Airborne Radar for High Resolution Mapping of Internal Layers in Glacial Ice to Estimate Accumulation Rate

Pannirselvam Kanagaratnam
Radar Systems and Remote Sensing Lab
University of Kansas
2335 Irving Hill Road, Lawrence, KS 66045.
Tel: 785/864-7735, Fax: 785/864-7789
E-mail: pkanagar@rsl.ku.edu

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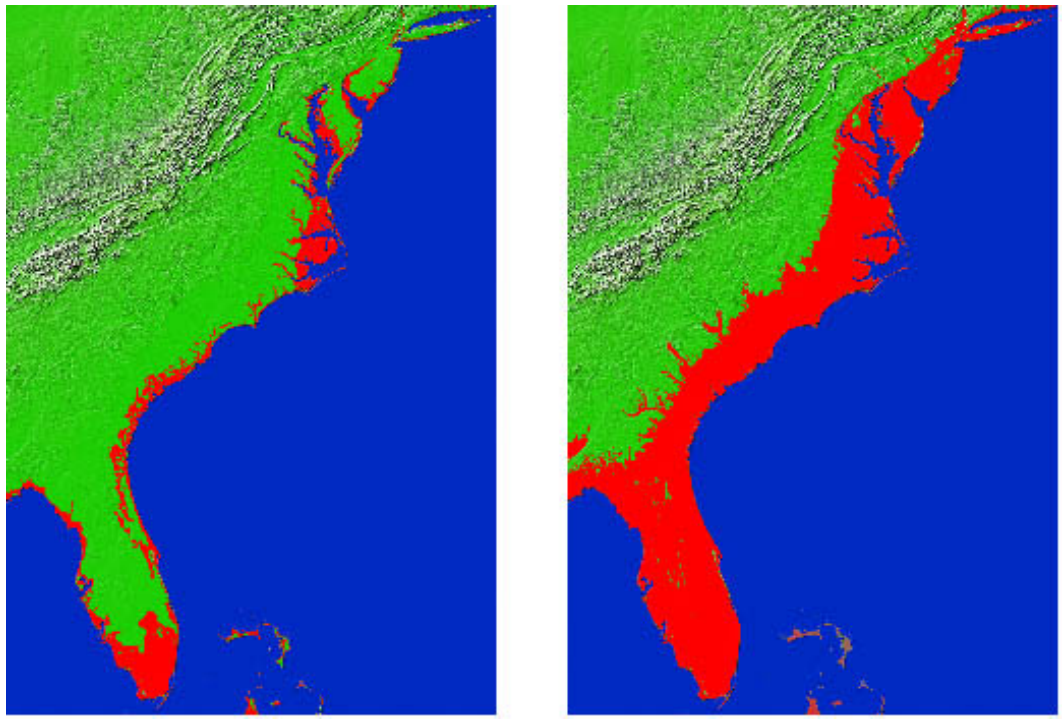
Department of Electrical Engineering and Computer Science

MOTIVATION

Motivation

- Strong correlation between climate change and sea-level rise
- Sea level rose by about 15 cm over the last century
- IPCC projected sea-level to rise 5mm/yr. over the next 100 years
- Potential impact
  - stronger storm surges in the coastal regions
  - coastal erosion
  - submerged islands
  - diminished fresh water supplies
  - loss of tourism
- “Prediction of climate change is a critical technological challenge” – IEEE, 2002

Consequence



Potential rise in sea level caused by melting of Greenland (left) and Antarctic ice sheets (right)

Source: NASA's Solid Earth Science Program

INTRODUCTION

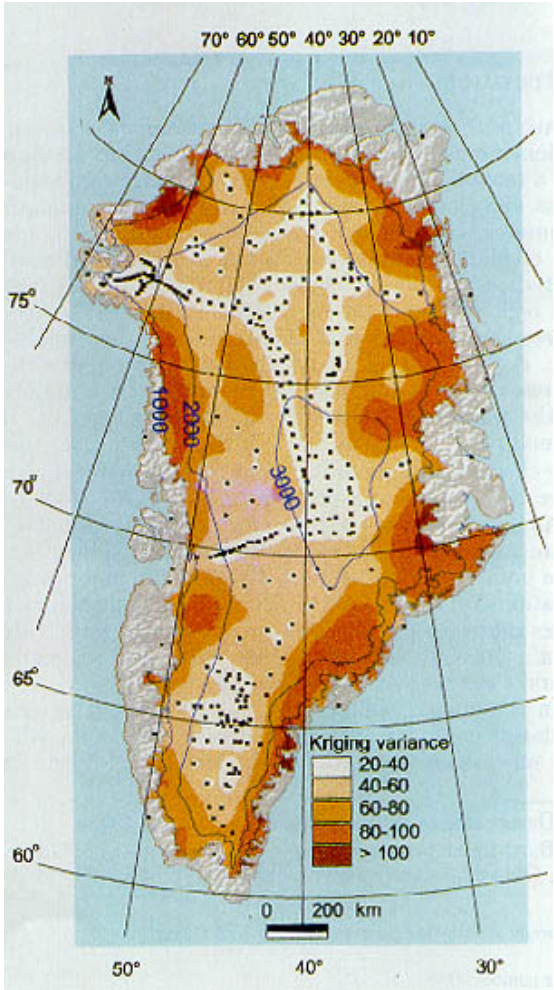
Introduction

- Sources of sea level rise
  - Thermal expansion of the ocean
  - Melting of mountain glaciers
  - Contribution from polar ice sheets
- Large uncertainty in the polar ice sheets' contribution
  - Accurate determination of the mass balance of these ice sheets is required
    - To assess their contribution
    - To develop models
      - To understand the causes
      - To predict future contribution in response to climate change

