# Snow Radar

## Summary

The Snow Radar data set contains L1B Geolocated Radar Echo Strength Profiles over Greenland, Canada, the Arctic Ocean and Antarctica taken with the CReSIS snow radar.

The L1B data set includes echograms with measurements for time, latitude, longitude, elevation, as well as flight path charts and echogram images.

The snow radar data have been collected on an ongoing basis since 2009 using grant funding from NASA. The most recent data were collected as part of the NASA Operation IceBridge field campaign (NNX10AT68G).

The data are stored in MATrix LABoratory (MATLAB) files with associated JPG, KML, and CSV files.

The data are available at [ftp://ftp.cresis.ku.edu/](ftp://ftp.cresis.ku.edu/) and [http://ftp.cresis.ku.edu/](http://ftp.cresis.ku.edu/). These two sites serve the same data, but use the ftp (port 21) and http (port 80) protocols respectively.

## FAQ

The most convenient way to browse the imagery quickly is through the JPG files in the images directory.

The quickest way to plot the whole dataset is to look at the browse files (KML or CSV) for the whole season in the kml and csv directories respectively.

The standard L1B files are in the CSARP_qlook directory. These are located in ftp://ftp.cresis.ku.edu/snow/{$season_name}/.

For the highest quality and most complete browsing of the data, use the Matlab image browser at [ftp://ftp.cresis.ku.edu/picker/](ftp://ftp.cresis.ku.edu/picker/). The guide for the picker also explains the picking process.

Mathworks MAT file readers for C and IDL including documentation from Mathworks are located at [ftp://ftp.cresis.ku.edu/mat_reader/](ftp://ftp.cresis.ku.edu/mat_reader/).

## Data Organization

The radar data are divided into segments. A segment is a contiguous dataset where 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 4-digit year (e.g. 2011), MM is the 2-digit month from 1 to 12, DD is the 2-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. Frames span 33 seconds covering 4 to 5 km dependent upon aircraft speed. Currently frames are aligned with raw data files (frame number matches raw file index), but this may not always be the case for future missions. 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 to match the order of data collection.

In a data casting sense, the data granule for L1B data is the frame.

# File Descriptions

On the ftp.cresis.ku.edu/snow page, L1B are in the snow radar folder (snow), arranged by Season ID (e.g. 2011_Greenland_P3). Since L1B files are specific to a season and contain only snow radar data, these files are stored together in the season ID folders under the directory snow.

## *L1B products*

### CSARP_{$processing_type}/{$segment_id}/Data{$image_id}_{$frame_id}.mat

For each data frame there may be many different L1B products depending on how waveforms, and channels are combined and how the processing is done. More details about the standard outputs are given in the Methods section. An example filename is:

CSARP_qlook/20110516_01/Data_0110516_01_006.mat

The {$processing_type} is a string. Currently the only processing type is qlook.

The {$segment_id} is explained in the Data Organization section.

The {$image_id} is a string which is always empty at this point.

The {$frame_id} is explained in the Data Organization section.

The file format is Matlab .MAT version 6.

### images/{$segment_id}/{$frame_id}_HHmmss_{0maps,1echo}.jpg

For each data frame there is a flight path file (0map) and an echogram file (1echo). The background images for 1) sea ice flights are the Bremen sea ice concentration maps based on AMSR-E measurements in the projection that is used by the Geotiff's from this site, or 2) Landsat-7 natural color imagery in polar stereographic format (70 deg true scale latitude, -45 deg

longitude is center for Greenland/Canada and -71 deg true scale latitude, 0 deg longitude is center for Antarctica). A few example filenames are:

images/20110507_01/20110507_01_001_110941_0maps.jpg
images/20110507_01/20110507_01_001_110941_1echo.jpg

HHmmss is the GPS time stamp for the first range line in the image where HH is 00-23 hours, mm is 00-59 minutes, and ss is 00-59 seconds.

The echograms are generated from the qlook data product.

The file format is JPEG.

## L2 products

### csv/{$segment_id}/Data_{$frame_id}_HHmmss.csv

FILES NOT CURRENTLY AVAILABLE.

Contains the ice surface and layering information. There is one file per data frame. An example filename is:

csv/20110407_06/Data_20110407_06_001_151055.csv

HHmmss is the GPS time stamp for the first range line in the csv file where HH is 00-23 hours, mm is 00-59 minutes, and ss is 00-59 seconds.

The file format is comma separated variable (CSV).

### csv/Data_{$segment_id}.csv

FILES NOT CURRENTLY AVAILABLE.

These files are provided for ease of download and file transfer. They are the same format as the individual data frame CSV files. These files have all the individual frames from the segment concatenated together. An example filename is

csv/Data_20110331_09.csv

### csv/{$season_id}.csv

FILES NOT CURRENTLY AVAILABLE.

These files are provided for ease of download and file transfer. They are the same format as the individual data frame CSV files. These files have all the individual frames from the whole season concatenated together.

The {$season_id} is a string that is formatted as YYYY_location_platform, YYYY is the 4-digit year *of when the season began*, location is the geographic location (e.g. Greenland or Antarctica), and platform is the airborne system used (e.g. P3, TO, DC8, Ground).

