IceBridge MCoRDS L1B Geolocated Radar Echo Strength Profiles, Version 2

USER GUIDE

How to Cite These Data

As a condition of using these data, you must include a citation:

Paden, J., J. Li, C. Leuschen, F. Rodriguez-Morales, and R. Hale. 2014, updated 2019. *IceBridge MCoRDS L1B Geolocated Radar Echo Strength Profiles, Version 2*. [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.5067/90S1XZRBAX5N. [Date Accessed].

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1 DETAILED DATA DESCRIPTION

The data set includes measurements for echograms, time, latitude, longitude, and elevation, as well as flight path charts and echogram images.

1.1 Format

The data files are in netCDF format. The echogram and flight path image files are JPEG files.

Each data file is paired with an associated XML file, which contains additional metadata.

Echogram.jpg files contain depth echograms. The echograms are useful for tracking internal layers and shallow ice thicknesses.

Map.jpg files show campaign flight locations and flight lines.

The y-axis in the JPEG files shows depth relative to a range around the surface. The surface is in the center of the y-axis and the y-axis is set to a fixed range, usually from 0 meters to 60 or 80 meters for the land ice, and 0 meters to 4 meters for sea ice.

The radar data are divided into segments. A segment is a contiguous data set in which the radar settings do not change. A day is divided into segments if the radar settings were changed, hard drives were switched, or other operational constraints required that the radar recording be turned off and on. The segment ID is YYYYMMDD_SS where YYYY is the four-digit year (e.g. 2011), MM is the two-digit month from 1 to 12, DD is the two-digit day of the month from 1 to 31, and SS is the segment number from 0 to 99. Segments are always sorted in the order in which the data was collected. Generally SS starts with 1 and increments by 1 for each new segment, but this is not always the case; only the ordering is guaranteed to match the order of data collection.

Each segment is broken into frames, analogous to satellite SAR scenes, to make analyzing the data easier. Most frames are 50 km long, but some may be longer or shorter so the breaks between frames lie at convenient locations. For example, if a grid is flown, the frames are aligned from adjacent lines. Once the frame boundaries are defined, they will not change from one release to the next or one processing method to the next. The frame ID is a concatenation of the segment ID and a frame number and follows the format YYYYMMDD_SS_FFF where FFF is the frame number from 000 to 999. Generally the FFF starts with 0 or 1 and increments by 1 for each new frame, but this is not always the case; only the ordering is guaranteed.

Frames may overlap slightly so data are duplicated where the overlap occurs. GPS time can be used to remove redundant data from the overlapped sections.

1.2 File Naming Convention

Example file names:

`IRMCR1B_20130426_01_063.nc`

`IRMCR1B_20130426_01_063_Echogram.jpg`

Files are named according to the following convention and described in more detail in Table 1.

`IRMCR1B_YYYYMMDD_xx_xxx.NNN`

`IRMCR1B_YYYYMMDD_xx_xxx_aaa.jpg`

Table 1. File Naming Convention

Variable	Description
`IRMCR1B`	Data set ID
`YYYY`	Four-digit year of survey
`MM`	Two-digit month of survey
`DD`	Two-digit day of survey
`xx`	Segment number
`xxx`	Frame number
`aaa`	Image type. Examples: Echogram, Echogram Picks, or Map (only used in JPEG file names)
`NNN`	Indicates file type. For example: netCDF (.nc), JPEG (.jpg), or XML (.xml)

1.3 Spatial Coverage

Spatial coverage for the IceBridge MCoRDS campaigns includes Antarctica and Greenland.

Antarctica:
Southernmost Latitude: 90° S
Northernmost Latitude: 63° S
Westernmost Longitude: 180° W
Easternmost Longitude: 180° E

Greenland:
Southernmost Latitude: 59° N
Northernmost Latitude: 83° N
Westernmost Longitude: 74° W
Easternmost Longitude: 12° W

1.3.1 Spatial Resolution

Spatial Resolution varies dependent on along-track, cross-track, and aircraft height characteristics. See the Derivation Techniques and Algorithms section for further detail on resolution and bandwidth.

1.3.2 Projection and Grid Description

Referenced to WGS-84 Ellipsoid.

1.4 Temporal Coverage

12 October 2012 to 16 November 2018

1.4.1 Temporal Resolution

IceBridge campaigns are conducted on an annually repeating basis. Arctic and Greenland campaigns are typically conducted in March, April, and May; Antarctic campaigns are typically conducted in October and November.

