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

Proposal submitted to
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1. Proposal Summary

Existing space and airborne remote sensing instruments have pushed the state-of-the-art in the characterization of ice sheet behaviors with the exception of one key parameter: internal ice sheet temperature. The proposed Ohio State University (OSU) led Ultra-wideband Software-Defined Microwave Radiometer (UWBRAD) will address this gap and provide researchers with the capability to measure ice sheet internal temperatures at depth. This data will enhance the research community's ability to determine the ease at which ice deforms internally and the rate at which the ice sheet flows across its base. It will also enhance the community's ability to compile mean annual temperatures and monitor climate change; other potential applications include the measurement of deep surface soil moisture as well as snow thickness.

The proposed UWBRAD is the product of modeling studies and research activities conducted at OSU, including analyses of key science results from ESA's 1.4 GHz Soil Moisture and Ocean Salinity satellite microwave radiometry data that probed deep ice sheet properties at Lake Vostok, Antarctica. These OSU research and technology development activities have confirmed that (1) relative changes in ice sheet internal temperature can be gleaned from multi-frequency emission data over the range 0.5 to 2 GHz, and (2) a multi-frequency radiometer has the potential to separate temperature and electromagnetic properties in the ice sheet through a model-based retrieval approach.

Today, there are many radiometers operating in the protected portion of L-band that provide only partial ice sheet temperature information due to their single frequency measurements. In contrast, UWBRAD will provide brightness temperatures in 15 channels over the ultra-wideband 0.5-2GHz range and in environments containing radio frequency interference (RFI). To enable operations outside the protected portion of the spectrum, UWBRAD incorporates full bandwidth sampling with software defined algorithms to provide real-time detection and mitigation of interference and a cognitive radiometry method for locating and utilizing portions of the spectrum free of RFI. The initial design of a 0.5-2 GHz antenna commensurate with instrument and science requirements and capable of airborne deployment has also been completed.

UWBRAD will (1) push the state-of-the-art for ultra-wideband software defined microwave radiometers and antennas; (2) provide NASA and the research community with a capability that can be adapted for use on a variety of aircraft with a path to operation in space; and (3) address key NASA climate variability and change issues including the determination of mechanisms that control the mass balance and dynamics of ice sheets of Greenland and Antarctica and the parameterization of predictive models of the contribution of land-based ice to sea level change.

A three-year program is proposed. Year one will complete the instrument and antenna design and construct and demonstrate a two-channel system in a laboratory environment. Expansion to 15 channels and additional laboratory demonstrations will be conducted in year two. Year three will include tests in a relevant environment through a Twin Otter (~ 24 science flight hours) deployment conducted in Greenland observing polar ice sheet temperatures and associated in-situ validation sites.

1.1 Quad Chart

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

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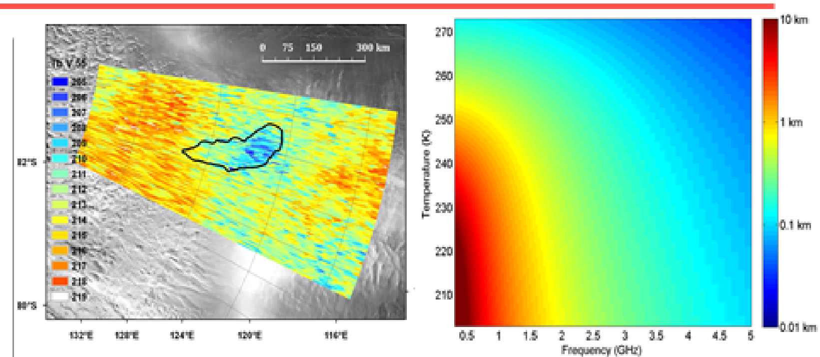
Objectives:

- 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



(left) 1.4 GHz SMOS Antarctic brightness temperatures showing cold anomaly at Lake Vostok (black outline)
(right) Pure ice penetration depth vs. frequency and temperature

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	8/2014
• Complete Dual Channel Implementation/Test	2/2015
• Complete Antenna Scale Model Fabrication/Test	2/2015
• Complete 15 Channel Implementation/Test	8/2015
• Complete Antenna Implementation/Test	8/2015
• Complete Laboratory Tests of Full System	2/2016
• Conduct Airborne Experiments	10/2016
• Complete Data Analysis	2/2017

$TRL_{in} = 3$, $TRL_{out} = 5$

Earth Science Technology Office

2. Project Description

2.1 Applicability to Earth Science Measurements and Relevancy Scenario

Spaceborne and airborne remote sensing instruments characterize most of the important variables necessary to understand current ice sheet behaviors and to predict future changes in ice sheet volume. Derived geophysical quantities include: ice sheet surface elevation change; mass change; ice sheet thickness; surface accumulation rate; internal layer stratigraphy; seaward bathymetry; and basal geology (Jezek, 2012). At present, internal ice sheet temperature is absent from this list, yet temperature at depth is a primary factor in determining the ease at which ice deforms internally and also the rate at which the ice flows across the base. Near the surface, 10 m depth temperatures are characteristic of mean-annual surface-temperature and so are recognized as an important climate monitoring parameter (Morris and Vaughan, 1994). Consequently, ice temperature information is important for monitoring the regional climate and is fundamental for better understanding changes in ice sheet mass balance and dynamics.

Temperature enters as a variable in glacier dynamics through a flow law typically taken as a power law relation between stress and strain rate (Van der Veen, 1999). The stiffness parameter inherent in such relationships is highly temperature dependent (Hooke, 1981). Because ice sheet temperature varies with depth, the stiffness parameter and hence strain rates vary with depth. Temperature at depth is therefore key information for modeling ice sheet flow.

Presently, the only information about ice sheet internal temperatures comes from models or from the small number of boreholes in which temperatures are directly measured. Present model predictions are subject to errors given uncertainties in the input parameters that significantly affect internal temperatures: surface temperature, ice sheet thickness, accumulation rate, internal velocities, and sub-surface geothermal heat flux, among others. Figure 1 (left) illustrates sample ice sheet temperature profiles from such models for varying ice sheet thicknesses and snow accumulation rate under the assumption of no horizontal velocities and a fixed surface temperature (-57 C). Higher temperatures at depth result from the insulating character of the overlying ice, and in some situations can reach values that approach the ice melting point. The substantial variations that occur for differing geophysical situations are also apparent. While a wide variety of temperature profiles are possible, the general case can be represented by a small number of parameters (for example, surface temperature, ice sheet thickness, a thermal "scale length", and an amplitude factor, or alternatively the coefficients of a polynomial function of depth.) Determination of these parameters can provide a description of temperature throughout the ice sheet.

We propose to *enable new Earth observation measurements* of ice-sheet internal temperatures through the use of multi-frequency microwave radiometry. While radiometric observations of ice sheets have long been conducted using the SMMR, SSM/I and other spaceborne instruments (Zwally, 1977), such measurements have occurred primarily at X-band or higher frequencies where attenuation in the ice sheet limits temperature information to the upper portions of the ice firn alone (Winebrenner et al, 2004). The temperature information contained in such measurements is highly affected by local meteorology (Van der Veen and Jezek, 1993), and is not indicative of the more temporally stable internal temperatures that are relevant for glacier dynamics or climate studies.