An example filename is:

csv/2011_Greenland_P3.csv

## csv/Browse_Data_{$segment_id}.csv

The same as the segment CSV file except only the first point is taken from each frame to keep the file size small.

csv/Browse_Data_20110331_09.csv

## layerData/{$segment_id}/Data_{$frame_id}.mat

For each data frame there is a layer data file. This file contains the full layer information for the ice surface and any other layers that have been picked *and is required by the image browser/layer picker*. An example filename is:

CSARP_layerData/20110516_01/Data_20110516_01_006.mat

The file format is Matlab .MAT version 6.

## *Browsing Files*

## kml/Browse_Data_{$segment_id}.kml

KML versions of the segment browsing CSV files.

## {$radar_id}_param_{$season_id}.xls

This spreadsheet file allows all of the radar and processing parameters to be browsed conveniently. These parameters are encapsulated in the L1B data files, but this spreadsheet provides another way to access this information. An example filename is:

snow_param_2011_Greenland_P3.xls

The {$radar_id} is a string containing the radar ID which is one of icards, mcrds, mcords, or mcords2.

## *General utilities and documents*

ftp://ftp.cresis.ku.edu/gps_ins/

See guide in this folder for more details. The individual GPS/INS files are stored with this naming convention:

{$season_id}/gps_YYYYMMDD.mat

A few examples are:

2011_Greenland_P3/gps_20110507.mat
2011_Greenland_P3/gps_20110516.mat

The file format is Matlab .MAT version 6.

ftp://ftp.cresis.ku.edu/matlab_MAT_reader/

Matlab MAT file reader for Matlab, C, and IDL. See guide in this folder for more details.

ftp://ftp.cresis.ku.edu/picker/

Echogram browsing tool (currently requires Matlab). See guide in this folder for more details

ftp://ftp.cresis.ku.edu/geographic_search/

Basic geographic search tool (currently requires Matlab). Convenient for searching all of the seasons of data and listing all of the frames and segments of interest.

ftp://ftp.cresis.ku.edu/loader/

Echogram loader tool (currently requires Matlab). See guide in this folder for more details. This tool has not been released yet since it is an alpha version, but is available upon request.

ftp://ftp.cresis.ku.edu/segy/

SEGY and SEG2 converter tool (currently requires Matlab). See guide in this folder for more details. This tool has not been released yet since it is an alpha version, but is available upon request.

ftp://ftp.cresis.ku.edu/rds/snow_readme.doc

The most recent version of this readme file.

## *L1B Matlab Files*

Data filenames start with "Data_" followed by the frame ID.
1. Data_20091224_01_001.mat

Each Matlab (.mat) file has the following variables:

| Name | Data |
|---|---|
| **Size/Axes** | M by N float32 array where M is fast time and N is slow time |
| **Units** | Represents relative received power (Watts) |
| **Range** | No restrictions |
| **Null Value** | NaN |
| **Description** | Radar echogram data. The data may be truncated. Presence of the Truncate_Bins variable indicates data has been truncated. Lack of the Truncate_Bins variable indicates data has *not* been truncated. |

| Name | Time |
|---|---|
| **Size/Axes** | $M_{ALL}$ by 1 double vector where $M_{ALL}$ is fast time |
| **Units** | Seconds |
| **Range** | Full double range |
| **Null Value** | NA |
| **Description** | Fast time (zero time is *approximately* the beginning of the transmit event) |

| Name | Depth |
|---|---|
| **Size/Axes** | $M_{ALL}$ by 1 double vector where $M_{ALL}$ is fast time |
| **Units** | Meters |
| **Range** | Full double range |
| **Null Value** | NA |
| **Description** | Range axis with the origin at the median of the Surface values in this frame and assuming a dielectric of 1.53 (Depth = (Time - median(Surface)) * c/2/sqrt(1.53)) |

| Name | Truncate_Bins (only available when data is truncated) |
|---|---|
| **Size/Axes** | M by 1 double vector where M is fast time |
| **Units** | NA |
| **Range** | Integer from 1 to $M_{ALL}$ |
| **Null Value** | NA |
| **Description** | These are the indices into the Time and Depth vectors for which the Data is available. |

| Name | Truncate_Mean (only available when data is truncated) |
|---|---|
| **Size/Axes** | N by 1 double vector where N is slow time |
| **Units** | NA |
| **Range** | No restrictions |
| **Null Value** | NA |
| **Description** | Represents a mean of the noise power for the truncated range bins before the surface return. When no range bins were truncated before the surface return the value is NaN. |

| Name | Truncate_Median (only available when data is truncated) |
|---|---|
| **Size/Axes** | N by 1 double vector where N is slow time |
| **Units** | NA |
| **Range** | No restrictions |
| **Null Value** | NA |
| **Description** | Represents a median of the noise power for the truncated range bins before the surface return. When no range bins were truncated before the surface return the value is NaN. |

| Name | Truncate_Std_Dev (only available when data is truncated) |
|---|---|
| **Size/Axes** | N by 1 double vector where N is slow time |
| **Units** | NA |
| **Range** | No restrictions |
| **Null Value** | NA |
| **Description** | Represents a standard deviation of the noise power for the truncated range bins before the surface return. When no range bins were truncated before the surface return the value is NaN. |

