Measurement of Thickness of the Greenland Ice Sheet and Investigation of Scattering Properties of Glacial Ice

Final Report

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Radar Systems and Remote Sensing Laboratory Technical Report 13720-11

October 2000

Supported by:

National Aeronautics and Space Administration
Washington DC 20546

NAG5-6345

Measurement of Thickness of the Greenland Ice Sheet and Investigation of Scattering Properties of Glacial Ice

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Abstract:

This is the final report for the project titled "Measurement of Thickness of the Greenland Ice Sheet and Investigation of Scattering Properties of Glacial Ice." The primary objectives of this project were to determine ice thickness and bottom topography using an airborne radar depth sounder and to improve interpretation of satellite synthetic aperture radar data over glacial ice. We developed two coherent radar depth sounders operating at 150 MHz and installed and operated these radars on the NASA P-3B aircraft. We collected a large volume of ice thickness data as a part of NASA's initiative for determining the mass of balance of the Greenland ice sheet. We obtained good ice thickness information over 90% of the flight lines flown as a part of the PARCA initiative. We published a number of technical reports with raw echograms and derived thickness data from these experiments. Also we performed microwave scattering measurements, in collaboration with the Byrd Polar Research Center at the Ohio State University, aimed at understanding the physics of scattering from glacial ice and using this information to interpret satellite radar data better.

1.0. Introduction

In 1991, NASA started a polar research initiative for determining the mass balance of the Greenland ice sheet. It consisted of coordinated surface, airborne and spaceborne measurements for determining the mass balance of the ice sheet. The initial program consisted of a laser altimeter and a Ku-band radar altimeter for measuring surface elevation of the ice sheet along selected flight lines from a low-flying aircraft. In 1993, the airborne instrumentation suite was expanded to include a radar depth sounder to collect ice thickness data along the same flight lines because ice thickness is a key variable in the time-dependent equation of continuity and is essential to any study of ice-sheet dynamics.

Raju, Xin and Moore [1990] developed a coherent radar sounder for measurements in the Antarctic. During the 1993 field season, we used this system to collect ice thickness data. Although we collected good quality data in the northern and central parts of the ice sheet, we could not measure ice thickness in temperate areas of the ice sheet with thick, warm ice in southern Greenland. To overcome system limitations and improve its performance, we developed two new systems—one using connectorized components and the other using Radio Frequency Integrated Circuits (RFICs). The transmitter and receiver prototypes for the system using RFICs were developed by senior undergraduate students as part of a capstone design project. We used these prototypes to develop an operational system that was used to collect much of the data starting in 1996. Both radar systems operate at the center frequency of 150 MHz with a chirped pulse of 1.6 μs duration and peak transmit power of about 200 W.

We installed these radars on the NASA P-3B aircraft and collected a large volume of data. We processed these data to obtain good ice thickness information over 90% of the flight lines flown as a part of the PARCA initiative. The areas over which we obtained good ice thickness data included the interior of the ice sheet, ice sheet margins, outlet glaciers and a few areas containing warm ice in southern Greenland. We supplied these data to the scientific community in a timely manner and several papers using the ice thickness data obtained through this project were published (see publication list in Appendix I). In collaboration with The Ohio State University, we also performed microwave backscatter measurements using ranging radars at 5.3 and 13 GHz, and we analyzed and reported results of these measurements [Jezek et al., 1994],

In summary we have met or exceeded all project objectives. We developed two coherent radars that can be used for routine ice thickness measurements, we collected and processed radar depth sounder data from over the Greenland ice sheet, and supplied these data to the scientific community in a timely manner; and we measured high-resolution backscatter data and analyzed these to determine the primary scattering mechanism for glacial ice in the percolation zone.

2.0. Radar System Description

The coherent radar depth sounder we used for measuring ice thickness on this mission was an improved version [Gogineni et al., 1998; Akins, 1998] of the original system described in Raju, Xin and Moore [1990]. The system was operated from a NASA P-3 aircraft that was also equipped with precision laser altimeter systems, Global Positioning System (GPS) receivers, and a nadir-looking video camera. This provided accurate registration of the depth sounder data with precise location information and independent ice surface elevation data. A detailed description of the system is given in an earlier report [Chuah, 1997] and journal paper [Gogineni, et al., 1998]; therefore, only a brief summary is provided here.

The transmitter generates a pulse that is frequency modulated (chirped) over a bandwidth of 17 MHz at 150 MHz with a duration of 1.6 μs and a peak power of 200 W. The radar uses separate transmit and receive antennas that are mounted under the wings. Each antenna is a four-element, half-wavelength dipole array. The receiver is protected during transmit events with a limiter and a blanking switch. It amplifies and compresses the received signal in a weighted SAW compressor to obtain a compressed pulse length of about 60 ns. This gives a depth resolution of 5 m in ice ($n = 1.78$). The end-to-end receiver gain is about 95 dB. The compressed signal is coherently detected, providing in-phase and quadrature (I and Q) analog outputs. Two 12-bit A/D converters digitize these analog signals at a sampling rate of 18.75 mega-samples/s (MSPS). Coherent integration is then performed by summing the complex data vectors from 256 consecutive transmit-receive periods. Power in each record is computed ($I^2 + Q^2$) and then integrated further (incoherent integration) by summing four consecutive data vectors. The data are displayed to the user and are also recorded, along with position and time data provided by the on-board GPS receiver, on a removable hard disk. Table 1 lists the principal radar system parameters.

