Final Technical Report

Pathfinder Advanced Radar Ice Sounder (PARIS)
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1. Preface

The Pathfinder Advanced Radar Ice Sounder (PARIS) Instrument Incubator Project was intended to demonstrate the first successful thickness measurement (sounding) of glacial ice by radar from a high-latitude aircraft. This objective was met. The success of the PARIS IIP project is due to the combined efforts of Johns Hopkins University Applied Physics Laboratory personnel. The two essential elements of such an enterprise are the radar, and subsequent data processing. Marshall Jose was the lead engineer for the development and field deployment of the radar, and Mary Keller was the lead scientist for the ice sounding data processing. These individuals are also the principal authors of their corresponding Appendices to this report. Several additional specialists contributed their particular skills for the design, implementation, and testing of sub-sections of the radar.

* Following no-cost time extensions
2. Subject Inventions/Reportable Items

The PARIS grant supported numerous conference presentations, workshop participation, journal articles, and other evidence of professional productivity. A detailed listing appears in Appendix 7. The items cited are comprised of:

- 1 United States patent
- 2 articles in professional journals
- 10 articles in conference proceedings
- 1 presentation at an international radar ice sounding workshop
- 1 special report to NASA in response to an RFI in advance of Ice Bridge 2009

3. Summary of Research

In July 2005, the Johns Hopkins University, Applied Physics Laboratory began “Pathfinder Airborne Radar Ice Sounder (PARIS)” funded under the NASA Instrument Incubator Program (IIP). The primary objective of this project was to demonstrate successful radar sounding of ice sheet layering and bottom topography from a high-altitude platform. This objective was met; as detailed in the appendices to this report. Major contributing factors included a high-fidelity 150-MHz radar, supported by along-track partially-coherent processing. “High-fidelity” implies very wide dynamic range, extreme linearity, and very low side-lobes generated by the transmitted pulse. The design of the radar (Appendices 1 and 2) includes in particular those critical features that contributed to the observed 90-dB dynamic range. “Partially-coherent processing” implies the delay-Doppler technique (Appendix 5), previously proven in airborne radar altimeter and low-altitude radar ice sounding embodiments. The radar was mounted on the NASA P-3, and deployed on a mission over the Greenland ice sheet in the spring of 2007. Data were recorded on board as well as displayed in flight on a quick-look processor. The data subsequently were processed in the laboratory to quantify performance characteristics, including dynamic range, side-lobe level control, and contrast improvement from the delay-Doppler algorithm.

The transmit waveform is a 5-MHz bandwidth chirp at a 150-MHz operating frequency with a trapezoidal envelope. Such severe weighting is essential to reduce the ringing commonly associated with the initial on-off transition of weakly-weighted waveforms. The 300-W (peak) linear-FM pulse has ~6 MHz bandwidth. The amplifier is class AB to help ensure the high linearity needed to suppress the internal clutter (side-lobes) generated by the chirp waveform. Laboratory measurements of the driver and power amplifier showed excellent linearity with a two-tone third-order inter-modulation of at least -26 dBc at 311 W peak power.

There is no down conversion or IF signal within the receiver, greatly simplifying the design, and eliminating most potential sources of distortion and inter-modulation. Upon reception, the radar samples the RF signal directly. The sample rate is well below Nyquist, but is chosen so that the resulting spectra shift an alias of the main signal to baseband in a clear channel. The receiver includes variable attenuators to adjust the voltage range of the signal input to the analog-to-digital converter as well as sensitivity time control (STC) to increase the effective dynamic range of the response as a function of depth of penetration. The overall noise figure of the receiver is less than 5.5 dB with a gain of over 60 dB and a 45 dBm third-order intercept point.
The digital components consist of a field programmable gate array (FPGA) radar synchronizer, a direct digital synthesizer (DDS), and an under-sampling analog-to-digital converter (ADC). All components of the digital subsection are clocked by a stable 66.6 MHz reference oscillator. The radar data are time-tagged by reference to GPS.

The flights included passes over the summit ridge, from which results show internal layering, and the bottom profile at several km depth.

The original objectives of the PARIS project were completed with considerable funds remaining. A no-cost time extension was approved, allowing time for enhancement of the radar to incorporate a second channel to accommodate the newly-invented polarimetric means of suppressing cross-track clutter. The design of PARIS-2 is described in more detail in Appendix 3.

PARIS-1 participated in an additional field campaign to Antarctica (2008), and PARIS-2 was part of Ice Bridge 2009 to Greenland. Those campaigns are summarized in Appendix 6. The original PARIS IIP grant was supplemented with additional NASA funds which enabled JHU/APL to prepare for, embark, and process the data from those two missions, for which separate reports have been submitted.

During the course of the project, Johns Hopkins University Applied Physics Laboratory was approached by a consortium of Harvard University and Aurora Flight Sciences, who were promoting the concept of a small ice sounding radar to be deployed on an optionally-piloted vehicle for systematic ice thickness surveys of Greenland’s ice sheet. This precipitated the design of a 435 MHz radar, described in Appendix 4. The concept was elaborated in response to NASA’s Earth Venture 1 opportunity, for which a proposal was submitted in November 2009.

4. Outlook

Radar

High-quality PARIS data were acquired from the summit and certain northern outlet glaciers of Greenland, and the ice shelves of the Antarctic Peninsula. These were processed through delay-Doppler and custom algorithms to extract and track basement locations to an accuracy of 1% of the overall depth. The results verify that data from the PARIS radar can be processed to provide accurate ice soundings over appropriate ice conditions.

Theoretical considerations (and controlled field measurements) support extrapolation of these results from the 150 MHz PARIS frequency to as high as 450 MHz for application against cold and moderately unfractured ice, since the dominant limiting factor under those conditions is in situ attenuation. However, for many of Greenland’s outlet glaciers (that have multiple crevasses, inclusion of impurities, ice lenses, or voids), internal scattering becomes the limiting loss factor. Rayleigh scattering, which occurs when the scattering elements are much smaller than the illuminating wavelength, becomes more severe in proportion to the fourth power of frequency ($f^4$), or, equivalently, the inverse fourth power of wavelength ($\lambda^{-4}$). Hence, lower frequency is recommended for radar ice sounding under such conditions. For example, a 435 MHz (P-band) radar would not be appropriate for ice sounding of Greenland’s central and southern outlet glaciers.
**Processing**

Our field experience and studies have shown that there are several aspects of the delay-Doppler and polarimetric processing that could be improved. First, the benefits and limitations of cross-track clutter suppression by polarimetric selectivity can be explored only if the radar radiates circular polarity, and is properly calibrated. There was not sufficient time in the PARIS (extended) grant to implement and test PARIS prior to field deployment in support of Ice Gap. The polarimetric implementation and processing are worthy of a future focused investigation.

Second, the Antarctic basement signature (especially under the marginal glaciers) typically appeared as a double line, rather than the single trace in the Greenland soundings. Whether this is an artifact of the processing, or a geophysical property of these smaller, faster-moving glaciers is unknown.

Third, the side clutter was significantly stronger in the Antarctic soundings, especially at depth, giving rise to hairpin-like features in the ice thickness profiles. In theory, and has been demonstrated in previous experiments, these should have been suppressed by our Doppler processing algorithm. There was insufficient time in the extended PARIS grant to determine the cause of these unwanted artifacts for the Antarctic deployment. The issue is of sufficient importance to warrant further investigation.
APPENDIX 1. PATHFINDER ADVANCED RADAR ICE SOUNDER: PARIS

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ABSTRACT

Demonstration of ice thickness sounding from a high-altitude airborne radar was the prime objective of the PARIS NASA Instrument Incubator Project. This paper describes key features of the system, including the radar and the processing algorithm. Test flights over the ice sheets of Greenland produced good results.