1.5 Parameter or Variable

This data set contains elevation, surface, and bottom measurements.

1.5.1 Parameter Description

The MCoRDS Radar netCDF files contain fields as described in Table 2.

Table 2. File Parameter Description

Parameter	Description	Units
Bottom	Two way travel time to bottom used during processing. Not the final picked bottom.	Seconds
Surface	Estimated two way propagation time to the surface from the collection platform. This uses the same frame of reference as the fasttime variable. This information is sometimes used during truncation to determine the range bins that can be truncated. Dimension is time.	Seconds
altitude	WGS-84 geodetic elevation coordinate of the measurement's phase center. Dimension is time.	Meters

Parameter	Description	Units
amplitude	Power detected radar echogram data matrix. The first dimension is fasttime and time is the second dimension. Power is relative to the current range line only. Each range line may contain a different bias and so power comparisons between range lines may not be possible.	Relative power (log scale)
fasttime	Fast time. Zero time is the time at which the transmit waveform begins to radiate from the transmit antenna.	Microseconds
fasttime_dim	This is a netCDF dimension but not a netCDF variable.	n/a
heading	Platform heading attitude (zero is north, positive to east). Dimension is time.	Degrees
lat	WGS-84 geodetic latitude coordinate of the measurement's phase center. Always referenced to North. Dimension is time.	Degrees
lon	WGS-84 geodetic longitude coordinate of the measurement phase center. Always referenced to East. Dimension is time.	Degrees
pitch	Platform pitch attitude (zero is level flight, positive is up). Dimension is time.	Degrees
roll	Platform roll attitude (zero is level flight, positive is right wing tip down). Dimension is time.	Degrees
time	UTC time of day. This is also known as the slow time dimension. The parameter "units" attribute contains a string of the form seconds since YYYY-MM-DD 00:00:00 which indicates the day related top this time parameter. This pertains to data sets that wrap over a UTC day boundary which will cause this parameter to be outside the range [0,86400].	Seconds

2 SOFTWARE AND TOOLS

CReSIS netCDF files are compatible with HDF5 libraries, and can be read by HDF readers such as HDFView. If the netCDF file reader you are using does not read the data, see the UCAR Unidata netCDF page and the NetCDF Resources page at NSIDC for more information.

CReSIS MATLAB readers are available for loading, plotting, and elevation compensation for CReSIS Level-1B radar products. These tools are provided by the Principal Investigator as a service to the user community in the hope that they will be useful. Please note that support for these tools is limited. Bug reports, comments, and suggestions for improvement are welcome and should be sent to nsidc@nsidc.org.

JPEG files may be opened using any image viewing program that recognizes the JPEG file format.

XML files can be read with browsers such as Firefox and Internet Explorer.

2.1 Quality Assessment

The high altitude data are generally lower quality than the low altitude data. This is because:

1. The cross-track antenna resolution is proportional to range creating severe layover problems in mountainous terrain.
2. The sidelobes from the 30 microsecond pulse duration mask out some of the returns that otherwise would have had a high enough signal to noise ratio.
3. The range to target is greater so the spherical spreading power loss is greater leading to a lower signal to noise ratio.

3 DATA ACQUISITION AND PROCESSING

For the standard processing output, the receiver-array elements are combined using boxcar or Hanning weights, depending on the frame.

Some of the results are processed through an improved array processing algorithm. The receiver-array elements are combined using the minimum variance distortionless response algorithm which provides improved cross-track clutter rejection. Cross-track clutter rejection is important because the footprint of the antenna array is very large in the cross-track dimension.

3.1 Theory of Measurements

When a pulse of RF energy is transmitted into the ice sheet, a portion of the energy is reflected from the ice surface, ice bottom, and any englacial targets; generally anywhere there is a contrast in the electromagnetic constitutive properties of the media. To detect the ice bottom, lower frequencies are used because they do not attenuate as quickly through ice (Paden, 2005).

Ice thickness is typically determined using data collected from waveforms with different pulse durations. Generally all receive channels are used to produce the best result. The difference in the propagation time between the ice surface and ice bottom reflections is then converted into ice thickness using an estimated ice index of refraction of ice (square root of 3.15). The media is assumed to be uniform, that is, no firn correction is applied. The specific measurement setups for four data collection modes are described in the Data Acquisition section for the four different data collection scenarios. See also the related MCoRDS Level 2 data set, *IceBridge MCoRDS L2 Ice Thickness*.