Table 1. Radar System Parameters

Parameter	Value	Units
Nominal aircraft altitude (AGL)	500	M
Nominal aircraft speed	110	M/s
Radar type	Coherent - Pulse	- -
Radar center frequency	150	MHz
Transmitted bandwidth	17	MHz
Transmitted pulse duration	1.6	μs
Compressed pulse duration	60	Ns
Peak transmit power	200	W
Pulse repetition frequency (PRF)	Programmable	Hz
STC dynamic range	70	DB
Number of coherent integrations	Programmable	- -
Number of incoherent integrations	Programmable	- -
Baseband bandwidth	8.5	MHz
A/D dynamic range	72 (12 bits)	DB
A/D sampling frequency	18.75 (53.3 μs)	MHz
A/D sample length	Programmable	- -
A/D sampling delay	Programmable; 100-ns precision	ns
Range (depth) resolution (in ice)	5	m
Range sample spacing (per pixel in ice)	4.494	m
Antenna type	4 element half λ dipoles	- -
Along-track 3-dB 2-way beamwidth	66	Degrees
Cross-track 3-dB 2-way beamwidth	18	Degrees
Effective 3-dB along-track beamwidth of coherent integration	7	Degrees

3.0. Data Processing

We have collected a large volume of ice thickness data as a part of the PARCA initiative over the last few years. We estimated ice thickness by tracking the peaks of surface and ice-bedrock interface and computing the number of range cells between the surface and the ice-bedrock interface peaks. We multiplied this number by 4.494, which is obtained by dividing the free-space range-cell dimension by the refractive index of ice, to estimate ice thickness. To estimate errors in the derived ice thicknesses, we compared the radar-derived ice thickness information with GISP and GRIP cores. The results showed that radar-derived ice thicknesses were within +/- 10 m of that for these cores. We did not make any correction for firn effect, which could reduce this error further.

For about 80% of the flight lines, we had to perform only a minimal amount of post processing—additional coherent integrations (two to four) and incoherent integrations (10-20) to reduce fading—to obtain good ice thickness data. The signal-to-noise (S/N) ratio for bottom echoes over areas with good bedrock echoes varied between 10 and 40 dB. Because of increased absorption loss for warm ice over some areas in the south and central parts of the ice sheet, we had to perform additional post processing using the *f-k* migration algorithm to extract ice thickness.

We obtained ice thickness information for an additional 10 percent of the flights after processing with the *f-k* migration algorithm. We could not apply this algorithm to the data collected before 1997 because only the amplitude of the received signal was saved for much of these data. Figure 1 shows locations where we obtained good ice thickness for all flight lines flown as a part of the PARCA initiative, which includes data processed with *f-k* migration algorithm. We generated this figure by dividing the ice sheet into a grid with a resolution of 0.02° and 0.06° latitude and longitude, respectively. The grid extends from about 59.5° to 84° N in latitude and 75° to 10° W in longitude. We identified grid cells with valid thickness data or no data along each flight line. We also uploaded these reprocessed data onto a server from which data can be downloaded electronically.

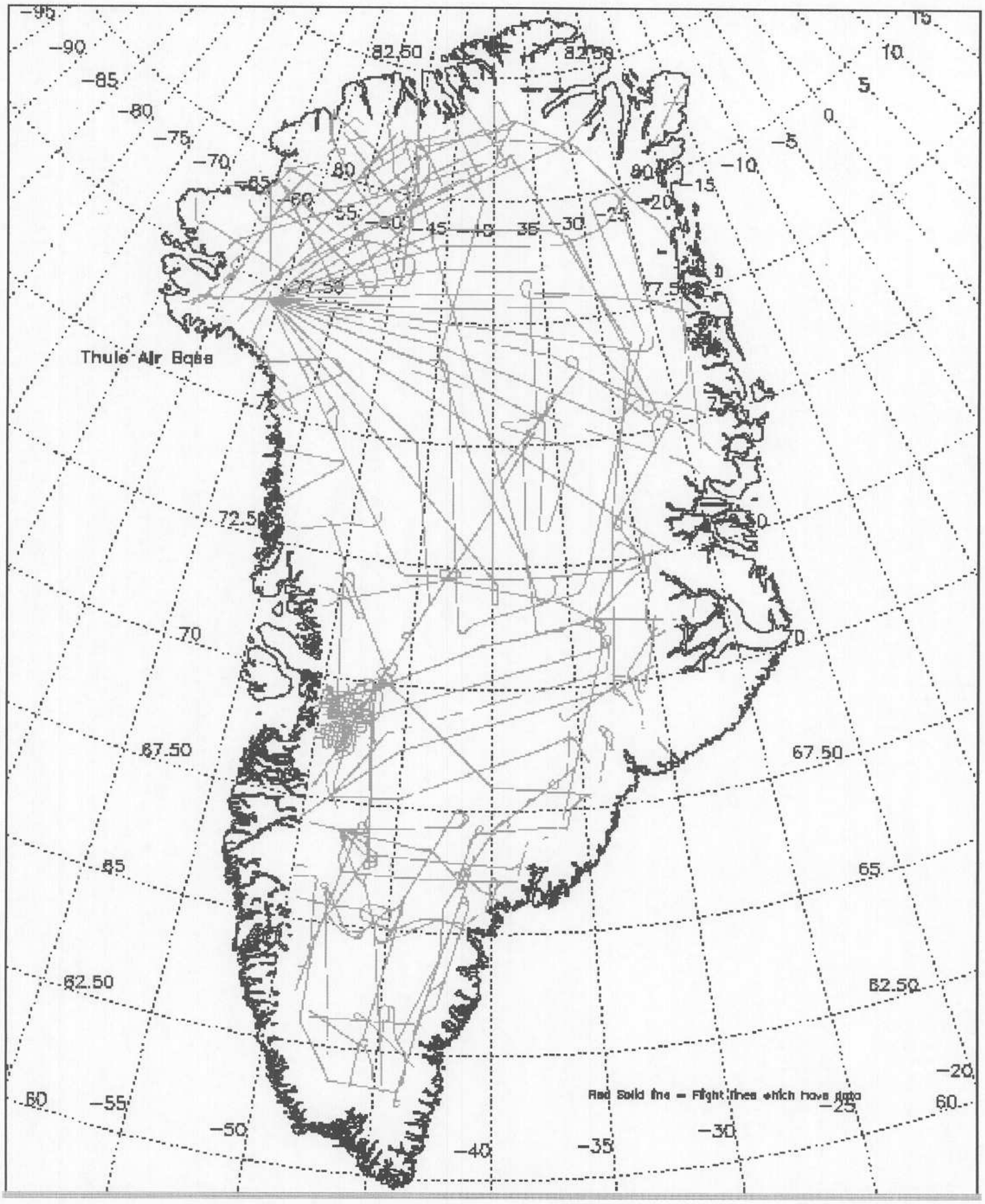


Figure 1. Map of where we obtained good ice thickness data.

