*Final Report*

**SRO-03M-09**

# Technical Support for the Deployment Of Radar and Laser Altimeters during LaRA 2002

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# LaRA 2002 – Final Report

**Abstract**
This report provides the final documentation for the 2002 Laser, Radar Altimeter (LaRA) inter-comparison field campaign. In 2002 May, the JHUAPL Delay/Doppler Phase monopulse (D2P) radar altimeter was flown aboard the NASA P-3 airplane with the Airborne Topographic Mappers (ATM)2/3 laser altimeters as a project to collect simultaneous radar and laser altimeter measurements over ice-sheets and sea-ice. The respective height measurements were cross-calibrated to +/- 1 cm. The principal objectives for the resulting datasets are to provide insight into the differences between the estimated height values extracted from coincidental laser (optical) and radar (rf) measurements over various ice and snow surface conditions. This report includes descriptions of the radar installation aboard the P-3 airplane, the flight tracks during the field campaign, the resulting datasets, FTP access to the data, radar calibration, radar tracking algorithms, and height comparisons. The goal of this report is to give any user sufficient information to process and analyze the datasets collected during the project.

**Introduction**
The need for simultaneous laser and radar height measurements over land and sea ice masses has been recognized by both NASA and ESA. To that end, these two agencies agreed to share the expenses of the radar portion of the airborne Laser-Radar Altimetry (LaRA) mission to the Arctic during calendar year 2002 to gather these data. The mission took advantage of the Johns Hopkins University Applied Physics Laboratory (JHU/APL) D2P radar altimeter mounted together with the ATM laser altimeters on board the NASA P-3 aircraft. There were four flights over land and sea ice from 18 May through 23 May during which simultaneous radar, laser, and video data were collected. The field campaign was conducted by Drs. Carl Leuschen and Rick Chapman, both of the Ocean Remote Sensing Group of the JHU/APL. Data analysis was the responsibility primarily of Dr. Leuschen.

Radar and laser altimeters operate at different wavelengths and there is a considerable difference in the electromagnetic properties of snow and ice at optical frequencies versus RF concerning reflection coefficients, attenuation, and penetration. The waveforms and height comparisons made available by this project will help to explain these differences and provide a means of quantifying forthcoming extensive space-based datasets.

**D2P Radar Altimeter**
The Delay/Doppler Phase-monopulse (D2P) radar is a coherent airborne radar altimeter that operates from 13.72 to 14.08 GHz. The system transmits a linear FM chirp signal at 5 Watts peak power, with pulse lengths ranging from 0.384 to 3.072 microseconds. The system uses two receiver channels and a pair of antenna arrays, separated by a 14.5 cm baseline, to provide for angle measurements in the cross track directions. The system can operate in five modes (standby, range sweep, calibrate, acquire, and track), and provides real time display of the delay/Doppler spectrum and cross-track phase of a burst sequence (typically 16 consecutive pulses). In tracking mode, the system uses a closed loop algorithm to maintain radar track of the surface. The calibrate mode allows systems testing with and without radiation. Table 1 lists system parameters and corresponding values.

**Table 1. D2P Radar Characteristics**

| Parameter | Value |
|---|---|
| radar frequency | 13.9 Ghz |
| pulse lengths | 3.072, 1.536, 0.768, 0.384 us |
| pulse bandwidth | 360 Mhz |
| peak transmit power | 5 watts |
| pulse repetition rate | 1250, 1000, 750, 500 Hz |
| antenna gain | 27 dBi |
| on-board processing | closed-loop range tracking and AGC, data quality quick-look display |
| data recording | full recording of all digitized data |

## NASA P-3 Installation

The D2P system was installed into the NASA P-3 airplane in April 2002. The system had previously been installed in a NRL P-3 airplane for the initial flight tests, but this was the first installation aboard the NASA aircraft. As a result, a requirement to interface the system with the aircraft GPS and INS systems was desired to provide a common reference for the radar/laser comparisons. The GPS interface was required to provide a universal clock to time-tag the data, while precise geolocation was made available post-flight from the Wallops Observational Science Branch (OSB). Real time GPS did not provide the necessary accuracy for the comparison. Unfortunately, the INS interface (ARINC 429 PCI card) did not provide a device driver that would work with the existing computer operating systems, and again, the Wallops OSB provided the necessary INS datasets for the comparison. (At the time of writing of this document, the D2P computer systems are being upgraded and will be capable of obtain INS data in real time.) The installation was completed in April, and a successful test flight was conducted on 5 May 2002.

Figure 1a shows the installation locations of the D2P rack/antenna, GPS antenna, and ATM2/3. The D2P system uses coaxial cable to connect the system to the antennas. Due to the attenuation levels at the operating frequency, these cable runs were kept short, and the system rack was mounted directly above the bomb-bay/antenna subsystem. The antennas were located in the bomb bay fairing at FS345, and the remaining D2P equipment was located in a double rack at FS360, starboard side. The moment arms between the D2P system and ATM2/3 were calculated to within a few cm, sufficient for accurate comparison of surface heights measured through the instruments. Figure 1b shows a more complete illustration of the relative positions of the instruments with respect to the airplane and each other.

Figure 2 shows the locations of the D2P subsystems and computers within the double rack. All equipment was mounted into the rack and tested at APL and shipped to Wallops for aircraft installation. Figure 2 also lists the approximate weight and power consumption of the system.

## Field Campaign

Project data were collected during four flights, including (1) a transit flight from Thule, Greenland to Longyearbyen, Svalbard, (2) a Svalbard mapping/Sea ice flight, (3) a dedicated Svalbard mapping flight, and (4) a dedicated northern sea-ice flight. The maps in Figure 3 indicate the flight tracks and the locations where corresponding datasets were acquired. In these images, blue refers to the D2P radar altimeter acquisition, yellow refers to video acquisition, and red refers to the laser altimeter acquisition.  These maps also indicate where open ocean (<10% ice), broken ice, and solid (>90% ice) ice are predicted based on data from SSMI.

In general, the radar and supporting systems operated very well. The problems that did occur were minor and did not hinder data collections.  These include vibration problems during take off, and temperature problems during initial startup. (These problems are currently being addressed with system upgrades.)

**Data Products**

During the 2002 Greenland/Svalbard field campaign, approximately 160 GB of data were collected by the D2P instrument.  (This volume does not include the GPS and INS datasets necessary for post processing.)  Of this total data volume, 130 GB was determined after review for internal consistency and quality control to be suitable for distribution and further processing. Following is a description of the datasets.

*Level 1*

The level-1 files are named according to the convention: **D2P DYYYYMMDD.XXX**
Each file consists of a series of 1040-byte blocks, and each block describes a single radar pulse. The blocks are divided into data a 16-byte header and 1024-byte data sections shown in Table 2.