| Name | GPS_time |
| --- | --- |
| Size/Axes | 1 by N double vector where N is slow time |
| Units | Seconds |
| Range | Full double range |
| Null Value | NA |
| Description | GPS time when data were collected (seconds since Jan 1, 1970 00:00:00). This is the ANSI C standard. |

| Name | Latitude |
| --- | --- |
| Size/Axes | 1 by N double vector where N is slow time |
| Units | Degrees |
| Range | -90 to +90 |
| Null Value | Not a Number (indicates that no GPS information is available) |
| Description | WGS-84 geodetic latitude coordinate. Always referenced to North. Represents the location of the origin of the trajectory data which is generally not the radar's phase center, but some other point on the aircraft (e.g. the GPS antenna or the INS). |

| Name | Longitude |
| --- | --- |
| Size/Axes | 1 by N double vector where N is slow time |
| Units | Degrees |
| Range | -180 to +180 |
| Null Value | Not a Number (indicates that no GPS information is available) |
| Description | WGS-84 geodetic longitude coordinate. Always referenced to East. Represents the location of the origin of the trajectory data which is generally not the radar's phase center, but some other point on the aircraft (e.g. the GPS antenna or the INS). |

| Name | Elevation |
| --- | --- |
| Size/Axes | 1 by N double vector where N is slow time |
| Units | Meters |
| Range | Full double range |
| Null Value | Not a Number (indicates that no GPS information is available) |
| Description | Referenced to WGS-84 ellipsoid. Positive is outward from the center of the Earth. Represents the location of the origin of the trajectory data which is generally not the radar's phase center, but some other point on the aircraft (e.g. the GPS antenna or the INS). |

| Name | Elevation_Correction (only available when data is elevation compensated) |
| --- | --- |
| Size/Axes | 1 by N double vector where N is slow time |
| Units | Range bins |
| Range | Integer |
| Null Value | NA |
| Description | Represents the number of zeros that were inserted during elevation compensation for each range line to simulate near-level flight. These zeros are not included in the truncation noise statistics. |

| Name | Surface |
|---|---|
| **Size/Axes** | 1 by N double vector where N is slow time |
| **Units** | Seconds |
| **Range** | Full double range |
| **Null Value** | Not a Number (indicates that no surface information is available) |
| **Description** | Estimated two way propagation time to the surface from the collection platform. This uses the same frame of reference as the Time variable. This information is sometimes used during compression to determine the range bins that can be truncated. |

| Name | *param* (multiple variables with a name containing the string "param") |
|---|---|
| **Size/Axes** | NA, data structures |
| **Units** | NA |
| **Range** | NA |
| **Null Value** | NA |
| **Description** | Contains: 1) Radar and processing settings, 2) Processing software version and time stamp information. Fields of structures are not static and may change from one version to the next. |

## L2 Matlab Files

| Name | GPS_time |
|---|---|
| **Size/Axes** | 1 by N double vector where N is slow time |
| **Units** | Seconds |
| **Range** | Full double range |
| **Null Value** | NA |
| **Description** | GPS time when data were collected (seconds since Jan 1, 1970 00:00:00). This is the ANSI C standard. |

| Name | Latitude |
|---|---|
| **Size/Axes** | 1 by N double vector where N is slow time |
| **Units** | Degrees |
| **Range** | -90 to +90 |
| **Null Value** | Not a Number (indicates that no GPS information is available) |
| **Description** | WGS-84 geodetic latitude coordinate. Always referenced to North. Represents the location of the origin of the trajectory data which is generally not the radar's phase center, but some other point on the aircraft (e.g. the GPS antenna or the INS). |

| Name | Longitude |
|---|---|
| **Size/Axes** | 1 by N double vector where N is slow time |
| **Units** | Degrees |
| **Range** | -180 to +180 |
| **Null Value** | Not a Number (indicates that no GPS information is available) |
| **Description** | WGS-84 geodetic longitude coordinate. Always referenced to East. Represents the location of the origin of the trajectory data which is generally not the radar's phase center, but some other point on the aircraft (e.g. the GPS antenna or the INS). |

| Name | Elevation |
|---|---|
| **Size/Axes** | 1 by N double vector where N is slow time |
| **Units** | Meters |
| **Range** | Full double range |
| **Null Value** | Not a Number (indicates that no GPS information is available) |
| **Description** | Referenced to WGS-84 ellipsoid. Positive is outward from the center of the Earth. Without motion compensation, this represents the location of the origin of the trajectory data which is generally not the radar's phase center, but some other point on the aircraft (e.g. the GPS antenna or the INS). This elevation may be modified during the "Elevation Compensation" step. |

| Name | layerData |
|---|---|
| **Size/Axes** | 1 x P cell array of structures, where P is the number of layers |
| **Units** | NA |
| **Range** | NA |
| **Null Value** | NA |
| **Description** | The first layer (layer_idx = 1) is the ice surface. |

| Name | layerData{layer_idx} |
|---|---|
| **Size/Axes** | 1 x P cell array of structures, where P is the number of layers |
| **Units** | NA |
| **Range** | NA |
| **Null Value** | NA |
| **Description** | The first layer (layer_idx = 1) is the ice surface. For the depth sounder, the second layer (layer_idx = 2) is the ice bottom. |

