GISMO: Arctic ’07 – Fall Deployment of the NASA P-3 to Greenland

Field Report

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Prepared by:

K. Jezek, S. Gogineni, F. Rodriguez, A. Hoch and J. Sonntag

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1.0 Introduction

GISMO is a concept for a spaceborne radar system designed to measure the surface and basal topography of terrestrial ice sheets and to determine the physical properties of the glacier bed. Our primary objective is to develop this new technology for obtaining spaceborne estimates of the volume of the polar ice sheets with an ultimate goal of providing essential information to modelers estimating the mass balance of the polar ice sheets and estimating the response of ice sheets to changing climate. Our technology concept employs VHF and P-band interferometric radars using a novel clutter rejection technique for measuring the surface and bottom topographies of polar ice sheets. Our approach will enable us to reduce signal contamination from surface clutter, measure the topography of the glacier bed, and paint a picture of variations in bed characteristics. The technology will also have applications for planetary exploration including studies of the Martian ice caps and the icy moons of the outer solar system. We have recently shown that it is possible to image a small portion of the base of the polar ice sheets using a SAR approach. Through the concept we are investigating, *we believe that, for the first time, we can image the base and map the 3-dimenional basal topography beneath an ice sheet at up to 5 km depth*

2.0 Objectives

We conducted airborne radar experiments during the fall of 2007 in Greenland to test the Global Ice Sheet Mapping Orbiter concept (GISMO) [1]. Our primary technical objectives were to acquire data at 150 and 450 MHz, which are the operating frequencies in our conceptual design, and over a variety of glacial regimes. Further, we sought to collect data with 6 receiving antennas and 2 transmitting antennas so as to enable formation of interferometric SAR image pairs with variable baselines, to acquire tomographic data, and to acquire data for multi-aperture beam formation investigations. All of the experimental configurations where designed to test the effectiveness of different clutter rejection schemes - that is, to determine whether radars operating at high altitude or from space can reliably sound the through the polar ice sheets and image the base. The experiments were also designed to characterize surface and volume clutter across different glacial regimes (such as the dry northern interior ice sheet, the seasonally melted central and south ice sheet, and crevassed zones) and to try and estimate total radar attenuation through the ice sheet by incorporating calibration measurements over the ocean.

We acquired data to validate the following specific GISMO objectives:

1) relative backscatter strength at 150 and 450 MHz
2) determine maximum swath width for interferometry
3) demonstrate clutter rejection approaches (InSAR, tomography, multiaperture beam formation)
4) investigate mosaic formation over areas suspected to have a wet bed
5) acquire data over thick and thin ice
6) acquire calibration data over the ocean

7) acquire data over all snow zones.

As described below, we achieved all of our measurement objectives. The data we collected will serve to help us identify strengths and weaknesses in the various clutter rejection algorithms we have identified.

3.0 Approach

The basic approach was to fly two radar systems over different glacial regimes. Flight lines were pre-selected so that data could be used to test various GISMO clutter rejection approaches including interferogram filtering, tomography and multi-aperture beam formation. Detailed information on the flight line selection is contained in the mission planning report.

3.1 Radar and Navigation Systems

Measurements were conducted with two radars operating sequentially at 150 and 450 MHz. Only one-frequency could be used for a particular flight. 8, quarter wave dipole antennas were mounted beneath the wings of the NASA P-3 aircraft. The dipoles were manually tuned to the resonance frequency by adding or removing an extension shaft (figure 1).

Figure 1. 150 MHz antennas installed on the right-wing antenna pod.

In the interferometric and tomographic configurations, the two inboard antennas were used to transmit and the 6 outboard antennas were used to receive in ping-pong mode. We transmitted 3 and 10 us chirps with bandwidths of 20 and 30 MHz for the 150 and 450 MHz radars respectively. The aircraft was equipped with global positioning systems and inertial navigation systems to provide detailed motion data. The radar operating parameters are listed in table 1. Parameters from the May 2006 Twin Otter flight are listed for comparison.

Table 1. Radar Operating Parameters

Parameters	**May 2006 150 MHz**	**Sept 2007 150 MHz**	**Sept 2007 450 MHz**
Carrier frequency	150 MHz	150 MHz	450 MHz
Sampling frequency	120 MHz	120 MHz	120 MHz
Chirp_start_freq (IF)	20 MHz	20 MHz	15 MHz
Chirp_Stop_freq (IF)	40 MHz	40 MHz	45 MHz
Pulse_duration	3 us	3/10 us	3/10 us
PRF	14992.5 Hz	10000 Hz	10000
Range_samples	4672	4672	4672
Echo_delay (range window)	3.5 us / 14 us	Variable	Variable
Reciever Attenuation		0-40 dB	0-40 dB
Number of waveforms (ping-pong mode)	4	4	4
Number of transmit channels	2	2	2
Number of receive channels	6	6	6
Transmit Power (high elevation)	N/A	800 W	1 kW
Transmit Power (low elevation	200 W	200 W	200 W
Presums	64	32	32
Flight Elevation (low)	N/A	500 m above ice sheet surface	500 m above ice sheet surface
Flight Elevation (high)	10000 ft above sea level (max)	17000-22000 ft above sea level	17000-22000 ft above sea level
Number of Antenna Elements	10	8	8

The radar as installed in the P-3 is shown in figure 2.