1. INTRODUCTION

In July 2005, the Johns Hopkins University, Applied Physics Laboratory began “Pathfinder Airborne Radar Ice Sounder (PARIS)” funded under the NASA Instrument Incubator Program (IIP). Until PARIS was demonstrated, virtually all airborne radar sounding of ice sheets had been restricted to altitudes no higher than about 500 m above the surface, due largely to the fact that the relative level of off-nadir clutter increases with sensor altitude, leading to unacceptable results. The primary objective of this project was to demonstrate successful radar sounding of ice sheet layering and bottom topography from a high-altitude platform. This objective was met. Major contributing factors included a high-fidelity 150-MHz radar, supported by along-track partially-coherent processing. The radar was mounted on the NASA P-3, and deployed on a mission over the Greenland ice sheet in the spring of 2007. Data were recorded on board as well as displayed in flight on a quick-look processor. The data subsequently were processed in the laboratory to quantify performance characteristics, including dynamic range, sidelobe level control, and contrast improvement from the delay-Doppler algorithm.

2. RADAR DESIGN FEATURES

“High-fidelity” in this context implies very wide dynamic range, extreme linearity, and very low sidelobes generated by the transmitted pulse. The radar’s architecture (Fig 1) is based on two key characteristics: signal modulation at the mean transmitted frequency, and analog-to-digital conversion operating directly on the received signal. These techniques have proven to be essential for radar sounders [1], since they circumvent the main sources of non-linearity and harmonic generation common to all up- or down-conversion frequency schemes.

The transmit waveform is a linear frequency-modulated chirp at a 150-MHz operating frequency with a trapezoidal envelope. Such severe weighting is essential to reduce the ringing commonly associated with the initial on-off transition of weakly-weighted waveforms. The 180-W (peak) pulse has ~6 MHz bandwidth. The amplifier is class AB to help ensure the high linearity needed to suppress the internal clutter (sidelobes) generated by the chirp waveform. Laboratory measurements of the driver and power amplifier show excellent linearity with a two-tone third-order inter-modulation of at least -26 dBc at peak power. To maximize average power, the radar is operated at a PRF several times higher than the Doppler bandwidth of the received waveforms. The effective PRF can be reduced by coherent pre-summing, implemented in PARIS as a part of the subsequent data processing.

In the receiver, there is no intermediate frequency, and no analog baseband down-conversion. Instead, the signals are sampled directly following the low-noise amplifier. The sample rate is well below Nyquist, but is chosen so that the resulting spectra shift an alias of the main signal to offset baseband in a clear channel (Fig 2). The radar ice sounding application demands a dynamic range of at least 90-dB. To help support this requirement, the receiver includes variable attenuators to adjust the voltage range of the signal input to the analog-to-digital converter as well as sensitivity time control (STC) to increase the effective dynamic range of the response as a function of depth of penetration. The overall noise figure of the receiver is less than 5.5 dB with a gain of over 60 dB and a 45 dBm third-order intercept point.

The digital components in the radar consist of a field programmable gate array (FPGA) radar synchronizer, a direct digital synthesizer (DDS), and
an under-sampling analog-to-digital converter (ADC). All components of the digital subsection are clocked by a stable 66.6 MHz reference oscillator. The radar data are time-tagged by reference to GPS.

3. DATA PROCESSOR FEATURES

“Partially-coherent processing” implies the delay-Doppler technique [2], previously proven in airborne radar altimeter and low-altitude radar ice sounding embodiments [3, 4]. Figure 3 shows the logical flow of this technique as would be required for a radar altimeter. The ice sounding application requires that the range curvature correction (the “delay shift” operation) and the resolved along-track data co-registration (the “Doppler shift” operation) must account for the retarded EM propagation speed within the ice sheet. There are three major advantages (illustrated in Fig 4) that follow from this method: rejection of clutter from Doppler selectivity, finer along-track footprint resolution, and more degrees-of-freedom resulting in substantial speckle reduction. Compatible methods to reduce clutter contributions from off-nadir sources to the side of the surface track are currently under investigation.

4. RESULTS

The flights included passes over the summit ridge at an aircraft altitude of 25,000 ft, from which results (Fig 5) show internal layering, and the bottom profile at several km depth. Analysis of returns such as these verify the 90-dB dynamic range performance of the system.

5. REFERENCES


Figure 2. Sub-Nyquist alias-to-baseband A/D method

Figure 3. Logical flow of the delay-Doppler algorithm, which is the optimum processing strategy to reduce self-clutter and improve along-track spatial resolution for a nadir-viewing radar sounder.
Figure 4. Processing low-altitude examples over the Greenland ice. (a) Unprocessed data. (b) Incoherent—decreased speckle with no surface clutter or resolution improvement. (c) Coherent—decreased clutter and improved resolution but no speckle reduction. (d) DD—decrease in speckle and clutter, increase in SNR, and also with improved resolution.

Figure 5. Example of processed data from PARIS over the crest of the Greenland ice cap. Note that the range scale must be reduced by the factor 0.6 to account for the slower EM propagation speed within the ice sheet itself. The resulting ice thickness is on the order of 3.3 km.
Appendix 2.

*Design Summary of PARIS 1*

The PARIS 1 radar sounder demonstrated a new and simpler architecture permitted by recent advances in digital electronics. The primary motivation for these innovations was to assure linearity sufficient to support the requirements imposed by ice sheet sounding from a remote platform to depths of several kilometers. The radar data are brought into the digital domain after a minimum number of analog processing steps. This improves the linearity of the entire system, which (among other benefits) substantially reduces the spurious inter-modulation products that could otherwise contaminate the data. The block diagram of the system is shown in Figure A1-1.

![Figure A1-1. PARIS 1 Block Diagram.](image-url)

The operational specifications of the PARIS 1 radar are shown in Table A1-1.
<table>
<thead>
<tr>
<th>Radar type</th>
<th>Chirped-pulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center frequency</td>
<td>150 MHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>6 MHz</td>
</tr>
<tr>
<td>Peak power</td>
<td>500W</td>
</tr>
<tr>
<td>Range resolution</td>
<td>17m in ice</td>
</tr>
<tr>
<td>Pulse rate</td>
<td>8 - 10 kHz</td>
</tr>
<tr>
<td>Pulse width</td>
<td>3 – 30 µs</td>
</tr>
<tr>
<td>Input noise figure</td>
<td>4 dB</td>
</tr>
<tr>
<td>Antenna</td>
<td>dipole array</td>
</tr>
<tr>
<td>Antenna polarization</td>
<td>linear</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>10 dBi</td>
</tr>
<tr>
<td>Prime power reqt.</td>
<td>500W</td>
</tr>
<tr>
<td>Electronics mass</td>
<td>110 kg</td>
</tr>
<tr>
<td>Electronics volume</td>
<td>350 dm³ (est.)</td>
</tr>
</tbody>
</table>

Table A1-1: Operational specifications of PARIS 1 radar.

Transmit path

The transmit waveform is a 5-MHz bandwidth chirp generated by a commercial direct-digital synthesizer (DDS) chip. The chip also applies a trapezoidal envelope to the pulse, minimizing unwanted sidebands. The 500W amplifier uses a class AB mode of operation to ensure the high linearity and thus preserve the pulse’s low sidebands. Bench tests of the amplifier demonstrated a two-tone third-order inter-modulation of better than -20 dBc was measured at $P_o = 500$ W.

Since PARIS 1 used an existing pair of independent, separated antennas, it was possible to split their roles into transmit and receive, removing the necessity for transmit/receive switching.

![Transmit Antenna](image)

Figure A1-2. Placement of PARIS radar antennas on P-3 aircraft.
Receive path

Since the radar samples the RF signal directly, there is no down-conversion or IF signal within the receiver; this greatly reduces the complexity of the analog section of the receiver. Immediately following the receive antenna is an absorptive transmit-receive switch to provide two levels of protection for the low noise amplifier (LNA) during the transmit cycles. The signal continues through amplification and filtering stages, without being down-converted; note that variable-gain amplifiers are employed to permit sensitivity time control, which increases the overall dynamic range of the system (see Fig A1-3). Total gain of the receive chain is 65-95 dB, with a +45 dBm third-order input intercept point. Band-pass filters ensure that the subsequent under-sampling operation will be uncontaminated.