**Table 2. Format of D2P Data Files**

| Byte | Desc. | Byte | Desc. | Bits | | |
|---|---|---|---|---|---|---|
| 1:16 | Header | 1:4 | Pulse Num. | | | |
| | | 5:8 | Status | 1:13 | Tracking range | (1)range index to track point |
| | | | | 14:15 | Pulse rep. freq. | 0: 1000 Hz |
| | | | | | | 1: 1250 Hz |
| | | | | | | 2: 1500 Hz |
| | | | | | | 3: 1750 Hz |
| | | | | 16:17 | Pulse length | 0: 3.072 μs (512 pts/channel) |
| | | | | | | 1: 1.536 μs (256 pts/channel) |
| | | | | | | 2: 0.768 μs (128 pts/channel) |
| | | | | | | 3: 0.384 μs (64 pts/channel) |
| | | | | 18:23 | Attenuation | 0-63 dB |
| | | | | 24 | Track lock | 0: no track |
| | | | | | | 1: track found |
| | | 9:12 | seconds | | | relative time of pulse |
| | | 13:16 | fraction | | | (2)sec. = sec. + 2*frac./1e7 |
| 17:1040 | Data | 1:512 | Ch. 1 | | | spectra of channel 1 and 2 |
| | | 513:1024 | Ch. 2 | | | (not dechirped) |

[1] *See range calculation in the calibration section for more information on the tracking range.*
[2] *Seconds are expressed in Unix time (seconds since 1 Jan 1970).*

*Level-1b*

The level-1b files are named according to the convention: **PYYYYMMDD.XXX**
Each file is composed of an alternating sequence of Data Headers and corresponding Waveform Data as described below.

**Table 3. Processed Data Format.**

| **Parameter** | **Byte #'s** | **Format** | **Description** |
|---|---|---|---|
| Valid Pulse | [0:3] | long int | 1: valid, 2: invalid |
| Seconds | [4:7] | long int | Seconds/1e3 (seconds of the day) |
| Latitude | [8:11] | long int | Degrees/1e6 |
| Longitude | [12:15] | long int | Degrees/1e6 |
| Altitude | [16:19] | long int | Meters/1e3 |
| Heading | [20:23] | long int | Degrees/1e3 |
| Pitch | [24:27] | long int | Degrees/1e3 |
| Roll | [28:31] | long int | Degrees/1e3 |
| Range | [32:35] | long int | Tracking Range Steps |
| Del | [36:39] | long int | Tracking Shift |
| Attenuation | [40:43] | long int | Receiver attenuation setting |
| Length | [44:47] | long int | Samples/Pulse |
| Dop. Bin Size | [48:51] | long int | Meters/1e3 |
| Data Array | [51:51+8*Length] | (float *real part*, float *imag part*) | Array of complex numbers. Magnitude. Cross-Channel Power Phase. Cross-Channel Phase |

**FTP Site**

A password-protected FTP site has been established to provide access by investigators to the various D2P and corresponding ancillary datasets. The site resides at "Srbdata3.jhuapl.edu" in the ./lara/pub directory. All users will be automatically placed in this directory upon successful login. (Username and password will be supplied by JHU/APL upon request to each investigator following approval by the sponsors ESA and/or NASA, according to their protocols.) The data are organized in directories first by date and then by the specific data product. Available data products include level-1 datasets (formatted D2P waveforms), GPS datasets, INS datasets, level-1b datasets (delay/Doppler-processed cross-channel calibrated waveforms), level-2 datasets (images), and corresponding maps of the flight lines. Table 4 gives an overview of the datasets available on the FTP site.

**Table 4. Current Status of the D2P (lara) ftp Site.**

| Directory on Srbdata3 | # of Files | Size kB |
|---|---|---|
| ./lara/pub/ | | |
| 20020503/ | | |
| data/ | 122 | 12077120 |
| 20020513/ | | |
| data/ | 105 | 10619308 |
| 20020215/ | | |
| data/ | 9 | 828560 |
| 20020517/ | | |
| data/ | 64 | 6481040 |
| 20020518/ | | |
| data/ | 339 | 33823044 |
| images/ | 203 | 483036 |
| maps/ | 17 | 12580 |
| processed/ | 17 | 1468916 |
| 20020520/ | | |
| data/ | 304 | 30476064 |
| images/ | 143 | 530196 |
| maps/ | 13 | 9620 |
| processed/ | 13 | 774084 |
| 200020522/ | | |
| data/ | 298 | 29847792 |
| images/ | 161 | 1246832 |
| maps/ | 16 | 11840 |
| processed/ | 16 | 962000 |
| 200020523/ | | |
| data/ | 358 | 1468916 |
| images/ | 169 | 535356 |
| maps/ | 17 | 12580 |
| processed/ | 17 | 1087500 |
| 20020610/ | | |
| data/ | 40 | 3947336 |
| gps/ | 7 | 19844 |
| ins/ | 19 | 102348 |
| notes/ | | |
| | | |
| TOTAL | | 136825912 |

## Calibration

### *Range Calculation*

Before providing a range calibration coefficient, the specific manner in which the height is extracted from a processed waveform must be defined. The range estimated by the D2P radar altimeter is a summation of the following values: (1) *Pulse Length*, (2) *Tracking Range*, (3) *Waveform Delay*, and the (4) *Calibration Offset*. The first three values, illustrated in Figure 4, can be determined from the level-1(b) datasets, and the calibration offset is defined below. During the majority of data collection flights, the *pulse length* was 1.536 us or 230.24 m. The tracking range is expressed in discrete (0.012 us or 1.79875 m) steps based on a 83.33 MHz tracking clock (i.e. a tracking range of 300 corresponds to 300*1.79875 m). The waveform delay is derived using a re-tracking algorithm (peak power was used for runway calibration). An additional "zero delay" is introduced by the receiver to place the peak signal in near the center of the waveform. This additional range is dependent on the pulse length as shown in table 5.

**Table 5. Radar delay coefficients.**

| Pulse Length | Samples/Waveform | Zero Delay |
|---|---|---|
| 3.072 us | 512 | 0.768 us |
| 1.536 us | 256 | 0.768 us |
| 0.768 us | 128 | 0.384 us |
| 0.384 us | 64 | 0.192 us |

Figure 4 illustrates the tracking process and is explained as follows. The waveform on the left-hand side of the image represents the transmitted waveform. After a time delay (counted out by the tracking computer and denoted by the tracking range), the receiver mixes a reference signal, top waveform right-hand side (rhs), with the reflected signal, middle waveform rhs. The resulting signal, converted to the time domain via FFT, is the desired waveform with an additional delay, bottom waveform rhs. The total range to the peak is the pulse length, plus the tracking range, plus the delay. To determine the range to the beginning of the waveform, the "zero delay" must be subtracted.