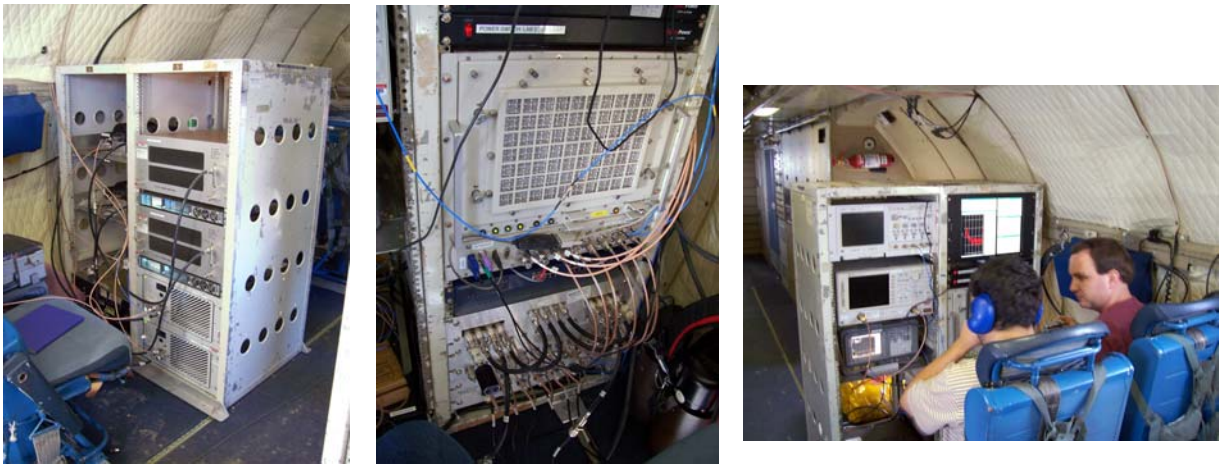

Figure 2. Radar power amplifiers (left), electronics chassis (center) and radar operation (right).

In addition to the radar systems, we operated Global Positioning System and Inertial Navigation System units to determine the position and attitude of the aircraft. To refine the motion of the antennas, we also installed two accelerometers on each antenna pod. However, we found that the accelerometers produced RF noise and so only used them only briefly for test purposes.

With help from Wallops Flight Facility, we also acquired nadir-looking photography along pre-determined sections of the flight line.

3.2 Radar Calibration

We collected the following radar calibration information.

During Installation:

1) Inject transmitter signal into each receiver through a known length of delay line and attenuation, and measure each receiver response.
2) Measure time delay from the rack to each antenna using a network analyzer.
3) Measure system response by flying over the ocean.
4) Measure antenna return loss while in flight.

During a mission:

1) Fly over the ocean to collect data over a distance of 10-20 km during each mission. Roll the plane to collect antenna pattern information.

3.3 Flight Line Descriptions

The aircraft was flown at altitudes as high as 6700 m above sea level and as low as 500 m above the ice sheet surface. Flight lines are shown in figure 3. The most northerly flight line (yellow line in figure 3) was designed to capture surface clutter conditions across outlet glaciers discharging into the Arctic Ocean, down the length of the floating portion of Peterman glacier, and to cross the dry snow zone including an over flight of the proposed NEEM deep drilling site. Measurements were also made along a 'race-track' where successive ovals of the race-track were displaced by 25 m. The race-track data will be used for radar tomography of a region where there is complex subglacial relief.