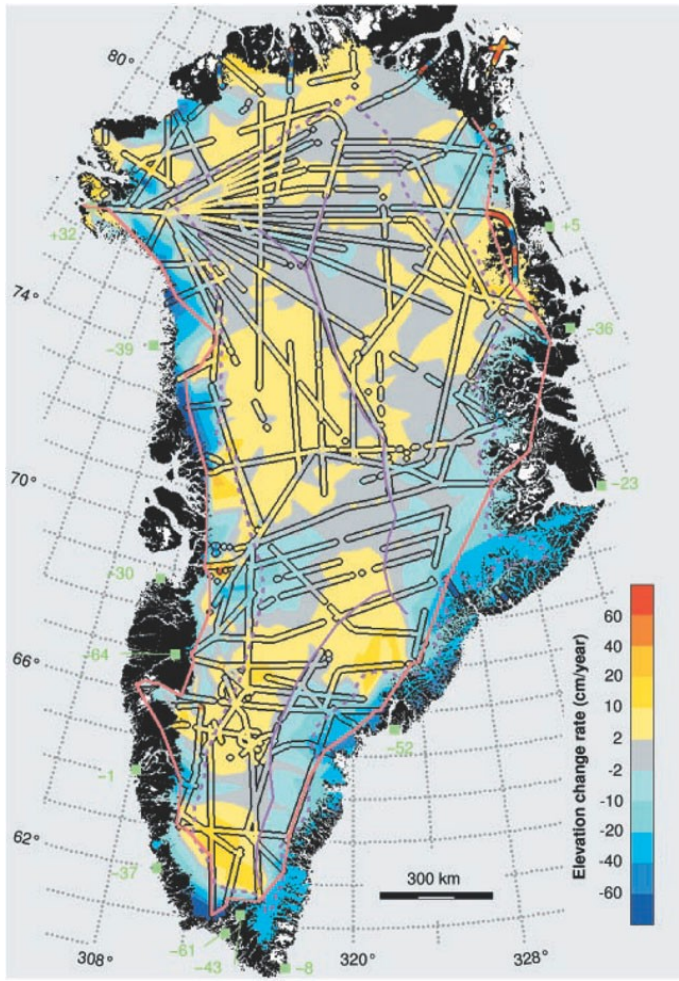
Mass Balance

- Volumetric Approach
  - Change in ice volume is measured
  - Altimeters
    - Satellite
    - Aircraft
  - Snow accumulation required for interpretation and validation
- Flux Approach
  - Measure components that go into mass balance equation
    - Ice thickness
    - Ice velocity
    - Topography
    - Ablation
    - Temperature
    - Snow accumulation

Accumulation Map



Bales et al., 2001



Krabill et al., 2001

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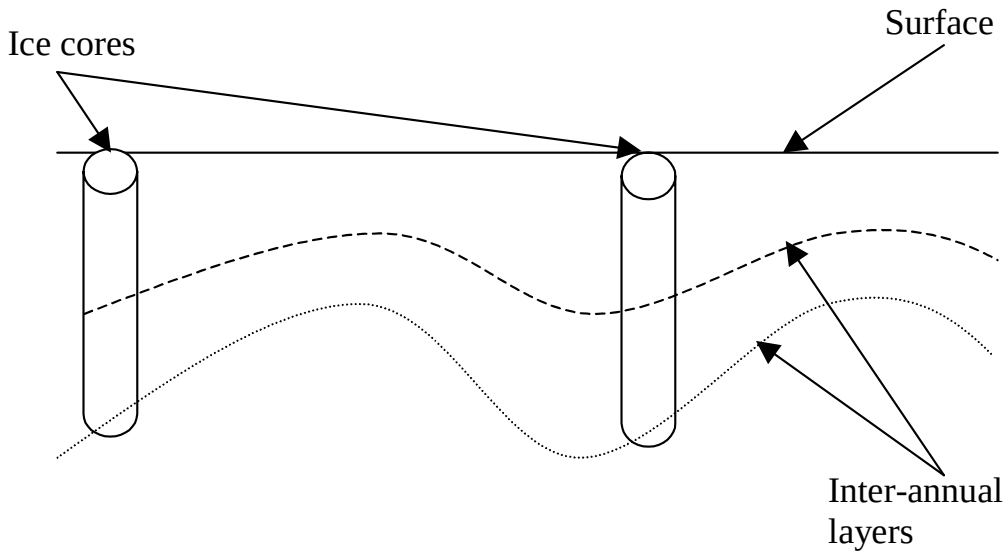
Ice core sampling



Computation of Accumulation Rate

$$A = \frac{dh}{dt}\frac{\rho_{layer}}{\rho_{water}}$$

Determine chronology of ice as a function of depth

- Ice flow models
- Counting annual layers
- Matching $\delta^{18}O$ record with another dated climatic record
- Radiocarbon dating of CO_2
- Identifying horizons of known age

APPROACH

Approach

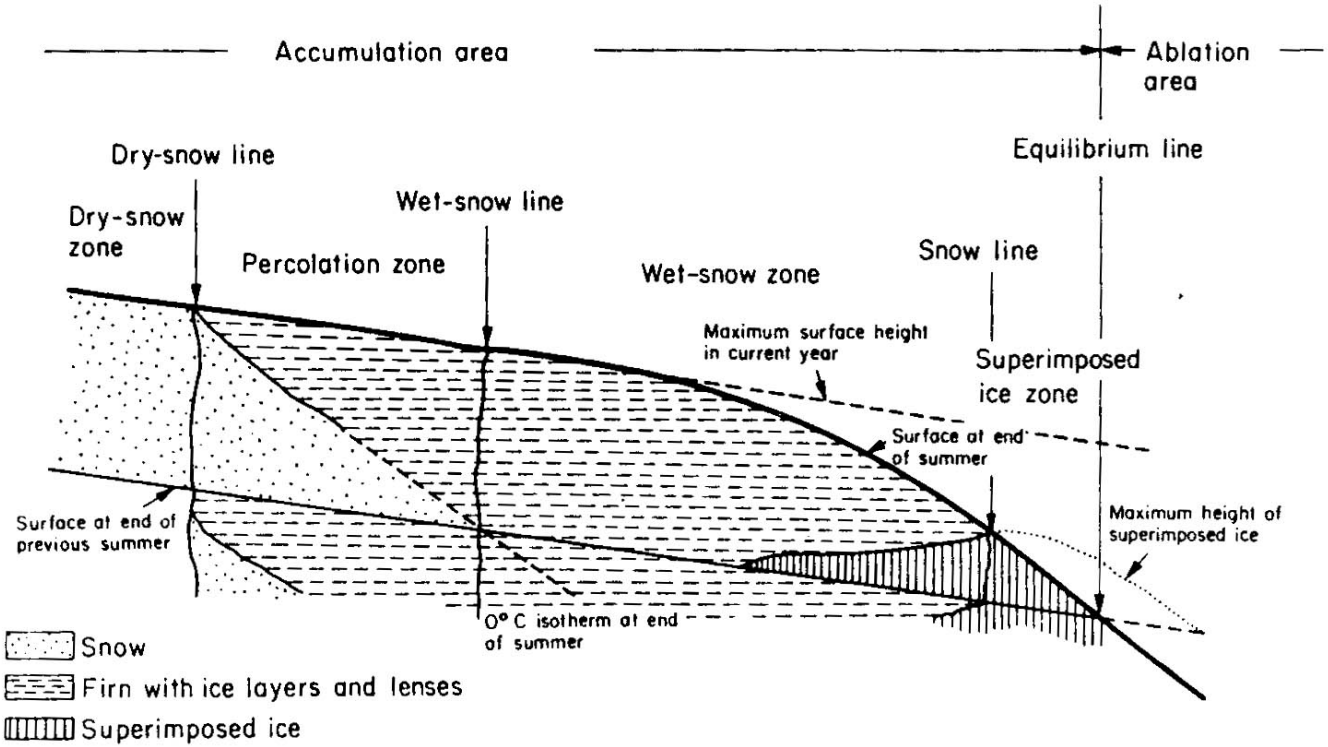
- Obtained ice core records
- Performed simple simulations
- Developed a surface-based radar system
- Determined optimum frequency
- Applied surface and volume scattering models to compute clutter
- Developed prototype airborne radar system
- Proved that internal layers can be mapped
- Developed operational system

DIELECTRIC PROPERTIES

Dielectric Properties of Glacial Ice

- Density changes
  - Pressure exerted by annual accumulation
  - Melt and subsequent refreezing in percolation and wet snow zones
  - Depth hoar layers
- Conductivity changes
  - Acidic deposits from volcanic eruptions
- Crystal-orientation fabrics

Accumulation Zones



Benson, C.S., Stratigraphic studies in the snow and firn of the Greenland Ice Sheet, Research Report 70, US Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire, 1962.