We supplied radar data in digital form to several investigators worldwide and sent RSL technical reports of results on data collected during 1993 - 1999 to all the PARCA (Program for Arctic Regional Climate Assessment) principal investigators. [Chuah et al., 1996a; Chuah et al., 1996b;

Legarsky et al., 1997; Wong et al., 1998; Tee et al., 1999]. We have collaborated with a few investigators at other institutions in the preparation of papers for publication in refereed journals [Rignot et al., 1997; Thomas et al., 1998; Joughin et al., 1999]. In addition we also prepared a paper highlighting the results over outlet glaciers [Allen et al., 1997] and results over Northwestern part of the ice sheet on a few internal features which we report as hills buried under the ice [Legarsky et al., 1998].

4.0. Results

The results of radar ice thickness measurements have been widely disseminated. The list of journal papers, conference proceeding publications and technical reports is given in Appendix I. In this section we show two examples of data collected over the Greenland ice sheet. One of these examples shows data where we obtained good ice thickness data without any processing and the other shows where we applied the *f-k* migration algorithm to improve the signal-to-noise ratio.

Starting in 1997, we collected much of the data with a radar PRF of 9.2 kHz and the integrator set to sum 256 samples coherently to reduce data volume. The aircraft was flown in a terrain-following mode at an altitude of about 450 m above the ice surface with an airspeed of about 130 m/s. The distance traveled in the time to collect 256 samples at 9.2 kHz PRF is about 3.6 m. This distance is much less than an unfocussed SAR aperture, which is about 21 m for a target located at a range of 450m. We processed the data further by coherently integrating two to four samples and incoherently integrating 10-20 samples to reduce fading. Figures 2a and 2b show an example echogram and derived ice thickness for data collected and processed over the interior of the ice sheet. Ice thickness varies between 3.1 and 2.9 km over a distance of 100 km from the start of this flight segment. The bottom topography is relatively flat over the first 120 km, with a small peak of 400 m at the end. The S/N ratio for the bottom echo varies between 30 and 40 dB for the data shown in the figure. This confirms that the radar can provide consistent ice thickness information for more than 3 km of cold ice. Also, echoes associated with internal layers are visible to a depth of about 2.5 km. The white band between100 and 200 pixels is the result of using a Sensitivity Time Control (STC) circuit to prevent receiver saturation by the strong primary and multiple echoes from the air-ice interface.

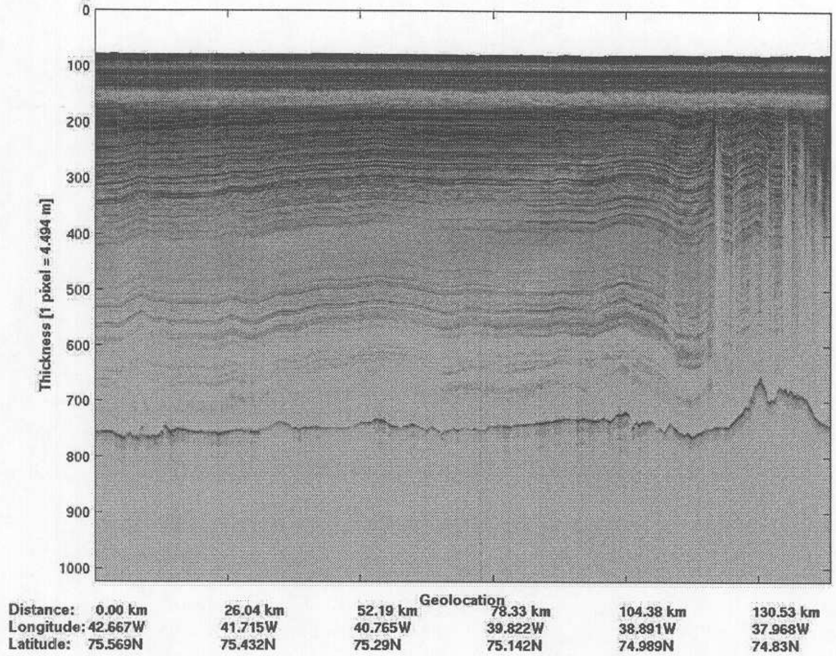


Figure 2a. Radar echogram from data collected over the interior of the ice sheet.

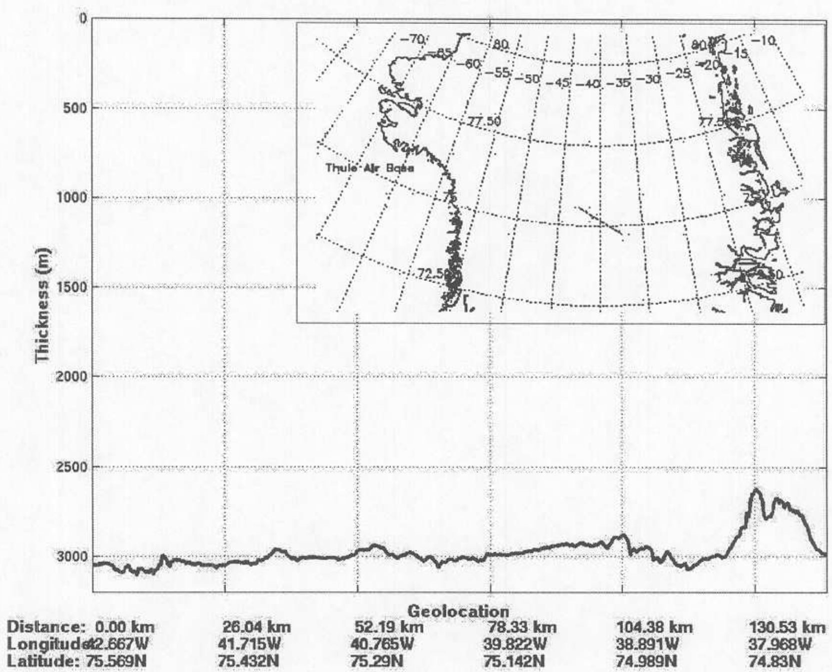


Figure 2b. Ice thickness obtained from radar data over the interior of the ice sheet.