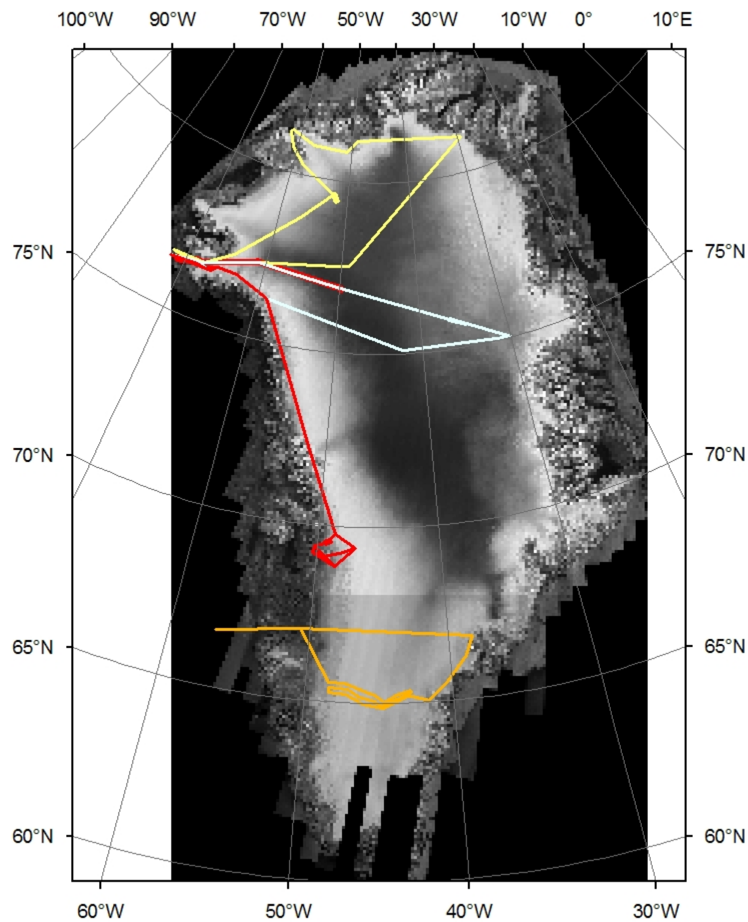

Figure 3. Flight operations carried out during September 2007 to test the GISMO concept.

The second northerly leg (light blue line in figure 3) again intercepted the dry snow zone and passed over the NGRIP deep drilling site. The eastern portion of the flight repeatedly crossed the North East Ice Stream which is suspected of being underlain in parts by water (figure 4). As the experiment unfolded, we decided to concentrate several flights over this region as it provided good baseline data. We over flew this line 4 times. We first operated at high altitude, at 450

MHz and in ping-pong mode. We next operated at lower altitudes in depth sounder mode (4 transmitting and 4 receiving antennas). We next operated at 150 MHz in ping pong mode at high elevation. Finally we flew the line outbound at 150 MHz in ping pong mode at high and low elevations (depending on clouds) and then configured the radar for the inbound leg in depth sounder mode at low elevation. The different combinations allowed us to look at clutter problems using different frequencies, different operating altitudes and different transmit and receive configurations. We acquired data down the Harold Moltke Glacier located near Thule on the return portion of the flight which may be the first radar sounding observation of this large glacier.

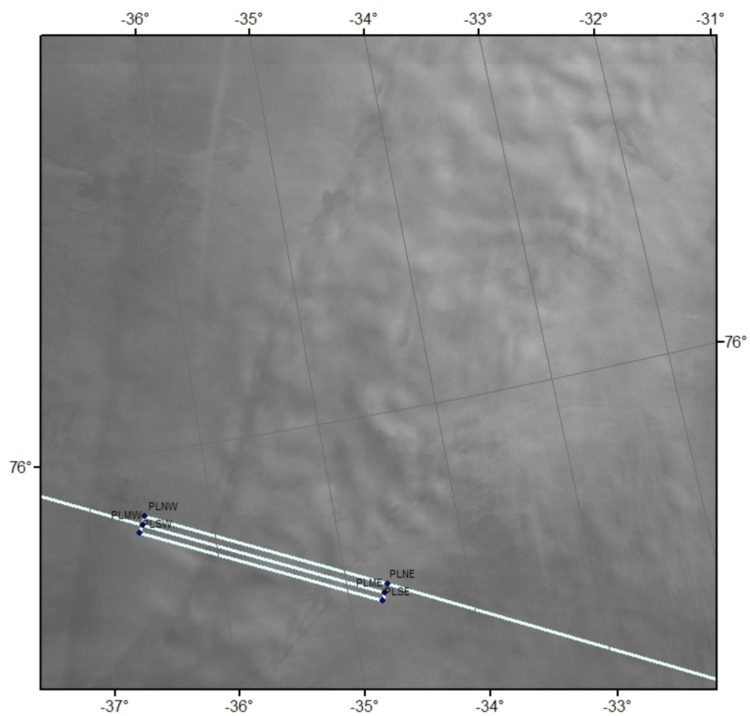

Figure 4. Details on the three parallel lines crossing the southern portion of the North East Ice Stream.

Additional lines were flown to collect data over other glacier regimes in Central and Southern Greenland where clutter issues are compounded by significant crevasses and/or substantial surface melt and refreezing of the upper firn layers. The red line in figure 1 runs along and across the heavily fractured surface of Jacobshavn Glacier. Details of the flights along and across Jacobshavn Glacier are shown in figure 5. The fractured margin of the ice stream and the iceberg clogged fjord are shown in figure 6. A second racetrack was executed near Swiss Camp in an attempt to tomographically image the drainage structure of moulins.

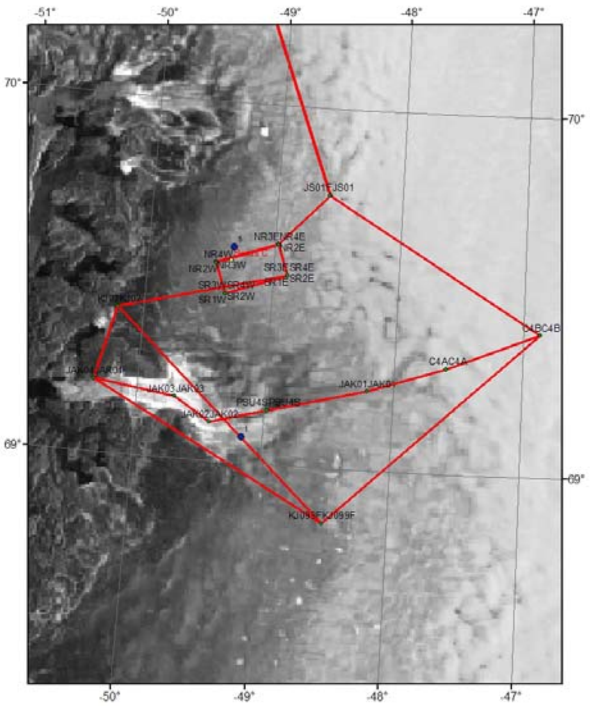

Figure 5. Details of the flights across and along Jacobshavn Glacier.