![Figure A1-3. Effect of Sensitivity Time Control (STC).](image)

Digital Section

The digital section of the radar contributes most of the functionality within, and permits miniaturization not formerly seen in ice sounders. During pulse transmission, the field-programmable gate array (FPGA) configures and triggers the direct digital synthesizer (DDS) to directly generate a transmit pulse at the 150 MHz operating frequency, which is then amplified by the power amplifier and emitted by the antenna. During reception, the FPGA accepts the under-sampled data stream from the analog-to-digital converter (ADC), filters it digitally and buffers it for transfer to the data acquisition laptop via a USB 2.0 interface. Figure A1-4 shows the frequency plan of the under-sampling strategy used.
Figure A1-5 shows examples of the digital processing performed by the FPGA. Fig. A1-4a shows a transmit waveform centered on 16.67 MHz after being under-sampled at 66.7 MHz, and Fig. A1-4b shows the same waveform after being passed through the finite-impulse response (FIR) digital band-pass filter. After decimation-by-5, the waveform appears as in Fig. A1-4c, sampled at 13.33 MHz, and centered on 3.33 MHz. If a matched filter is applied to this waveform (by cross-correlating it with an analytical replica of the transmit waveform), the result can be seen in Fig. A1-4d, demonstrating side-lobe levels of -40 dB below peak.
Figure A1-4. Waveform representation of the data processing.

The FPGA time-tags each transmit pulse by relying on a 1 pulse-per-second (1 PPS) signal from a GPS receiver; this time tag is used during processing to geo-locate each radar pulse. The FPGA also paces radar transmission pulses and supervises application of STC gain changes. All components of the digital subsection are clocked by a stable 400 MHz reference oscillator.
Appendix 3

PARIS 2 Redesign Summary

Changes

The chief PARIS 2 goal was to obtain radar data over the Greenland ice sheet while participating in the Ice Bridge 2009 mission of NASA’s Cryospheric Science Branch. A secondary objective was to radiate in circularly-polarization, and to receive on two orthogonal linear polarizations. This required a two-channel receiver that would independently receive and record the radar returns from the ice sheet.

Polarimetric mode operation required two receive channels, which might have been costly in time and money to achieve if a two-channel radar had to have been built from scratch. However, given that two copies of the PARIS 1 radar were fabricated for the original task as “primary” and “backup” respectively, it was decided instead to use them both, operating in tandem (Figure A2-1).

Figure A2-1. Block diagram of modified PARIS radar for tandem recording.

At the time of Ice Bridge, NASA’s P-3 aircraft was no longer deemed air-worthy to fly the original 150 MHz antenna arrays under the wings, so a new antenna had to be designed, fabricated, and flight-qualified. The antennas used in the original 2007 mission were designed for only one linear polarization, so that to support the polarimetric mission, it was necessary for APL to design a new antenna assembly for the P-3 aircraft. These two considerations led to a compact antenna design to fit within the bomb bay of the P-3, thus satisfying both the air-worthiness and the radar compatibility requirements.
Another significant change from the original PARIS operation mode was the necessity to deal with antenna “sharing” between transmitter and receiver. This came about as a consequence of insufficient room on the NASA P-3 to mount a separate transmit and receive antenna, as was used during the 2007 PARIS flights. Fast, high-power transmit/receive (“T/R”) switches were required to switch the antennas between their respective transmit and receive path.

An additional consequence of this change was a reduction in receiver sensitivity, whose mitigation was prevented by the urgency of the schedule. However, since the radar was secondary to NASA’s ATM lidars, and since they required the aircraft to fly relatively close to the ice, it was felt that the consequent reduction in path loss would likely compensate for the loss of sensitivity. This turned out to be true for much of the collected data, although penetration through thicker ice was compromised.

Field Performance

In the field the tandem radar pair performed as intended over the 6-week mission, collecting some 1.4 TB of data using the two laptop computers simultaneously. Comparison of the data collected demonstrated that the radar receivers were able to stay in lockstep, even over 6 hours’ continuous recording. However, there was not sufficient time to tune the antenna pair such that high-quality circular polarization was radiated. As a result, the polarimetric objectives were not fully realized.
Appendix 4

435 MHz UAV Design

Requirements

The recent challenge posed to the PARIS team asked what it would take to make the PARIS design operate on an unmanned aerial vehicle (UAV), with a view to greatly expanding the body of data describing the Greenland ice sheet. Several design decisions emerged in response to that challenge:

- UAVs are typically smaller and less powerful than manned aircraft, so everything about the radar would have to be reduced: power use, mass, volume, and wavelength.
- Power is at a premium on a UAV, so the statically-biased transmit amplifier used with the first PARIS radar would have to be replaced by a dynamically biased, or gated, power amplifier.
- The shorter wavelength (by a factor of three) necessitated a new antenna, and consequently the link budget (radar propagation and in-situ losses) would have to be re-estimated.
- The original PARIS design emphasized technical achievement, while putting less emphasis on scientific performance, i.e., “seeing” through 3 km of ice to the bedrock, using a small number of commercially available parts. The new design would have to employ a better transmit waveform which will minimize pulse-compression sidelobes, in order to maximize the signal-to-noise ratio obtainable.
- The new design would have to be able to receive two channels at once (in order to support polarimetric operation), while creating one data stream containing the data from the two channels.
- The new radar would have to make range and gain adjustments autonomously, based on real-time feedback of sounder data and a built-in thickness model of the ice-sheet it is flying over.

Proposed Design

Figure A6-1 shows a block diagram of the system which resulted from the design effort. It retains most of the technical ideas used in PARIS:

- substantial digital integration using an FPGA
- reliance on direct digital synthesis of the transmit waveform
- direct sub-sampling of the received signal
Figure A6-1: Block diagram of proposed UAV-based ice sounder with PARIS heritage.

The higher frequency is necessary to accommodate a recent International Telecommunications Union (ITU) frequency recommendation for earth remote sensing, namely the 432-438 MHz P-band. The width of this band happens to be the same bandwidth as that used by PARIS, so the new radar will have the same resolution as the PARIS radar. Losses in the ice are approximately the same (for cold clean ice) at this higher frequency. However, internal (Rayleigh) scattering losses increase as the fourth power of frequency, so performance of the higher-frequency radar would be compromised over more challenging ice conditions, such as those typical of Greenland’s southern outlet glaciers.
Table A6-1 presents a signal-to-noise ratio calculation for the proposed radar design.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xmit pulse-peak-power</td>
<td>53 dBm</td>
</tr>
<tr>
<td>Avg.-to-peak power ratio</td>
<td>-6 dB</td>
</tr>
<tr>
<td>Two-way antenna gain</td>
<td>20 dB</td>
</tr>
<tr>
<td>Center frequency</td>
<td>435 MHz</td>
</tr>
<tr>
<td>System bandwidth</td>
<td>6 MHz</td>
</tr>
<tr>
<td>Noise figure</td>
<td>4 dB</td>
</tr>
<tr>
<td>kTBF</td>
<td>-102.2 dB</td>
</tr>
<tr>
<td>Pulse width [µs]</td>
<td>15.0 µs</td>
</tr>
<tr>
<td>cT/2 in air [m]</td>
<td>2250 m</td>
</tr>
<tr>
<td>cT/2 in ice [m]</td>
<td>1268 m</td>
</tr>
<tr>
<td>Compression gain (T x BW)</td>
<td>19.5 dB</td>
</tr>
<tr>
<td>Presuming number</td>
<td>32 → 15.1 dB</td>
</tr>
<tr>
<td>Ice bulk attenuation (2-way)</td>
<td>12.90 dB/km</td>
</tr>
<tr>
<td>Ice scattering losses (2-way)</td>
<td>13.3 dB/km</td>
</tr>
<tr>
<td>Backscatter on ice surface</td>
<td>56.5 dB</td>
</tr>
<tr>
<td>2-way air-to-ice path loss</td>
<td>-157.9 dB</td>
</tr>
<tr>
<td>Pr at antenna from ice</td>
<td>-34.5 dBm</td>
</tr>
<tr>
<td>SNR with process gain</td>
<td>102.3 dB</td>
</tr>
<tr>
<td>Backscatter at bedrock</td>
<td>55.4 dB</td>
</tr>
<tr>
<td>Ice ε_r at 435 MHz</td>
<td>3.15</td>
</tr>
<tr>
<td>2-way air-to-bedrock space loss</td>
<td>-171.6 dB</td>
</tr>
<tr>
<td>Attenuation through ice</td>
<td>-78.6 dB</td>
</tr>
<tr>
<td>Pr at antenna from bedrock</td>
<td>-127.8 dBm</td>
</tr>
<tr>
<td>SNR with process gain</td>
<td>9.0 dB</td>
</tr>
<tr>
<td>ε_0 at ice</td>
<td>-2.5 dBsm</td>
</tr>
<tr>
<td>50 at bedrock</td>
<td>0 dBsm</td>
</tr>
<tr>
<td>Ice thickness</td>
<td>3000 m</td>
</tr>
<tr>
<td>Distance to ice</td>
<td>2500 m</td>
</tr>
<tr>
<td>Aircraft altitude</td>
<td>5500 m</td>
</tr>
<tr>
<td>2-way air-to-ice time</td>
<td>16.67 µs</td>
</tr>
<tr>
<td>2-way air-to-bedrock time</td>
<td>29.58 µs</td>
</tr>
<tr>
<td>Min. PRI</td>
<td>61.2 µs</td>
</tr>
<tr>
<td>Min. PRI</td>
<td>16.3 kHz</td>
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<tr>
<td>f = 4.35E+08 Hz</td>
<td></td>
</tr>
<tr>
<td>ω = 3.15</td>
<td></td>
</tr>
<tr>
<td>σ = 0.000144 S/m</td>
<td></td>
</tr>
<tr>
<td>α = 1.48E-02 Np/m</td>
<td></td>
</tr>
<tr>
<td>6.45 dB/km</td>
<td></td>
</tr>
<tr>
<td>Power_{ICE} - Power_{BEDROCK} =</td>
<td>93.4 dB</td>
</tr>
</tbody>
</table>