The increased penetration inherent for lower microwave frequencies motivates their use for obtaining deeper temperatures. Recent measurements (Jezek et al, 2012) of Antarctica and Greenland from the L-band (1.4 GHz) radiometer onboard the European Space Agency's Soil

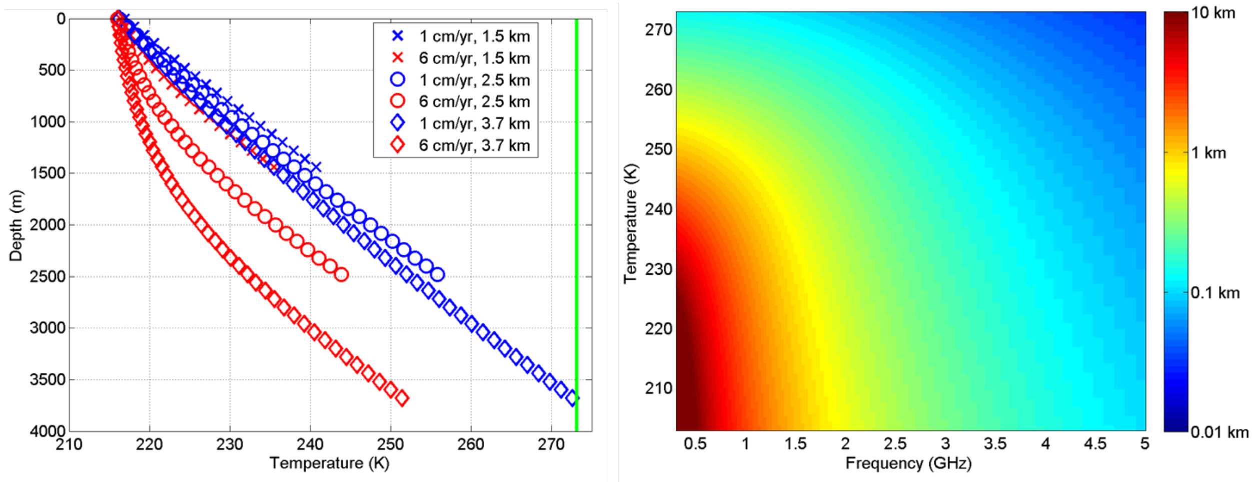


Figure 1: (left) Sample modeled ice sheet temperature profiles for a fixed surface temperature (-57C) and varying accumulation rates and ice sheet thickness. Green line marks 0 C. (right) Penetration depth in pure ice (Matzler, 2006) as a function of frequency and temperature.

Moisture and Ocean salinity (SMOS) mission show clear evidence of the influence of deeper subsurface emissions. Because the brightness temperature of an ice sheet results from a combination of emission, attenuation, and scattering effects from many internal ice sheet "layers", the retrieval of even depth-averaged temperatures from a single frequency brightness temperature alone is challenging. The use of multiple frequencies, however, can provide measurements in bands which may be more or may be less influenced by particular properties (scattering for example) and with varying penetration (i.e. lower frequencies experience increased penetration, while higher frequencies experience less.) Figure 1 (right) plots power penetration depths in pure ice as a function of observation frequency and ice temperature, and shows significant changes as both parameters are varied, as well as penetration depths of several km (for pure ice) at lower frequencies and cold temperatures neglecting scattering effects.

Due to these properties, the combination of multiple frequency brightness temperatures offers a tantalizing opportunity to obtain internal temperature information as a function of depth (i.e. a temperature profile within the ice sheet.) This concept is similar in some aspects to radiometer methods for measuring atmospheric temperature profiles (Ulaby, Fung, and Moore, 1986) in which multiple frequency channels near an atmospheric absorption resonance line yield differing temperature "weighting functions" due to the varying atmospheric attenuation with frequency. However ice sheet temperature sensing is distinct in the absence of a strong absorption resonance, the potential impact of medium inhomogeneities or impurities, and the fact that absorption in the ice sheet is dependent on temperature. Nevertheless, multi-frequency radiometer observations will clearly provide depth-dependencies that vary with frequency, so that temperature information versus depth is inherent in such measurements and retrievable through a model-based retrieval method.

We will develop the Ultrawideband Software-Defined Microwave Radiometer (UWBRAD) to demonstrate this concept and to provide brightness temperature measurements in 15 channels from 0.5-2 GHz for ice sheet internal temperature sensing. The system will fully digitize the 1.5 GHz observational bandwidth, and will implement real-time detection and mitigation of radio frequency interference (RFI) in order to exploit all available unoccupied spectrum. The highly resolved frequency information to be obtained will also allow any evidence of strong internal reflection to be determined by searching for oscillations in observed brightness temperatures as a function of frequency. A novel ultrawideband antenna will also be constructed for the system to provide nadiral, single polarization measurements from an airborne platform. The system will be designed for deployment on Twin Otter and possibly other aircraft, and will be demonstrated in 2016 in airborne observations of ice sheets in Greenland and possibly Antarctica.

UWBRAD will achieve many technology innovations and firsts, including the first fully digitized 0.5-2 GHz microwave radiometer for Earth Science measurements, the first internal ice sheet temperature remote sensing system, and the first example of a "cognitive" microwave radiometer for Earth Science applications. The latter is achieved through "software defined radio" concepts to allow real-time determination of unoccupied spectrum as well as operation in the presence of other transmitting sources. The combination of these technologies into a single instrument for airborne observations will provide unprecedented science information on ice sheet temperatures. Though initially focused on ice sheet applications, UWBRAD measurements are also applicable to many other science applications where penetration into a medium is of interest, including deep subsurface or sub-forest canopy soil moisture information, sea ice thickness sensing, and biomass observations.

Our research directly addresses NASA's focus area on *climate variability and change*. We will also address two of NASA's specific climate questions: *What changes are occurring in the mass of the Earth's ice cover? How is global sea level affected by natural variability and human-induced change in the Earth system?* By seeking to improve estimates of internal temperature, we will better *determine the mechanisms controlling mass balance and dynamics of the ice sheets of Greenland and Antarctica; including studies aimed at improving fundamental understanding of ice flow.* We will make extensive and novel use of remote sensing data to improve temperatures that can be used subsequently to *parameterize predictive models of the contribution of land-based ice to sea level change, especially in the coming century.*

2.2 Project Objectives

- The design and implementation of UWBRAD, an airborne nadir observing microwave radiometer that fully digitizes the entire 0.5-2 GHz bandwidth
- The development of "software defined" algorithms to provide real-time RFI detection and mitigation for UWBRAD as well as a determination of unoccupied spectrum regions that can be utilized for radiometry
- Ground-based and airborne demonstrations of UWBRAD performance, including 2016 demonstration flights on a Twin Otter aircraft including polar ice sheet measurements
- Science demonstration and validation of UWBRAD results and associated development of multi-frequency retrievals of subsurface temperature information
- Development of an experiment plan for continued deployment of UWBRAD to support future large scale science observation of ice sheet temperatures
- Development of a plan for transition of project technologies into spaceborne operations
- Training of four graduate students participating in the project in microwave radiometry, sensor development, and ice sheet dynamics

2.3 Ice Sheet Thermal Emission Physics

Ice sheets are typically represented as a layered medium when modeling their microwave thermal emission; each layer is described by its physical temperature (so that a temperature profile results), its mass density (from which fractional volumes of ice and air can be determined), the "grain size" of particles within the layer, and the concentrations of any impurities in the ice itself (Koenig, 2008). As new surface snow becomes firn (first few cm of