3.1.1 Dynamic Range

The signal from the ice surface is typically much larger than the signal from the ice bottom. This is because of the attenuation of RF signals in ice. Generally speaking this requires that different receiver gains are used to capture these signals. Three methods have been used by the radar systems.

The Sensitivity Timing Control (STC) is a fast-time gain control where the receiver gain is modified in real-time as the echoes are received. The original sensitivity timing control used a hand dial to control the STC and the STC was analog (not discrete). Radiometric calibration of the data is nearly impossible with these data sets.

Low and high gain channels means that two separate recordings of the data are made: one with low receiver gain and one with high receiver gain. It provides the most flexible and best quality dynamic range, but generally doubles the data rate and much of the hardware must be duplicated to capture two channels.

A waveform playlist allows low and high gain channels to be multiplexed in time. The low gain channel typically requires fewer integrations to be useful and so only a small penalty is paid for time multiplexing. If time was split equally it would be 3 dB, but typical configurations lose less than 1 dB of sensitivity. Alternatively, two waveforms, one with a short pulse duration and one with a long pulse duration, generally provide better coverage than a single pulse duration. The short pulse duration is used for close-in targets that typically do not require high sensitivity and so this waveform doubles as the low gain channel and effectively no penalty is paid for time multiplexing the gain settings. For example, a waveform with a 1-μs duration and lower receiver gain settings is used to measure the round-trip signal time for the ice surface echo, while a waveform with a 10-μs duration and higher receiver gain settings is used to measure the round-trip signal time for the ice bottom echo. As stated above, the two different waveforms are used because of the large dynamic range of signal powers that are observed. The 10-μs duration and higher receiver gain settings are more sensitive to the bottom echo, but the signal is generally saturated and unusable from the ice surface and upper internal layers.

For high altitude data, the difference in power between the ice surface and ice bottom is small enough that a single high gain setting is possible.

3.2 Data Acquisition Methods

3.2.1 P-3 Low Altitude

A waveform with a 1-μs duration and lower receiver gain settings is used to measure the round-trip signal time for the surface echo, while a waveform with a 10-μs duration and higher receiver gain settings is used to measure the round-trip signal time for the bed echo. The two different waveforms are used because of the large dynamic range of signal powers that are observed. The

10-μs duration and higher receiver gain settings are more sensitive to the bed echo, but the signal is generally saturated from the ice surface and upper internal layers.

3.2.2 DC-8 Low Altitude

The same concept is used as for the P-3. However, during the first two field seasons (2009 Antarctica DC-8 and 2010 Greenland DC-8), extra antennas inside the cabin were used to detect the ice surface delay time because the Transmit/Receive (TR) switches did not meet their switching time specification. The TR switches have not been fixed in subsequent field seasons, but the TR switch control signals have been set so that the surface echo is generally still detectable, although with diminished power, even for very low altitudes down to 600 feet Above Ground Level (AGL).

3.2.3 P-3 High Altitude and DC-8 High Altitude

The dynamic range between the ice surface and ice bottom echoes is much smaller and a single high-gain and long pulse duration waveform is used to capture both echoes.

3.3 Derivation Techniques and Algorithms

3.3.1 Range Resolution

The range resolution, defined as the minimum range difference to distinguish the return power from two targets with 16 dB of isolation, is determined as:

$$\frac{K_t c}{2\mathrm{B}\sqrt{\varepsilon_{\mathrm{r,ice}}}}$$

(Equation 1)

Where:

Table 3. Flat Surface Depth Resolution

Variable	**Description**
k_t	Window widening factor. 0.88 for no windowing and 1.53 for 20% Tukey time-domain window on transmit and receive and a Hanning frequency-domain window on receive.
c	Speed of light in a vacuum
B	Bandwidth
$\varepsilon_{r,ice}$	3.15, the approximate dielectric of ice

The window widening factor is computed numerically. Windowing is applied to improve the isolation between targets at different ranges, but causes the resolution to become worse.

Table 4 gives the range resolution for several bandwidths.