Table A6-1: Signal-to-noise ratio calculation for proposed radar.
Appendix 5

Summary of Data Processing

Sounding with ice-penetrating radars is strongly dependent not only on the linearity, power, and system response of the RF technology developed. It is equally a function of the processing and analysis developed to enhance basement signatures and properly extract ice thicknesses. To detail this component of the program as it developed, this appendix will be split into three parts. The first two will describe the delay-Doppler processing of the PARIS-I data acquired over Greenland in May 2007 and Antarctica in October 2008, respectively, while the third will describe initial analysis of the polarimetric data taken over Greenland in the spring of 2009. Additionally, the initial basement detection algorithm with be described in Section 1 with the Antarctic enhancements following in Section 2.

Section I: PARIS-I Greenland '07

Two objectives of the first measurement campaign were to show that the delay-Doppler hardware and process could successfully retrieve basement depths over the summit of the Greenland ice sheet from high altitudes at a resolution of 1% of the ice depth. To achieve this, the delay-Doppler algorithm of Raney [1998] was implemented for the PARIS design and process. However, for optimum basement retrieval, several enhancements were explored, developed, and applied over the course of the analysis.

A. Initial Processing Decisions

PARIS-I data from the Arctic '07 campaign were initially processed using all available bins (16, for the most part, with the nadir bin set at 9) to take full advantage of the noise-reduction and resolution enhancement provided by the delay-Doppler processing technique (see Raney [1998]). However, since data were acquired from an airplane, not from a satellite for which the incident wave front is essentially flat, second-order range-curvature effects were found to be significant for data processing. Specifically, the volumes for the outer Doppler bins, after being correctly located along-track and in depth relative to the nadir range bin, were tilted out of the band of intersection (in depth) with the nadir range bin, even given the slower velocities in ice (1.78 times slower than in air). Thus, they were sensing from a different assemblage of ice layers, adding self-noise to the data. As a result, Doppler bins much beyond the center bin at altitudes less than ~ 7km, and beyond the center three bins for altitudes greater than 7 km, could not be used for sounding in these aircraft data (see Raney, [2008]). These nadir or near-nadir bins have been referred to in previous presentations as the radar sounder “sweet spot.”

From delay-Doppler unambiguous sampling theory (see pp. 1586-1587, Raney [1998]), for a data rate of ~200 Hz, 64 deep (30 micro-second, 150 MHz) pulses should be averaged for each Doppler resolution cell. Initially, an equivalent number of pulses were averaged coherently for the shorter-pulse (10 micro-seconds and shorter) data. However, significant Moiré patterning was evident in the resolved ice layers for the shorter-pulse data. Moiré patterns occur when lines in a
pattern are sampled at a resolution too close to the line spacing. They may be eliminated by changing the overall sample spacing, since the spacing of the lines being sampled is fixed. For PARIS, the pulse lengths are themselves fixed, and for short-pulse data only the nadir bin is used, so the Moiré patterning can only be eliminated by decreasing the number of pulses in the coherent average for the short-pulse data. Ice layers and the basement signature are spatially extensive, not random points like ocean waves, so using fewer pulses (within limits) will not result in a detection failure, and any coherent averaging will serve to enhance the signal to noise ratio (see Raney [2009]). The two parts of Figure 1 shows a sample of the short-pulse data where Moiré patterns are present, and then mitigated by changes in processing. In Figure 1a, where 64 pulses were used in the initial coherent average, the reader is directed to the uppermost 500 meters of the soundings, where the internal ice layering signatures are the strongest. The Moiré patterns are present as the wavy lines superimposed on the mostly horizontal ice layers. In Figure 1b, the averaging has been reduced to 16 pulses, and the Moiré patterns are gone. An 8-pulse coherent average (not shown here) had too little signal-to-noise to prove useful, while a 32-pulse average (also not shown here) still exhibited Moiré patterning. Based on these results, a 16-pulse coherent average will be used in all future short-pulse processing, except with the polarimetric data.

Figure 1(a): 64 pulses in coherent average. Note the Moiré patterns (wavy lines). The thick line just below the 1000m mark is the double-bounce signature.
The receiver was sufficiently sensitive to pick up, in addition to the returns from dry ice layers and the basement, energy that bounced off the basement, back up and off the metal underside of the aircraft, back down and off the basement, and finally, back into the antenna. This signature is wrapped around inside of the ice soundings, and may appear above, below, or on at the same depth as, the basement signature to be extracted. In a normal radar sounder where only a single beam is used, this interference would be extremely problematic. However, because this is a delay-Doppler sounder, there are multiple bins interrogating the ice layers and the basement. The specular scatter off the belly of the plane should be, by Snell’s Law, highly angle-dependent, while the basement, being spatially extensive, should reflect, albeit less strongly, over a broader angle range. An initial approach to avoiding the double-bounce signature was simply to search for the basement in the delay-Doppler processed outer bins, where the double-bounce signature should be absent. This was true for the nadir +/- 3 and beyond bins, but, in those, the basement signature was too weak to be reliably retrievable. A second, and successful, approach was to use a combination of near-nadir bins to cancel the double-bounce signature. After some experimentation, the optimum bins were found to be the nadir – 2, nadir, and nadir + 2 bins, with the magnitudes combined as follows:

\[(\text{nadir} - 2) + (\text{nadir} + 2) - (0.4 \times \text{nadir}).\]

Figures 2 and 3 show the detection of the basement signature in the composite bin and partially-coherent delay-Doppler images for short-pulse data acquired on 7 May 2007 between 12:41:09 and 13:43:17 GMT. A further discussion of these images is in the section on automated basement detection.
Figure 2: Composite-bin image for short-pulse data. The x-axis pixels are along-track pixels and correspond to sounding # in this processing run, while the y-axis pixels are depth pixels from first return, not the peak from the surface, which is at about depth pixel 80. The green crosses represent provisional basement detections, and are discussed in depth for automated basement detection in Section I-D.
Figure 3: Delay-Doppler image for data in Figure 2. The x-axis pixels are along-track pixels and correspond to sounding number in the processing run, while the y-axis pixels are depth pixels from first return. Green lines represent the extent of the automated basement detection region. See automated basement detection section (I-D) for further details. The flat line at depth pixel 10 is the surface signature. The line descending from around depth pixel 190 at track pixel 0 to depth pixel 235 at track pixel 980 is the double-bounce signature. The hairpin curve imposed on the ice layers between depth pixels 100 and 200 at around track pixel 400 is side clutter.
For wet ice close to the coast (for an example, see Figure 6), the double bounce signature was not present (ice layering and basement signatures, while stronger in parts of the data, were also more variable in magnitude, and of poorer quality), so basement detection could proceed without creating composite images for searching.