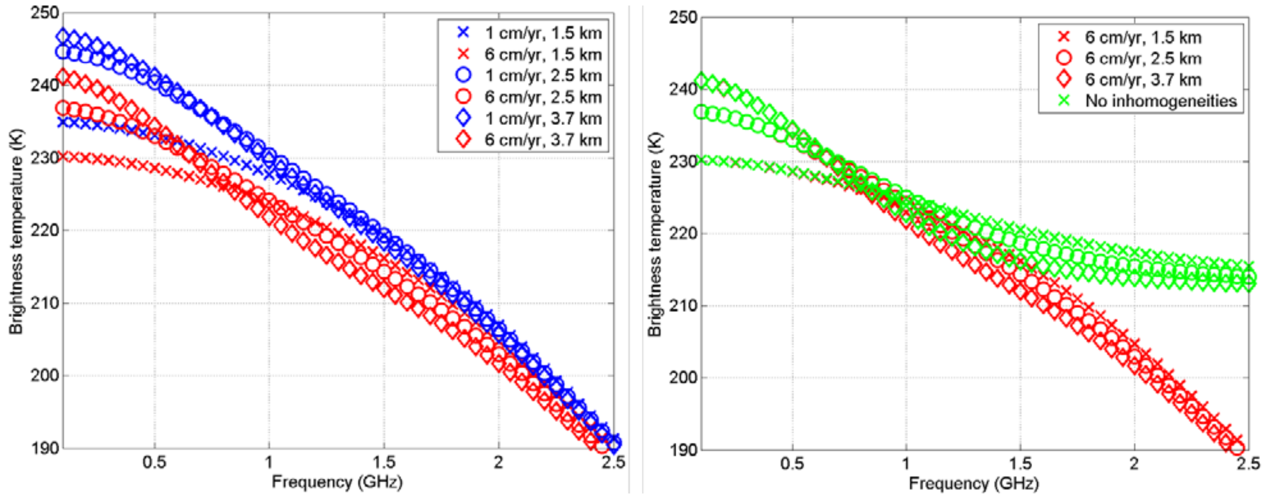


Figure 2: (left) Ice sheet brightness temperatures versus frequency (at nadir) from DMRT-ML model for temperature profiles from Figure 1. A 3mm inhomogeneity size is assumed (3 mm ice grains in air for densities < 4.5 g/cc, 3 mm air voids in ice for higher densities); scatterer fractional volumes vary from 40% at the surface to < 1% at 250 m depth. (right) Comparison of brightness temperatures versus frequency with and without inhomogeneities.

depth with average density 0.3 g/cc) and then more dense ice at greater depths (reaching 0.9 gm/cc around 100 m depth), the medium transitions from an air background containing ice particles to an ice background containing air voids. In the upper layers, both ice and air have significant volume fractions, so that a "dense medium" results electromagnetically (Tsang, Kong, and Shin, 1985). In such situations, the dense-medium radiative transfer theory is required to model the emitted brightness temperature.

A variety of implementations of this approach exist; the results to be shown in what follows were produced using the DMRT-ML (Picard et al, 2012), which has been widely and successfully used to model thermal emission both from ice sheets (Brucker et al, 2011a) and from snowpacks (Brucker et al, 2011b). Inhomogeneities in the ice sheet have two potential effects: first, their presence causes scattering which if significant must be modeled in the radiative transfer, and second, they cause a change in the effective permittivity of a layer that must be modeled if significant. Both of these effects decrease as the scatterers become smaller compared to the electromagnetic wavelength. Therefore it should be expected that the influence of scattering will be a function of frequency, with reduced effects occurring at lower frequencies.

Figure 2 (left) plots DMRT-ML brightness temperatures corresponding to the temperature profiles of Figure 1. These results were computed for a soil base, and for a 3 mm radius of inhomogeneities (ice in air in the upper layers, air voids in ice in the lower layers.) Note that in this frequency range, the real part of the pure ice dielectric constant is essentially constant, while the small imaginary part of the dielectric constant varies with temperature and frequency. The results show significant variations with frequency of up to ~40 K, with the strongest frequency variations occurring over the 0.5-2 GHz range. In general, the higher brightness temperatures at lower frequencies result from increased sensitivity to the higher physical temperatures at greater depths in the ice sheet. Decreased brightnesses at higher frequencies are impacted by the "darkening" effect associated with scattering. Differing functions of frequency result for differing ice sheet thicknesses and accumulation rates, so that the relationship between the physical and brightness temperatures requires model-based interpretation. Nevertheless, it is

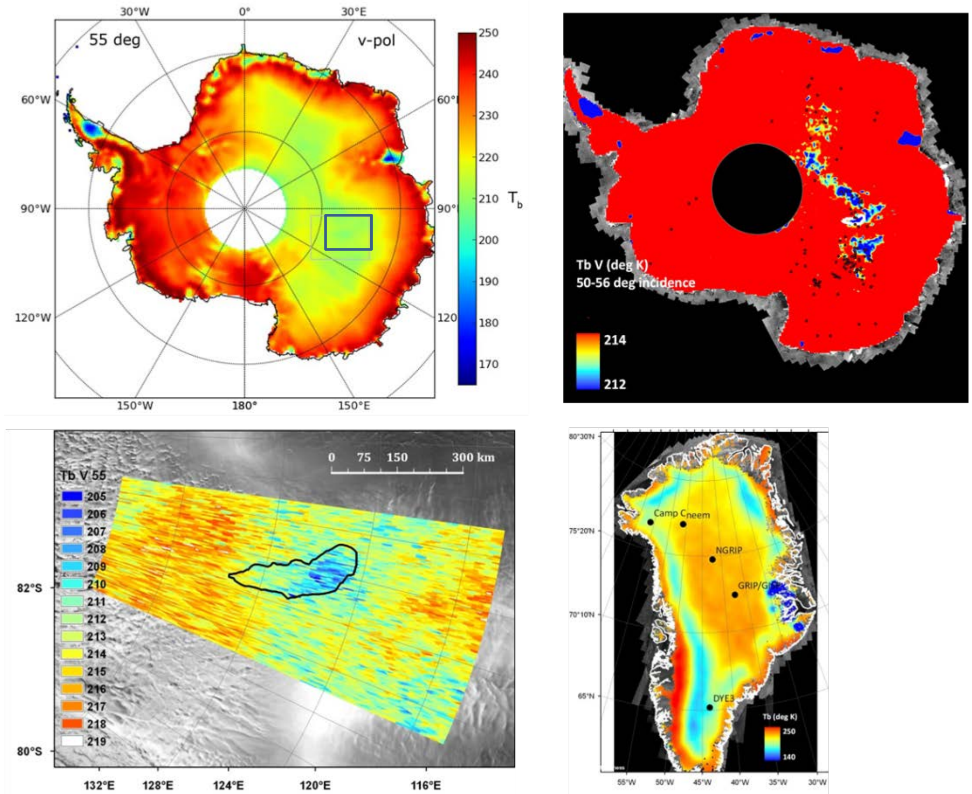


Figure 3: SMOS 1.4 GHz brightness temperature observations (55 degrees, vertical polarization) of Antarctica and Greenland. *Upper left:* Antarctic map with wide color scale; cold anomaly marked by box. *Upper right:* Color scale highlighting cold anomalies; Lake Vostok marked by white outline; other subglacial lakes indicated by markers. *Lower left:* Zoom of Vostok region showing cold anomaly with Vostok outline. *Lower right:* SMOS image of Greenland. Dry snow facies in interior have relatively warm brightness temperatures. Cold brightness temperatures around the perimeter are associated with the melt facies. Very warm temperatures at the ice margin are associated with the ablation facies. Also shown are the locations of deep core sites.

clear that sensitivity to temperature at depth is present. Figure 2 (right) provides further motivation for temperature sensing by comparing DMRT-ML predictions with and without the presence of inhomogeneities. The negligible impact of inhomogeneities over the 0.5-1 GHz range shows that retrieval analyses will be minimally affected by such effects especially at our lowest frequencies. Other investigators have proposed sensitivity to emissions only to around 800 m depth in thick cold ice at 1.4 GHz due to attenuation caused by scatterers (Drinkwater et al, 2004). Our analysis and discussion to follow supports our contention that the use of lower frequencies increases sensitivity to contributions from even the deepest portions of the ice sheet.