Figure 6. Jacobshavn Glacier terminus (right side of image). Icebergs clog the fjord downstream of the glacier (left side).

The yellow line in figure 3 proceeds along several strain rate clusters first installed by Ian Whillans of The Ohio State University in 1980 (figure 7). Surface elevation and bottom topography data were acquired in 1981 and surface elevation measurements were made along these lines are recently as 2004. The wealth of historical data makes the clusters a good site for assessing our system performance.

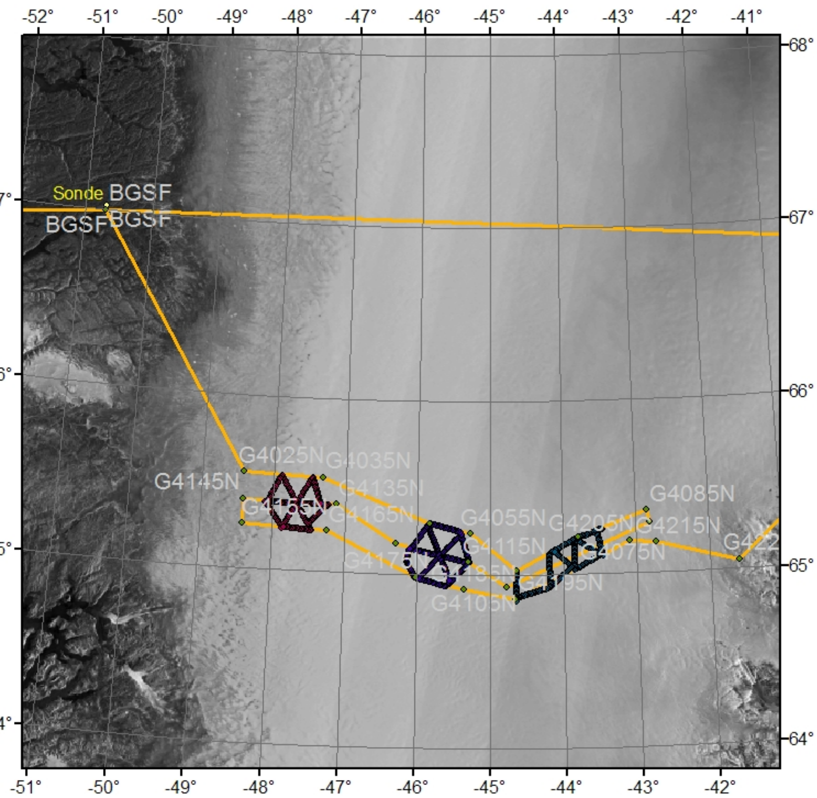

Figure 7. Observations along the strain rate cluster installed by OSU in 1980. Basal topography was measured using surface based radar in 1981. Surface elevation has been repeatedly measured over these sites through 2004.

Specifics on dates, locations and flight descriptions are listed in Appendix 1.

3.4 Flight Hour Summary

Flight durations are summarized in Table 2 below. Data collection time is less than total flight time because the radar was disabled during banking turns and climbs.

Table 2. Flight Hours Devoted to GISMO

Flight line (# of flights)	Total flight time (hours)	Approximate data collection time (hours)
Thule 2 (1)	6.1	5.4

Thule 1 (4)	21.1	19
Jacobshavn (2)	15.2	13
Clusters (1)	4.7	4.7
Total for all	47.1	42.1

4.0 Preliminary Observations and Data Set Quality

We observed range compressed echoes in real time during each flight (figure 2). Upon return to our quarters at either Thule or Kangerlussuaq Greenland, we were also able to conduct initial analysis of the data including range compressing substantial portions of the data set into intensity modulated displays of echo amplitude along the flight path and to roughly process some of the data into range and azimuth compressed SAR images. We were unable to apply motion corrections during the SAR processing in the field but will do so once the refined ephemeris data are available.

Figure 8 shows a range compressed intensity modulated display of 150 MHz data collected across the North East Ice Stream on September 12. All 6 receiver channels were averaged and 25 along track observations (each representing a 32 sample presume) were averaged. At 500 m above the ice sheet surface, there is minimal surface clutter and a strong basal echo.

