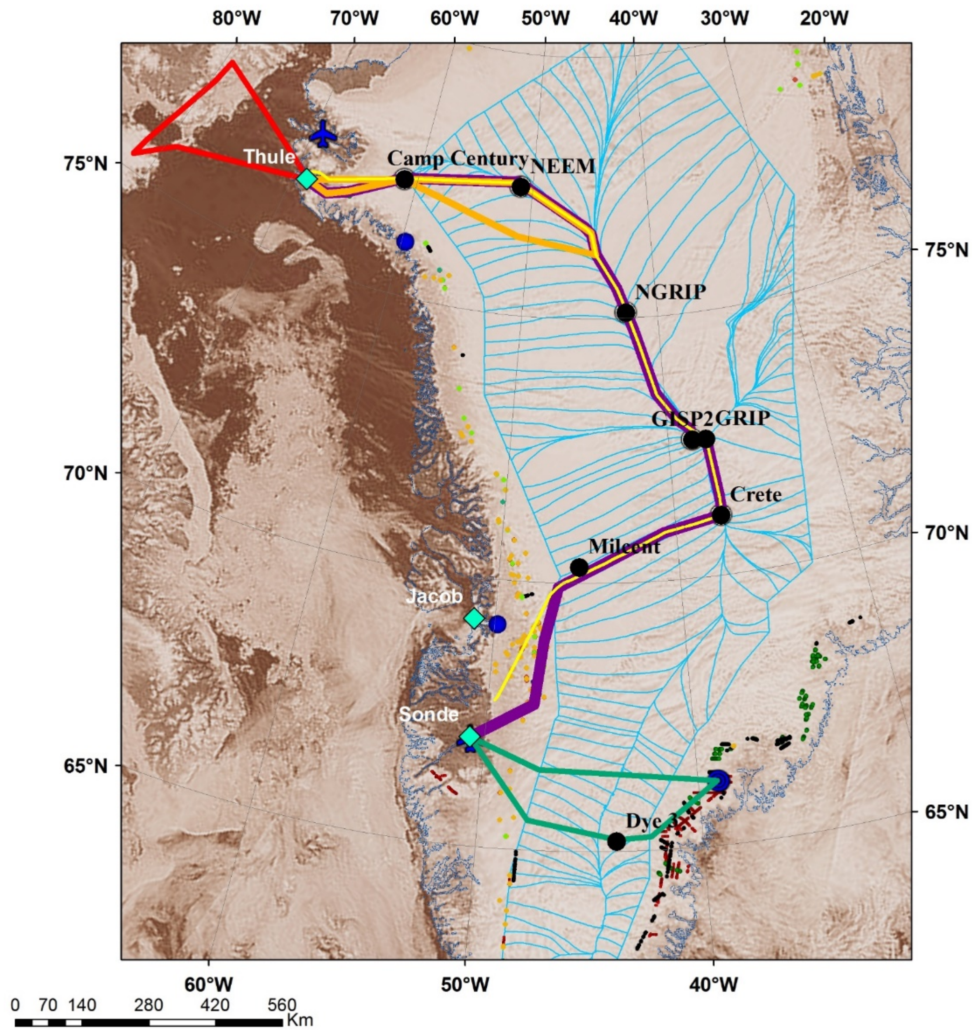
# Prep for Greenland Campaign

- 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

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

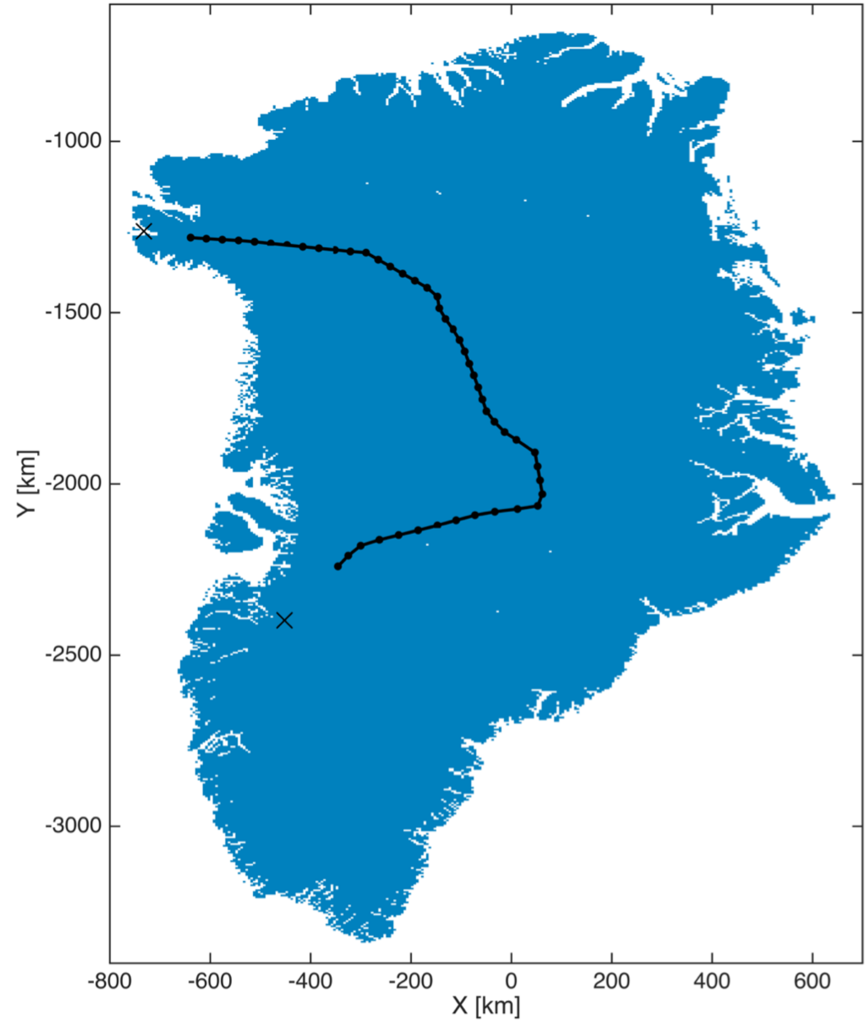
# UWBRAD virtual mission

## 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

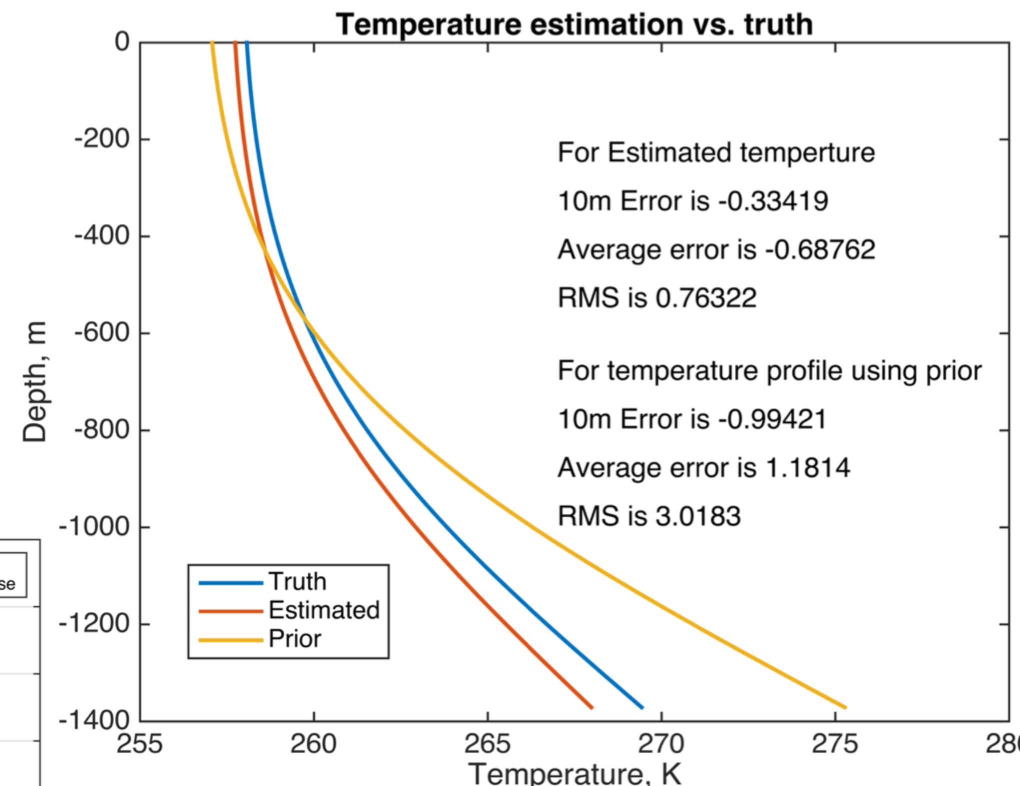
- Surface Temperature and accumulation rate from RACMO reanalysis
- Ice sheet thickness from Operation Ice Bridge
- Geothermal heat flux from Community Ice Sheet Model
- Mean density profile fit from Summit borehole data
- Density variations fit from Liz Morris' neutron probe data