Further evidence for the ability of radiometry in this frequency range to provide deep subsurface information is provided by 1.4 GHz measurements from SMOS (Kerr et al, 2010). A SMOS brightness temperature map of Antarctica (vertical polarization, 55 degrees observation angle: selected for coverage considerations from the multi-angle SMOS dataset) is shown in the upper left portion of Figure 3. Close examination reveals a moderate cold spatial anomaly in the box illustrated. Additional confirmation of this anomaly is provided in the upper left figure, which saturates the color scale outside the 212-214 K cold range and includes markers for the locations of known sub-glacial lakes (Siegert et al, 2005). This image reveals localized cold features, one of which is associated with Lake Vostok, a lake beneath ~ 3.7 km of ice sheet whose extent is marked by the white outline. An additional zoom of the Vostok region is provided in the lower left figure, and shows strong correlation of the cold feature with the known lake extent. Spatial transects show the anomaly to be up to 5 K when examined in a variety of SMOS polarizations and incidence angles. Model results (and the penetration depth information from Figure 1) suggest that emission at 1.4 GHz from the ice sheet bottom (3.7 km depth) may be observable (neglecting scattering effects) in the case of cold, dry ice as is expected at the Vostok location. Other investigators have proposed that these anomalies may result from subsurface layering effects; such effects if present would provide clear oscillatory brightness temperatures versus frequency. In general, these results again confirm the utility of 0.5-2 GHz radiometry for sensing internal ice sheet properties. The lower right portion of the figure is a similar image for Greenland, and illustrates the changes in brightness temperatures that occur in the wet snow facies (i.e. cooler brightness temperatures where annual summer thaws result in large grain sizes and increased scattering effects) and dry snow facies (warmer brightness temperatures near the Greenland interior). The presence of subsurface water tables at 10-20 m depth that have been observed in-situ in Greenland (Forster, 2013) may also provide interesting opportunities for focused UWBRAD observations. The locations of deep ice core sites that provide in-situ temperature measurements are also shown. It is noted that emissions from celestial sources can produce significant effects at L-band and lower frequencies when reflected from the Earth scene; however current missions have shown that effective procedures exist for modeling and compensating such effects (Reul et al, 2008).

2.4 Science Goals and Retrieval Concept

Based on these results and on consideration of the science impact of subsurface temperature information, the following science goals listed in order of increasing risk have been determined for UWBRAD observations of Antarctic and Greenland ice sheets as well as Canadian and Russian ice caps:

- 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 and so represent 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.

While initial evidence suggests that these goals are achievable targets, extensive modeling and retrieval analysis studies will be conducted throughout the project to assess and refine the UWBRAD design and retrieval procedures to approach these goals.

Because the retrieval process will be based on model-fitting to determine a set of temperature profile parameters (as discussed previously), a robust and accurate forward model is required. The validation of models for predicting ice sheet brightness temperatures will therefore be a key aspect of early project studies. While the DMRT-ML method used to date has shown some success, alternative approaches based on higher fidelity medium descriptions, such as the "bicontinuous medium" characterization (Ding et al, 2010), and on fully numerical determination of the scatterer phase function, will also be considered to ensure robust forward modeling.

Frequency Channels	0.5-2 GHz, 15 x 100 MHz channels
Polarization	Single (Right-hand circular)
Observation angle	Nadir
Spatial Resolution	1 km x 1 km (1 km platform altitude)
Integration time	100 msec
Ant Gain (dB) /Beamwidth	11 dB 30°
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 in 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

Table 1: Summary of UWBRAD properties

Two preliminary retrieval studies have been conducted based on the creation of a “database” of 0.5-2 GHz brightness temperatures for varying temperature profile parameters and scatterer properties. Individual brightness temperature results were selected as “truth” and corrupted with simulated UWBRAD noise properties (see next section.) One retrieval study used a simple least squares matching of the corrupted measurements to the database (i.e. a maximum-likelihood approach), and showed initial success in determining temperature profile parameters sufficient to meet the specified science goals. A second approach assumed a-priori knowledge of ice sheet thickness and surface temperature, and used the Bayesian Metropolis Markov Chain Monte Carlo method (Durand and Liu, 2012) to estimate the temperature profile via a surface accumulation rate proxy. Again the results showed success is meeting the proposed science requirements, including temperature profile measurement to within 1 K rms error. While these initial results are promising, they are based on the assumption of an accurate forward model. The project will continue these studies to refine knowledge of temperature sensing performance and to assess the approach and forward model with existing single-frequency measurements.

2.5 Description of Proposed Technology

2.5.1 Operational Concept

Table 1 provides a summary of UWBRAD properties. UWBRAD will provide single polarization, nadiral brightness temperatures in 15 independent channels, each sampling 100 MHz of bandwidth, to achieve full 0.5-2 GHz observations. The antenna will be designed to provide a spatial resolution of 1 km at 1 km altitude in both the along- and cross-track dimensions; this implies a ~16 second transit of a single footprint for a typical 120 knot Twin Otter airspeed. A 100 msec antenna observation time for a 100 MHz channel and assumed receiver properties results in a noise equivalent delta-temperature (NEDT) of ~ 0.4 K. The multiple 100 msec measurements acquired for each footprint will allow further averaging to reduce brightness temperature uncertainties. The instrument will include internal reference load and noise diode calibration sources to provide short term radiometric stability, and airborne deployments will include sky and water surface measurements for external calibration.

Because UWBRAD will operate outside portions of the spectrum protected for microwave radiometry, the detection and mitigation of RFI is crucial, even in polar regions where spectral occupancy is expected to be reduced but still present. A unique UWBRAD aspect is its full