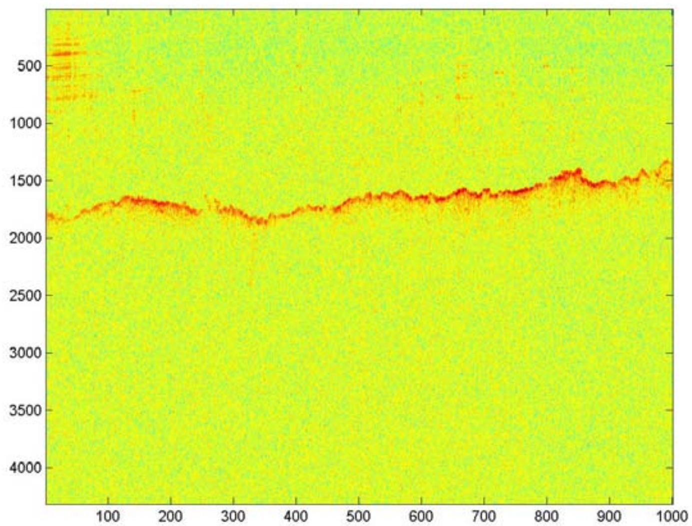

Figure 8. 49 km section of 150 MHz data across the North East Ice Stream. The vertical units are .0085 us samples delayed by 15 us from the start of transmission. The ice thickness is approximately 2300 m. Sensor was operated in ping-pong mode and flown at 500 m above the ice sheet surface. The record proceeds from east to west.

Figure 9 shows the same section using the 150 MHz radar but flown at an altitude of 6700 m above sea level (about 4400 m above the ice sheet surface). Notice the increase in surface/volume clutter which partly obscures the bottom echo. The data were collected on September 11

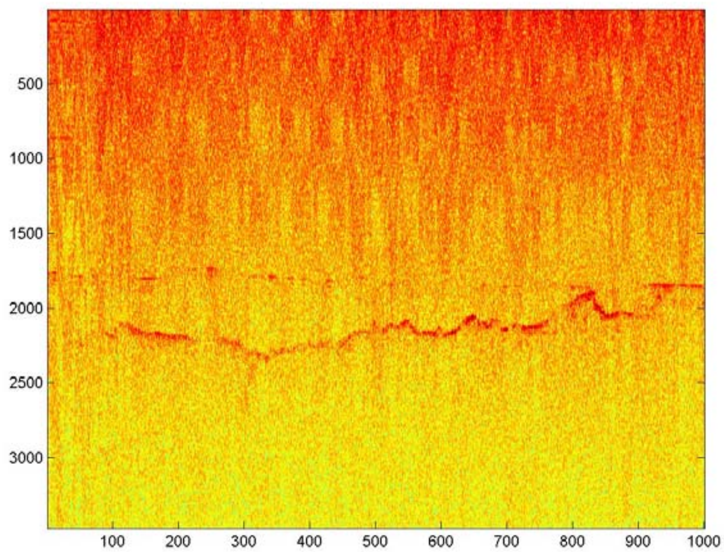

Figure 9. 49 km section of 150 MHz data across the North East Ice Stream. The vertical units are samples. Sensor is operated in ping-pong mode and flown at 4400 m above the ice sheet surface. Faint echo at about 1800 units is the surface multiple.

Figure 10 shows the same line flown at 500 m elevation above the ice sheet surface and measured at 450 MHz. In this case, 4 transmitting antennas were used and 4 receiving antennas were used. The basal return is relatively free from clutter. The data were collected on September 10.

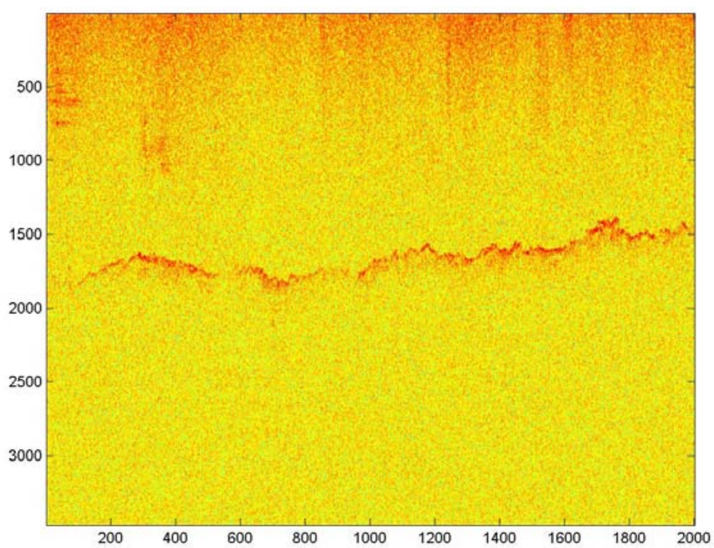

Figure 10. 49 km section of 450 MHz data across the North East Ice Stream. The vertical units are samples. Sensor is operated in nadir sounding mode and flown at 500 m above the ice sheet surface.

Figure 11 shows the same line flown on September 8 at 6700 m above sea level and at 450 MHz in ping-pong mode. The bottom echo is completely obscured by clutter.