*Antenna Pattern*

The D2P uses an antenna with a 4-degree along-track beamwidth, and an 8-degree cross-track beamwidth. Delay/Doppler processing effectively narrows the along-track beamwidth, and provides precise along-track pointing information. However, the cross-track pointing direction of the antenna is not well known. The cross-track pattern was estimated by analyzing data from an S-turn over a stretch of open ocean. The pattern was estimated by comparing the amplitude *versus* roll during this turn. This pattern shows the expected 8-degree cross-track beamwidth, but the pointing angle is at about 2.5 degrees off nadir.

*Cross Channel Phase*

The D2P radar uses two receiver antennas and corresponding channels to calculate the cross-channel phase difference between the two receive phase-centers separated by a baseline distance of 14.5 cm. Slight differences in the receive channels introduces a constant cross-channel phase offset. This offset was calculated to be approximately -2.8 radians by analyzing data from a known target. All processed data available on the FTP site have been corrected by 2.8 radians to remove this effect.

*GPS/Radar Range Comparison*

On 03 May 2002, the system was flown over the Wallops runway to estimate the range offset of the system. The runway also was surveyed using GPS, and was used as a calibration standard. Two runway overflights were used to calculate the range offset of the system. The first overflight was at 300-m altitude and 0.768-us pulse length. The second was at 600 m and 1.536 us. Figure 5 shows a comparison of the D2P and GPS runway heights for each overflight (24.98 meters was subtracted from the D2P data to overlay the images), and Table 6 gives the mean offset and variance of each overflight. All processed data available on the FTP site have already been corrected by 24.98 m.

**Table 6. Runway Calibration Results.**

| Pass | Height | Pulse Length | mean: D2P-GPS | std: D2P-GPS |
|---|---|---|---|---|
| 1 | 300 m | 0.768 ms | 23.9811 m | 0.0173 m |
| 2 | 600 m | 1.536 ms | 23.9674 m | 0.0191 m |

**Radar Tracking**

Preliminary height tracking of the D2P waveforms involved extracting the peak power point of each processed waveform. As a result, the waveforms required sampling at scales on the order of the desired precision (a few centimeters). To preserve the signal bandwidth needed to achieve this desired sampling, it was necessary to oversample the waveforms prior to the cross-track phase calculation (i.e. multiplication of channel 1 with the conjugate of channel 2), as the multiplication process had an effect of doubling the signal bandwidth and could potentially alias the higher frequency components[1]. Oversampling was accomplished by padding zeros to the raw waveforms prior to the frequency/delay FFT in the Delay/Doppler processing algorithm. Once a suitable set of waveforms was processed, the following steps were used to obtain the height estimate.

1. Resample (FFT method, sin(x)/x filter) the waveform to desired precision.
2. Detected the location of maximum power as the track point for the each waveform.
3. Along-track filter to reduce height variance (Hanning/power weighted average).

Peak-power tracking will provide more accurate measurements over flat surfaces with sharp waveform responses. However, as the random characteristics of the surface begin to influence the radar response, a tracking algorithm should be employed that is more suitable to the surface characteristics and platform geometry. Random surface scattering will begin to become apparent as the surface roughness increases, and as the height of the instrument increases and illuminates a larger area (sufficient to statistically model the surface scatterers). Alternative tracking algorithms could include leading edge midpoint methods, similar to those used with satellite ocean-observing altimeters, and more complicated model-based algorithms suited to unique situations such as significant subsurface penetration, or when approximations based on a large number of statistically-independent scatterers do not apply.

**Radar/Laser Comparisons**

Initial comparisons of height estimates between the radar and laser altimeter were conducted on selected datasets. Radar height estimates were obtained using the method described above. Corresponding laser estimates were calculated by averaging the laser values extracted only from those locations within the scan pattern that are coincident with the radar antenna footprint on the surface. Figure 6 illustrates how this rule constrains laser shots in both the along- and cross-track direction. Doppler limits on the radar samples constrain the pattern in the along-track direction. The cross-track pattern is limited by the radar pulse width, and by the cross-track pointing direction to the first-surface return determined from the cross-channel phase. Furthermore, selection of the laser measurements must be weighted by the radar's antenna pattern. This rule is more important at low altitudes at which the radar measurements become beam-limited.

Figure 7a shows a comparison of the heights measured by the two instruments over a section of the Greenland ice sheet. It is obvious that there was significant penetration by the radar at this location, as many of the near surface accumulation layer can be identified. The corresponding laser height is indicated as the white line near the initial radar peak. The upper plot in the image is a magnified comparison of the radar and laser heights (the scale is on the right). It is assumed

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[1] J. Robert Jensen, Radar Altimeter Gate Tracking: Theory and Extension, *IEEE Trans. Geosci. and Remote Sensing*, vol. 37, pp. 651-658, 1999.

that the ~1.8 meter difference corresponds to an overlying layer of snow. This seems to imply that the main peak detected by the radar is the snow/ice interface, while the laser is detecting the air/snow interface. It follows from this interpretation that the dielectric contrast between the snow/ice interface is more significant than the initial contrast at the air/snow interface, at least at Ku band.

At microwave frequencies, the dielectric constant of the overlying dry snow is given by the equation, $\varepsilon_r = 1.0 + 1.9\rho_s$, where $\rho_S$ is the snow density and is usually less than 0.5 (g/cm$^3$) ["Microwave Remote Sensing, Vol. 3," Ulaby et al., 1986]. This puts limits on the dielectric constant of dry snow to range between 1.0 and 1.8. Assuming relatively low density (< 0.25 g/cm$^3$) snow, the reflection from the snow/ice ($\varepsilon_{ice}$ = 3.15) is approximately 5dB greater than the initial air/snow reflection. Figure 7b shows a dB plot of the radar waveform corresponding to location (76.066 N, 301.466 E) with the laser extracted height indicated by the vertical red line. It can be readily seen that the laser is detecting the air/snow interface, while the peak radar return due to the snow/ice interface is about 4 dB higher.

In regions where the snow cover thickness is closer to the resolution of the radar system, it becomes more difficult to separate the responses from the air/snow and snow/ice interfaces. In these cases, the radar waveform displays only a combination of the two responses as a single peak. Figure 8a shows a comparison of the two instruments over a region with less (estimated) snow cover. Again, figure 8b shows a dB plot of the radar waveform (76.974 N, 296.079 E) with the laser extracted height overlaid. Although a separate peak is not apparent, a small anomaly in the rising slope is noticeable and coincident with the laser height. Using the laser data as an interpretive aid, this feature can be identified as the reflection from the air/snow interface and does fall with the expected level (4-10 dB down) with respect to the main peak.

Figure 9 shows a comparison over northern sea-ice. The waveforms collected over sea-ice indicate a larger range of surface roughness variations. As indicated in the image, there are very specular areas where the snow cover almost non-existent (most likely open water) as well as rough areas where there seems to be greater snow coverage. In these areas, it is more difficult to identify individual reflections in the radar waveforms; however, the differences between the radar and laser heights estimates still seem to be related to and give a quantitative indication of the snow cover.