For about 80 percent of the flight lines, we had to perform only a minimal amount of post processing—additional coherent integrations (two to four) and incoherent integrations (10-20) to reduce fading—to obtain good ice thickness data. Results over these lines are similar to those discussed above with the S/N ratio for bottom echoes varying between 10 and 40 dB. Because of increased absorption loss for warm ice over some areas in the south and central parts of the ice sheet, we had to perform additional post processing using the *f-k* migration algorithm to extract ice thickness. Gazdag and Sguazzero [1984] and Stolt [1978] provide a detailed discussion of the *f-k* migration technique.

Figures 3a and 3b show radar echograms generated with normal processing and the *f-k* migration algorithm. The inset in these figures shows the amplitude of echoes as function of depth. The S/N ratio for the bottom echo using conventional data processing is about 4 dB, whereas the S/N ratio for data processed with the *f-k* migration algorithm is 10 dB. Over the entire image we obtained 4-6 dB improvement in the S/N ratio for data processed with the *f-k* algorithm over that obtained with conventional processing. We processed only data with weak bottom echoes with *f-k* migration because it is computationally intensive. We obtained good thickness information for about an additional 10 percent for the flight lines beyond the 80 percent obtained with conventional processing. The areas where we could not obtain ice thickness consisted primarily of the deep, narrow channel beneath the Jacobshavn outlet glacier and that near the margins of the ice sheet where bottom echoes were merged with multiples of the ice surface. Much of the radar data over the Jacobshavn area were collected in incoherent mode during 1997, and we could not post-process these data to improve the S/N ratio. We believe that we can obtain ice thickness within the narrow channel with these radars if the measurements are made in coherent mode before significant surface melt starts and near the ice sheet margins with the aircraft flown at different altitudes for the remaining 10 percent of the flight lines.

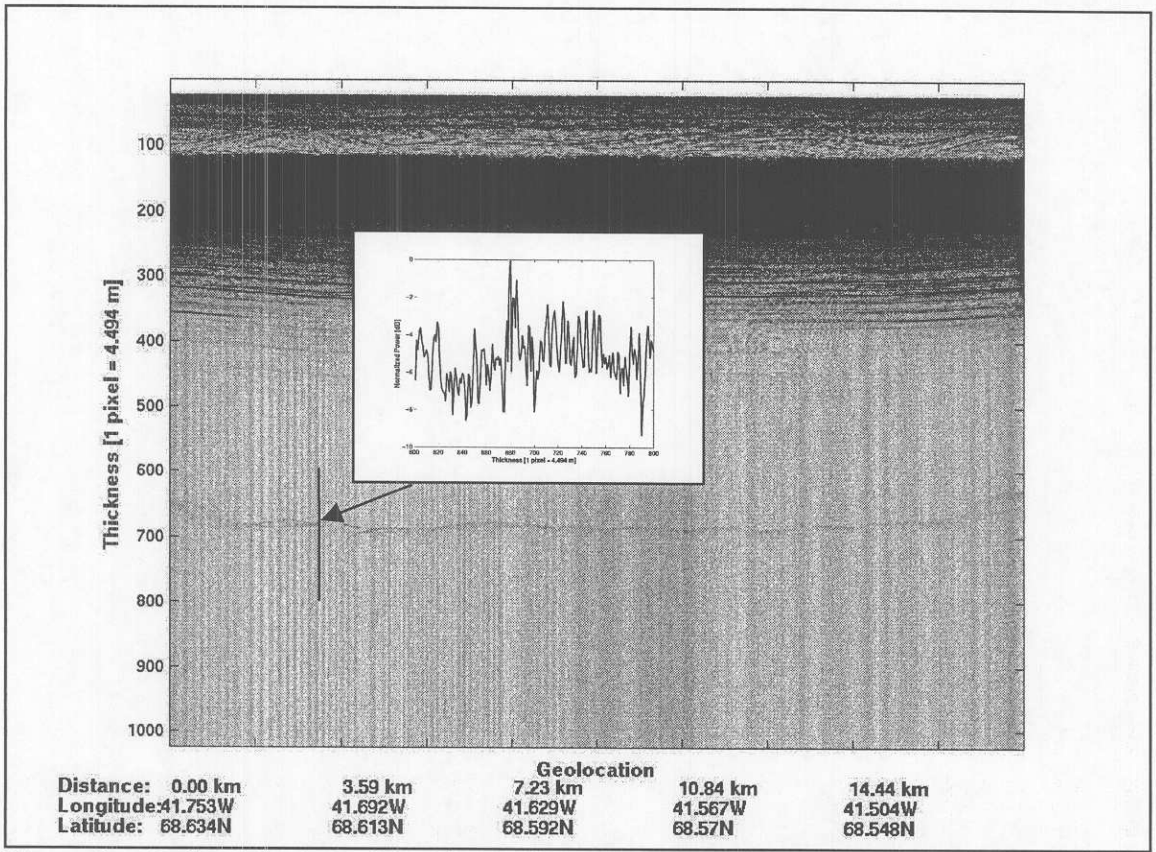


Figure 3a. Radar echogram from data collected over the central part of the ice sheet.