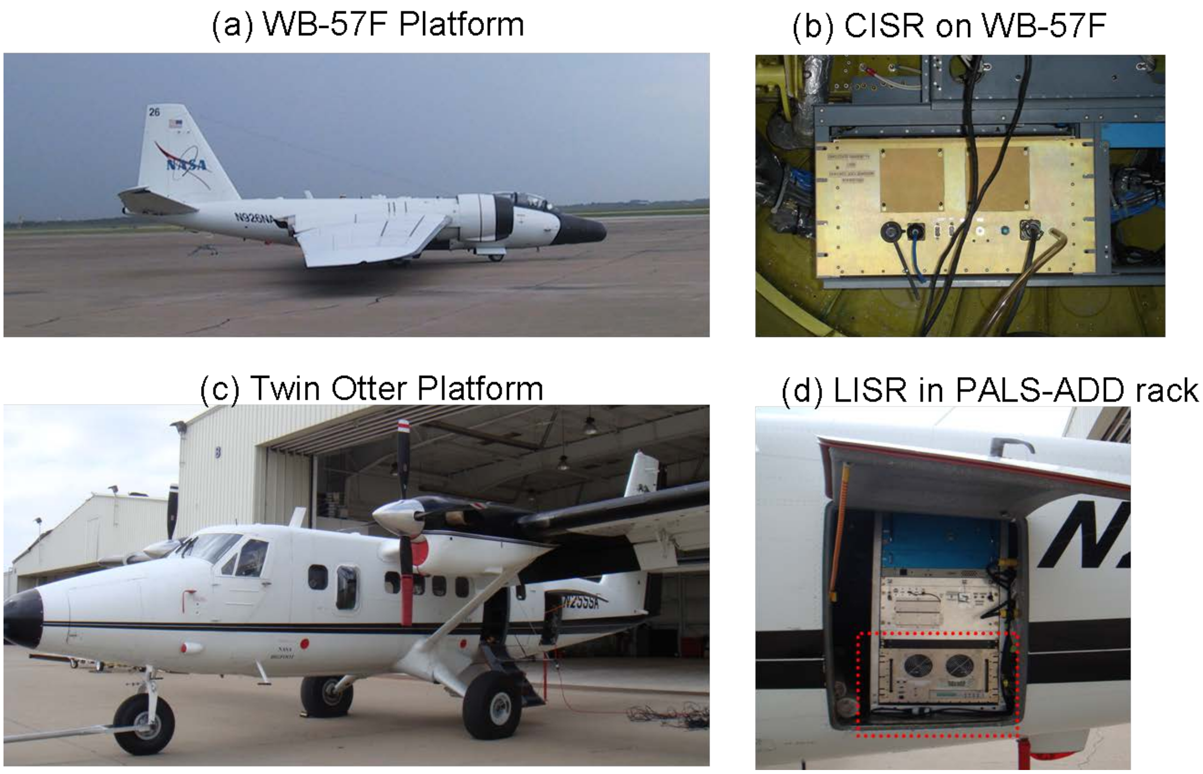


Figure 4: Past RFI detection and mitigation systems developed by The Ohio State University: WB-57F platform in 2005 (a)-(b) for C-band observations (Guner et al, 2007), and on the Twin Otter Platform in 2008 (c)-(d) for L-band observations (Park et al, 2011).

sampling of each channel's 100 MHz bandwidth at 250 MSPS per channel into a processing computer. This sample rate for 15 channels results in a data rate of 7 Gigabytes per second if fully recorded. This high data rate is not required for UWBRAD however, due to the ~16 second interval available to observe a single footprint. Accordingly, it is proposed to operate UWBRAD at a 10% duty cycle (i.e. channels are sampled only 100 msec out of every 1 second.) The resulting 700 Megabyte per second datarate will be shared among four processing computers (each managing up to 4 UWBRAD channels.)

The purpose for fully sampling each channel's bandwidth is the detection, mitigation, and avoidance of RFI. Each processing computer will perform these functions in real time to produce a final integrated power for the 100 MHz bandwidth of each channel. The archived measurement data (and associated information on the amount and properties of RFI detected) will therefore occur at a greatly reduced and much more manageable datarate.

2.5.2 General system architecture

UWBRAD will consist of three primary subsystems representing the RF, digital, and antenna components. All subsystems will be implemented so that they are compatible with deployment on the Twin Otter, P-3, or DC-8 platforms. A preliminary design study has been conducted, and the full system design will be completed in the early portions of the proposed project, including thermal and environmental analyses for airborne deployment.

The multi-channel UWBRAD design is similar in concept to that of the 37 channel 2-18 GHz Multi-Frequency Radiometer (MFRAD) system at The Ohio State University (Johnson et al, 2002). The higher frequencies of MFRAD however are not suited to deep subsurface observations, and the MFRAD system uses a direct detection, non-sampling architecture that is

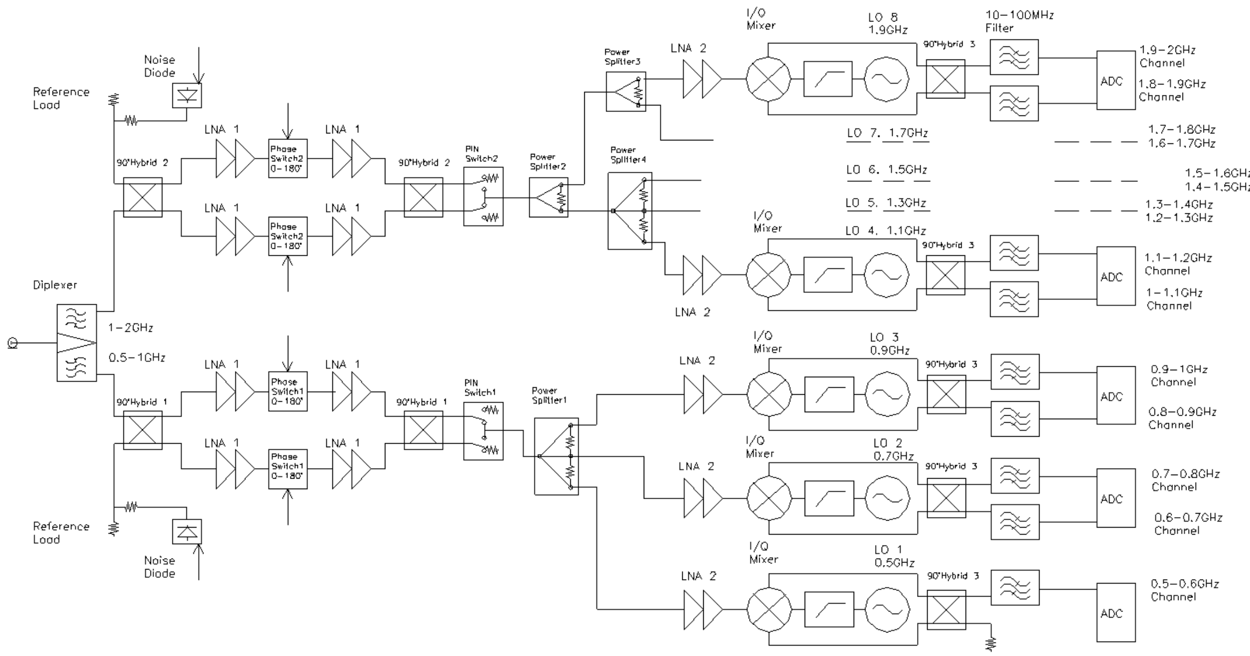


Figure 5: Schematic of RF Subsystem

highly susceptible to RFI corruption. UWBRAD also leverages past experience at The Ohio State University in the development of RFI detecting and mitigating systems (e.g. Guner et al, 2007); Figure 4 illustrates past FPGA-based systems developed and deployed on the WB-57F (upper) and Twin Otter (lower) aircraft that were capable of sampling 100 MHz in a single channel. UWBRAD will incorporate RFI algorithms optimized from this experience, expand the channel set to 15 100 MHz channels, and implement “software defined” methods that eliminate the past need for FPGA firmware development. The experience of these previous projects will directly transition into the UWBRAD development to allow a low-risk implementation.

2.5.3 RF Subsystem

The UWBRAD RF subsystem (Figure 5) implements the functions of channel separation, provision for internal calibration standards, signal amplification, and downconversion to IF frequency 10-100 MHz. The front end design adopted is a “hybrid based” radiometer (Aja et al, 2005), which improves the system noise figure by replacing the typical Dicke switch component with a switched hybrid method. Using this architecture, the input can be switched between the antenna port and the calibration port by control of a 0-180 degree selectable phase shifter. The incorporation of subsequent PIN diode switch provides further capabilities of observing both of the hybrid paths to enable additional balancing and calibration of signal paths. Each of 15 channels is created by mixing with local oscillators at 500, 700, 900, …, MHz; the number of oscillators required (eight) is reduced by creating channels through high- and low-side LO injections. Channel selection filters are designed to provide a minimum isolation of 30 dB between adjacent channel center frequencies. Note the multiple oscillators will not be required to be phase locked because coherency across channels is not required (although coherency will be available within the 100 MHz of each channel.)