**Summary and Conclusions**

LaRA has shown that temporally and spatially coincident laser- and radar-derived heights of snow-covered ice sheets can be obtained from a suitable combination of instruments mounted on the same aircraft, and operated simultaneously. Further, we have shown that such data may be relatively calibrated in height to +/- 1 cm. To our knowledge, LaRA was the first field campaign in which such a standard was met.

Analyses of selected portions of LaRA data suggest that the heights so measured by laser and radar means may be identical (within the precision of the instruments), and also may be significantly different. We conclude that these differences or similarities in measured surface heights are a direct consequence of the prevailing snow and ice conditions, and are not a consequence of differences between the instruments themselves.

The D2P radar altimeter has been proven to be a valuable instrument, qualified to undertake measurements for scientific purposes, including in particular campaigns in support of calibration and validation of other sensors, either airborne or space-based. The greatest value of simultaneous laser and radar surface measurements, however, can be realized only if there are independent ancillary determinations of the prevailing local snow and ice sheet conditions.

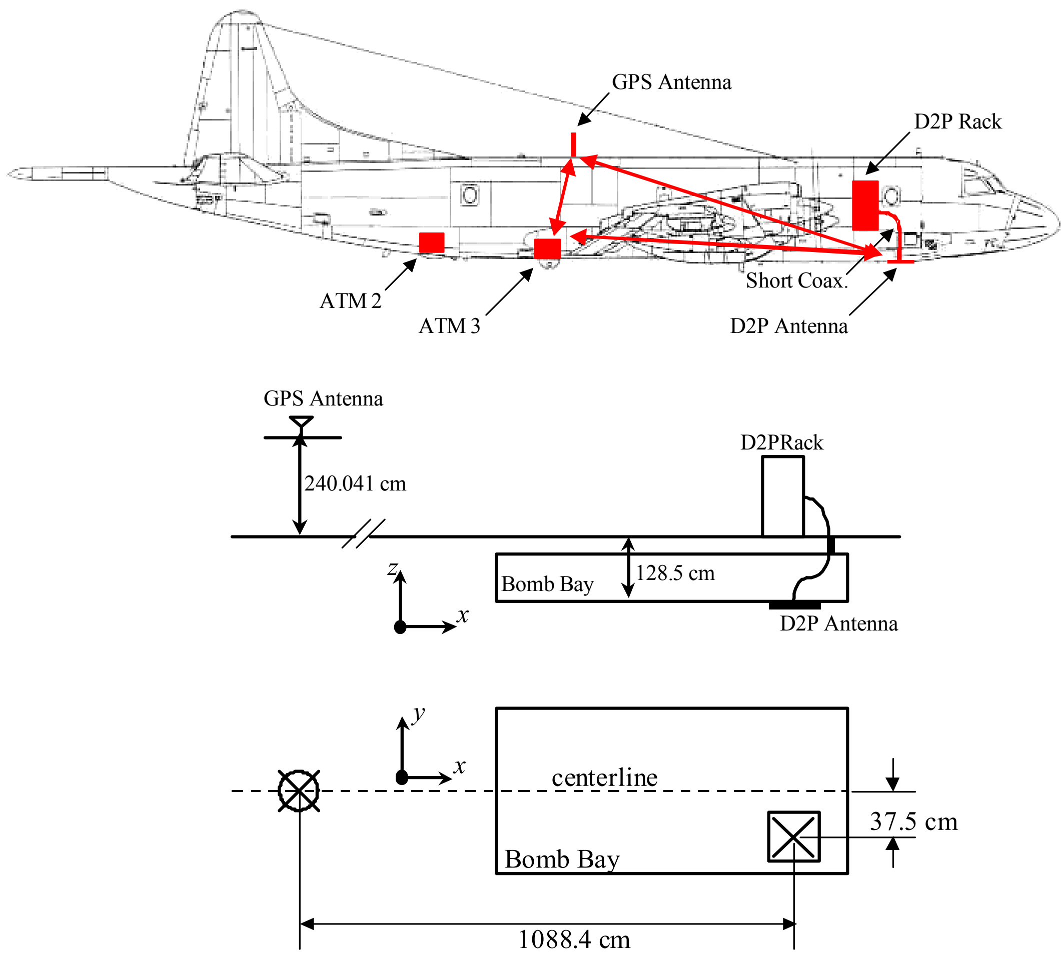


**Figure 1. Sensor layout in the NASA P-3 aircraft. (a) relative to the aircraft. (b) relative to each other.**

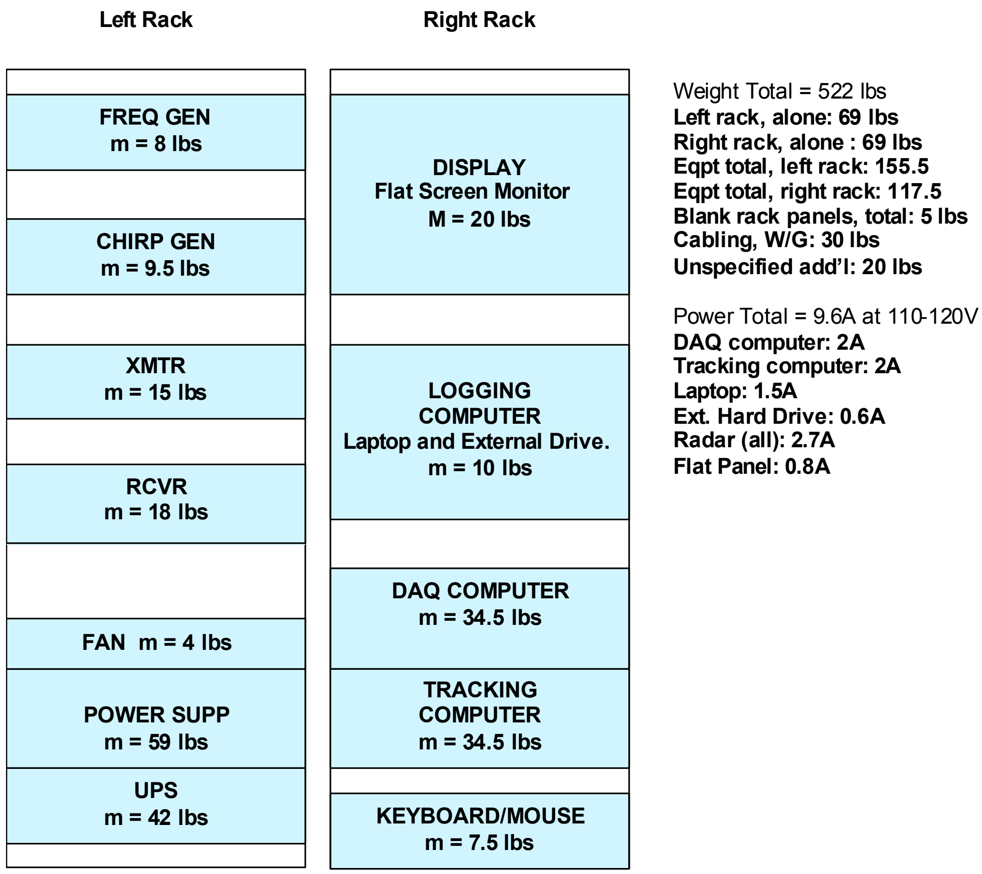


**Figure 2. Rack layout, weight, and power consumption.**

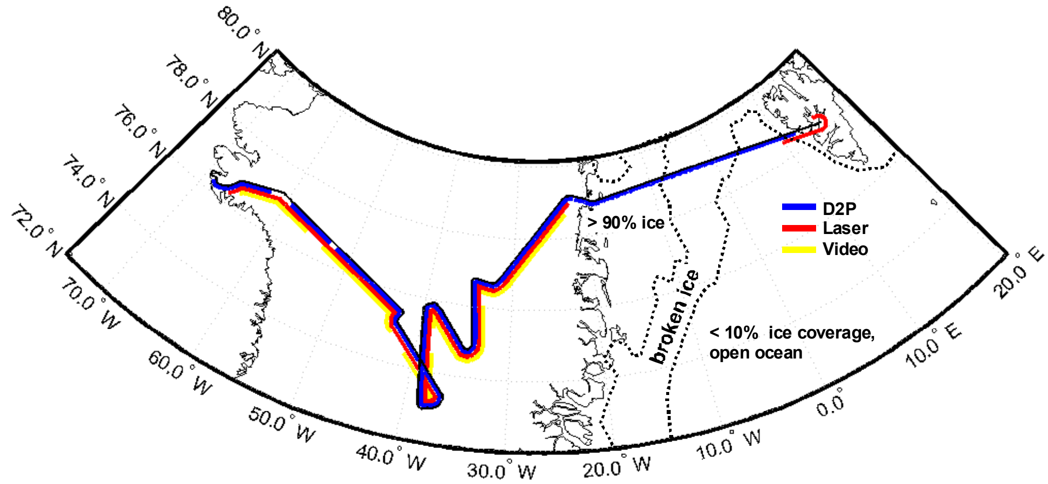


**Figure 3a. May 18, 2002: Transit from Thule to Svalbard.**

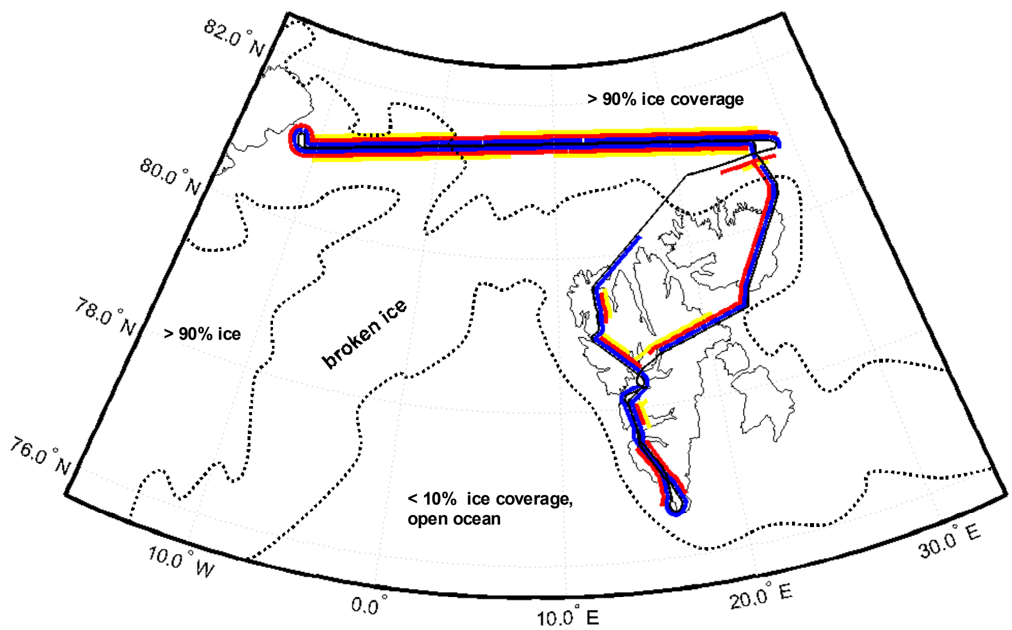