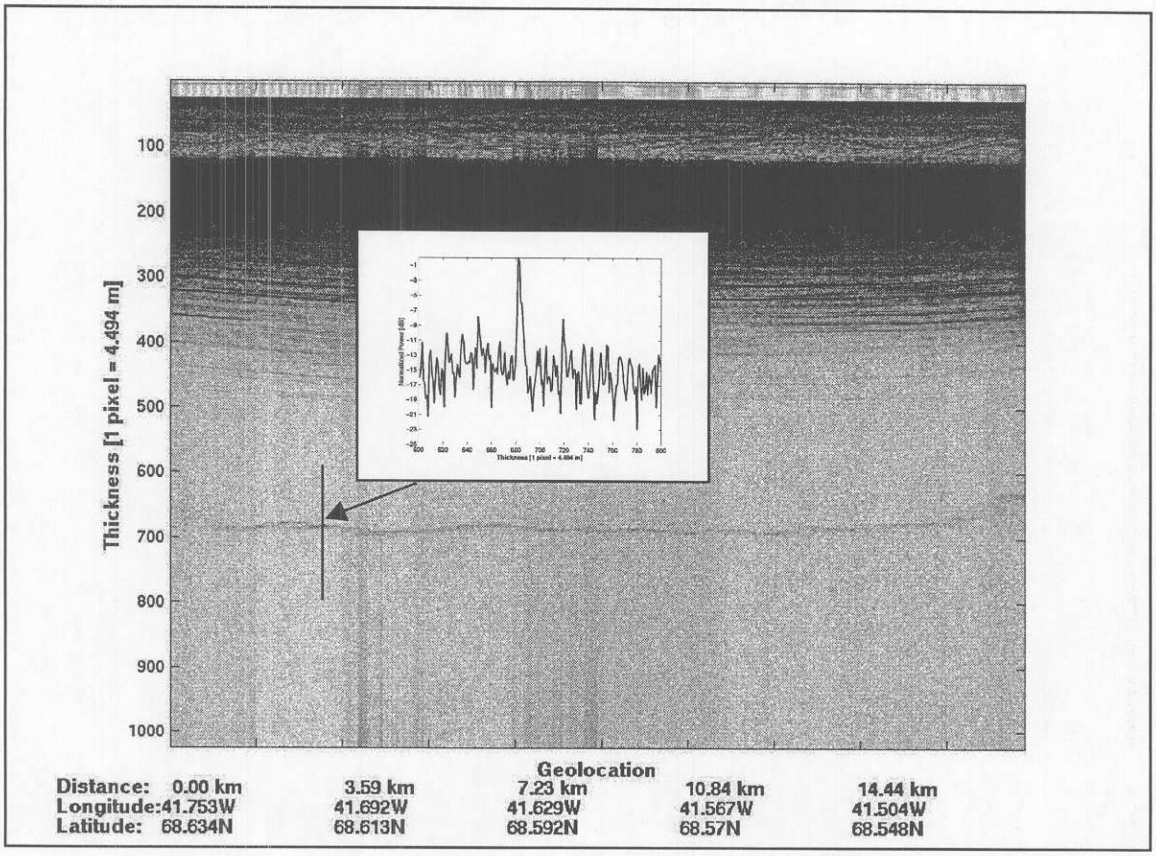
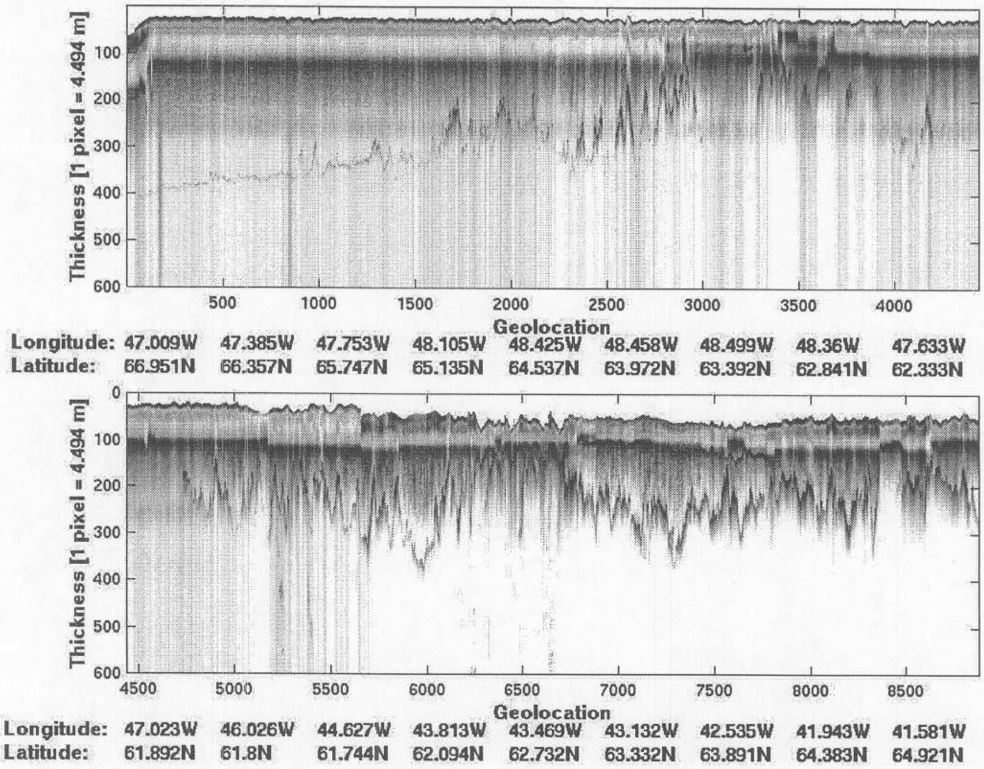
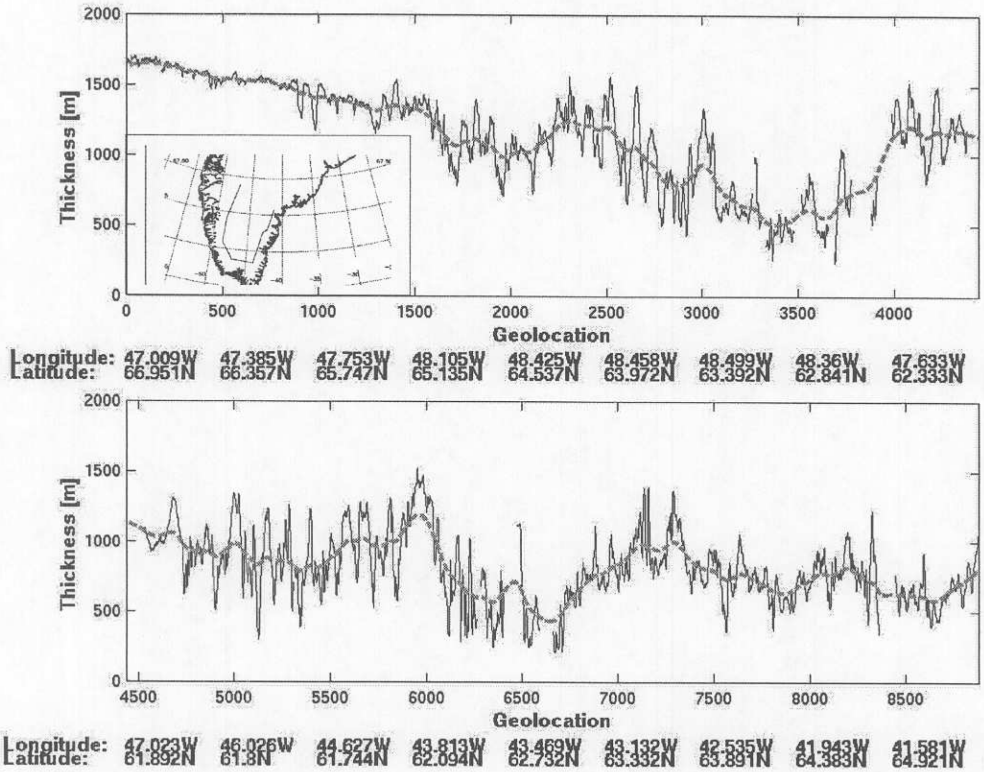