Table 1 provides a quick summary of the extra processing steps required for optimum basement retrieval. These are also the initial assumptions as they would be expanded for the Antarctic data.

<table>
<thead>
<tr>
<th>Aircraft Altitudes</th>
<th>Less than 7 km</th>
<th>More than 7 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doppler Bin Selected</td>
<td>Nadir bin only</td>
<td>Nadir – 1, nadir, and nadir + 1</td>
</tr>
<tr>
<td><strong>Pulse Length</strong></td>
<td><strong>Long pulses (30 microseconds)</strong></td>
<td><strong>Short pulses (10 microseconds and fewer)</strong></td>
</tr>
<tr>
<td>Coherent averages (number of pulses)</td>
<td>64</td>
<td>16</td>
</tr>
<tr>
<td><strong>Data locations</strong></td>
<td><strong>Inland data (dry ice)</strong></td>
<td><strong>Coastal data (wet ice)</strong></td>
</tr>
<tr>
<td>Double-bounce signature removal</td>
<td>Process delay-Doppler product as defined above, but also process separately the nadir-2, nadir, and nadir + 2 bins.</td>
<td>Extra bins provide no added benefit, so simply process as defined above</td>
</tr>
</tbody>
</table>

Table 1: Initial Processing Decisions

B. Aircraft Altitude Corrections

As a part of data acquisition, the system was set to receive returns from just before the first surface returns through those from the entire ice column down to the basement and slightly beyond. The timing delay required was a function of, among other things, sensor altitude. Now, for a satellite, the altitude should be nearly invariant, but for an airplane, the altitude varies for reasons both voluntary and involuntary, from pulse to pulse, and sounding to sounding. So, the timing delay before PARIS began to receive returns was dialed in manually, and changed as conditions required. As such, it varied within a given run, often abruptly. To provide correct depth-to-basement determinations, the soundings in the data must be properly adjusted for aircraft motion.

Once a Doppler bin is formed, either on its own to be used for basement determination, or composited to create a partially-coherent delay-Doppler stack, the resultant sounding is adjusted in height at final output. First, a larger profile than the sounding data themselves was created by adding a pad of fifty pixels to the top and the bottom. Second, the sounding was adjusted based on changes in the altitude. Third, if the changes in altitude required the sounding data to be shifted further than the 50 pixel pad, the data were wrapped around from top to bottom, or vice versa, as required. Nonzero data values inserted in the pad for ease of further display and analysis were set at 20dB below the image maximum.
The primary aims of the post-processing codes were to provide gain-equalization and basement detection. But, for depth determination, the sounding was arbitrarily shifted so the surface returns sat at a uniform depth of zero across a run. For data from the summit of Greenland, this is a good approximation, since the top of the ice sheet is flat or only very gently sloping except in regions of crevassing. In coastal regions, processed data will have a counterintuitive appearance (see Figure 17 for an example), but, all data in a run could be labeled with a single true ice depth axis, as opposed to simply a length scale. After experimentation, it was determined the altitude corrections should be handled differently for different types of data, namely, [1] the partially coherent delay-Doppler stack, [2] the off-nadir Doppler bins, which had higher speckle and noise than the partially-coherent delay-Doppler stack, and [3] near-coast data with “wet” ice.

First, the partially-coherent delay-Doppler stack: The altitude correction was performed in two stages for these data with higher signal to noise and more detailed returns in the ice. The fall-off to the processing noise floor in the non-gain-equalized data was from -120dB to approximately -300dB. Since the pad data values were 20dB below the image maximum, the fall-off to noise and rise to the pad values provided a sharp minimum that was used to correct for wraparound for prolonged ascents and descents. In data over “wet” ice close to the coast, this minimum was often deeper and narrower than the maximum at the surface was strong. Then, a finer alignment based on the maximum return was applied.

Second, the off-nadir Doppler bins: These data had lower signal to noise than the partially-coherent delay-Doppler stack, and showed little beyond the surface return, the basement signature, and the double bounce signature. Altitude corrections based on aligning the maximum return at the surface were all that were possible.

Third, the near-coast data: The “wet” ice close to the surface typically created a broad surface peak, and the fewer sensed ice layers were themselves characterized by broad peaks. The non-gain-equalized returns for these layers were more non-linear than those from the “dry” ice of the interior. A two-stage altitude correction, as was used on the partially coherent delay-Doppler stack, was critical for these data. In addition, a preliminary gain-equalization was performed in the second stage of altitude correction to pull out the surface signature as a maximum from the sounding (see Figure 6 for a sample near-coast segment).

C. Gain Equalization

Gain-equalization, by de-trending the returns from the surface to the basement in a sounding, brought the ice layer variations and the basement signature onto the same scale as the surface return for analysis and comparison. When ice conditions varied, gain equalization also had to be handled differently.

For interior “dry” ice, gain-equalization was conducted in two stages. First, a high-order polynomial fit was calculated and subtracted from the entire sounding, including the surface signature. At this stage, the deepest pixels of the surface signature usually have a per-sounding minimum in magnitude. This was an unexpected, but not unappreciated, feature of the gain-equalization. Since this condition remained true, with adjustments for wet ice, it provided a useful
criterion for completely separating the surface signature from the ice/bedrock only returns. There remained oscillation in the initial gain-equalized sounding in the ice/bedrock. The oscillations are mitigated by calculating and subtracting a second high-order polynomial fit from this minimum to the bottom of the data. In soundings from longer pulse data, non-linear variations in gain at middle depths could still leave a bulge and confuse the basement detection algorithm, even after the second fitting stage. Figures 4 and 5 show the gain equalization process for a sounding taken at along-track pixel 790 in Figures 2 and 3.

Figure 4: Full sounding from delay-Doppler processing, before gain equalization. Note that the surface signature is partially truncated due to timing adjustments, while the drop-off to the processing floor of ~300 dB is distinct.
Figure 5: Data-only portion of sounding at along-track pixel 790, showing the progressive effects of the two gain equalizations in dry ice. Note that the local strength of the basement peak is not affected by the gain equalization. Note also the sounding minimum at depth pixel 30, which served to separate the surface signature from the ice signatures.
For near-coast “wet” ice, only the first stage of gain-equalization enhanced the handling of the soundings. Ice layer variations were strong enough that a second gain-equalization did not contribute a significant improvement to the detection of surface or basement signatures. Further, intermediate ice layer signatures were often as broad as the surface signature and had minima nearly as low as that from the surface, so defining an “ice” region separate from the surface signature was problematic. Figure 6 shows an example of soundings from coastal glacial ice. Figures 7 and 8 show a sounding from short-pulse data acquired on 04 May 2007 at around 12:24 GMT, before and after gain equalization for “wet” ice. This sounding occurs just before the data shown in Figure 6. In it, the surface peak is much lower than the overall image maximum (recall that the pad level was set to be 20 dB below the image maximum), and about 3 db less than the peak from a near-surface “wet” ice layer. Figure 8 shows the data-only portion of the same sounding, once gain-equalization is applied. Note that the minimum value in the ice occurs at around pixel 100, between two ice layers at a calculated depth of around 500 m.