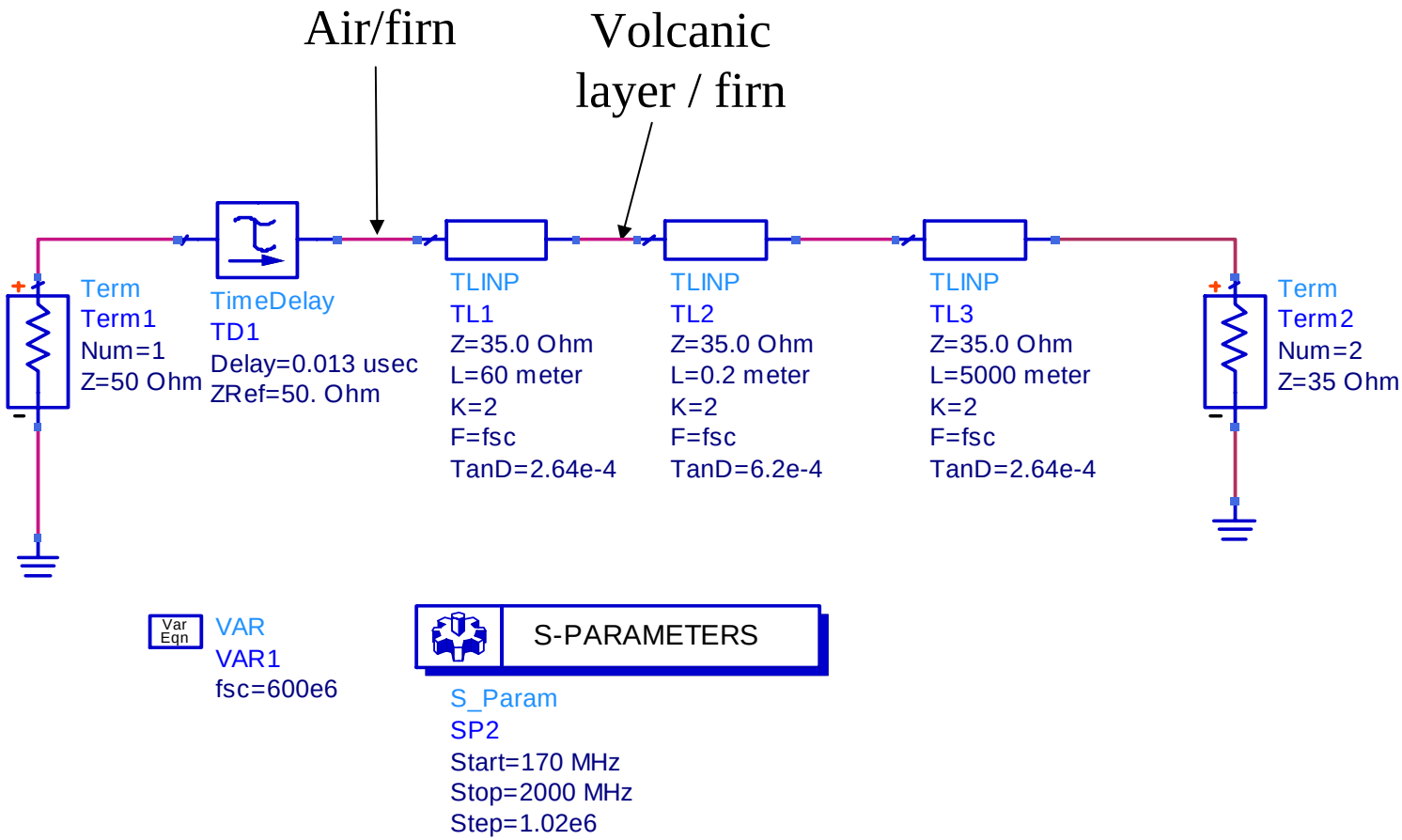
Müller, F., Zonation in the accumulation area of the glacier of axel Heiberg island, N.W.T., Canada, *J. Glaciol.*, **4**, pp. 302-313, 1962.