Figure 3b. Radar echogram from these data after processing with the *f-k* migration algorithm.

Figures 4a and 4b show radar echograms and Figures 4c and 4d show derived ice thicknesses along the 2000-m contour line in the south. We collected these data with a radar PRF of 15 kHz and the integrator set to pre-sum 128 returns coherently. We post-processed recorded data by coherently integrating four pre-summed returns and incoherently summing 30 coherently integrated returns. With an airspeed of about 130 m/s, spacing between points along the x-axis is approximately 130 m. We low-pass filtered the derived ice thickness data and plotted the average ice thickness obtained after low-pass filtering, shown as a dashed line in Figures 4c and 4d. Ice thickness gradually decreased from about 1700 m at the start of the flight line (inset in figure 4c) to about 1500 m over the first 100 km. It then decreased rapidly from about 1500 m to about 600 m over the next 350 km with significant surface relief. The maximum peak-to-peak ice thickness deviation is about 800 m in this region. The small gap in ice thickness between 3500 and 3700 units is caused by weak bottom echoes submerged in clutter from off-angle surface returns and ice-surface multiples. The average ice thickness increased from about 500 to 1200 m over the next 10 km, and then it decreased gradually from 1200 to 800 m over the next 200 km. Bottom topography is very rough in this area with peak-to-peak deviations of about 700 m over a distance of about 10 km. We believe that these are the first high-quality ice thickness data collected over this region of the ice sheet.



Figures 4a, b. Radar echograms of data collected along the 2000-m contour line in the south.



Figures 4c, d. Ice thickness obtained from radar data along the 2000-m contour line in the south.

5.0. Conclusions

We developed two coherent radar depth sounders operating at 150 MHz. These systems have and continue to be used to collect high-quality ice thickness data over the Greenland ice sheet. We processed data collected from all experiments, starting in 1993, and used these data to support our research as well as that of several other PARCA investigators. We also developed a SAR processing algorithm and applied it to a few data sets to enhance weak bottom echo for obtaining ice thickness.

References

Allen, C., S. Gogineni, B. Wohletz, K. Jezek and T. Chuah, Airborne Radio Echo Sounding of Outlet Glaciers in Greenland," Int. J. Remote Sensing Letters, vol. 18, no. 14, pp. 3103-3107, 1997.

Akins, T. L., "Design and Development of an Improved Data Acquisition System for the Coherent Radar Depth Sounder," MS Thesis, University of Kansas Department of Electrical Engineering and Computer Science, November 1998 (also Radar Systems and Remote Sensing Laboratory Technical Report 13720-9, November 1998).

Chuah, T., S. Gogineni, C. Allen, & B. Wohletz, "Radar Thickness Measurements over the Southern Part of the Greenland Ice Sheet," Radar Systems and Remote Sensing Laboratory Technical Report 10470-2 [1993 data], April 1996a.

Chuah, T., S. Gogineni, C. Allen, & B. Wohletz, "Radar Thickness Measurements over the Northern Part of the Greenland Ice Sheet," Radar Systems and Remote Sensing Laboratory Technical Report 10470-3 [1995 data], April 1996b.

Chuah, T. S., Design and Development of a Coherent Radar Depth Sounder for Measurement of

Greenland Ice Sheet Thickness, Ph.D. Dissertation, University of Kansas Department of Electrical Engineering and Computer Science, January 1997 (also Radar Systems and Remote Sensing Laboratory Technical Report 10470-5), January 1997, 125 pages.

Gazdag, J., and P. Sguazzero, Migration of seismic data, *Proceedings of the IEEE, 72*, 1302-1315, October 1984.

Gogineni, S., T. Chuah, C. Allen, K. Jezek & R. K. Moore, "An Improved Coherent Radar Depth Sounder," *J. Glaciology*, vol. 44, no. 148, pp. 659-669, 1998.

Joughin, I., M. Fahnestock, R. Kwok, P. Gogineni, and C. Allen, "Ice Flow of Humboldt, Petermann, and Ryder Glaciers," *J. Glaciology,* vol. 45, no. 150, pp. 231-241, 1999.