Figure 6: Short-pulse soundings in near-coast “wet” ice. Note the paucity of fine-scale ice layering in these data.
Figure 7: Delay-Doppler processed sounding for data taken near the coast. The return from the surface is the first peak at depth pixel 80, while a brighter near-surface ice layer has a peak at depth pixel 90.

Figure 8: Data-only portion of the sounding in figure 5 (from between pixels 52 and 372 in that figure) showing how gain-equalization has enhanced the surface peak. Ice layer peaks at depth pixels 75 and 130 are nearly as strong as the surface peak (pixel 11).
D. Automated Basement Detection

Intuitively, basement detection should be nothing more than extracting the deepest, brightest signature in the gain-equalized data. However, the basement signature is highly variable in magnitude, even discontinuous on a sounding to sounding basis. Often, the deepest bright feature was the double bounce line, as discussed in Section I-A. The automated basement detection algorithm attempted to account for this when assigning a location to the basement.

The double bounce signature was not present in data acquired near the coast, where signature from the ice layers where often as strong as the surface signature. For these data, the partially coherent delay-Doppler stack was used to detect the basement. For data from the interior, a composited image, created using off-nadir and nadir bins after gain-equalization of the separate bin images, as detailed in Section I-A, was searched for the basement signature. For both wet and dry glacial ice, the variability in the strength of the basement signature was reduced in the search images (not in the partially-coherent delay-Doppler stack) by using a running window average.

Several steps were required to define and select the final search region for the basement in the search images. First, the mean and standard deviations of the composite-bin sounding, below the surface signature, were calculated. Second, peaks above the statistical threshold were identified, and the deepest peak location saved. Figure 2 shows preliminary basement detections in a composited image for data from 7 May 2007 between 12:41:09 and 13:43:17 GMT. Third, the whole image was divided into along-track segments, where the number of segments varied based on the length of track over which the image was generated. This accounted for runs where the basement depths were changing along-track. Fourth, the median peak location was calculated for each segment. Fifth, the provisional basement locations were checked against the median for the segment. It is assumed that the actual basement, while it would have peaks and valleys, would not be truly discontinuous. So, if the median and per-sounding location diverged significantly, with significantly a function of pulse width and track length, the median value was substituted for the provisional basement location. Once provisional basement locations had been determined or substituted from the median, a bound was added above and below the provisional location to set a search region. The depth added or subtracted was directly proportional to pulse width. Figure 3 shows calculated search bounds for the data of Figure 1 plotted on top of the partially-coherent delay-Doppler data, just prior to the final basement search.

At this point, the partially-coherent delay-Doppler image was searched, sounding by sounding, within the depth bounds determined for the search region, until a maximum for each sounding was found. These maxima were then defined as the actual basement locations, assuming the peak to occupy, at most, two pixels. Once the basement signature maximum location was determined, the basement signal strength was simply the difference between the peak return at this location and the mean in the gain-equalized sounding below the surface signature.

E. Ice Velocities

Searches for errors in the speed of EM propagation within the ice volume (ice velocity) used to calculate depth were conducted during the processing, with inconclusive results.
Coherently-averaged data were examined for the presence of hyperbolae which would indicate errors in the ice velocity. However, the speckle in the coherently averaged data in coastal areas was strong, so only the presence or absence of wet ice layers was apparent in the data. In soundings from the summit, the coherently-averaged data are more confusing, and show no evidence of much other than slight surface and basement signatures, again, without bright hyperbolae that would indicate ice velocity variations. Data from Antarctica may provide better evidence of ice velocity errors.

Section II: PARIS-I Antarctic '08

The objectives of the second measurement campaign were to acquire radar soundings over the marginal glaciers of the Antarctic Peninsula and to retrieve basement depths under these less-than-optimum ice conditions. Since PARIS shared the Chilean P-3 with NASA Wallops Branch 614.1 Airborne Topographic Mapper (ATM), the altitude requirements for that system drove the experiment. Given that the ATM requires low altitudes for optimum performance, all the PARIS data over Antarctica were acquired in short-pulse mode. The data acquired prompted significant changes, both in the gain equalization portion of the processing and in enhancements to the automated basement detection.

A. Modified Initial Processing Decisions

Relying solely on the center bin for accurate basement depth retrievals quickly proved nonproductive, so alternative bins were examined. With no double bounce present, no particular advantage arose to assembling a weighted sum of nadir-2, nadir, and nadir+2 bins. However, the presence of strong side-clutter could be mitigated by examining the nadir-2 and the nadir+2 bins separately, as well as by combining the nadir-2 and nadir+2 bins into a single composite image. Thus, a new processing option “marg” (for “margin”) was created to automatically output the nadir -2 bin, the nadir bin, the nadir+2 bin, and the composite sum of the nadir-2 and nadir+2 bins.

B. Aircraft Altitude Corrections

The near-coast data corrections for aircraft altitude developed under Paris-I required no modifications for application to the Antarctic data.

C. Modified Gain Equalization

In addition to a single-stage polynomial fit and subtraction, two other gain-equalizations were employed to enhance the basement signature. Visually, the basement signature in some of the plateau regions had a strong shadow above and/or below it, suggesting that change in power with depth might have advantages for basement searching. So, a version of the soundings as change in power with depth was created. Also, the gain non-linearities as a function of depth (not intermediate ice layer signatures as in the Greenland data) could be stronger with these data. In such cases, subtracting a smoothed version of the gain-equalized sounding from itself was found to provide the most optimal equalization.
Flight tracks for the Antarctic mission followed those of previous ice-monitoring missions, and were designed to overfly as many points of interest as possible in the least amount of time. As such, they involved many tight turns and loops. Now, the delay-Doppler approach works best when the flight tracks are linear, forcing the division of the data into smaller chunks for processing than used in Paris-I. Also, given the extreme variability in side clutter and background conditions, there was no easy prediction of which sounding bin and gain equalization combination would offer the best basement signature. So, a global approach was employed. All gain equalization variations were applied to all bin combinations, and the results were visually examined for the strongest signature. Once the “best” signature was determined, the automated detector would be applied to that bin/equalization combination. Table 2 shows the distribution of combinations used with the Antarctic data.

<table>
<thead>
<tr>
<th>Bin Used (relative to nadir)</th>
<th>One-level fitting (1)</th>
<th>(1) plus Change in Power</th>
<th>(1) plus Smoothed Power Subtracted</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2</td>
<td>1.90%</td>
<td>1.00%</td>
<td>3.00%</td>
</tr>
<tr>
<td>0</td>
<td>10.70%</td>
<td>17.60%</td>
<td>20.50%</td>
</tr>
<tr>
<td>2</td>
<td>4.00%</td>
<td>0.90%</td>
<td>6.90%</td>
</tr>
<tr>
<td>(-2) + (+2)</td>
<td>5.90%</td>
<td>4.60%</td>
<td>7.40%</td>
</tr>
</tbody>
</table>

Table 2: Processing case combination as a percent of total usable data (5% not categorized)

Figures 9 through 14 show the effects of the different gain equalizations on the basement retrievals. In each case, the odd-numbered figures display the soundings after delay-Doppler processing only, while the even-numbered figures show the basement detections after gain equalization.

Figures 9 and 10 show the results of the subtraction of a single polynomial fit. These data are from the SCAR Inlet shelf, the remaining portion of the Larson B ice shelf. The basement signature at about 400m depths has a doubled signature at 800m, which may be related to the fact the data were acquired over floating, as opposed to grounded, glacial ice.
Figures 11 and 12 show soundings in ice from the summit, such as it is, of the Antarctic Peninsula west of the Larson C ice shelf. Here, the ice is attached to the bedrock, and shows a strong shadow region above and below the basement signature, with bright returns not driven by the pulse nonlinearities above and below these. The area of maximum change in power with depth was generally just above the basement signature in ice cases similar to this one while the bright signatures above and below had strengths close to that of the basement signature itself. A peak-based search in this case would have been more prone to error, but, a max change in power signature search easily located the basement depths.

Figure 10: Gain-equalized delay-Doppler soundings with basement detection for one-level fitting case.
Figure 11: Delay-Doppler soundings for change-in-power after one-level fitting case.