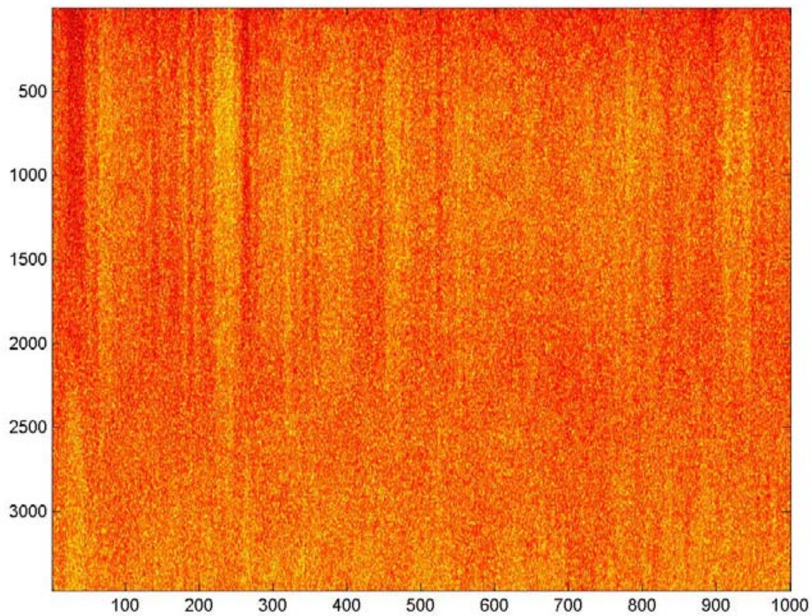

Figure 11. 49 km section of 450 MHz data across the North East Ice Stream. The vertical units are samples. Sensor is operated in ping-pong mode and is flown at 4400 m above the ice sheet surface. The hill at range line 850 in figure 9 is barely visible in this image at the same location.

Because of the strong scientific interest in Jacobshavn Glacier and because of the challenges posed to sounding through the highly fractured surface, we conducted two missions from Thule to the Jacobshavn area. Measurements from the iceberg clogged fjord to the interior along the central flow line of the glacier are shown in figure 12 and 13. Both are data acquired at low altitude where at least some of the clutter issued could be mitigated. While the navigation information is only approximate, figure 12 suggests we were able to sound the lesser crevassed flanking areas of the ice stream at 150 MHz. The bottom echo near the calving margin is obscured in figure 13 which is transected by surface and volume clutter, side probable echoes and complex diffraction hyperbolas. As planned, GISMO processing techniques will be applied to both of these images to investigate optimal approaches for separating the bottom return from the clutter signal.

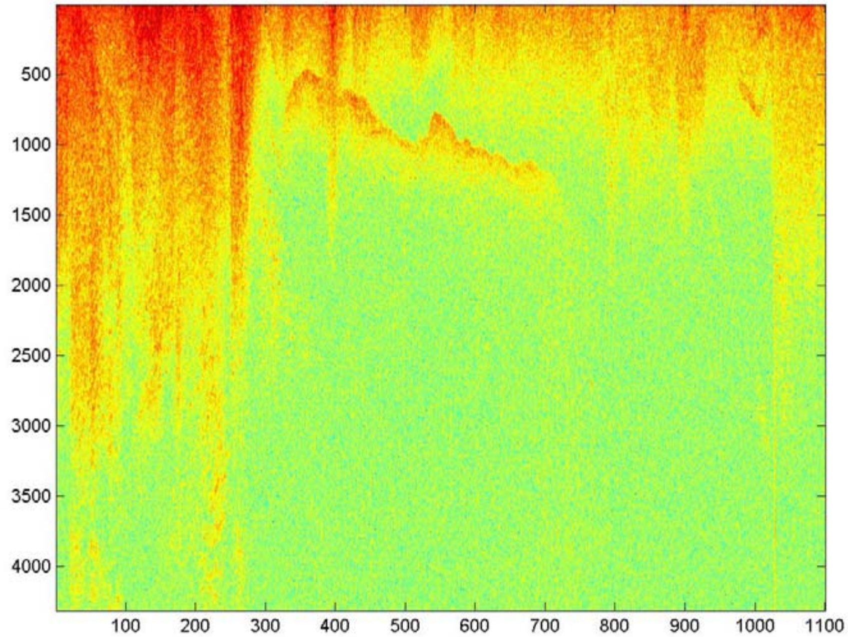

Figure 12. Low elevation 150 MHz data crossing over the Jacobshavn Glacier channel. The stronger bottom return flanks the channel. The image starts at about 69.1 N, 49.2 W.