Table 4. Range Resolution

Bandwidth (MHz)	**Range Resolution without Windowing (m)**	**Range Resolution with Windowing (m)**
9.5	7.8	13.6
10	7.4	12.9
17.5	4.2	7.4
20	3.7	6.5
30	2.5	4.3
150	0.5	0.9
180	0.4	0.7

If there is only one target, the range accuracy to that one target is dependent on the Signal to Noise Ratio (SNR), and is given by:

$$\frac{K_t c}{2\mathrm{B}\sqrt{\varepsilon_{\mathrm{r,ice}}}\sqrt{2\cdot \mathrm{SNR}}}$$ **(Equation 2)**

Table 5 repeats Table 4 with SNR of 20 dB.

Table 5. Range Resolution - One Target

Bandwidth (MHz)	**Range Resolution without windowing (m)**	**Range Resolution with windowing (m)**
9.5	0.55	0.96
10	0.53	0.91
17.5	0.30	0.52
20	0.26	0.46
30	0.18	0.30
150	0.04	0.06
180	0.03	0.05

3.3.2 Along-track Resolution

The along-track resolution depends on the processing. The default processing parameters since March 1, 2012 are described here. For the Single Look Complex (SLC) SAR-processed image (not quick look), a fixed along-track resolution of σx,SLC = 5 m is used. The final product has 11 along-track looks and 1 range look and is then decimated by 6. Therefore, the final product has an along-track resolution of σx = 55 m and a sample spacing of 30 m. The synthetic aperture length, L, is approximately:

$$L \approx \frac{\lambda_c \left(H + T / \sqrt{\varepsilon_{\mathrm{r,ice}}}\right)}{2\sigma_{x,SLC}} K_x$$

(Equation 3)

Where:

Table 6. Synthetic Aperture Length

Variable	Description
λ_c	wavelength at the center frequency
H	height above the air/ice interface
T	ice thickness
$\varepsilon_{r,ice}$	3.15, the approximate dielectric of ice
K_x	1.1, the along-track windowing factor for a 20% tukey window
$\sigma_{x,SLC}$	5 m fixed along track resolution

The Doppler beam width, βx, used in the SAR processing is approximately:

$$\beta_x \approx \frac{\lambda_c}{2\sigma_{x,SLC}} K_x = 9.7 \ \text{deg}$$

(Equation 4)

3.3.3 Cross-track Resolution

While the range and along-track position are known with fine resolution, the cross-track resolution is poor. For a rough surface, the off-nadir echoes can mask the nadir echo and an off-nadir return may be selected as the ice bottom rather than the nadir return. The best case is to have crossovers in the dataset so you can estimate the precision of the ice bottom layer picks.

For a smooth surface with no appreciable roughness, the cross-track resolution is constrained to the first Fresnel zone, which is approximately:

$$\sigma_{y,\mathrm{Fresnel-limited}} = \sqrt{2\left(H + T / \sqrt{\varepsilon_{\mathrm{r,ice}}}\right)\lambda_c}$$

(Equation 5)

Where:

Table 7. Smooth Surface Cross-track Resolution

Variable	Description
H	height above the air/ice interface
T	ice thickness
$\varepsilon_{r,ice}$	3.15, the approximate dielectric of ice
λ_c	wavelength at the center frequency

Table 8 gives the cross-track resolution for several frequencies.

Table 8. Cross-track Resolution

Center Frequency (MHz)	Cross-track Resolution H = 500 m T = 2000 m (m)	Cross-track Resolution H = 8000 m T = 2000 m (m)
125	88.3	209.2
150	80.6	191.0
195	70.7	167.5
210	68.2	161.4

For a rough surface with no appreciable layover, the cross-track resolution is constrained by the pulse-limited footprint, which is approximately:

$$\sigma_{y,\text{pulse-limited}} = 2\sqrt{\frac{\left(H + T/\sqrt{\varepsilon_{\text{r,ice}}}\right)cK_t}{B}}$$ **(Equation 6)**

Where:

Table 9. Rough Surface Cross-track Resolution

Variable	Description
H	height above the air/ice interface
T	ice thickness
$\varepsilon_{r,ice}$	3.15, the approximate dielectric of ice
c	speed of light in a vacuum
K_t	window widening factor
B	bandwidth

Table 10 gives the cross-track resolution with windowing.