Patterson, 1998

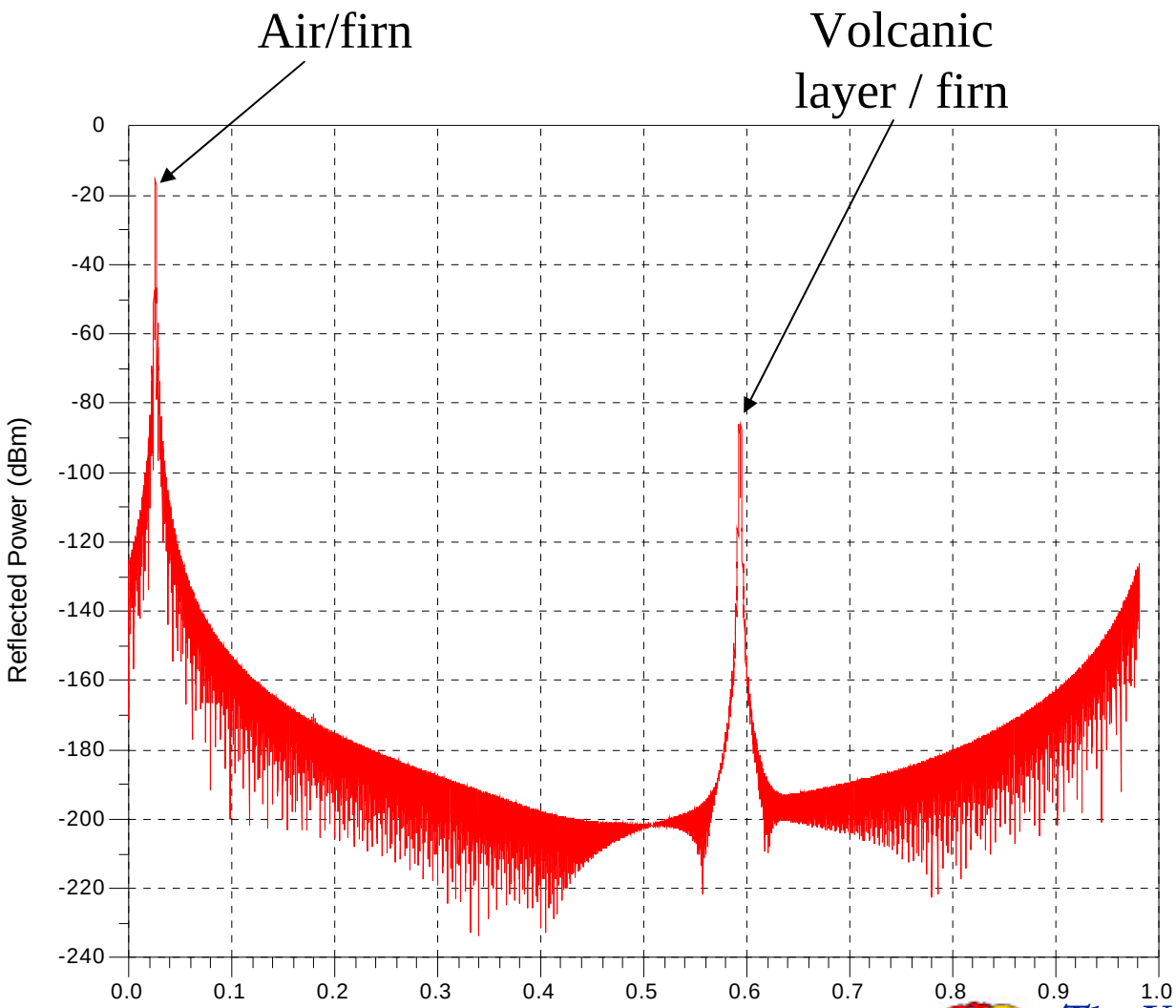
Annual Layers in Snow

National Geographic, Dec. 2001

Simple Simulation



Simulation Results



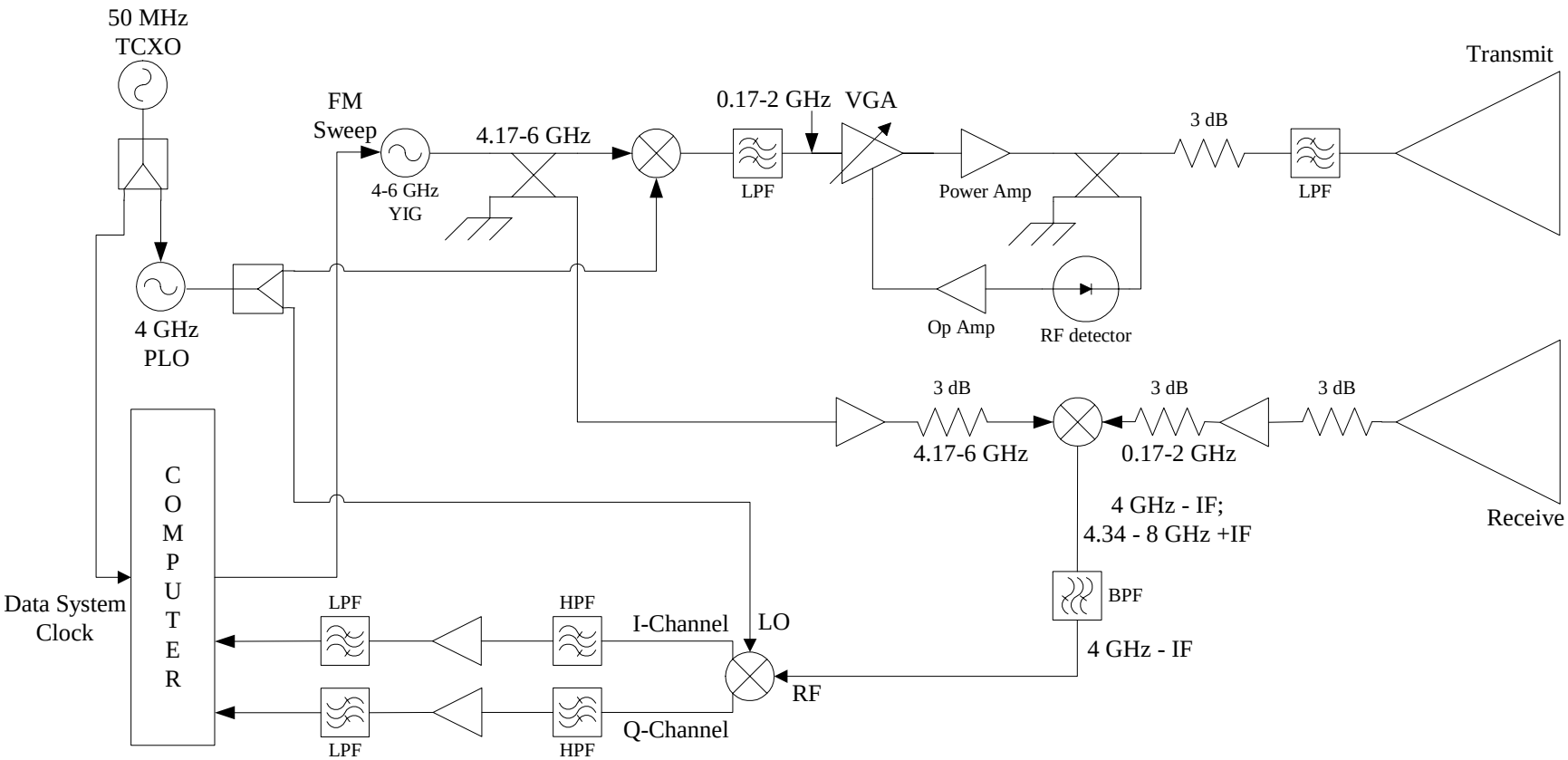
SURFACE-BASED SYSTEM

Surface-Based System

- Frequency-Modulated Continuous Wave (FM-CW) radar

Frequency	170 – 2000 MHz
Sweep Time	125 ms
Transmit Power	0.1 Watt
Number of Coherent Integrations	8
Antennas	TEM Horn
A/D Dynamic Range	12-bit, 72 dB
Sampling Rate	1 MHz