| Name | layerData{layer_idx}.name |
|---|---|
| **Size/Axes** | character array, arbitrary length |
| **Units** | NA |
| **Range** | NA |
| **Null Value** | NA |
| **Description** | Name of the layer ("surface" and "bottom" are reserved for ice surface and ice bottom respectively) |

| Name | layerData{layer_idx}.value{pick_idx} |
|---|---|
| **Size/Axes** | 1 by 2 cell array of structures |
| **Units** | NA |
| **Range** | NA |
| **Null Value** | NA |
| **Description** | There are two pick types: the manual picks are stored in pick_idx = 1 and the automated picks are stored in pick_idx = 2. |

| Name | *layerData{ layer_idx}.value{pick_idx}.data* |
|---|---|
| **Size/Axes** | 1 by N double vector |
| **Units** | Seconds |
| **Range** | Full double range |
| **Null Value** | Not a Number (indicates that no surface information is available for this particular index and pick type) |
| **Description** | Estimated two way propagation time to the layer from the collection platform. |

| Name | *layerData{ layer_idx}.quality* |
|---|---|
| **Size/Axes** | 1 by N double vector |
| **Units** | NA |
| **Range** | 1, 2, or 3 |
| **Null Value** | NA |
| **Description** | Quality level of the data (1-3), 1 represents high confidence, 2 represents low confidence or large error bars, and 3 represents a derived or estimated result based on information beyond just the present data frame |

# Theory of Measurements:

The snow and kuband radars use a frequency modulated continuous wave (FMCW) architecture (Carrara 1995). This is done to reduce the required sampling frequency of the ADC and is possible when the range gate is limited. Currently, the range gate is limited to low altitude flights to achieve the full bandwidth. In these FMCW radars, a long chirp signal is generated (~250 μs) which sweeps linearly in frequency from the start frequency to the stop frequency. This signal is transmitted and also fed to a mixer in the receiver to be used to demodulate the received signal. Signals outside the range gate are suppressed and aliased by the system.

The dominant scattered signal is the specular or coherent reflection from the air-snow surface and shallow layers beneath this. A bistatic antenna configuration is used to provide isolation between the transmit and receive paths which is important because the FMCW system receives while transmitting and too little isolation means that the direct path from the transmitter to the receiver will be too strong and saturate the receiver. The antennas are mounted so that the main beam is pointed in the nadir direction to capture the specular surface and layer reflections.

The pulse repetition frequency (PRF), or along-track sampling rate, does not necessarily capture the full Doppler bandwidth for point scatterers without aliasing. However, since the target energy is mostly coherent, it occupies only a small portion of the Doppler spectrum so that the undersampling in along-track is not generally a problem. Since the coherent portion of the surface and layer scattering is the primary signal of interest, to lower the data rate, presumming is used which effectively low pass filters and decimates the Doppler spectrum.

## Radar System

The following table lists the nominal properties of the radar system. The antenna used on the P-3 and the DC-8 is an ETS Lindgren TEM horn antenna model ETS 3115.

| | Frequency | Pulse | Transmit | Noise | Antenna |
|---|---|---|---|---|---|

| | Spectrum (GHz) | Duration (μs) | Power (W) | Figure (dB) | Beamwidth Along x Cross (deg) |
|---|---|---|---|---|---|
| 2009 Greenland P3 | 2.5-7.0 | 270 | 0.1 | | 45 x 45 |
| 2009 Antarctica DC8 | 4-6 | 100-240 | 0.1 | | |
| 2010 Greenland DC8 | 2-6.5 | 250 | 0.1 | | |
| 2010 Greenland P3 | 2-6 | 250 | 0.1 | | |
| 2010 Antarctica DC8 | 2-6.5 | 250 | 0.1 | | |
| 2011 Greenland P3 Land Ice | 2-6 | 255 | 0.1 | | 45 x 45 |
| Sea Ice | 2-6.5 | 250 | 0.1 | | 45 x 45 |
| 2011 Antarctica DC8 Land Ice | 2-6 | 255 | 0.1 | | 45 x 45 |
| Sea Ice | 2-6.5 | 250 | 0.1 | | 45 x 45 |

| | Pulse Repetition Frequency (Hz) | Hardware Averages | Polarization Along-track |
|---|---|---|---|
| 2009 Greenland P3 | 2000 | 4 | H-plane |
| 2009 Antarctica DC8 | 2000 or 3000 | 4 | |
| 2010 Greenland DC8 | 2000 | 4 | |
| 2010 Greenland P3 | 2000 | 4 | E-plane |
| 2010 Antarctica DC8 | 2000 | 4 | E-plane |
| 2011 Greenland P3 | 2000 | 4 | |
| 2011 Antarctica DC8 | 2000 | 4 | H-plane |

## Range Gate

The FMCW radar captures the full signals from a window in time after the transmission. Signals arriving before or after the window are suppressed and *alias back into the window.* A mapping of the aliasing effect is shown in the figure below for a desired time gate corresponding to 1000 to 2000 ft. Note how 1000 to 2000 ft actual range maps perfectly to measured range, but all other actual ranges are also mapped into the same 1000 to 2000 ft. For example, if a signal arrives from 2100 ft it will be upside down and at 1900 ft. The signal will also be attenuated by the time gate filter since it lies outside the pass band from 1000 to 2000 ft.
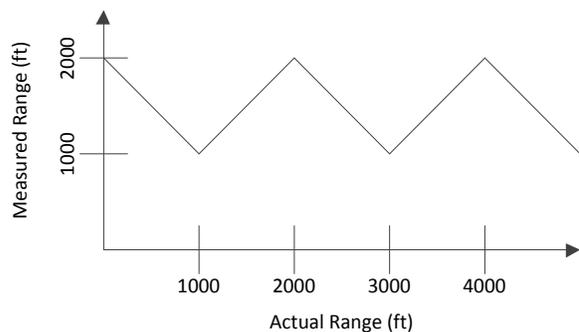
# L1B Processing Steps:

The following processing steps are performed.