The design proposed is well proven, and the 0.5-2 GHz frequencies facilitate its construction (as multiple circuit boards) with low cost, high performance components. In addition, the use of 16 bit data acquisition (as discussed in the next section) reduces the required gain of the RF subsystem. A reduced gain improves system stability and also reduces the potential for amplifier

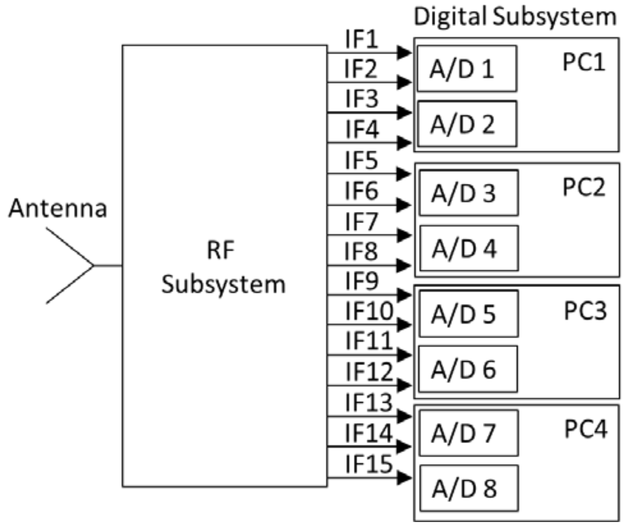


Figure 6: System block diagram including digital subsystem components

saturation by out-of-band interference. Active thermal control of the RF subsystem will also be implemented to improve system stability further.

2.5.4 Digital Subsystem

The digital subsystem (Figure 6) is based on the ATS9626 16 bit, 250 MSPS dual-channel data acquisition card from Alazartech, Inc. The project team has previous experience with this card, and has experienced the high throughput of raw A/D samples that is achieved to a host computer via the PCI Express interface. The 250 MSPS sample rate will allow 100 MHz bandwidth to be sampled in the first Nyquist zone, and it is intended to have two cards per computer sampling two channels each. The digital subsystem therefore consists of four host computers to receive and process the 15 x 100 MHz channels. The project team also has previous experience with the software interface to the ATS9626 card, along with the implementation of real-time processing of received data. System computers will be selected in accordance with AlazarTech, Inc. recommendations for achieving maximum throughput with the ATS9626. Each computer of the digital subsystem will archive data independently to internal hard drives in removable enclosures. Digital subsystem components will be mounted in a rack enclosure along with a display interface that is selectable to each of the system computers. The digital subsystem will also implement control of switching for calibration cycling in the RF subsystem.

Real-time RFI detection, mitigation, and “cognitive radiometry” functions will be implemented on the host computers. A variety of algorithms exist for these purposes, including cross-frequency, time-based, kurtosis, and other approaches (Misra et al, 2009). Because the algorithms will be implemented in a software environment, greater flexibility for algorithm development will exist beyond that typically available in previous FPGA-based systems. The use of multi-core host processors will also facilitate parallel data transfer, processing, and archiving. The availability of fully sampled data will also enable the intermediate creation of brightness temperatures that are highly resolved in frequency (e.g. through the use of an FFT). While typical geophysical situations do not produce brightness temperatures that vary rapidly in frequency, some geometries (for example layered media having strong dielectric contrasts between layers) can produce brightness temperatures that oscillate in frequency (Johnson et al, 2002). Such effects correspond to the correlations in time that are sought in “wideband autocorrelation” radiometric sensing (England, 2013). Algorithms for detecting such effects will be implemented, with the option of triggering the recording of fully resolved temporal data when

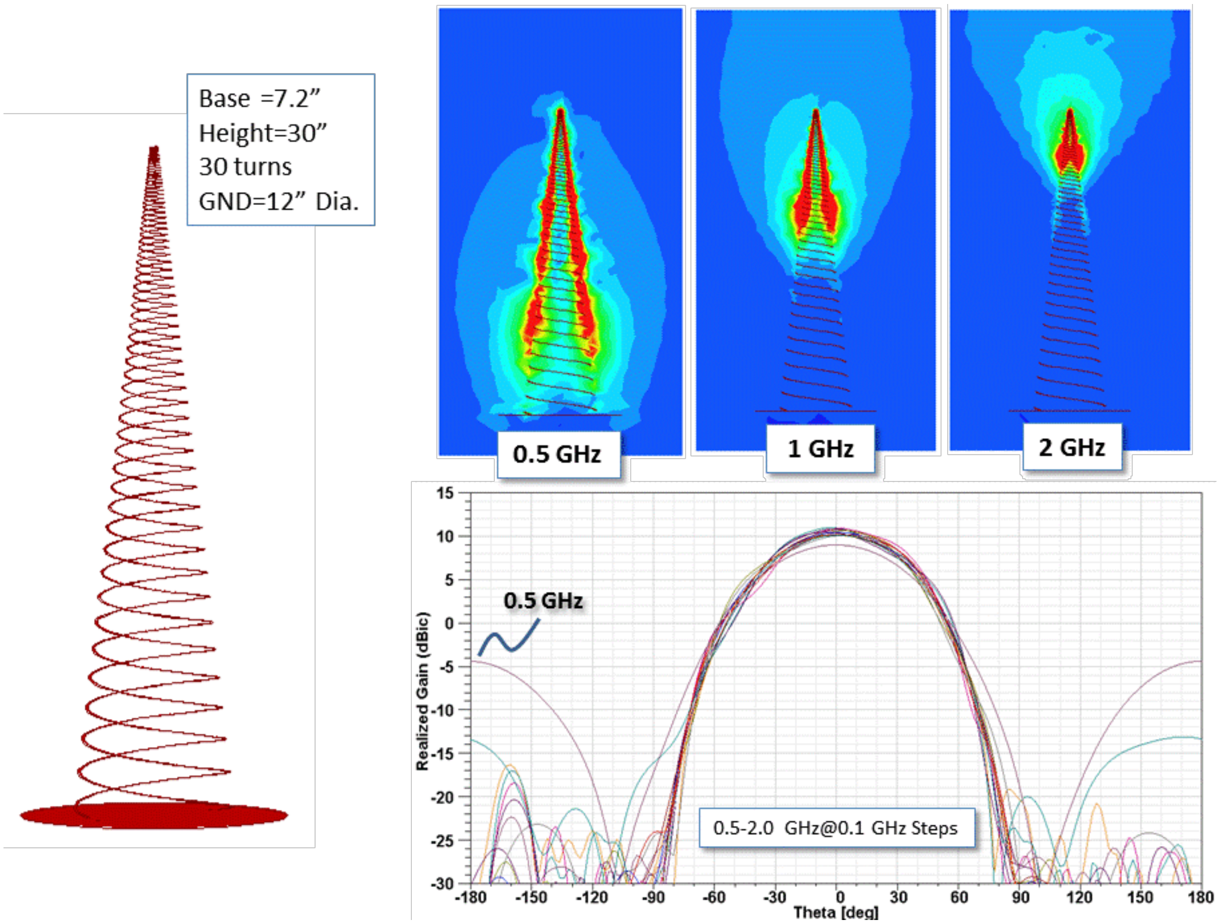


Figure 7: UWBRAD Antenna Design Illustration

such effects are observed. Typical archived datasets however will consist of the RFI mitigated brightness temperature in each of 15 channels over 100 msec integration periods (and at 10% duty cycle).