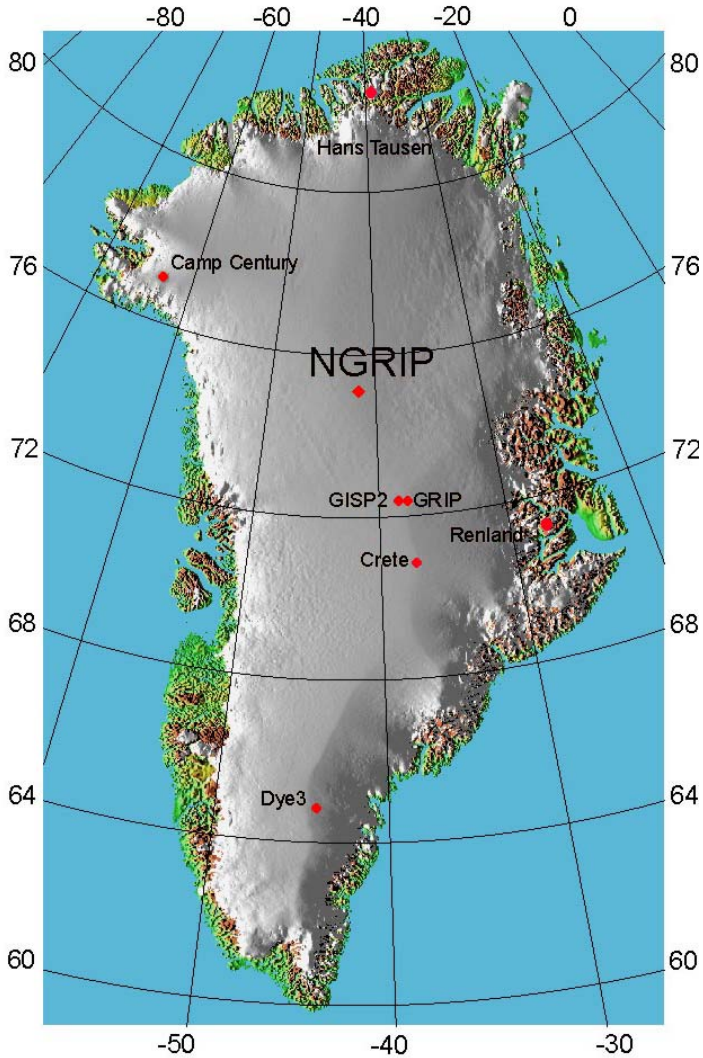
Surface-Based System



Experiment

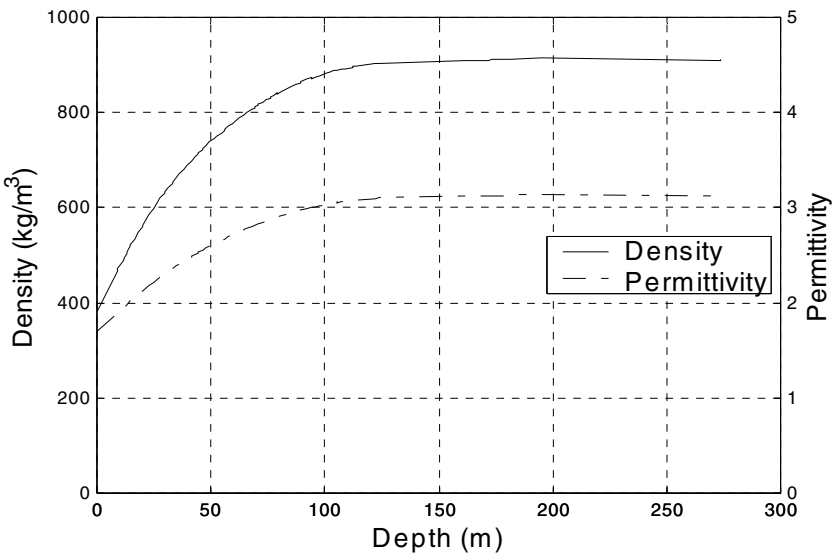
- Shallow radar sounding at the North Greenland Ice core Project (NGRIP) site during July, 1998 and August 1999.
- Mounted the radar on a tracked vehicle and collect data over a 2-km transect in 1998 and a 10-km transect in 1999.

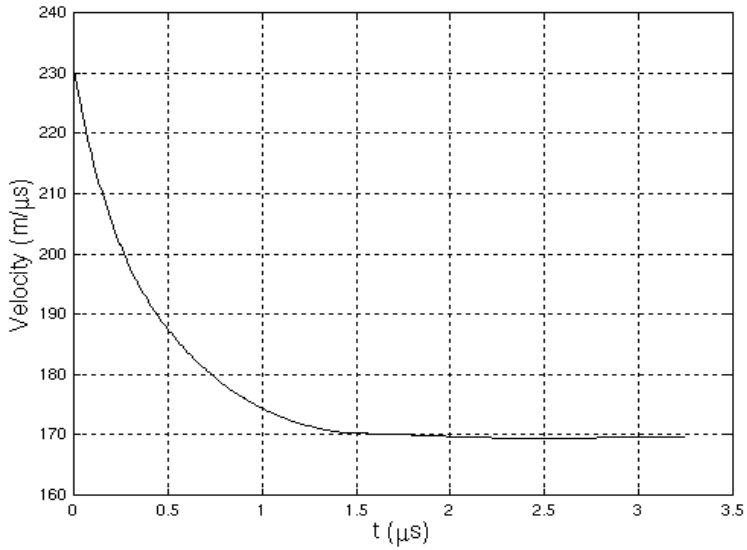
Location


-80
-60
-40
-20
0
80
76
72
68
64
60
-50
-40
-30
Hans Tausen
Camp Century
NGRIP
GISP2
GRIP
Renland
Crete
Dye3

Experiment Setup

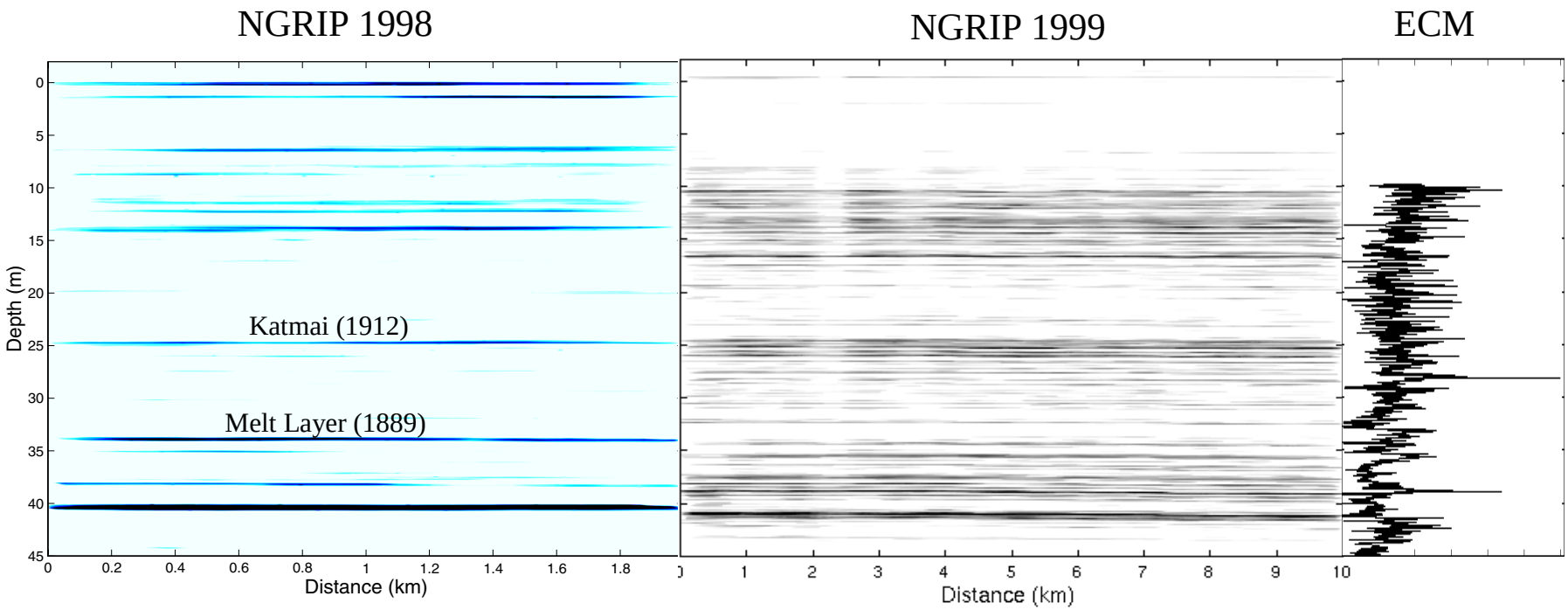
Range Computation





$$\varepsilon = \left[\left(\varepsilon_2^{1/3} - \varepsilon_1^{1/3}\right)v + \varepsilon_1^{1/3}\right]^3$$