1. Set digital errors to zero (error sequences are 4 samples in length and occur once every few thousand range lines)
2. Synchronization of GPS data with the radar data using the UTC time stored in the radar data files
3. Conversion from quantization to voltage at the ADC input
4. Removal of DC-bias by subtracting the mean
5. The quick look output is generated using presumming or unfocused SAR processing for a total of 16 coherent averages which includes hardware and software averages. If the pulse repetition frequency (PRF) is 2000 Hz, the new effective PRF is 125 Hz.
6. A fast-time FFT is applied with a Hanning window to convert the raw data into the range domain (analogous to pulse compression). The data are flipped around based on the Nyquist zone.
7. A high pass filter is applied in the along-track to remove coherent noise
8. A 1 range-bin by 5 along-track-range-line boxcar filter is applied to the power detected data and then decimated in along-track by 5.
9. The quick look output is used to find the ice surface location (fully automated).
10. The output is then elevation compensated (with radar range bin accuracy) and then truncated in fast time based on the data posting settings in the parameter spreadsheet.

The purpose of the elevation compensation, when applied, is to remove the large platform elevation changes to make truncation more effective. *The process is not designed to perform precision elevation compensation and is probably not sufficient for scientific analysis.* The following steps are performed:

1. Let:
   "Elevation_Orig" be the 1 by N elevation vector before elevation compensation
   "Data_Orig" be the M_orig by N data matrix before elevation compensation
   "Time_Orig" be the M_orig by 1 fast-time time axis before elevation compensation
   "Elevation" be the 1 by N vector from the data product file
   "Data" be the matrix from the data product file
   "Time" be the M by 1 fast-time time axis from the data product file
   maxElev = max(Elevation_Original)
2. dRange = maxElev - Elevation_Original
3. dt = Time_Orig(2) – Time_Orig (1)
   a. Sample spacing in fast-time (i.e. one range bin)
4. dBins = round(dRange / (c/2) / dt)
   a. This is a 1 by N vector of the number of range bins for each range line we will shift "Data_Orig". In other words, this is the elevation compensation for each range line written in terms of range bins.
5. M = M_orig + max(dBins)
6. The original data matrix is zero padded to M and then each range line is shifted by the corresponding entry in dBins.
   a. Because of the "round" function for creating dBins, the elevation compensation is only done with range bin accuracy.
   b. The new "Data" matrix is similar to what would have been collected if the aircraft had flown at a constant elevation of maxElev.
7. The elevation matrix is modified according to the elevation compensation so that:
   Elevation_Orig = Elevation – dBins*dt*c/2

Once again, because of the "round" function, the Elevation vector will be nearly constant, but not quite: the quantization noise caused by the round function remains.

8. The Time_Orig vector is extended in length by the maximum bin shift to create the new Time vector

## *Loading Data with Elevation Compensation and Fast-Time Truncation*

This example shows how to load the data in Matlab and IDL and generate typical figures.

```
snow = load('Data_20110316_03_035.mat');

figure(1); clf;
imagesc([],snow.Depth(snow.Truncate_Bins),10*log10(snow.Data));
colormap(1-gray(256));
xlabel('Range line');
ylabel('Depth (m)');
hc = colorbar;
set(get(hc,'ylabel'),'string','Relative power (dB)');

figure(2); clf;
imagesc([],1e6*snow.Time(snow.Truncate_Bins),10*log10(snow.Data));
hold on;
plot(1e6*snow.Surface);
hold off;
colormap(1-gray(256));
xlabel('Range line');
ylabel('Time (us)');
hc = colorbar;
set(get(hc,'ylabel'),'string','Relative power (dB)');

figure(3); clf;
h1 = plot(snow.Truncate_Mean);
hold on;
h2 = plot(snow.Truncate_Median,'r');
h3 = plot(snow.Truncate_Std_Dev,'g');
hold off;
xlabel('Range line');
ylabel('Power');
title('Truncated bins noise statistics');
legend([h1 h2 h3], 'Mean', 'Median', 'Std Dev');

% To reconstruct original data as closely as possible
Data = zeros(length(Time),size(snow.Data,2));
Data(snow.Truncate_Bins,:) = snow.Data;
c = 2.997924580003452e+08;
dt = snow.Time(2)-snow.Time(1);
dr = dt * c/2;
for rline = 1:size(Data,2)
  Data(:,rline) = circshift(Data(:,rline),-snow.Elevation_Correction(rline));
  snow.Elevation(rline) = snow.Elevation(rline) -
snow.Elevation_Correction(rline)*dr;
  snow.Surface(rline) = snow.Surface(rline) -
snow.Elevation_Correction(rline)*dt;
end
figure(4); clf;
imagesc([],snow.Time,10*log10(Data));
hold on;
plot(snow.Surface);
hold off;
colormap(1-gray(256));
```

```
xlabel('Range line');
ylabel('Range bin');
hc = colorbar;
set(get(hc,'ylabel'),'string','Relative power (dB)');
```