Table 10. Cross-track Resolution with Windowing

Bandwidth (MHz)	Cross-track Resolution $H = 500$ m $T = 2000$ m (m)	Cross-track Resolution $H = 500$ m $T = 8000$ m (m)
9.5	561	1328
10	546	1294
17.5	413	978
20	386	915
30	315	747
150	141	334
180	129	305

For a rough surface where layover occurs, the cross-track resolution is set by the beamwidth βy of the antenna array. The antenna beamwidth is approximately:

$$\beta_y = \sin^{-1} \frac{\lambda_c}{N d_y}$$ **(Equation 7)**

Where:

Table 11. Rough Surface with Layover Cross-track Resolution

Variable	Description
B_y	beamwidth of antenna array
λ_c	wavelength at the center frequency
N	number of elements
d_y	element spacing

Table 12 gives the beamwidth for the various platforms.

Table 12. Beamwidth for Various Platforms

Platform	N	d_y (λ_c)	Beamwidth (deg)
P-3 original	4	0.5	30.0
TO	4	0.5	30.0
TO	5	0.5	23.6
TO	6	0.5	19.5
P-3 new (center-array only)	7	0.5	16.6
DC-8	5	0.25	53.1

3.3.4 Antenna Beamwidth

The antenna beamwidth-limited resolution is:

$$\sigma_{y,\text{beamwidth-limited}} = 2\left(H + \frac{T}{\sqrt{\varepsilon_{\text{r,ice}}}}\right)\tan\left(\frac{\beta_y K_y}{2}\right)$$

(Equation 8)

Where:

Table 13. Antenna Beamwidth-limited Resolution

Variable	**Description**
H	height above the air/ice interface
T	ice thickness
$\varepsilon_{r,ice}$	3.15, the approximate dielectric of ice
β_y	beamwidth of antenna array in radians
K_y	K_y = 1.3, the approximate cross-track windowing factor for a Hanning window applied to a small cross-track antenna array.

Examples of antenna beamwidth-limited resolution are shown in Table 14.

Table 14. Antenna Beamwidth-limited Resolution

Platform	***N***	**d_y (λ_c)**	**Cross-track Resolution H = 500 m T = 2000 m**	**Cross-track Resolution H = 500 m T = 8000 m**
P-3 original	4	0.5	1152	3546
TO	4	0.5	1152	3546
TO	5	0.5	893	2747
TO	6	0.5	732	2252
P-3 new (center-array only)	7	0.5	620	1909
DC-8	5	0.25	2237	6887

3.3.5 Dielectric Error

The dielectric error is expected to be on the order of one percent for typical dry ice (Fujita et al., 2000) and no compensation has been done for a firn layer in SAR processing where the ice is treated as a homogeneous medium with a dielectric of 3.15. The dielectric error using the first term of the Taylor series creates an ice thickness dependent error given by:

$$\Delta T = \frac{-T}{2}\varepsilon_{\%\mathrm{error}} = \frac{-T}{200}$$ **(Equation 9)**

So for an ice thickness of T = 2000, a one percent dielectric error creates a 10 m thickness error.

3.3.6 System Loop Sensitivity

The system loop sensitivity is the SNR with no channel losses (spreading loss, extinction, and backscattering), which is:

$$SNR = \frac{P_t (N_c G \lambda_c)^2 N_{ave} B T_{pd}}{4\pi k T B F \cdot \mathrm{m}^2}$$ **(Equation 10)**

Where:

Table 15. System Loop Sensitivity

Variable	**Description**
P_t	total transmit power including system losses
N_c	number of channels on transmit and receive used in echogram formation
G	individual antenna element accounting for the ground plane
λ_c	wavelength at the center frequency in air
N_{ave}	approximate number of pulses that may be averaged in SAR processing and presumming
B	bandwidth
T_{pd}	pulse duration
k	1.38e-23 WsK^{-1}, Boltzmann's constant
T	290 K, the approximated noise temperature before the receiver
F	2, the approximate noise figure of the receiver
m^2	1 meter squared to cancel out units

System loop sensitivity values are shown in Table 16.

Table 16. Loop Sensitivity Values

Platform	P_t	N_c	**G**	N_{ave}	T_{pd} **(Âµs)**	λ_c**(m)**	**Loop Sensitivity (dB)**
MCORDS DC-8	300	5	1	3200	10	1.54	220
MCORDS P-3	166	7	4	3200	10	1.54	230
MCORDS Twin Otter (150 MHz)	300	6	4	3200	10	2	233
MCRDS TO	300	6	4	3200	10	1.54	231

3.3.7 Processing Steps

The following processing steps are performed by the data provider.