Internal Layers at NGRIP (I)

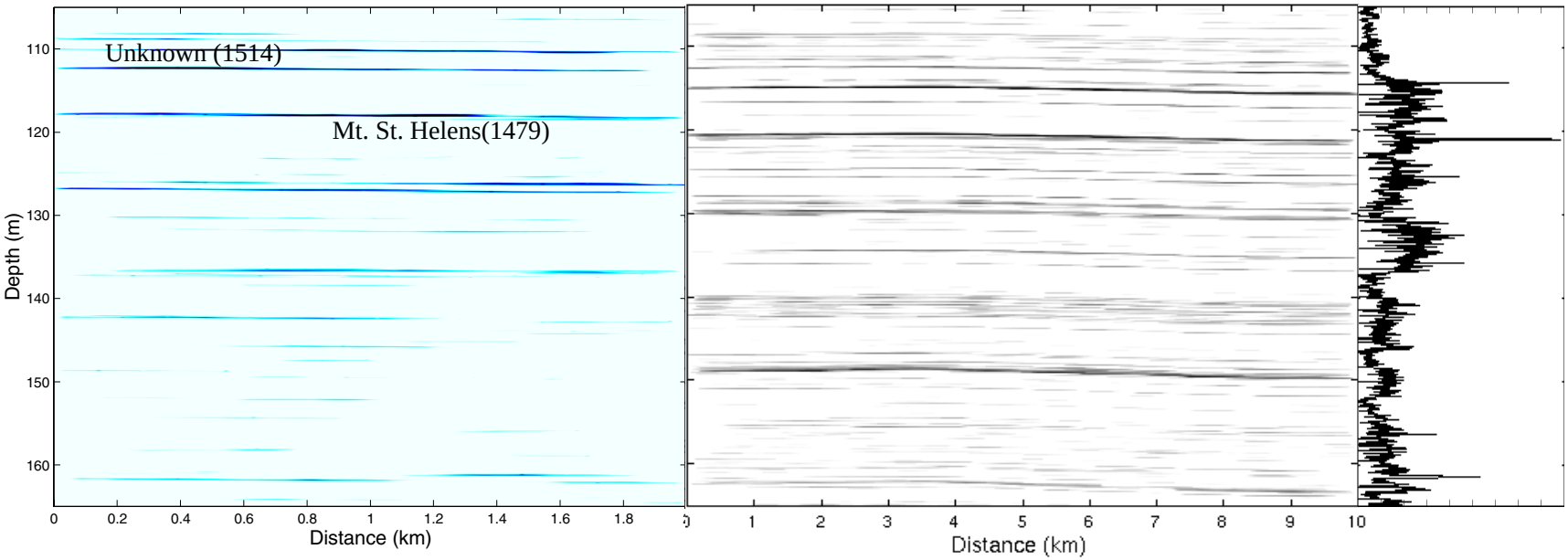


Internal Layers at NGRIP (II)

NGRIP 1998

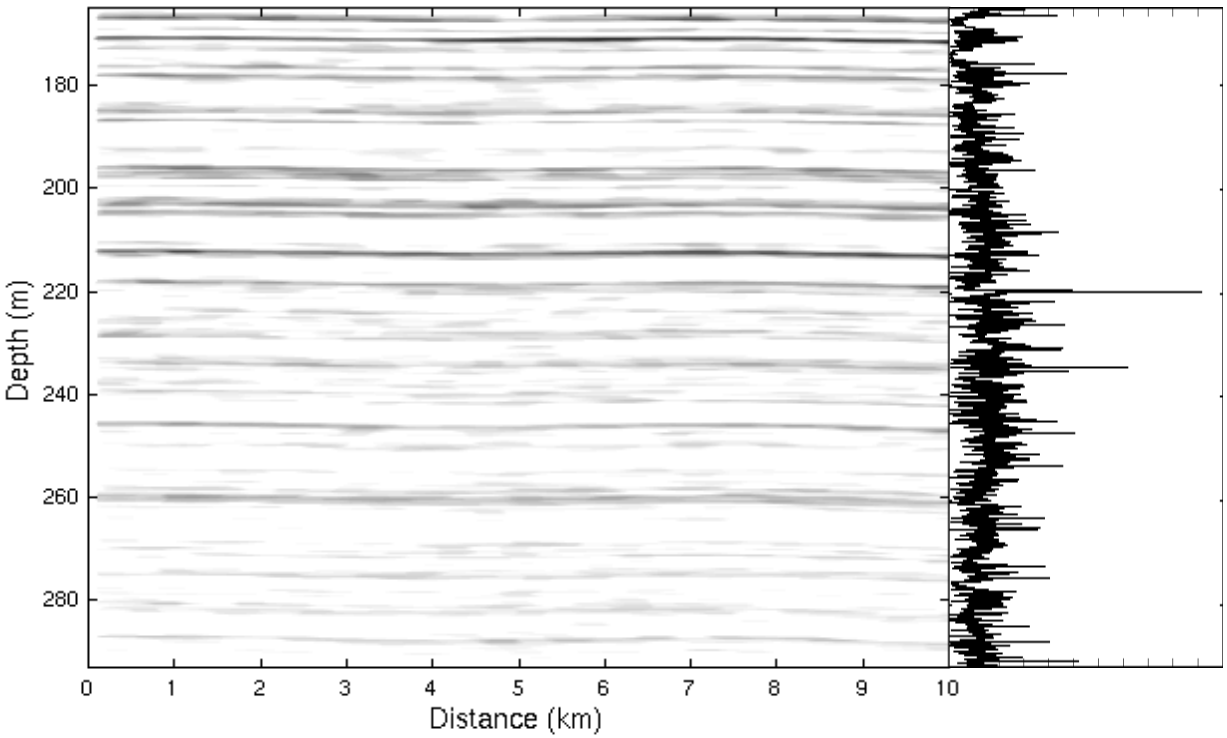
NGRIP 1999

ECM



Internal Layers at NGRIP (III)