Truncated bins noise statistics
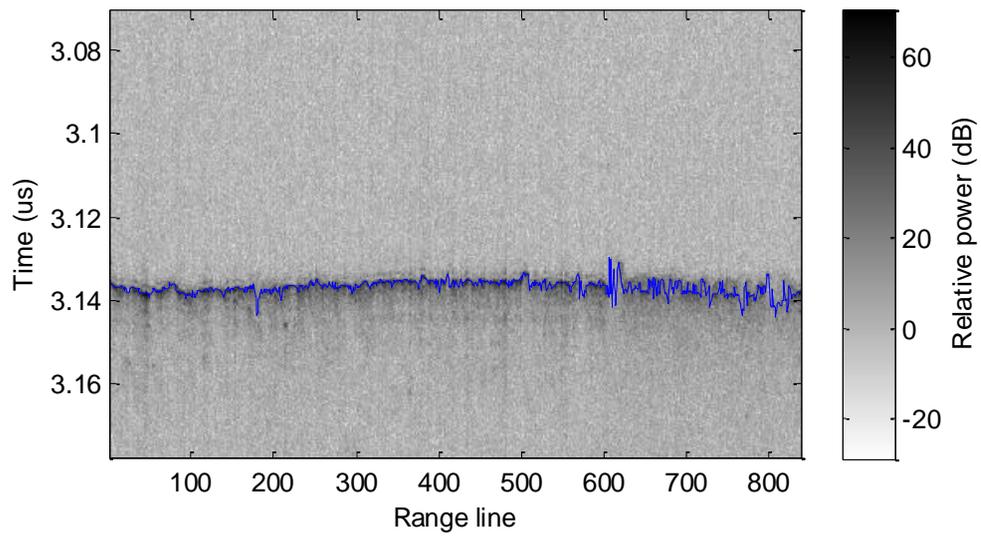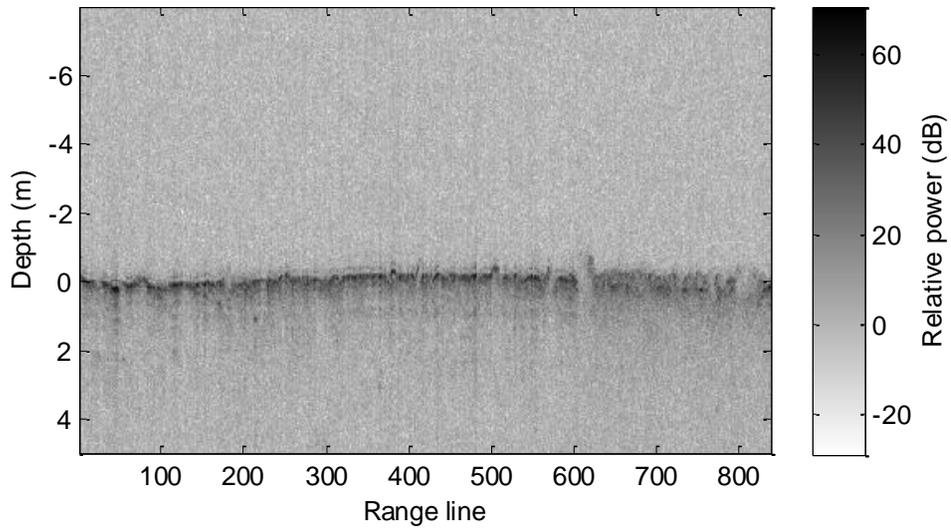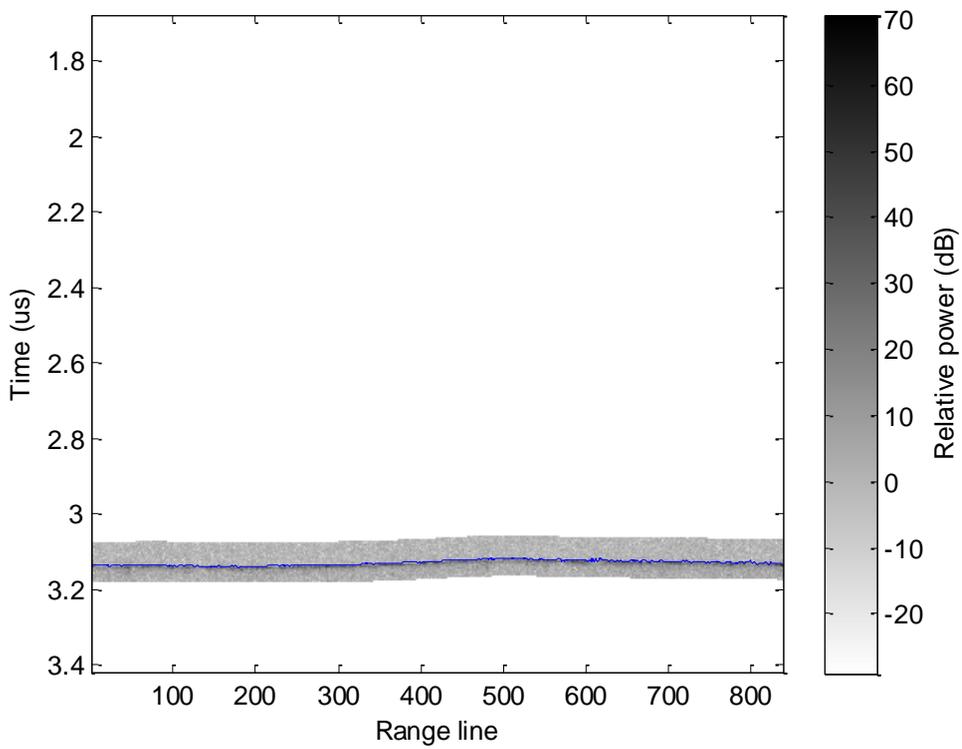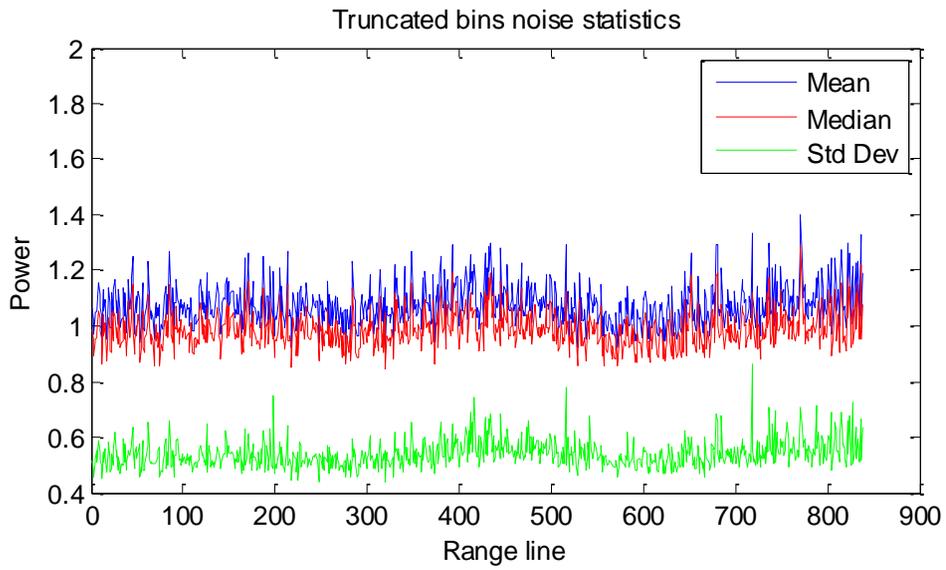