Legarsky, J., S. P. Gogineni, C. Allen, T. S. Chuah, & Y. C. Wong, Radar Thickness Measurements over the Northern Part of the Greenland Ice Sheet—1996 Results," Radar Systems and Remote Sensing Laboratory Technical Report 10470-6, March 1997.

Legarsky, J., A. Wong, T. Akins, & S. P. Gogineni, "Detection of Hills from Radar Data in Central-Northern Greenland," correspondence, *J. Glaciology,* vol. 44, no. 146, pp. 182-184, 1998.

Raju, G., W. Xin, and R. K. Moore, "Design, Development, Field Operations and Preliminary Results of the Coherent Antarctic Radar Depth Sounder (CARDS) of the University of Kansas, USA," *J. Glaciology*, vol. 36, 123, 247-258, 1990.

Rignot, E. J., Rignot, E. J., S. P. Gogineni, W. B. Krabill, & S. Ekholm, "North and Northeast Greenland Ice Discharge from Satellite Radar Interferometry," *Science*, vol. 276, pp. 934-937, 9 May 1997.

Stolt, R. H., Migration by Fourier transform, *Geophysics, 43*: 23-48, 1978.

Tee, K. L., W. K. Chong, H. Coulter, T. Akins, S. P. Gogineni, C. Allen, and J. Stiles, "Radar Thickness Measurement over the Southern Part of the Greenland Ice Sheet: 1998 Results," Radar Systems and Remote Sensing Laboratory Technical Report 13720-10, July 1999.

Thomas, R., B. Csatho, S. Gogineni, K. Jezek, and K. Kuivinen, "Thickening of the Western Part of the Greenland Ice Sheet," J. Glaciology, vol. 44, no. 148, pp. 651-656, 1998.

Wong, Y. C., S. Gogineni, C. Allen, J. Stiles, J. Legarsky, T. Akins & K. L. Tee, "Radar Thickness Measurements over the Greenland Ice Sheet: 1997 results," Radar Systems and Remote Sensing Laboratory Technical Report 10470-7, February 1998.

Appendix I

Publications

Journal Papers

Jezek, K. C., S. Gogineni & M. Shanableh, "Radar Measurements of Melt Zones on the Greenland Ice Sheet," *Geophysical Research Letters,* vol. 21, no. 1, pp. 33-36, 1994.

Rignot, E. J., Rignot, E. J., S. P. Gogineni, W. B. Krabill, & S. Ekholm, "North and Northeast Greenland Ice Discharge from Satellite Radar Interferometry," *Science*, vol. 276, pp. 934-937, 9 May 1997.

Dahl-Jensen, D., N. S. Gundestrup, K. Keller, S. J. Johnsen, S. P. Gogineni, C. T. Allen, T.S. Chuah, H. Miller, S. Kipfstuhl and E. D. Waddington, "A Search in North Greenland for a New Ice Core Drill Site," *J. Glaciology,* vol. 43, no. 144, pp. 300-306, 1997.

Allen, C., S. Gogineni, B. Wohletz, K. Jezek and T. Chuah, Airborne Radio Echo Sounding of Outlet Glaciers in Greenland," *Int. J. Remote Sensing Letters*, vol. 18, no. 14, pp. 3103-3107, 1997.

Legarsky, J., A. Wong, T. Akins, & S. P. Gogineni, "Detection of Hills from Radar Data in Central-Northern Greenland," correspondence, *J. Glaciology,* vol. 44, no. 146, pp. 182-184, 1998.

Thomas, R., B. Csatho, S. Gogineni, K. Jezek, and K. Kuivinen, "Thickening of the Western Part of the Greenland Ice Sheet," *J. Glaciology,* vol. 44, no. 148, pp. 651-656, 1998.

Ekholm, S., K. Keller, J. L. Bamber, S. P. Gogineni, "Unusual Surface Morphology from Digital Elevation Models of the Greenland Ice Sheet, *Geophys. Res. Lett.,* vol. 25, no. 19, p. 3623, 1998.

Gogineni, S., T. Chuah, C. Allen, K. Jezek & R. K. Moore, "An Improved Coherent Radar Depth Sounder," *J. Glaciology,* vol. 44, no. 148, pp. 659-669, 1998.

Joughin, I., M. Fahnestock, R. Kwok, P. Gogineni, and C. Allen, "Ice Flow of Humboldt, Petermann, and Ryder Glaciers," *J. Glaciology,* vol. 45, no. 150, pp. 231-241, 1999.

Forster, R. R., K. C. Jezek, J. Bolzan, F. Baumgartner, and S. P. Gogineni, "Relationships between Radar Backscatter and Accumulation Rates on the Greenland Ice Sheet," *Int. J. Remote Sensing*, vol. 20, nos. 15 & 16, pp. 3131-3147, 1999.

Conference Presentations

Joughin, I., R. Kwok, M. Fahnestock, S. Gogineni, & C. Allen, "Interferometrically Derived Topography, Velocity, and Ice-Flux Estimates for the Petermann Glacier," 1995 Fall AGU Meeting, San Francisco, CA, December 11-15, 1995.

Jezek, K. C., P. Gogineni, & E. Rignot, "Radio Echo Sounding of Outlet Glaciers, Western Greenland," 1995 Fall AGU Meeting, San Francisco, CA, December 11-15, 1995.

Bindschadler, R., E. Rignot, K. Jezek, M. Fahnestock, K. Steffen, S. Gogineni, D. Winebrenner, S. Hensley, R. Kwok, J. Van Zyl, & H. Zebker, "The 1995 Campaign of the NASA/JPL Topographic SAR Instrument in Greenland," 1995 Fall AGU Meeting, San Francisco, CA, December 11-15, 1995.

Allen, C., B. Wohletz & S. P. Gogineni, "Radar Sounding of Glaciers in Greenland," *IGARSS'96 Digest*, 96CH35875, 27-31 May 1996, Lincoln NE, pp. 1932-1934, 1996.

Wohletz, B., T. S. Chuah, C. Allen, & S. Gogineni, "Radar Sounding of Greenland Outlet Glaciers," URSI General Assembly, Lille, France, August 28 to September 5, 1996 [invited paper].