Figure 12: Basement detections from gain-equalized change-in-power after one-level fitting case.
Finally, Figures 13 and 14 show an hour of data taken as the P-3 transited north along the east coast of the peninsula. The delay-Doppler processed soundings have significant velocity and altitude variations, yet, after subtracting a smoothed version of each sounding from itself, a strong basement signature emerged. The cause of the multiple strong reflections at 80 km of track remains to be determined.

Figure 13: Delay-Doppler soundings for subtracting a smoothed version after one-level fitting case.
D. Modified Automated Basement Detection

As with the initial automated basement detection algorithm, this modified algorithm attempted to implement an idea that seemed intuitively obvious: namely, regardless of track and side-clutter conditions, and in the absence of sea ice, the basement itself should be continuous, even if the basement signature was not. Applying this concept to these noisy data required a basement detection algorithm split into several steps.

1. Initial peak location: Since ice thickness could vary significantly over very short flight distances, and since the basement signature peak was not necessarily the strongest peak in any gain-equalized sounding, a set of locations of all significant power (or change-in-power) peaks for each sounding was generated across the entire data run under analysis. A peak was defined as significant if the power at the peak was greater than the per-sounding mean plus 0.4 times the per-sounding standard deviation. This threshold was determined empirically as the “best” over several ice conditions (i.e. grounded on the peninsula, from outflow glaciers, and from parts of remaining Larsen Ice Shelf), specifically, over data acquired on 21 October 2008 between 16:01:27 and 17:01:57 GMT.

2. Determining approximate maximum possible sounding to sounding depth change for the
basement signature, or, for lack of a better term, basement jumps: The change in locations of the maxima in the ice-only portion from sounding to sounding provided an initial value (and upper limit) for maximum “real” change in basement depths. In some (and ideally, most) cases, these jumps will be equivalent to the change in the basement depths from sounding to sounding. In reality, however, some of these will be due to noise, some to cross-track contamination. An empirical statistical approach was used to find the approximate threshold between true basement depth differences and those due to erroneous sources. The threshold detection was straightforward, once enough data (see above) were examined. A histogram of absolute values of changes in basement depth for a run was generated, then, the number of absolute changes less than a given jump size was summed. Once the number of summed jumps reached a threshold percentage of all jumps present in the data, defined empirically as 61% (again, by working over several data runs), a maximum meaningful jump size for that data run was defined. With an approximate determination of the maximum “real” depth change for that data set in hand, all that remained was to extract and connect the continuous provisional basement determinations.

3. Extracting the best provisional depth eventually required passing through the data run three times.

   a. On the first pass, any sounding maximum with depth, i. e. a “raw” basement location, was tagged as good if the power is above about a quarter of the mean power for the ice/rock-only portion of that sounding, the change in raw location from the previous sounding is less than the empirically-determined maximum “real” jump size, and if the depth is above 60%, again, a threshold empirically-determined, of the maximum sounding depth. This set maximum depth will vary between the Arctic and the Antarctic, and between marginal regions and the summit in either hemisphere.

   b. On the second pass, a run is broken into bins of a few soundings, with few, again, being dependent on the overall data run being processed. If there were raw basement locations determined to be good on the first pass in the bins, those were used to set search bounds for the rest of the basement locations, generally the mean depth index +/- a multiplier of the maximum real jump size. Any raw (max power or change-in-power) basement locations found within those bounds for the bin were also tagged as good. These points were then interpolated over to get a basement search region that filled in the gaps in the good data.

   c. On the third pass, the array of all significant peak locations was checked, and if a peak was found within the search region for a sounding where no basement has been declared, that peak was set to be the provisional basement location. Any missing values in the final provisional basement locations array were determined by interpolation. As before, having found the best provisional basement depth, a search region was set using a pulse-length dependent definition around that depth, the returns within that depth band were searched, and the maximum values encountered therein were saved as the basement depth.
E. Comparisons with Manual Detections

During the acquisition of the Antarctic data, NASA Wallops personnel independently developed their own manual detection algorithm for the PARIS soundings. As a sanity check, the basement retrievals from a relatively benign location (ice shelf over the peninsula) was used for comparison. The data eventually selected were in a 78 km section centered between the Jason Peninsula and Renaud Island and acquired on 26 October 2008 between 15:44:05 and 15:53:56 GMT. Figure 15 shows the gain-equalized soundings with the automated basement retrievals over-plotted, and Figure 16 shows the comparison with the manual retrievals. The retrieval comparison plot is reversed from left to right relative to the gain-equalized soundings for reasons related to the analysis at the time. Overall, the two methods agree well with each other, with the exception that, since the automated detector tries to work with bins, rather than absolute sounding-to-sounding differences, the automated detector will tend to undershoot depth variations on along-track length scales significantly shorter than the bin size used to define them.

Figure 15: Gain-equalized sounding with automated basement detections over-plotted. The bin/equalization combination used for best retrievals was the nadir-2 plus nadir+2 bins, with a smoothed version subtracted.
Figure 16: Comparison of manual and automated basement detections for the data in Figure 15. The manual detections are in blue, the automated in green.

F. Application to IceSat Gap Filler Data

As a final note, the modified automated basement detection algorithm was applied to one of the Greenland outflow glaciers over-flown during March and April 2009, namely, the Petermann Glacier. Figure 17 shows the gain-equalized soundings with the automated basement locations over-plotted. Even with a confused doubling signature under the flooded section (first 50 km of track) similar to that seen from the remnant Scar section of the Larsen B Ice Shelf (see Figures 9 and 10), the enhanced automated basement detector retrieved good basement detections here.
G. Differences between Greenland’07 and Antarctic’08 data

The Antarctic data were different in several important ways from the Greenland data. Since many of the runs were up or down narrow outflow glaciers, side clutter was increasingly a problem. Figure 18 shows basement detections over the Crane glacier, which once fed the Larsen B Ice Shelf, but is now emptying directly into the Weddell Sea. Here, the side clutter had several different expressions in the soundings. “Hairpins” representing velocity mismatches from side clutter were much more frequent in these data. Also, the side clutter itself had the appearance of the basement as seen in the Greenland, while the basement signature often showed up as a double line. In Figure 18, the basement signature is the faint double line at about 400m depth. Efforts continue to explain these differences, as working out their cause will be conducive to further improvements in the delay-Doppler algorithm as applied to ice sounders.
Section III: PARIS-II Polarimetric Processing

A. Polarimetric retrieval software developed

Several changes were made to the data acquisition software to derive polarimetric quantities. First, since two antennas were acquiring data simultaneously, the individual returned pulses were saved in two separate time-tagged data sets using the preexisting PARIS data acquisition hardware and software. Then the separate sets were unified into a single data stream, with time-tagged pulses from the two antennas alternating. To save time while processing to purely for non-polarimetric total power, coherent averaging over 16 pulses was implemented at this point to create a “pre-summed” data set. However, for development and testing of polarimetric processing, and to insure no phase information was lost, the original two sets of data were handled without coherent averaging at any stage. Instead, individual pulses from the two antennas were interleaved in an initial processing stage.

Delay-Doppler codes were modified accordingly, removing any coherent averaging there as well. The PARIS returns are actually complex quantities, but, to extract their real and imaginary components, received power was multiplied by the complex conjugate of the transmit waveform in the frequency domain. As a first-cut in the processing codes, the in-phase and quadrature (I and Q)
generation was only augmented by aircraft altitude corrections. Delay-Doppler corrections were not performed. This would mean returns from the basement would not be as visually obvious, but, at this stage, since coherent averaging had not been applied, delay-Doppler enhancements were less effective on individual returned pulses.

Finally, with the outputs of the two antennas saved as I and Q for each, a separate set of codes was written to generate the Stokes vector and child products. See Raney [2007], for a thorough description of the hybrid-polarity concept and process. Since an early deployment to Greenland for the IceGap Filler mission prevented proper characterization of the antenna, child products were calculated for the case of arbitrary elliptical, as opposed to purely circular, transmission. See Keller [2009] for further details and derivation of child products in the elliptical case.