**Figure 3b. May 20, 2002: Flight Over Svalbard Glaciers and Sea Ice**

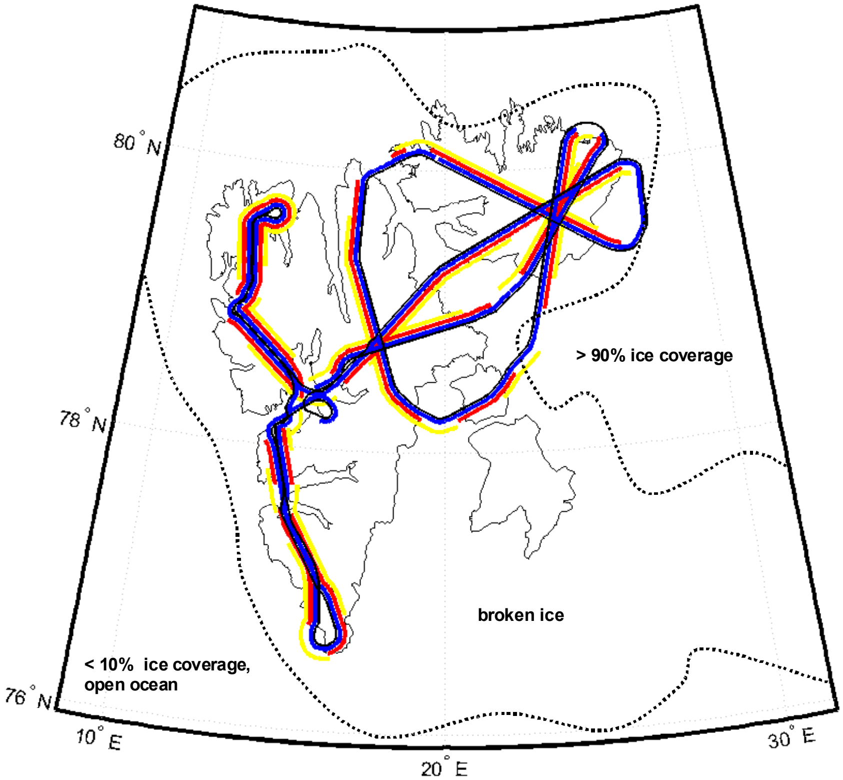


**Figure 3c. May 22, 2002: Main Svalbard Mapping Flight.**

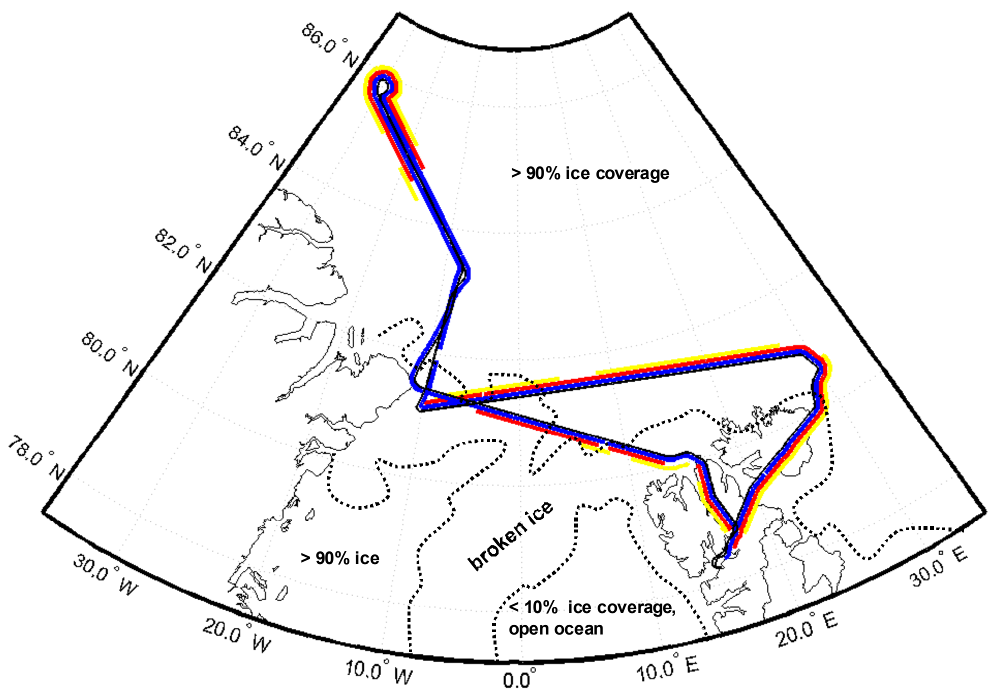


**Figure 3d. May 23, 2002: Final Flight Over Northern Sea Ice.**

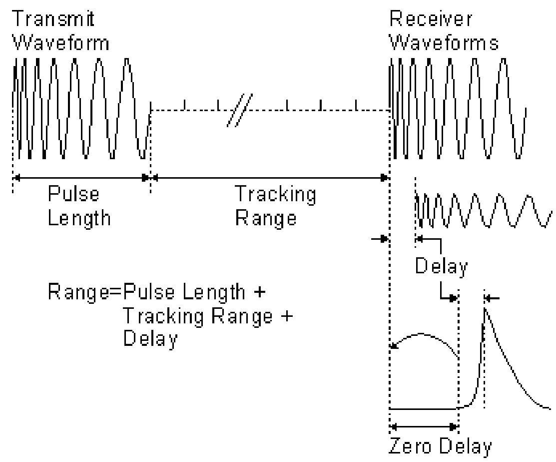


**Figure 4. Radar delay calculations.**

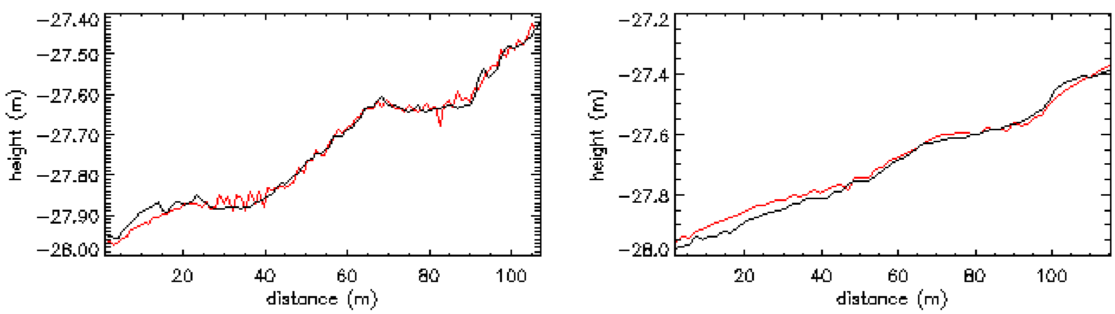


**Figure 5. Comparison of GPS and D2P heights during the calibration flight.**

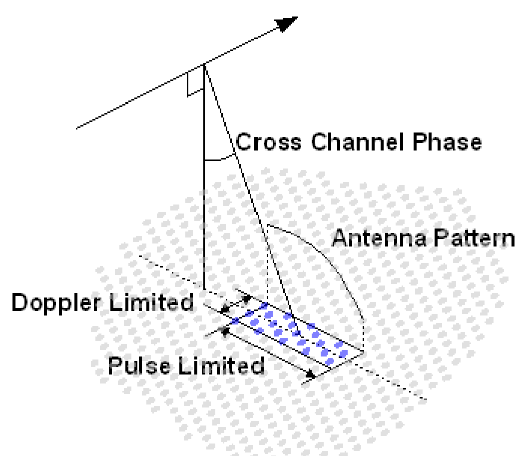