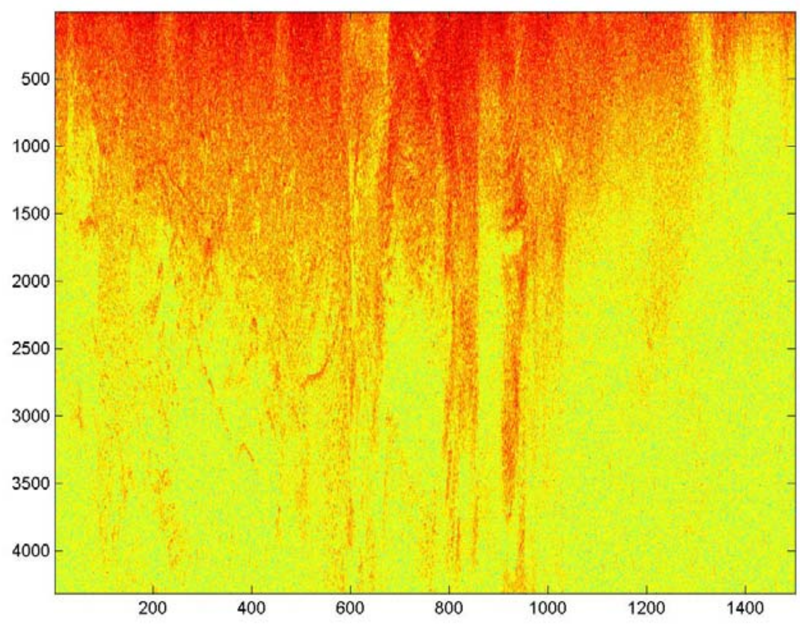

Figure 13. Low elevation data collected at 450 MHz along Jacobshavn Glacier. Clutter precludes any visual interpretation of these data. The calving margin is located near the left center of the image.

To verify that the data could be compressed in both the range and azimuth directions, we processed several scenes to SAR images. The processing is rough because we have not yet include motion data. Figure 14 shows one SAR processed image strip. Prior to processing, little evidence of the bottom echo was detectable in individual return wave forms. After rough SAR processing (we have not yet applied motion compensation), the basal echo was observable.

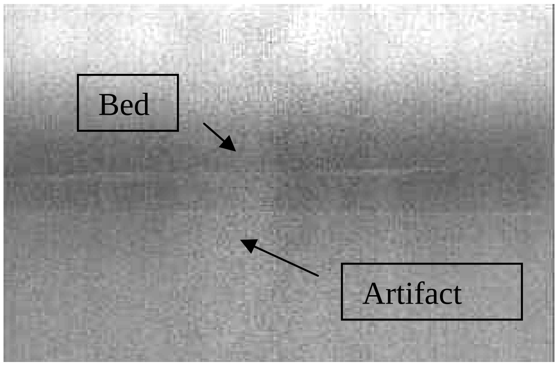

Figure 14. Range and azimuth compressed 450 MHz data acquired over north central Greenland. The image is delayed 40 us from the start time of the transmit pulse. The image is about 5 km long. The lower echo is a system artifact. The intermediate echo is the glacier bed. The bed echo was largely undetectable prior to SAR processing because of surface clutter.

A second SAR processed image is shown in figure 15. The diffraction hyperbola do not collapse presumably because of the small size of the SAR aperture.

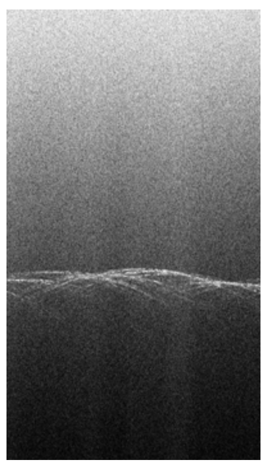

Figure 15. 150 MHz echogram across the North East Ice Stream, which is likely underlain by water. Image is about 5 km wide. It is displayed at a narrower width than figure 15 to highlight the hyperbolic shape of several bed echo patterns. Image starts 40 us after start of transmit pulse. Aircraft altitude was approximately 22000 feet

Preliminary comparison between the echo strength observed over the ice stream and open ocean water at low altitude and at both frequencies suggests that the attenuation through the ice is consistent with that reported by Paden and others [2].

5.0 Summary

We successfully operated 150 and 450 MHz ice sounding radars during a NASA aircraft deployment to Greenland during September 2007. The radars were used to collect data over a variety of glacial regimes. The data will be used to test GISMO clutter rejection concepts. Our initial assessment is that the radars performed very well and that we have an exceptionally rich and diversified data set from which to test GISMO ideas.

As many other investigators have noted since the earliest ice-sheet radio-echo-sounding campaigns, surface and volume clutter are issues for airborne ice sounding [3] but which can be overcome by flying low over the ice sheet surface. We found this to again be true at both of our operating frequencies. At higher altitudes we only obtained satisfactory preliminary results at our lower frequency. Retrieval of echoes in clutter filled regions and from high altitudes await further processing which we will conduct over the coming months. Nevertheless, the preliminary results point to the fact that surface and probably volume clutter must be factored into any ice sounding radar designed to fly at high altitudes and even across what are usually considered to be radar-benign glacier regimes.

6.0 References

[1] Jezek, K.C., E. Rodriguez, P. Gogineni, A. Freeman, J. Curlander, X. Wu, J. Paden, and C. Allen. Glaciers and Ice Sheet Mapping Orbiter Concept. J. Geoph. Res – Planets, , J. Geophys. Res., 111, E06S20, doi:10.1029/2005JE002572, 2006.