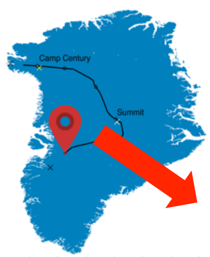


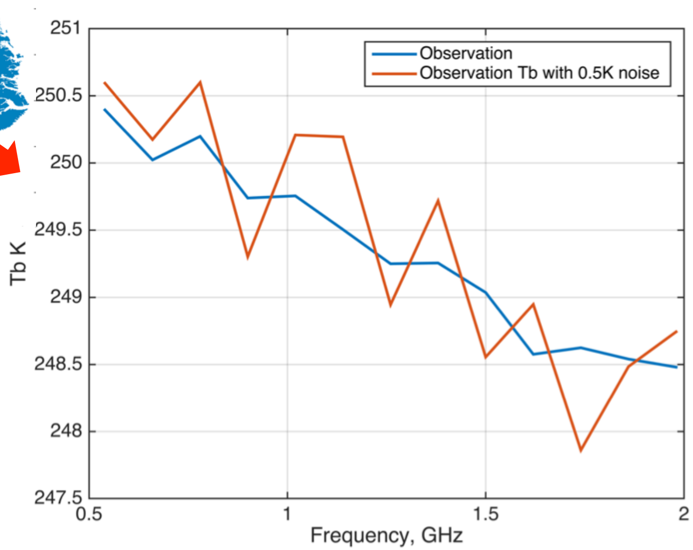
# Estimation results: point 47

## 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%



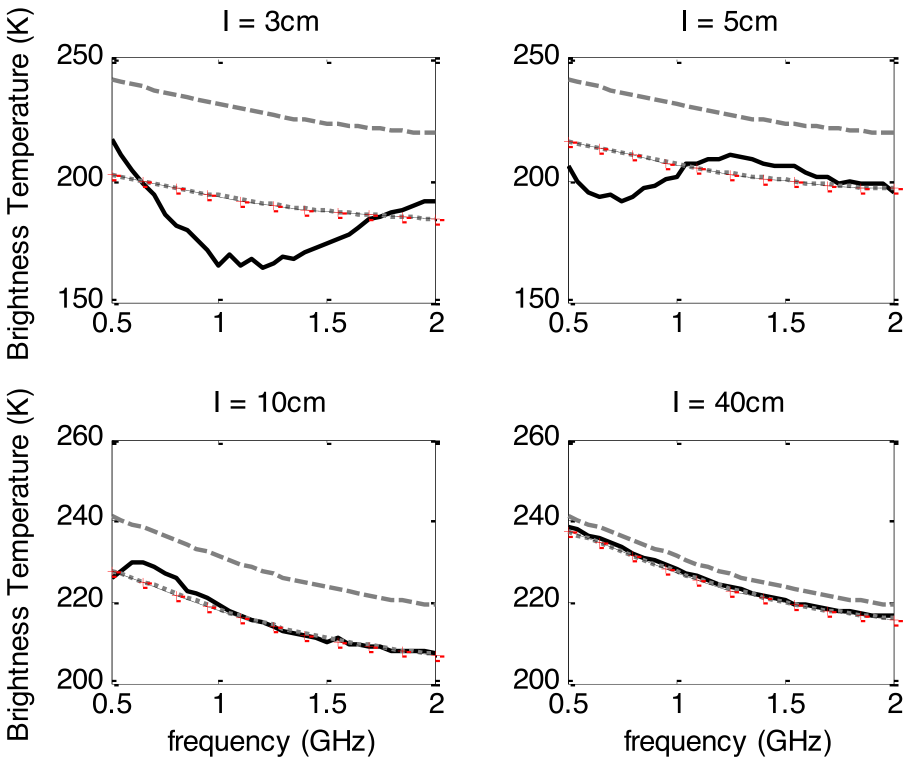



# Forward Models

- 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

# Model Examples



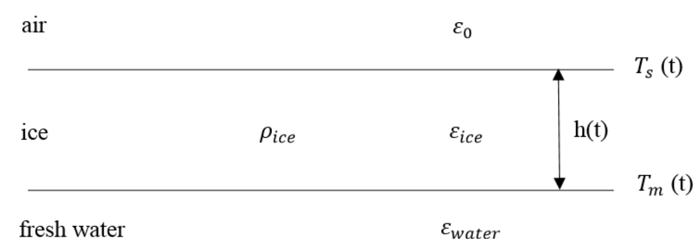

Brightness temperature comparison between the incoherent and coherent models for different correlation lengths of density fluctuation. Cloud Model: grey dashed curve; DMRT-ML: grey dotted; MEMLS: black-dashed with red markers; Coherent: black solid.

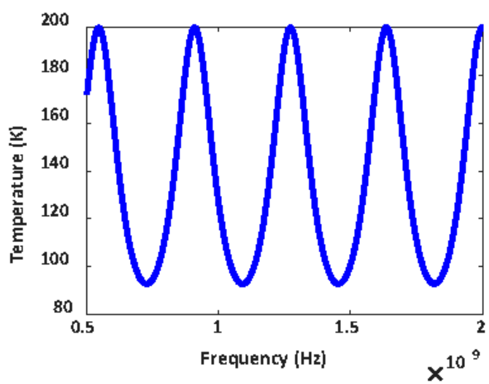
- Model results are different for short correlation lengths of density fluctuation (less than half a wavelength)
- The coherent model is the baseline algorithm and gives correct prediction in the UWBRAD frequency range.