# Resolution and Error Bounds

For a flat surface, the range resolution is:

$$\sigma_r = \frac{k_t c}{2 \text{Bn}},$$

where $B$ is the bandwidth and is nominally 4500 MHz (2 to 6.5 GHz), $n$ is the index of refraction for the medium, $c$ is the speed of light in a vacuum, and $k_t = 1.5$ is due to the application of a Hanning time-domain window to reduce the range sidelobes of the chirped transmit waveform. Note that the bandwidth for a particular segment can be determined by reading the param_radar structure in the echogram data file or by looking at the parameter spreadsheet values f0, f1, and fmult and doing the following calculation

> B = (param_radar.f1-param_radar.f0)*param_radar.fmult.

The range resolution for several indices of refraction is given in this table.

| Index of Refraction | Range Resolution (cm) | Medium |
|---|---|---|
| 1 | 5.0 | Air |
| sqrt(1.53) | 4.0 | Snow |
| sqrt(3.15) | 2.8 | Solid ice |

The index of refraction can be approximated by $n = \left(1 + 0.51\rho_{snow}\right)^3$ where $\rho_{snow}$ is the density of the snow in grams per cm$^3$. In the data posting, a dielectric of 1.53 is used which corresponds to a snow density of 0.3 g per cm$^3$ (Warren 1999).

In the along-track dimension, the raw data before any hardware or software coherent averages have a resolution derived in the same manner as the cross-track resolution. However, a basic form of focusing is applied called unfocussed synthetic aperture radar (SAR) processing (also known as stacking or coherent averaging). If all affects are accounted for, the data may be coherently averaged to a SAR aperture length of $L = \sqrt{\dfrac{H\lambda_c}{2}}$ or for $H = 500$ m, they may be averaged to a length of 4.3 m. The resolution turns out to be approximately equal to this with the exact definition given below. However, these data are only coherently averaged 16 times which includes both hardware and software averaging, and decimated by this same amount. At a platform speed of 140 m/s this is an aperture length, $L$, of 1.12 m (the sample spacing is likewise 1.12 m). The actual resolution is substantially less fine. It is approximately given by

$$\sigma_{x,SAR-qlook} = H \tan\left(\sin^{-1}\left(\frac{\lambda_c}{2L}\right)\right).$$

For $H = 500$ m, the along-track resolution is 16.7 m.