1. Conversion from quantization to voltage at the 50 ohm antenna.
2. Removal of DC-bias by subtracting the mean from each record.
3. Channel compensation between each of the antenna phase centers. This includes time delay, amplitude, and phase mismatches. The channel equalization coefficients are found by monitoring the relative returns from each channel from the ocean surface at high altitude, smooth bed returns, and deep internal layers.
4. Pulse compression with time and frequency domain windows. Before the 2009 Antarctica DC-8 campaign, the transmitted pulse had a boxcar window. From 2009 Antarctica DC-8 and forward, all transmitted pulses typically have a 20 percent Tukey window applied in the time domain. The matched filter applied to the received signal is identical to the transmitted waveform, typically assuming an ideal transmission, with a frequency domain window applied. The frequency domain window is usually a boxcar or Hanning window.
5. Motion compensation for attitude and trajectory lever arm.
6. SAR processing with along-track spatial frequency window using f-k migration. The dielectric model for f-k migration is always a layered media with variation in the z-axis only.
7. Channel combination. Currently, channel combination usually combines channels within a sub-array. Standard SAR processed output applies a normalized array window before summing channels. Minimum Variance Distortionless Response (MVDR) algorithm is used for channel combination, and the spatial correlation matrix is estimated from a neighborhood of pixels surrounding the image pixel being combined. Channel combination also includes multi-looking or spatial incoherent power averaging followed by along-track decimation.
8. Waveform combination. Echograms from low and high gain channels are combined to form a single image. Generally combination is done Tpd seconds after the surface return where Tpd is the pulse duration of the transmitted chirp.

3.3.8 Version History

Version 1: Currently IceBridge MCoRDS L1B Geolocated Radar Echo Strength Profiles (IRMCR1B) data for 2009 through the 2012 Greenland campaign are in binary format stored separately as IRMCR1B Version 1. For details on the IRMCR1B Version 1 data, see the Version 1 documentation.

Version 2: Beginning with the 2012 Antarctica campaign, all data are provided in netCDF format. In the near future, data from all campaigns prior to 2012 Antarctica will be replaced with netCDF data and added to Version 2.

3.3.9 Error Sources

GPS Time Error:
The CReSIS accumulation, snow, MCoRDS, and kuband data acquisition systems have a known issue with radar data synchronization with GPS time. When the radar system is initially turned on, the radar system acquires UTC time from the GPS National Marine Electronics Association (NMEA) string. If this is done too soon after the GPS receiver has been turned on, the NMEA string sometimes returns GPS time rather than UTC time. GPS time is 15 seconds ahead of UTC time during this field season. The corrections for the whole day must include the offset (-15 second correction). GPS corrections have been applied to all of the data using a comparison between the accumulation, snow, and kuband radars which have independent GPS receivers. A comparison to geographic features and between ocean surface radar return and GPS elevation is also made to ensure GPS synchronization. GPS time corrections are given in the vector worksheet of the Parameter Spreadsheet.

A time stamp error was discovered in the 2012 Antarctica and 2013 Greenland data. The latest leap second (July 1, 2012) was not accounted for in the GPS times for these campaigns.

The error affects Version 2 of the Level 1B CReSIS data sets. MCoRDS data are affected for the time period: October 2012–2014. In the near future, the NSIDC DAAC will publish updated data files with a correction to the 'Time' field.

Additional Error Sources:
The data are not radiometrically calibrated. This means that they are not converted to some absolute standard for reflectivity or backscattering analysis. The MCoRDS science team is working on data processing and hardware modifications to do this.

The primary error sources for ice penetrating radar data are system electronic noise, multiple reflectors also known as multiples, and off-nadir reflections. Each of these error sources can create spurious reflections in the trace data leading to false echo layers in profile data. Multiple reflectors arise when the radar energy reflects off three surfaces back-and-forth in the vertical dimension, and then returns to the receive antenna. They occur in situations when multiple surfaces are present with high impedance, such as the upper surface (air/ground), the base of the ice or an ice-water interface, and the aircraft body which is also a strong reflector. The radar receiver only records time since the radar pulse was emitted, so the radar energy that traveled the additional path length appears later in time, apparently deeper in the ice or even below the ice-bedrock interface. Note that multiples of a strong continuous reflector have a similar shape but all slopes appear magnified, that is, doubled in the simplest geometric cases, relative to the main reflection.