NGRIP 1999

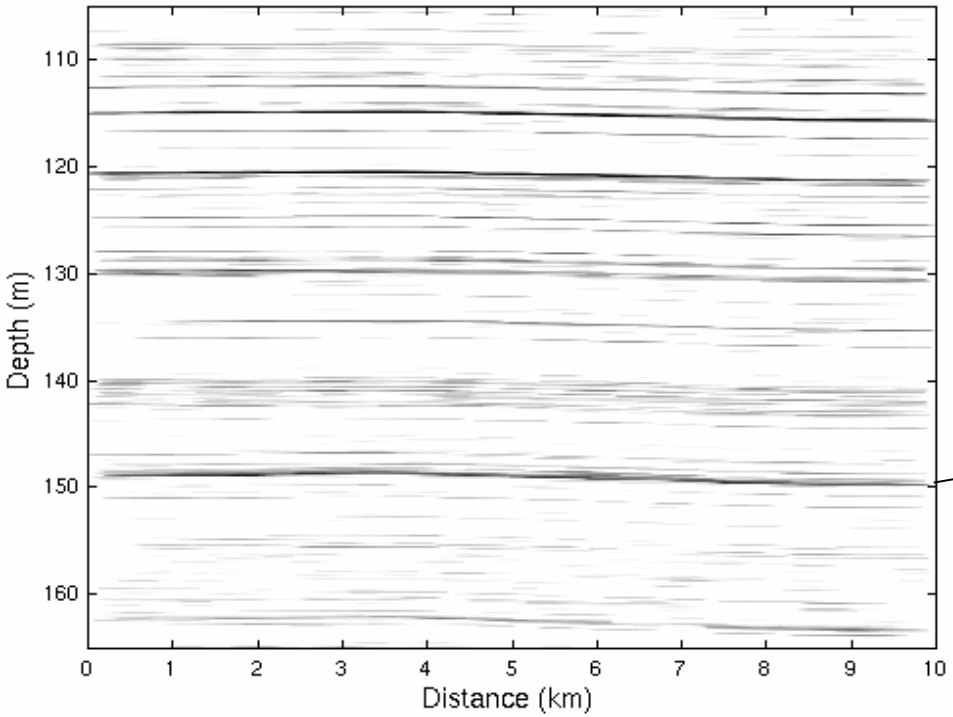


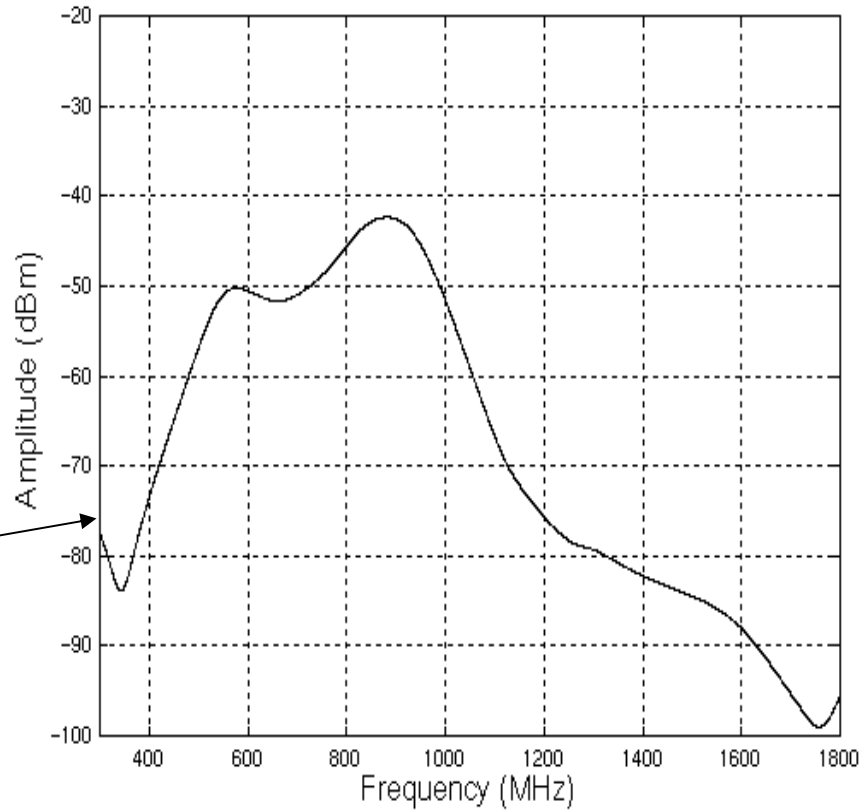
Computed Accumulation Rate

Year	*Measured Thickness (m)*	*Avg. Density (g/cm^3)*	*cm/yr.*	% Error
1912-1997	25	0.50	14.59	1.49
1889-1912	10	0.63	27.49	2.47
1816-1889	20	0.71	19.59	1.43
1783-1816	6	0.77	14.05	1.35
1601-1783	41	0.84	18.96	1.14
1514-1601	13	0.89	13.33	0.87
1479-1514	5	0.90	12.87	1.32
1259-1479	43	0.91	17.76	0.99
		Mean=	**17.3**	±4.12%

Accumulation rate computed from core=17.1 cm/yr.

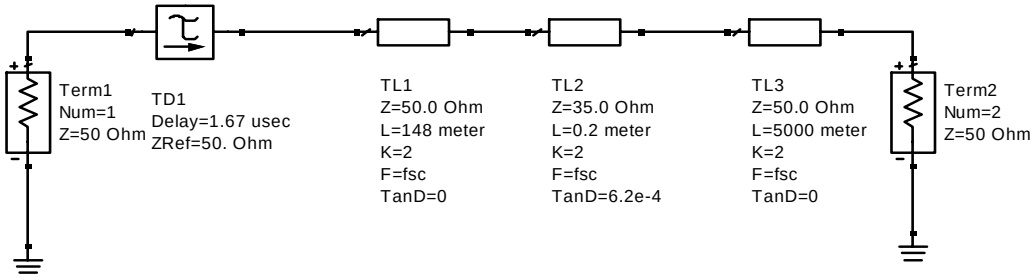
Frequency Response of Layer





$$\Gamma = \frac{\sqrt{\varepsilon_{r2}} - \sqrt{\varepsilon_{r1}}}{\sqrt{\varepsilon_{r2}} + \sqrt{\varepsilon_{r1}}} 2\sin\left(\frac{2\pi l}{\lambda_m}\right)$$