A 1 range-bin by 5 along-track-range-line boxcar filter is applied to the power detected data and then decimated in the along-track by 5 so the data product has an along-track sample spacing of 5.6 m.

For a smooth or quasi-specular target (e.g. internal layers), the primary response is from the first Fresnel zone. Therefore, the directivity of specular targets effectively creates the appearance of a cross-track resolution equal to this first Fresnel zone. The first Fresnel zone is a circle with diameter given by

$$\sigma_{y,\text{Fresnel-limited}} = \sqrt{2(H + T/\sqrt{3.15})\lambda_c} \,,$$

where $H$ is the height above the air/ice interface, $T$ is the depth in ice of the target, and $\lambda_c$ is the wavelength at the center frequency. The table below gives the cross-track resolution for this case.

| Center Frequency (MHz) | Cross-track Resolution H = 500 m T = 0 m (m) |
|---|---|
| 3500 | 8.7 |

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

$$\sigma_{y,\text{pulse-limited}} = 2\sqrt{\frac{(H + T/\sqrt{3.15})ck_t}{B}} \,.$$

The table below gives the cross-track resolution with windowing.

| Bandwidth (MHz) | Cross-track Resolution H = 500 m T = 0 m (m) |
|---|---|
| 4500 | 14.1 |

The antenna installed in the bomb bay of the P-3 and the wing roots of the DC-8 is an ETS Lindgren 3115. The E-plane of the antenna is aligned in the along-track for the P-3 and in the cross-track for the DC-8. The approximate beamwidths are 45 deg in along-track and 45 deg in cross-track. The cross-track resolution is set by the footprint which is a function of range

$$\sigma = 2H \tan\left(\frac{\beta}{2}\right),$$

where $\beta$ is the beamwidth in radians and $H$ is the height above ground level. For $H = 500$ m, the footprint is 414 m in cross-track.

System loop sensitivity calculations section is not completed.

# Season Specific Information

The data are not radiometrically calibrated. This means that they are not converted to some absolute standard for reflectivity or backscattering analysis. We are working on data processing and hardware modifications to do this.

The data have not been motion compensated. We are working on data processing modifications to do this.

## 2009 Greenland P3

Not completed

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Data Backups and IT: Heather Owen, Ben Panzer
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## 2009 Antarctica DC8

This section not completed.

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This section not completed.

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## *2010 Antarctica DC8*

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## *2011 Greenland P3*

### Known Issues

The accum, snow, 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 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 all 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. This issue is closed on all data segments except those listed in the parameter spreadsheet with open issues.

### Coverage

Not completed

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## *2011 Antarctica DC8*

This section not completed.

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Post Data Processing (for this release): Shashanka Jagarlapudi, John Paden, Ben Panzer

# Acknowledgement and Citing the Data:

# References and Related Publications

CReSIS Website (https://www.cresis.ku.edu/).

IceBridge Data Web site at NSIDC (http://nsidc.org/data/icebridge/index.html).

IceBridge Web site at NASA (http://www.nasa.gov/mission_pages/icebridge/index.html).

ICESat/GLAS Web site at NASA Wallops Flight Facility (http://glas.wff.nasa.gov/).

ICESat/GLAS Web site at NSIDC (http://nsidc.org/daac/projects/lidar/glas.html).

Carrara, W. G., R. S. Goodman, R. M. Majewski, Spotlight Synthetic Aperture Radar: Signal Processing Algorithms, Artech House, Norwood, MA, 1995, pp. 26-31.

Kanagaratnam, P., T. Markus, V. Lytle, B. Heavey, P. Jansen, G. Prescott, P. Gogineni, "Ultrawideband radar measurements of thickness of snow over sea ice," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 45, no. 9, Sept 2007, pp. 2715-2724.

Panzer, B.; Leuschen, C.; Patel, A.; Markus, T.; Gogineni, S.; , "Ultra-wideband radar measurements of snow thickness over sea ice," *Geoscience and Remote Sensing Symposium (IGARSS), 2010 IEEE International* , vol., no., pp.3130-3133, 25-30 July 2010 doi: 10.1109/IGARSS.2010.5654342.

Panzer, B., C. Leuschen, W. Blake, R. Crowe, A. Patel, P. S. Gogineni, T. Markus, *Wideband radar for airborne measurements of snow thickness on sea ice,* Abstract C21D-01 presented at 2010 Fall Meeting, AGU, San Francisco, Calif., 13-17 Dec, 2010.

Kwok, R., C. Leuschen, B. Panzer, A. Patel, N. T. Kurtz, T. Markus, B. Holt, P. S. Gogineni, *Radar surveys of snow depth over Arctic sea ice during Operation IceBridge*, Abstract C21D-02 presented at 2010 Fall Meeting, AGU, San Francisco, Calif., 13-17 Dec, 2010.

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, *Development of a Multi-Frequency Airborne Radar Instrumentation Package for Ice Sheet Mapping and Imaging*, Proc. 2010 IEEE Int. Microwave Symp., Anaheim, CA,  May 2010, pp. 157 – 160.

Warren, S., I. Rigor, and N. Untersteiner, *Snow Depth on Arctic Sea Ice*, *Journal of Climate*, Vol. 12, pg. 1814-1829, 1999.

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