Off-nadir reflections can result from crevasse surfaces, water, rock outcrops, or metal structures. Antenna beam structure and processing of the MCoRDS system are designed to reduce these off-nadir reflected energy sources.

For Standard processing output from Waveform One only, for thin ice, the longer pulse duration of the high gain waveform may mean that sidelobes from the surface echo mask the bottom return. In these cases, Waveform Two, with short pulse duration, can provide a better measurement.

3.4 Sensor or Instrument Description

As described on the CReSIS Sensors Development Radar Page, the Multichannel Coherent Radar Depth Sounder operates over a 180 to 210 MHz frequency range with multiple receivers developed for airborne sounding and imaging of ice sheets. Measurements are made over two frequency ranges: 189.15 to 198.65 MHz, and 180 to 210 MHz. The radar bandwidth is adjustable from 0 to 30 MHz. Multiple receivers permit digital beamsteering for suppressing cross-track surface clutter that can mask weak ice-bed echoes and strip-map SAR images of the ice-bed interface. These radars are flown on twin engine and long-range aircraft including NASA P-3, Twin Otter (TO), and DC-8.

All radar and processing settings are stored in the MATLAB and netCDF files. GPS time corrections and frames where no good sync information was available are given in the vector worksheet in the Parameter Spreadsheet.

4 REFERENCES AND RELATED PUBLICATIONS

Akins, Torry Lee. 1999. *Design and development of an improved data acquisition system for the coherent radar depth sounder*, Department of Electrical Engineering and Computer Science: Master's Thesis, University of Kansas.

Allen, Christopher, Lei Shi, Richard Hale, Carl Leuschen, John Paden, Benjamin Panzer, Emily Arnold, William Blake, Fernando Rodriguez-Morales, John Ledford, Sarah Seguin. 2011. Antarctic Ice Depth Sounding Radar Instrumentation for the NASA DC-8, submitted for publication to *IEEE Transactions on Aerospace and Electronic Systems*, August 2011.

Blake, W., J. Ledford, C. Allen, C. Leuschen, S. Gogineni, F. Rodriguez-Morales, Lei Shi. 2008. A VHF Radar for Deployment on a UAV for Basal Imaging of Polar Ice. *Geoscience and Remote Sensing Symposium*. IGARSS 2008. IEEE International, 4: IV-498-IV-501, doi: 10.1109/IGARSS.2008.4779767.

Byers, K. J. 2011. *Integration of a 15-Element, VHF Bow-Tie Antenna Array into an Aerodynamic Fairing on a NASA P-3 Aircraft*, Department of Electrical Engineering and Computer Science: Master's Thesis, University of Kansas.

Byers, Kyle J., A. R. Harish, Sarah A. Seguin, Carlton Leuschen, Fernando Rodriguez-Morales, John Paden, Emily Arnold and Richard Hale. 2011. A Modified Wideband Dipole Antenna for an Airborne VHF Ice Penetrating Radar, submitted to *IEEE Transactions on Instrumentation and Measurement*, June 2011.

Chuah, T. S. 1997. Design and Development of a Coherent Radar Depth Sounder for Measurement of Greenland Ice Sheet Thickness, *CReSIS Technical Report*, 151: 175.

Fujita, Shuji, Takeshi Matsuoka, Toshihiro Ishida, Kenichi Matsuoka, and Shinji Mae. 2000. A Summary of the Complex Dielectric Permittivity of Ice in the Megahertz Range and its Application for Radar Sounding of Polar Ice Sheets. *Physics of Ice Core Records*, (185-212). T. Hondoh, Editor. Hokkaido University Press, Sapporo.

Gogineni, S., T. Chuah, C. Allen, K. Jezek, and R. K. Moore. 1998. An Improved Coherent Radar Depth Sounder, *Journal of Glaciology* 44(148): 659-669.

Gogineni, S., D. Tammana, D. Braaten, C. Leuschen, T. Akins, J. Legarsky, P. Kanagaratnam, J. Stiles, C. Allen, and K. Jezek. 2001. Coherent Radar Ice Thickness Measurements Over the Greenland Ice Sheet, *Journal of Geophysical Research-Atmospheres* 106(D24): 33761-33772.

Li, Jilu, John Paden, Carl Leuschen, Fernando Rodriguez-Morales, Richard Hale, Emily Arnold, Reid Crowe, Daniel Gomez-Garcia and Prasad Gogineni. 2011. High-Altitude Radar Measurements of Ice Thickness over the Antarctic and Greenland Ice Sheets as a part of Operation Ice Bridge, submitted to *IEEE Transactions on Geoscience and Remote Sensing*, September 2011.