**Figure 6. Radar constrained laser measurements.**

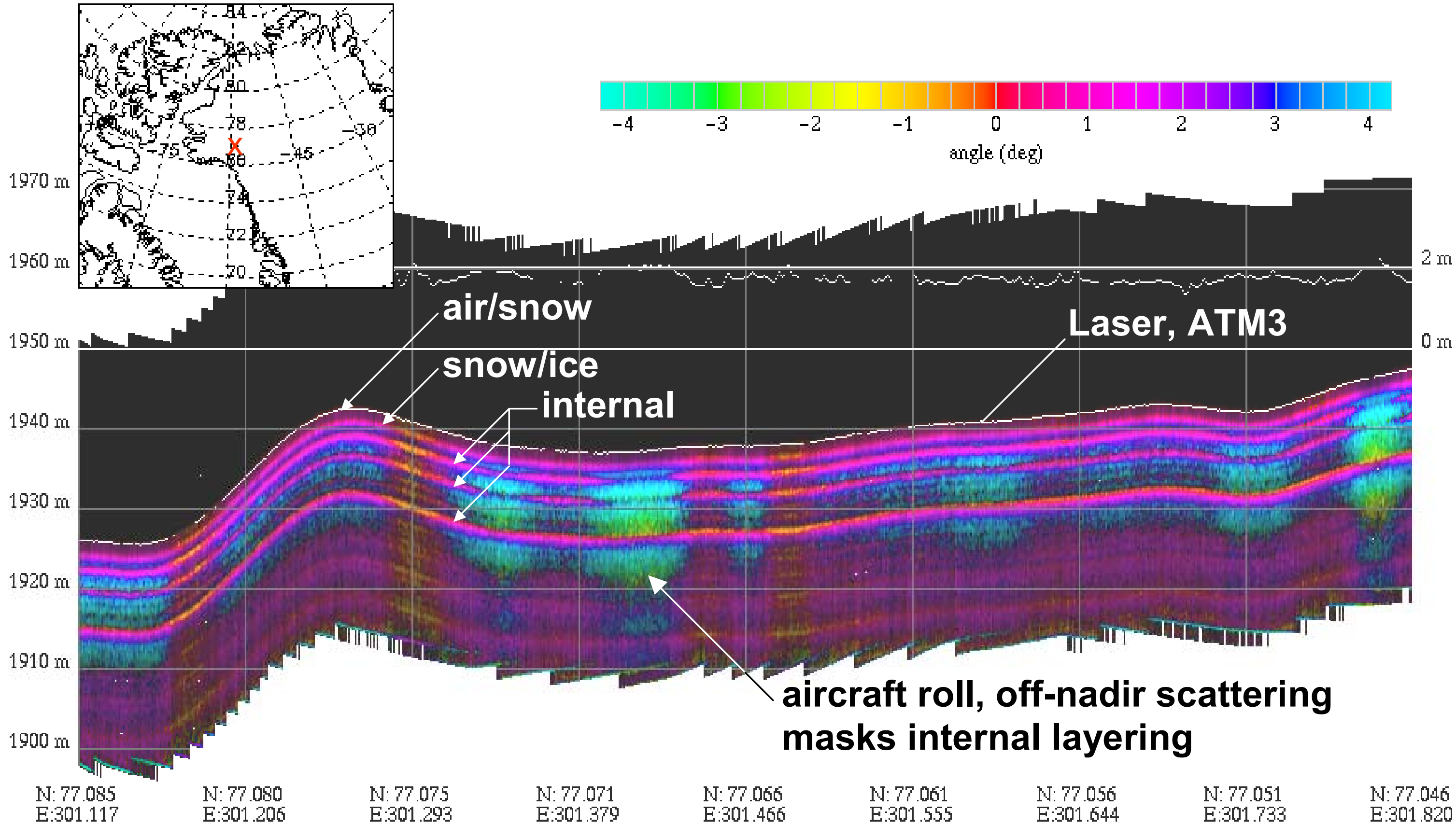


**Figure 7a. Comparison over Greenland ice sheet with significant snow cover.**


**Figure 7b. Waveform at (76.066 N, 301.466 E) with laser height indicated in red.**

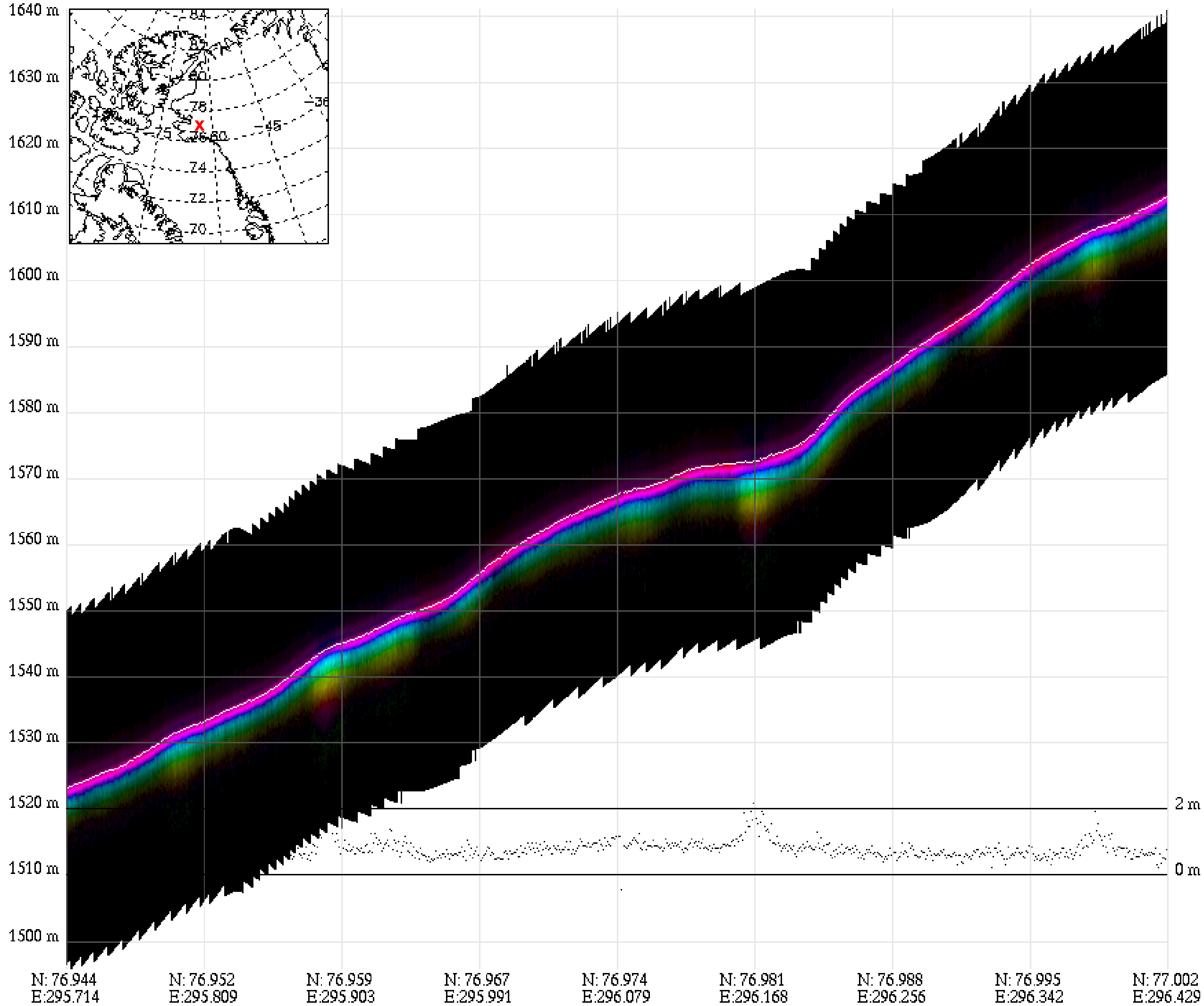


**Figure 8a. Comparison over Greenland ice sheet with limited snow cover.**

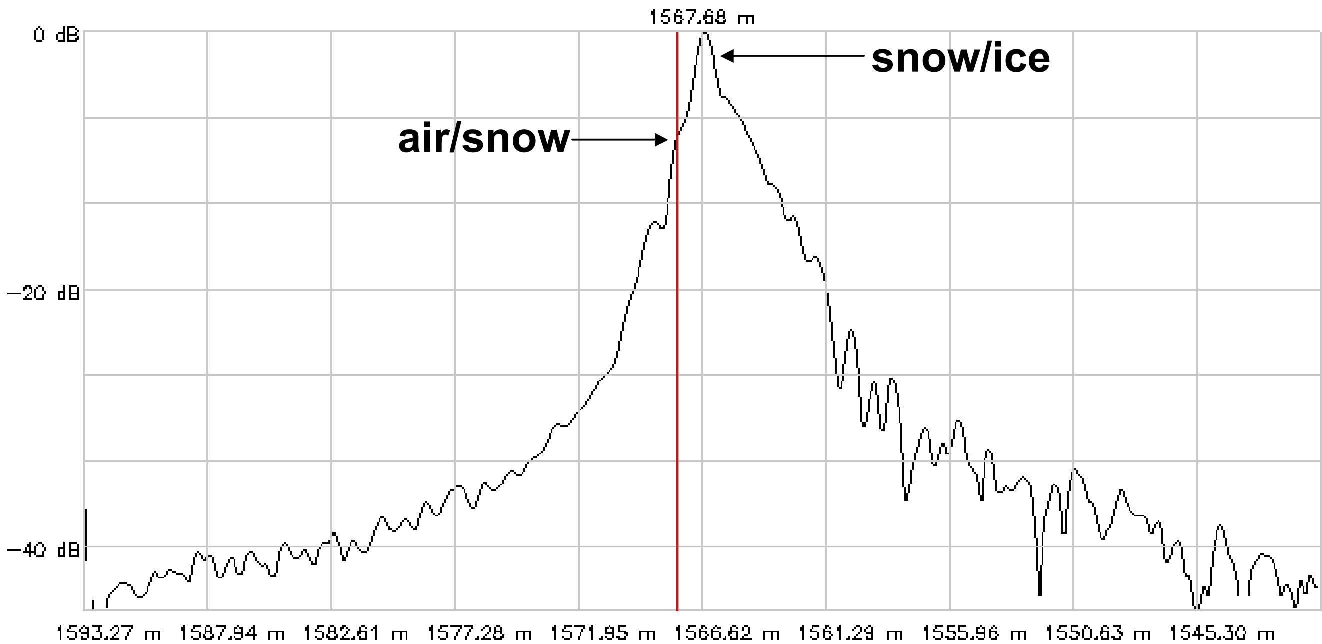


**Figure 8b. Waveform at (76.974 N, 296.079 E) with laser height indicated in red.**

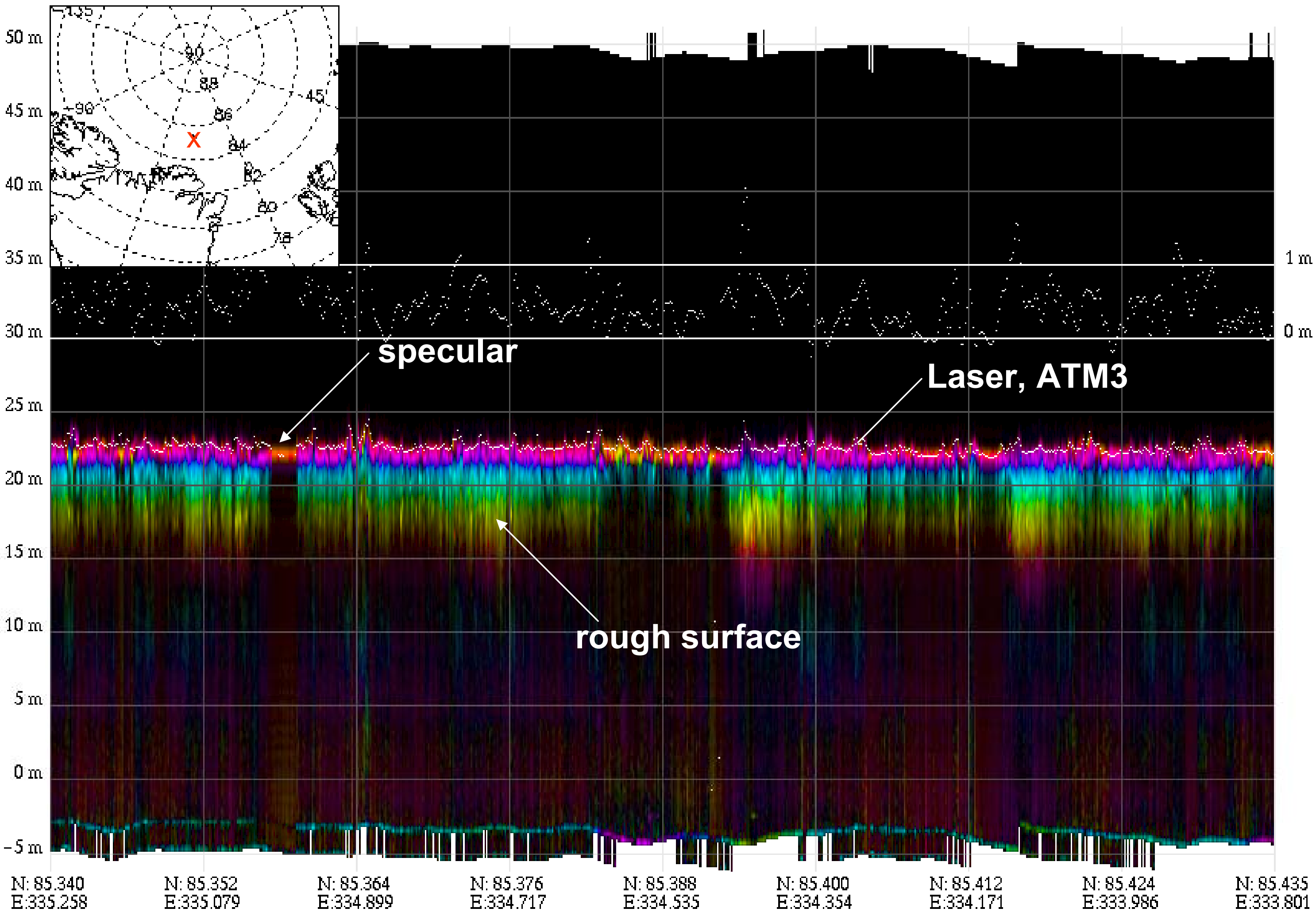


**Figure 9. Comparison over northern sea-ice.**