- The coherent model takes longer time to run due to the large number of realizations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

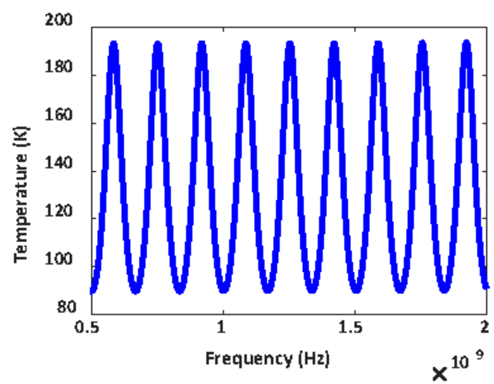
$\Delta=0.040$g/cm↑3 ;
$a=30$m

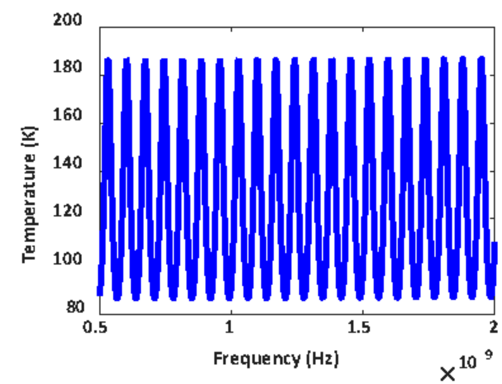
# Other Applications

- 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
- Abililty 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

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.

Tan, S., M. Aksoy, M. Brogioni, G. Macelloni, M. Durand, K. Jezek, T. Wang, L. Tsang, J. T. Johnson, M. Drinkwater, L. Brucker, “Physical models of layered polar firn brightness temperatures from 0.5-2 GHz,” **IEEE JSTARS**, vol. 8, pp. 3681-3691, 2015.

Brogioni, M., S. Pettinato, F. Montomoli, K. Jezek, and G. Macelloni, “Simulating multi-frequency ground based radiometric measurements at DOME-C Antarctica,” accepted by **JSTARS**, 2015.