Lei Shi, C. T. Allen, J.R. Ledford, F. Rodriguez-Morales, W. A. Blake, B. G. Panzer, S. C. Prokopiack, C. J. Leuschen, and S. Gogineni. 2010. Multichannel Coherent Radar Depth Sounder for NASA Operation Ice Bridge, *Geoscience and Remote Sensing Symposium* (IGARSS), IEEE International, (1729-1732), doi: 10.1109/IGARSS.2010.5649518.

Leuschen, Carl, Chris Allen, Prasad Gogineni, Fernando Rodriguez, John Paden, and Jilu Li. 2011, updated current year. *IceBridge Snow Radar L1B Geolocated Radar Echo Strength Profiles*, [list dates of data used]. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media.

Leuschen, Carl, Chris Allen, Prasad Gogineni, Fernando Rodriguez, John Paden, Jilu Li. 2011, updated current year. *IceBridge MCoRDS L2 Ice Thickness, Surface, and Bottom*, [list dates of data used]. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media.

Leuschen, Carl, Chris Allen, Prasad Gogineni, Fernando Rodriguez, John Paden, and Jilu Li. 2011, updated current year. *IceBridge MCoRDS L3 Gridded Ice Thickness, Surface, and Bottom*, [list dates of data used]. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media.

Namburi, S. P. V. 2003. *Design and Development of an Advanced Coherent Radar Depth Sounder*, Department of Electrical Engineering and Computer Science, Master's Thesis, University of Kansas.

Paden, John, Christopher Allen, Sivaprasad Gogineni, Kenneth Jezek, Dorthe Dahl-Jensen, and Lars Larsen. 2005. Wideband measurements of ice sheet attenuation and basal scattering, *IEEE Geoscience and Remote Sensing Letters*, 2(2).

Paden, J. 2006. *Synthetic Aperture Radar for Imaging the Basal Conditions of the Polar Ice Sheets*, Department of Electrical Engineering and Computer Science, PhD Dissertation, University of Kansas.

Paden, J., T. Akins, D. Dunson, C. Allen, and P. Gogineni. 2010. Ice-sheet bed 3-D tomography, *Journal of Glaciology* 56(195): 3-11.

Player, K., Lei Shi, Chris Allen, Carl Leuschen, John Ledford, Fernando Rodriguez-Morales, William Blake, Ben Panzer, and Sarah Seguin. 2010. A Multi-Channel Depth-Sounding Radar with an Improved Power Amplifier, *High-Frequency Electronics*, October 2010: 18-29.

Rodriguez-Morales, F., P. Gogineni, C. Leuschen, C. T. Allen, C. Lewis, A. Patel, L. Shi, W. Blake, B. Panzer, K. Byers, R. Crowe, L. Smith, and C. Gifford. 2010. Development of a Multi-Frequency Airborne Radar Instrumentation Package for Ice Sheet Mapping and Imaging, *Proc. 2010 IEEE Int. Microwave Symp.*, Anaheim, CA, 2010: 157–160.

Shi, Lei, C. T. Allen, J. R. Ledford, F. Rodriguez-Morales, W. A. Blake, B. G. Panzer, S. C. Prokopiack, C. J. Leuschen, and S. Gogineni. 2010. Multichannel Coherent Radar Depth Sounder for NASA Operation Ice Bridge, *Geoscience and Remote Sensing Symposium (IGARSS), 2010 IEEE International*, 25-30 July 2010: 1729-1732, doi: 10.1109/IGARSS.2010.5649518.

4.1 Related Data Collections

IceBridge MCoRDS L2 Ice Thickness

IceBridge MCoRDS L3 Gridded Ice Thickness, Surface, and Bottom

IceBridge Accumulation Radar L1B Geolocated Radar Echo Strength Profiles

IceBridge Ku-Band Radar L1B Geolocated Radar Echo Strength Profiles

IceBridge Snow Radar L1B Geolocated Radar Echo Strength Profiles

4.2 Related Websites

CReSIS website

CReSIS Sensors Development Radar web page

IceBridge data website at NSIDC

IceBridge website at NASA

ICESat/GLAS website at NASA Wallops Flight Facility

ICESat/GLAS website at NSIDC

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