2.5.5 Antenna subsystem

The UWBRAD antenna subsystem will provide a single port output for 0.5-2 GHz antenna observations. The design of an “ultrawideband” antenna suitable for UWBRAD is challenging; typical planar spiral wideband designs are narrowband or else can provide only low gains if wideband operation is sought. The UWBRAD design overcomes this challenge by extending the antenna in the vertical direction to achieve an “end fire” gain pattern. Figure 7 illustrates the proposed antenna concept based on a 2-arm conical spiral design; the spiral structure shown would be deployed toward nadir in airborne measurements. The preliminary simulated performance (lower right) shows that this design can support the proposed 0.5 to 2 GHz frequency range with a very desirable constant antenna pattern and gain as a function of frequency. Such properties will ensure that all radiometer channels view the same scene, reducing the impact of any spatial inhomogeneity on the brightness temperature versus frequency. Additional design efforts will reduce sidelobe levels at lower frequencies.

The antenna’s main structure is made of two small spirally wound conducting wires with a feed located at the spiral tip, making the design relatively light weight. The preliminary design achieves a beamwidth both along and cross track of approximately 30 degrees even at 0.5 GHz. Higher antenna gain and narrower beam width can be achieved by increasing the antenna height

Table 2: Instrument Specifications

Volume	40” (height), 40” (width), 40” (length) for electronics
Environment	Antenna operable at ambient environment at up to 32 kft altitude and 400 mph airspeed Electronics designed for Twin Otter cabin conditions
Weight	Less than 300 lbs
Power	28 VDC, 90 amp max or 115 VAC, 60-400Hz, 21 A max
Control	Data acquisition computers have network interface; simple operator in-flight interface
Data	Continuously measures radiometer returns in 15 channels @ 100 msec integration time; internal storage for 100 hours of flight
GPS	GPS time server to provide time synchronization/location. Connection to external GPS antenna

and the number of spiral turns. Studies in year one of the project will optimize the design in accordance with aircraft accommodation requirements, and full aircraft impact studies will be performed. The proposed location for the antenna is the Twin Otter central “camera” port with post-takeoff deployment. The year one antenna development will include fabrication of a scaled-down antenna prototype that will be mounted on a scaled aircraft; measurements of the resulting gain and pattern will be performed inside the OSU compact range. Two full scale antennas (one backup) will then be fabricated and tested in year 2. The project team has extensive past experience with wideband antenna development (e.g. Chen et al, 2003), and will leverage in-house design, computational, and test facilities to ensure successful antenna development.

2.5.6 System Integration and Target Platforms

Individual subsystems will be tested throughout the project as they are implemented to ensure that performance and interface requirements (as defined by the project engineering team) are met. Integration of subsystems will take place upon successful test completion by the subsystems, and will occur at The Ohio State University. The integrated system will also undergo testing in a laboratory environment to ensure functionality. The integrated UWBRAD system will be deployed in ground-based sky observations at OSU to produce the first UWBRAD dataset for characterizing system performance. Sub-system test activities and project system engineering efforts will greatly reduce risk in the integration stage, and the experience of the project team with previous developments has defined sufficient task intervals to address any problems that may arise in the UWBRAD implementation. These activities will allow considering potential opportunities for transition to future deployment on airborne platforms other than the Twin Otter (including the NASA P-3 and DC-8 platforms). Table 2 provides estimated system specifications, which are compatible (size/volume accommodation, power requirements, thermal environment, etc.) with the Twin Otter, P-3, and DC-8 platforms.

We anticipate field tests of the instrument and inversion algorithms in 2016. While some uncertainty is present in current planning for 2016 operations, our nominal plan is to perform observations of deep ice core validation sites in Greenland (see Figure 3) on board a Twin Otter aircraft operated by Twin Otter International (headquartered in Grand Junction, CO). Twin Otters are routinely used in Greenland and Antarctica to support scientific research, and provide desirable low cost flight operations and extensive availability. We propose 24 science flight hours to enable coverage of ice core validation sites (particularly those in the “dry” ice sheet regions) as well as exploration of brightness temperatures in the “water table” portions of Southern Greenland. Discussions with Twin Otter International confirm that such flights are within the aircraft capabilities particularly given the Greenland “Summit Camp” refueling station. A system test flight based in Grand Junction is also proposed to ensure system operations before the Greenland deployment. Other potential opportunities that could modify this plan include the potential to cooperate with NASA's Operation IceBridge (OIB), which flies the NASA P-3 from McMurdo, Antarctica. OIB will conduct its first flights from McMurdo this coming year and there is much operational uncertainty associated with this first deployment to the ice runway, so that a commitment to 2016 operations is difficult at present. NASA DC-8 flights from Punta Arenas Chile also could be another partnering opportunity with OIB.

These test flights in general will be designed to verify fully system functionality and to provide useful science observations to evaluate multi-frequency temperature retrieval algorithms. Validation studies will include both forward model assessment and refinement as well as temperature retrieval performance studies. After successful validation of the approach through ice core-site matchups, extended area maps of temperature information will be produced as an indicator of UWBRAD science value and potential.

The final year of the project will also include a plan for future extended science operations and an assessment of technology transition into space. Several challenges for spaceborne operation clearly exist, including the influence of the Earth's ionosphere at lower frequencies, a more challenging RFI environment, and requirements for increased antenna directivity from space. Assessment of the science performance with a reduced frequency range (e.g. 1.4 GHz combined with one other channel) will also be conducted for future space applications. The potential use of similar technologies for the exploration of ice sheets on other solar system planetary bodies will also be addressed.

2.6 Comparative Technology Assessment

UWBRAD will bring unprecedented capabilities for ice sheet internal temperature sensing; no other system exists for providing such measurements over large spatial scales. UWBRAD will therefore open new avenues for ice sheet science and ice sheet dynamics studies. UWBRAD will also be applicable to deep surface soil moisture measurements or snow thickness measurements; extensions to these applications will be considered in the final year of the project.

While radiometer systems operating in the protected portion of L-band (e.g. SMOS, Aquarius, SMAP) do provide partial temperature information, the use of multi-frequency radiometry is a unique UWBRAD aspect that will enhance temperature information retrieval. UWBRAD's use of full channel digitization is similar to that of JPL's IBOB receiver (Misra et al, 2013), the GREX instrument of NASA GSFC (Bradley et al, 2012), and other JPL radiometer research (NASA Tech Briefs, 2012). However none of these instruments achieve digitization of a 1.5 GHz channel bandwidth, perform real-time RFI detection and mitigation, or are developed for ice sheet internal temperature measurements. The wideband autocorrelation radiometry proposed in (England, 2013) is based on the use of higher frequencies for thickness sensing of snowpacks of thickness ~10 m or less. The temporal autocorrelation features sought in such approaches are also available to UWBRAD either in terms of temporal autocorrelation functions of the thermal noise or in terms of oscillations in the brightness temperature as a function of frequency.

2.7 TRL Assessment

Many of the component innovations of UWBRAD have been demonstrated in part, and recent analyses have shown the clear potential for ice sheet temperature sensing. Therefore a TRL of 3 is assessed as the overall entry point. Project activities in years 1 and 2 will advance the system to TRL 4 through subsystem and laboratory tests. A final exit at TRL 5 will be achieved following successful flight demonstration of ice sheet internal temperature measurements. Additional TRL assessments for individual UWBRAD aspects are listed in Table 3.