[2] Paden, J., C. Allen, S. Gogineni, K. Jezek, D. Dahl-Jensen, and L. Larsen. Wideband Measurements of Ice Sheet Attenuation and Basal Scattering. IEEE Geoscience and Remote Sensing Letters, vol 2, no. 2, p. 164-168.

[3] Robin, G. De Q., S. Evans and J. T. Bailey, Interpretation of Radio Echo Sounding in Polar Ice Sheets. Phil. Trans. Royal Soc. London, Series A, Mathematical and Physical Sciences, vol, 265, no. 1166, pp 437-505, 1969.

Appendix 1

Description of GISMO flights conducted during September 2007.

Date	Location	Run ID	Frequency	Transmit mode	Altitude (ft)	Comments
20070906	Wallops-Thule	transit	450	GISMO	23000	antenna calibration data collected
						delay line data collected files 0-4
						ocean data collected
						roll data files 19, 20, 21
20070907	Thule	Thule 2 (Peterman)	450	GISMO	22000	Detect an Echo near NEEM
						Record echo manually around file 44
						File 169 Crevasses Below
						Peterman Files 289-290 Broken Sea ice
						Mt Gogineni Race Track Files 343-396
						End File 491
						Accelerometers on and creating noise
20070908	Thule	Thule 1 (Ice Stream)	450	GISMO	22000	Begin with accelerometers but turn them off after file 94
						Ice Stream Files 148-184
						Weak Echos at best during flight
20070910	Thule	Thule 1	450	Depth Sounder	1500 to 5000 ft	Start with 3 and 10 us pulses
						Switch to 3 us and 3 us pulses at file 21
						Switch to 3/10 at file 42 and descend to 1500 ft
						Ice Stream File 141-219 with large return in file 209
						File 248 Laser on increase elevation to 14000 ft
						1500 ft over NGRIP file 427
						Change altitude repeatedly

						File 735-746 Rolls
20070911	Thule	Thule 1	150	GISMO	22000	Ice Stream Files 116-152
						Strong returns in file 210 Near NGRIP
						Accelerometers on at File 273
						File 396 over Harold M. Strong Echo
						~Files 400 ocean data and rolls
						Stop File 418
20070912	Thule	Thule 1	150	GISMO/CARDS	1500 to 14000	File 0 is Delay line
						Echo in F22 between CC and KJ
						Climb to 10000 ft
						Pulse lengths 3/3 us
						GISMO Run over Ice Stream Files 144-183 at 1500 ft
						Reconfigure to Cards Mode
						CARDS run over ice stream files 184-230
						Laser was on during several but not all legs
						Pulse lengths 3/10
						Redo outer loop of ice stream files 231-280
						Stop recording prior to 570
						Collect ocean data and rolls
20070913	Thule	ATM Humboldt	150	CARDS	1500	ATM Run CARDS operation
20070914	Thule	Thule-Jacobshavn	150	GISMO	22000 outbound - 1500 ft inbound	GISMO Evaluation
						Rcvr malfunction in files 0-5; bypass filter

						adjust delays and attenuation while searching for echo
						File 127 near Rinks Glacer
						File 128 strong echo which persist till north of Jacobshavn
						Swiss Camp Race Track files 185-225
						Jacobshavn hi-elev run files 285-315
						Decrease elevation to 1500 ft
						Cross channel file 344
						Low elevation run up Jacobshavn files 388-394
						Laser on
						Strong echo at and after F435
						Stop near kj51f because of disk usage
						Problems with open water cal
20070915	Thule	Thule-Jacobshavn	450	GISMO	22000ft outbound 1500 ft inbound	Initial problem with rcvr 3 fixed
						F44 strong echo
						F126 Rinks glacier no echo
						Echo near glacier edge in file 136
						Swiss Camp Race track Files 190-217; navigation is challenging
						File 247 Channel at hi-elev
						Hi elev Jacob run files 293-321
						Descend to 1500 ft
						Low elev Jacob run F 392-415
						Change attuation near JAK01 because clutter tails off very rapidly to noise level
						End run about 416

						Radar off F508 for return loss measurements
						F512 open water
						F514 rolls at 8500 ft
20070917	Thule	Thule-Sonde Transit	150	Cards	1500 - 17000 ft	ridgeline flight
						Large blue-ice lake observed at 48 degrees 20 west on inbound leg over lower cluster
						Antennas iced-up upon landing at Sonde
20070918	Sonde	Clusters	150	GISMO	17000 ft	file 12 bottom echo at 37 us
						approximate start of first leg file file 20
						File 56 start first dye3 leg
						echo at 40 us file 57
						file 70 end first cluster leg
						file 85 start second leg west
						elev 5060 m
						file 93 echo at 39 us
						file 140 echo at 39 us
						file 146 end second leg
						file 154 start third leg east
						file 168 65.18 N 46.97 W
						File 181 64.9 N 45.75W
						File 208 65.18 N 43.11 W end clusters run
						LVIS on at 43 W on return leg
						LVIS off past 50 W
						F0367 Begin Ocean cal and rolls
						F 378 End