Jezek, K. C., J. T. Johnson, and M. Aksoy, ``Radiometric approach for estimating relative changes in intra-glacier average temperatures,'' **AGU Fall meeting**, proceedings, 2012.

M. Aksoy, J. T. Johnson, and K. C. Jezek, “Remote sensing of ice sheet subsurface temperatures,“ **MicroRad**, 2014.

G. Macelloni, M. Brogioni, M. Aksoy, J. T. Johnson, K. C. Jezek, and M. Drinkwater, ``Understanding SMOS data in Antarctica,'' **IGARSS**, 2014.

M. Aksoy, J. T. Johnson, K. C. Jezek, M. Durand, M. R. Drinkwater, G. Macelloni, and L. Tsang, ``An examination of multi-frequency microwave radiometry for probing subsurface ice sheet temperatures,'' **IGARSS**, 2014.

Macelloni, G., J. T. Johnson, K. C. Jezek , M. Durand, M. Aksoy, M. Brogioni, L. Tsang and M. R. Drinkwater, “UWBRAD: A multifrequency microwave radiomter for measuring subsurface ice sheet temperatures,” **ESA Workshop on novel mission concepts for snow and cryosphere research**, 2014.

A. Bringer, et al, ``An examination of models for predicting the 0.5-2 GHz brightness temperature of ice sheets,'' **IGARSS**15.

T. Wang, L. Tsang, J. T. Johnson, K. C. Jezek, and S. Tan, “Partially coherent model for the microwave brightness temperature of layered snow firn with density variations and interface roughness,” **IGARSS**, 2015.

J. T. Johnson et al, ``The ultra-wideband software-defined radiometer (UWBRAD) for ice sheet internal temperature sensing: instrument status and experiment plans,'' **IGARSS**, 2015.

# Publications (cont'd)

- Y. Duan, M. Durand, K. Jezek, C. Yardim, A. Bringer, M. Aksoy, J. T. Johnson, "A Bayesian retrieval of Greenland ice sheet internal temperature from UWBRAD measurements," **American Geophysical Union** Fall Meeting, 2015.

- A. Bringer, J. T. Johnson, K. C. Jezek, M. Durand, Y. Duan, M. Aksoy, G. Macelloni, M. Brogioni, L. Brucker, S. Tan, M. Drinkwater, L. Tsang, "Ultra-wideband radiometry for internal ice sheet temperature measurements: modeling and experiments," **American Geophysical Union** Fall Meeting, 2015.

- M. Andrews, J. T. Johnson, H. Li, M. Aksoy, K. Jezek, G. Macelloni, M. Brogioni, "Calibration of the ultra-wideband software defined microwave radiometer (UWBRAD) for ice sheet thermometry," **Microrad 2016**.

- G. Macelloni, M. Brogioni, J. T. Johnson, K. C. Jezek, M. Andrews, H. Li, M. Aksoy, D. Belgiovane, and C. C. Chen, "Deployment of the UWBRAD radiometer at DOME-C: first results of the Antarctic campaign," **Microrad 2016**.
- L. Tsang, S. Tan, T. Wang, J. T. Johnson, K. C. Jezek, "A partial coherent model of layered media with random permittivities and roughenss for polar ice sheet emission in UWBRAD," **Microrad 2016.**

- J. T. Johnson, K. C. Jezek, M. Aksoy, A. Bringer, C. Yardim, M. Andrews, C. Chen, D. Belgiovane, V. Leuski, M. Durand, Y. Duan, G. Macelloni, M. Brogioni, S. Tan, T. Wang, L. Tsang, "The ultra-wideband software defined radiometer for ice sheet internal temperature sensing: results from recent observations," **IGARSS 2016**.
- 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**.
- D. Belgiovane, C. C. Chen, and J. T. Johnson, Conical log spiral antenna development for the UWBRAD ice sheet internal temperature sensing, **IEEE Antennas and Propagation Symposium**, 2016.
- A. Bringer, J. T. Johnson, M. Aksoy, K. C. Jezek, M. Durand, L. Tsang, S. Tan, T. Wang, G. Macelloni, M. Brogioni, Modeling UHF band spectra of lake ice brightness tempeatures, **23rd IAHR International Symposium**, May 31-June 3rd, 2016.

# Conclusions

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