Table 3: UWBRAD TRL Assessment

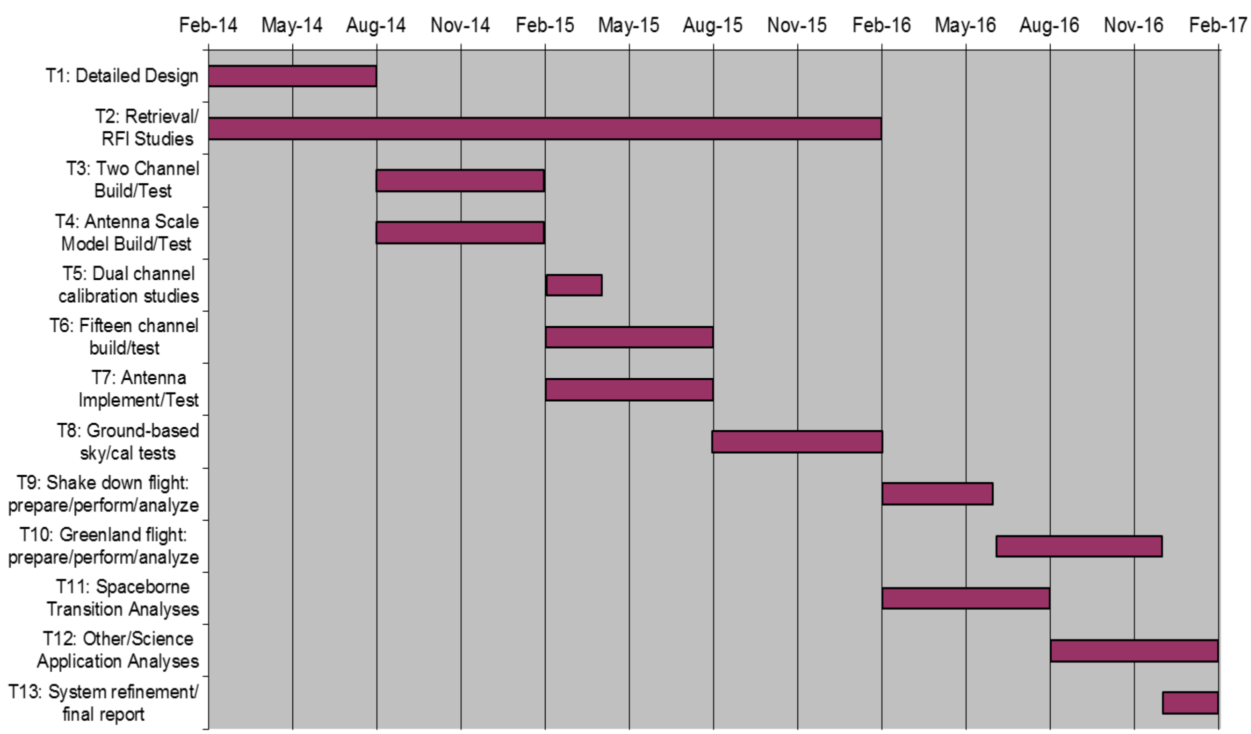
Technology	Heritage	Entry TRL	Planned Exit TRL	Success Criteria
Icesheet Subsurface Temperature Sensing	Analyses and SMOS radiometry	3	5	Successful airborne demonstration
Multi-frequency 0.5-2 GHz radiometry	MFRAD System (37 channels, 2-18 GHz)	3	4	Subsystems integration and ground test
			5	Successful airborne demonstration
Software defined radiometry with real-time RFI processing	Previous FPGA-based RFI processors; JPL's IBOB and GSFC GREX Systems	3	4	Demonstration in ground test
			5	Successful airborne demonstration

2.8 Research Management Plan

2.8.1 Statement of Work

The project will begin with a detailed design study (Task 1) supported by science retrieval and RFI algorithm analyses (Task 2) in year 1. A two channel system will be implemented and tested in Q3/Q4 of year 1 (Task 3), along with a scale model of the antenna (Task 4). Two channel system performance will be verified through calibration studies (Task 5) early in year two, which will occur in parallel with implementation and test of the fifteen channel system (Task 6) and full scale antenna (Task 7). Ground-based sky observation and calibration test of the fifteen channel system with antenna (Task 8) will then occur in Q3/Q4 of year two. Year three will focus on shakedown flight (Task 9) and Greenland demonstration (Task 10) activities, in combination with analyses of transition into space (Task 11) and extended science/other applications (Task 12). Final system refinements and analyses will be provided in the project final report (Task 13).

2.8.2 Schedule



2.8.3 Personnel and management plan

The development of UWBRAD will be a low-risk activity due to the previous experience of project participants with the component technologies and science methods. **Prof. Joel T. Johnson** of Ohio State University will serve as the lead PI, and will supervise all project activities and ensure that all goals and reporting requirements are met on schedule. Prof. Johnson has 20 years of experience in conducting microwave remote sensing research, including the development of sensor hardware for a variety of applications. He has previously served as the lead or co-PI on 2 IIP projects and a subsequent AITT program that has successfully transitioned new RFI mitigation technology into the SMAP mission. Science PI **Prof. Ken Jezek** will lead science impact and retrieval studies, and is an expert in glaciology and co-science lead for the Operation Ice Bridge mission. Co-I **Prof. C. C. Chen** of Ohio State will serve as the lead engineer for the antenna subsystem, and brings his extensive experience in ultrawideband antenna design to the project. Co-I **Prof. Leung Tsang** of U. Washington is an expert in modeling thermal emission in polar regions, and will support retrieval studies for the instrument design. Co-I **Prof. Michael Durand** of Ohio State has extensive experience in the retrieval of snowpack parameters from radiometer measurements, and will support UWBRAD retrieval algorithm studies. Collaborator **Dr. Giovanni Macelloni** of CNR- Italy is an expert in radiometric ice sheet observations, and will provide advice and guidance on data analysis. The team will be further supported by **four graduate students** (3 OSU, 1 U. Washington), a **senior research associate** (digital subsystem lead), and a **technician**. In addition, **Dr. V. Leuski** will be contracted for support of UWBRAD RF subsystem integration. The team will also implement Continuous Risk Management (CRM) in a manner consistent with standard practice.

Individual project teams (RF, Digital, Antenna, and Science/Retrieval) will conduct weekly meetings, with an entire team telecon conducted bi-weekly. Annual interim and full-year reviews will also be conducted with dates/locations determined in coordination with ESTO.

2.8.4 Facilities and Equipment

Project activities will be conducted at the Ohio State University and at The University of Washington. All necessary laboratories and facilities are available to conduct the required investigations. The ElectroScience Laboratory of Ohio State maintains extensive RF test and evaluation facilities and a compact range measurement facility that is available for scale model antenna tests. Computer resources for design and data analysis are also available.

2.9 Special Matters

OSU team members will conduct their work at The Ohio State University ElectroScience Laboratory (ESL), a center of excellence in radio frequency technologies, sensor implementation, and antenna design and fabrication, and at the Byrd Polar Research Center (BPRC), a center of international excellence in polar studies. Team members at ESL have completed several successful airborne sensor deployments in recent years, including the high altitude WB-57 platform. Project team members at the University of Washington are leading experts in modeling microwave sensor responses and will utilize this expertise to create robust forward models for UWBRAD observations.

2.10 Foreign Participation

Participation of foreign collaborator G. Macelloni of CNR-Italy will be limited to science observation planning and data analysis. Any foreign graduate students will also not participate in spaceborne transition analyses. No detailed information on spaceborne hardware will be shared with any foreign participants. Information will be handled and protected in accordance to applicable legislation (ITAR, Patent Office, Copyright, etc.).

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