B. Initial application to ice soundings

Given the good results retrieved from the Petermann Glacier, initial polarimetric analysis concentrated on one of the cross-cuts from this area. Figure 18 shows the results of standard PARIS processing on the pre-summed version of these data, where only the returns from one antenna were processed through delay-Doppler correction, gain-equalization, aircraft altitude correction, and automated basement detection.

As indicated on Figure 19, an initial pulse pair was selected for polarimetric analysis. Figure 20 shows a simple sanity check on the data, where the total power of the polarimetric returns (i.e. not delay-Doppler processed) from each antenna are plotted against each other and
tagged for basement signature and surface signature. The basement and surface data cluster separately, suggesting further analysis may be of use in extracting polarimetric signatures of the surface, the basement, and side clutter.

Figure 20: Plot of total power returns as a function of depth for sounding indicated in Figure 19. The returns from the surface and the basement have been color-coded as indicated. The spiral in the blue basement signature is due to noise.

However, when the Stokes parameters are calculated from this same pulse pair, as shown in Figure 21, the fourth Stokes is too small by a factor of four (relative to the first Stokes). The child products were equally confusing. So, analysis shifted to what engineering test data were available from the IceSat gap filler flights.
C. Field calibration data

As time and data conditions permitted, engineering check-out was performed on the new antenna and polarimetric process, beginning with a 27 March 2009 test flight over the Atlantic Ocean prior to the mission, antenna delay characterizations during a 31 March set of data flights over sea ice, and a specific termination of transmission from one of the antennas while continuing to receive on both on 17 April 2009.

1. Water data: At 150 MHz, the horizontally-polarized and vertically-polarized (H and V) returns from water should, if a system is properly characterized, be of equal magnitude and completely from the water surface, thus serving as a specular calibration target. Calibration coefficients retrieved from these data and applied to the returns were still insufficient to correct the magnitude of the fourth Stokes parameter, as shown in Figure 22. The child products were, again, confusing.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{stokes_parameters.png}
\caption{Stokes parameters calculated for pulse pair shown in Figure 19. Note that the fourth Stokes is about one fourth the expected magnitude relative to the first Stokes.}
\end{figure}
All this pointed to some as yet undetermined problem with the polarimetric set-up, whether hardware or software.

![Graphs showing S1, S2, S3, and S4 for water data](image)

**Figure 22: Stokes parameters calculated from open ocean data test flight (27 March 2009). Here again, the Fourth Stokes is too small.**

2. Sea Ice data: Sea ice, at 150 MHz, provides an alternate calibration target to water, with all reflections from the specular surface and H and V polarized returns of, ideally, equivalent magnitudes. A flight over purely sea ice on 31 March 2009 was used for engineering check-out of the new configuration to attempt to explain the source of the system problems. Multiple cable lengths were interposed to assess relative delays between the two antennas. Calibration and conversion to Stokes parameters, as with the glacial ice and open ocean test data, were performed for data at the different delays, with similar results as before. But, the delay line variations could also be used to check the linearity of the H-V relative phase separate from the Stokes formulation (see Raney [2007] or Keller [2009] for the Stokes expressions for relative linear phase). Figure 23 shows the phase as a function of induced delay, with the response being reasonably linear over the
delays tested. With a delay length of 6 inches on the Master antenna, the two antennas were fairly well-balanced. However, simply operating with this quick-fix would not necessarily yield good polarimetric results, so any excess differential delay was removed for the remainder of the flights.

![Graph showing linear phase vs. added coax length](image)

*Figure 23: Added delay effect on relative H-V phase for Sea Ice Runs (31 March 2009).*

3. Linear data: For these data, acquired on 17 April 2009, the signal path between the 90° channel from the hybrid and antenna 1 was terminated, while leaving both receive chains unchanged. This created a configuration that was single linear polarization on transmit, dual on receive, as shown in Figure 24. Figure 25 shows the resulting Stokes vector, for which the fourth Stokes should be small. However, this is not the case. One potential cause could be cross-coupling, but further analysis of these engineering check-outs would require antenna characterization, which will require additional time and funding.

![Schematic of single linear transmit modifications](image)

*Figure 24: Schematic of single linear transmit modifications for engineering testing, 17 April 2009.*
D. Transmitted axial ratio

Finally, Poincare (elliptical) coordinates were calculated from the Stokes vectors derived from the test flight over the Atlantic Ocean (see Raney [2007] or Keller [2009] for the details). The degree of ellipticity and the orientation angle were 19.55 and 59.39 degrees, respectively. These agree with a rough measure of the ellipticity as obtained by plotting raw returns of the two antennas against each other, indicating calculations of the Stokes parameters were not inducing further error in the results. Solving for the transmit axial ratio using matrix relationships, such as those given in Ruck et. al. [1970], yields values on the order of 56.06. This is highly non-circular, since balanced left and right circular polarizations should have a ratio of one.

E. Observations and Suggestions for Future Work

High-quality PARIS data have been acquired from the summit and margins of Greenland, and from the summit, outflow glaciers, and ice shelves of the Antarctic Peninsula. These have been processed through delay-Doppler and custom basement detection algorithms to extract and track basement locations to an accuracy of 1% of the overall depth. The results shown in this and other appendices indicate PARIS can be used to provide accurate ice soundings over a wide variety of glacial ice conditions present today.

That having been said, there are several aspects of the PARIS process that could use improvement, and questions we were unable to answer satisfactorily within the scope of this IIP project. First and foremost, given the difficulties retrieving polarimetric values from the IceGap Filler data, plans will need to be developed to characterize the antenna system as flown, calibrate the system properly, and finally achieve side-clutter reduction using polarimetric techniques.

Figure 25: Stokes for single linear transmit case (17 April 2009). Here, the fourth Stokes is too large.
Secondary, yet still significant questions remain. The Antarctic basement signature, especially under the marginal glaciers was a double line not seen in the Greenland soundings. This is different from an echo of the basement signature at twice the depth in regions where the basement had been flooded at the coast was seen in both hemispheres. Whether this is an artifact of the processing, or a geophysical property of these smaller, faster-moving glaciers is unclear at this time. Also, the side clutter (hairpins) was significantly stronger in the Antarctic soundings, especially at depth. Whether this is a hardware, or processing, or signal issue also remains to be determined. When the PARIS system is (if all goes well) implemented for large-scale flights, these issues will need to be addressed, as they inhibit rapid, accurate basement retrievals.

References


Appendix 6

PARIS Field Campaigns

May 1-12, 2007: Initial PARIS Proof-of-Concept Flights

PARIS flew aboard the NASA P-3, accompanying the NASA Cryospheric Science Branch’s “Arctic ‘07” experiment in Greenland. Roughly 1 TB of radar data were collected, along about 7,000 nautical miles of flown track.

Tracks of all flights made by the NASA P-3 aircraft during Arctic ‘07.
October 8-27, 2008: Flight of opportunity in Chile and Antarctica

The PARIS radar filled a gap in the NASA Cryospheric Science Branch’s sensor suite during an Antarctic survey (“Hielo III”) conducted jointly by NASA and the Chilean Navy. The platform was a Chilean Navy P-3. Roughly 640 GB of radar data were collected, along 8,050 nautical miles of flown track.

2008 Laser/Radar Flights

Tracks of all flights made by the Chilean Navy’s P-3 aircraft during Hielo III.
March 31 – May 2, 2009: Primary radar instrument for NASA’s Ice Bridge 2009 mission

This was an answer to an urgent call by NASA’s Cryospheric Science Branch for a combined ice-pack and sea-ice sensing mission. The mission’s intent was to provide continuity starting from the expected end of IceSat’s mission, where the data collections which would be relied-upon until IceSat 2 was online. Roughly 1.4 TB of radar data were collected, along 24,400 nautical miles of flown track.

Tracks of all PARIS flights made by the NASA P-3 aircraft during Ice Bridge 2009.
Appendix 7

Publications and Presentations