Jezek, K. C., P. Gogineni, E. Rignot, & R. Kwok, "Dynamics of the Petermann Glacier, Northern Greenland," URSI General Assembly, Lille, France, August 28 to September 5, 1996 [invited paper].

Gogineni, S., R. Thomas, J. Legarsky, & T. Akins, "An Airborne Radio Echo Sounder for the Measurement of the Greenland Ice Sheet Thickness, *Proceedings of Third International Airborne Remote Sensing Conference,* vol. 2 July 7-10, 1997, Copenhagen, Denmark, pp. 545-550 [received Best of Session Award], 1997.

Kanagaratnam, P, S. P. Gogineni, & K. Jezek, "Modeling and Interpretation of Ultra-Wideband Microwave Scattering Measurements of Simulated Sea Ice," *IGARSS'97 Digest*, 97CH36042, 4-8 August 1997, Singapore, pp. 1305-1307, 1997.

Legarsky, J., T. Chuah, & S. P. Gogineni, "Next-Generation Coherent Radar Depth Sounder for Measurement of Greenland Ice Sheet Thickness," *IGARSS'97 Digest*, 97CH36042, 4-8 August 1997, Singapore, pp. 996-998, 1997.

Akins, T., J. Legarsky, S. P. Gogineni & K. Jezek (presented by C. Allen), "An Improved Radio Echo Sounder for the Measurement of the Greenland Ice Sheet Thickness", *Proceedings of Fifth International Conf. Remote Sensing for Marine and Coastal Environments,* San Diego, CA, 5-7 October 1998, pp. II-419-II-425, 1998 [invited presentation].

Kanagaratnam, P., S. Gogineni, J. Legarsky, T. Akins, N. Gundestrup, L. Larsen, & J. Kipfstuhl, "High-Resolution Monitoring of Internal Layers at NGRIP," *IGARSS'99 Digest,* 28 June to 2 July 1999, Hamburg, Germany, pp. 95-97, 1999.

Legarsky, J. J., S. P. Gogineni, P. Kanagaratnam, T. L. Akins & Y. C. Wong, "Ice Thickness Measurements of the Southwest Greenland 2000-m Contour Line," *IGARSS'99 Digest*, 28 June to 2 July 1999, Hamburg, Germany, pp. 89-91, 1999.

Baumbartner, F. K. Jezek, R. R. Forster, S. P. Gogineni & I. H. H. Zabel, "Spectral Land Angular Ground-Based Radar Backscatter Measurements of Greenland Snow Facies," *IGARSS'99 Digest*, 28 June to 2 July 1999, Hamburg, Germany, pp.1053-1055, 1999.

Gogineni, S. & P. Kanagaratnam, "Wideband Radar for Determination of Snow Accumulation over the Greenland Ice Sheet," *Proceedings of the 26th General Assembly of URSI,* 13-21 August 99, Toronto, Canada, p. 722, 1999 [invited presentation].

Technical Reports and Memoranda

Chuah, T., S. Gogineni, C. Allen, & B. Wohletz, "Radar Thickness Measurements over the Southern Part of the Greenland Ice Sheet," Radar Systems and Remote Sensing Laboratory Technical Report 10470-2 [1993 data], April 1996a.

Chuah, T., S. Gogineni, C. Allen, & B. Wohletz, "Radar Thickness Measurements over the Northern Part of the Greenland Ice Sheet," Radar Systems and Remote Sensing Laboratory Technical Report 10470-3 [1995 data], April 1996b.

Legarsky, J. J., "V-antenna for Coherent Depth Sounding Radar: 1996 Sled Expedition," Radar Systems and Remote Sensing Laboratory Technical Memorandum 10470-1, June 1996.

Chuah, T. S., "Design and Development of a Coherent Radar Depth Sounder for Measurement of Greenland Ice Sheet Thickness," Ph.D. Dissertation, University of Kansas Department of Electrical Engineering and Computer Science, January 1997 (also Radar Systems and Remote Sensing Laboratory Technical Report 10470-5), January 1997, 125 pages.

Chuah, T. S., "Component characterization and data sheets for Design and Development of a Coherent Radar Depth Sounder for Measurement of Greenland Ice Sheet Thickness," Radar Systems and Remote Sensing Laboratory Technical Memorandum 10470-2, January 1997, (120 pages).

Legarsky, J., S. P. Gogineni, C. Allen, T. S. Chuah, & Y. C. Wong, "Radar Thickness Measurements over the Northern Part of the Greenland Ice Sheet—1996 Results," Radar Systems and Remote Sensing Laboratory Technical Report 10470-6, March 1997.

Akins, T., "Greenland Digital Format," Radar Systems and Remote Sensing Laboratory Technical Memorandum 13720-1, December 1997.

Wong, Y. C., S. Gogineni, C. Allen, J. Stiles, J. Legarsky, T. Akins & K. L. Tee, "Radar Thickness Measurements over the Greenland Ice Sheet: 1997 results," Radar Systems and Remote Sensing Laboratory Technical Report 10470-7, February 1998.

Akins, T. L., "Design and Development of an Improved Data Acquisition System for the Coherent Radar Depth Sounder," MS Thesis, University of Kansas Department of Electrical Engineering and Computer Science, November 1998 (also Radar Systems and Remote Sensing Laboratory Technical Report 13720-9, November 1998).

Legarsky, J. "SAR Processing of Glacial-Ice Depth-Sounding Data, Ka-Band Backscattering Measurements and Applications," Ph.D. Dissertation, University of Kansas Department of Electrical Engineering and Computer Science, April 1999 (also Radar Systems and Remote Sensing Laboratory Technical Report 13720-8, April 1999).

Tee, K. L., W. K. Chong, H. Coulter, T. Akins, S. P. Gogineni, C. Allen, and J. Stiles, "Radar Thickness Measurement over the Southern Part of the Greenland Ice Sheet: 1998 Results," Radar Systems and Remote Sensing Laboratory Technical Report 13720-10, July 1999.