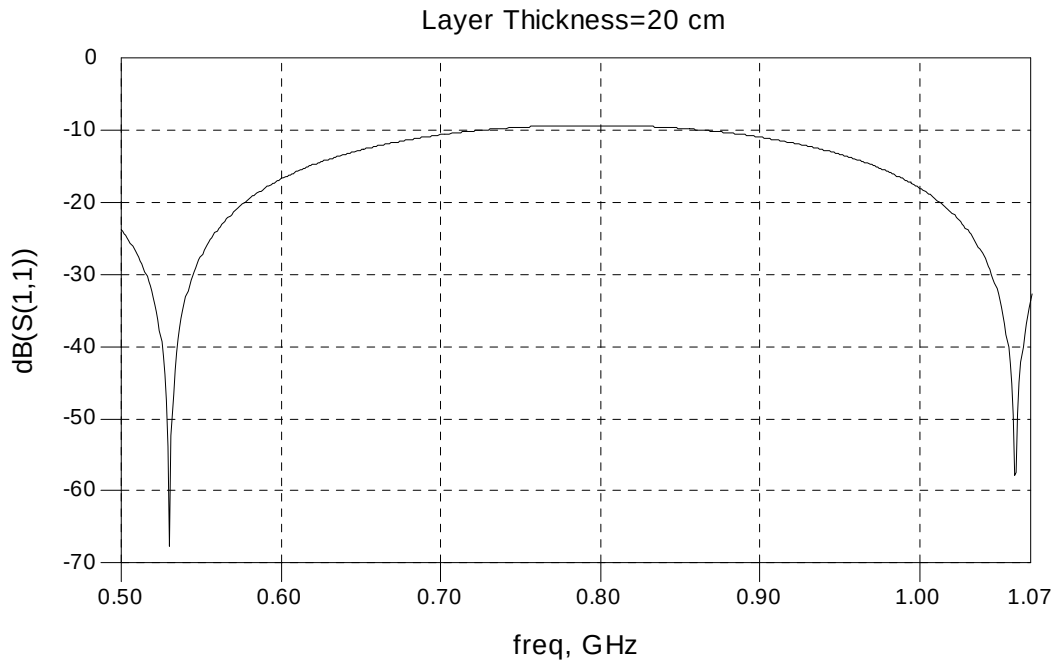
Reflection Coefficient of Snow Layer



Var Eqn
VAR1
fsc=600e6

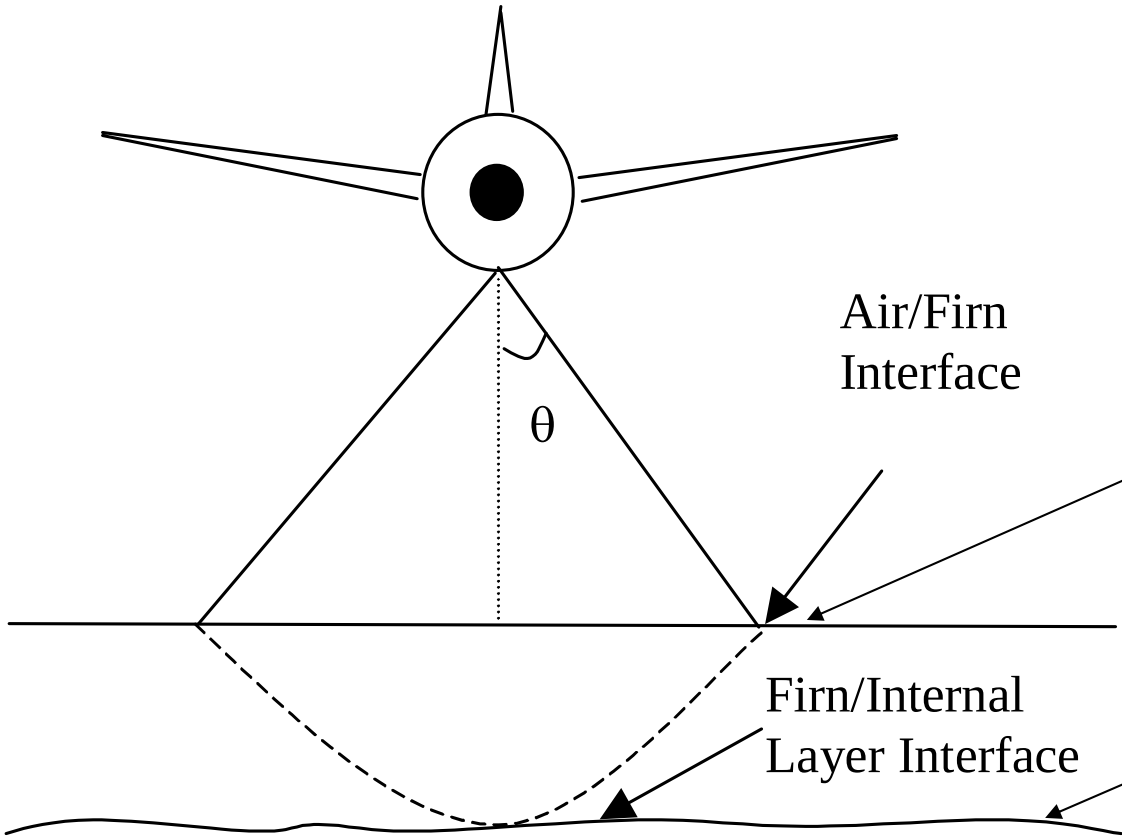
S-PARAMETERS

SP2
Start=170 MHz
Stop=2000 MHz
Step=1.02e6



CLUTTER

Clutter Problem

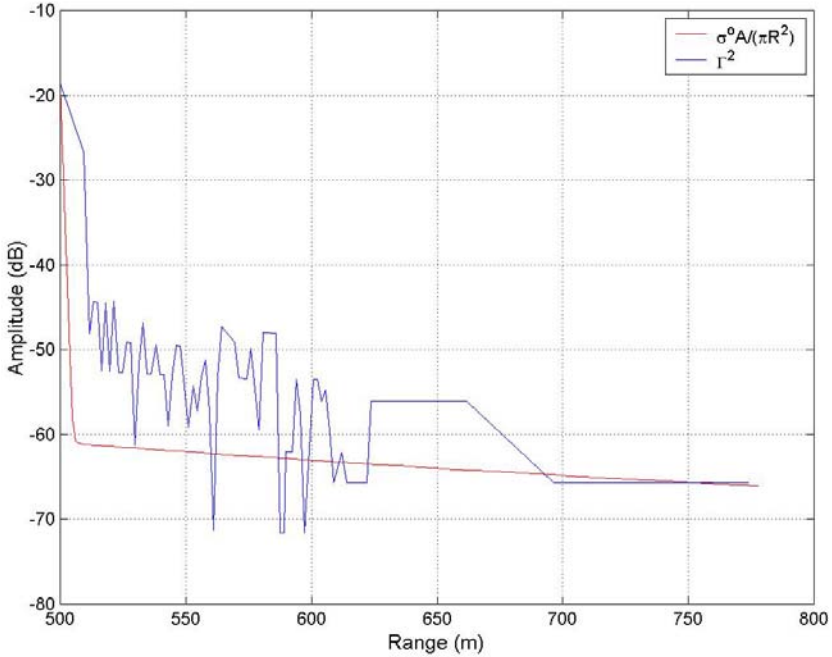


$$C = \frac{P_t \lambda^2 G^2 \sigma^o A}{(4\pi)^3 R^4}$$

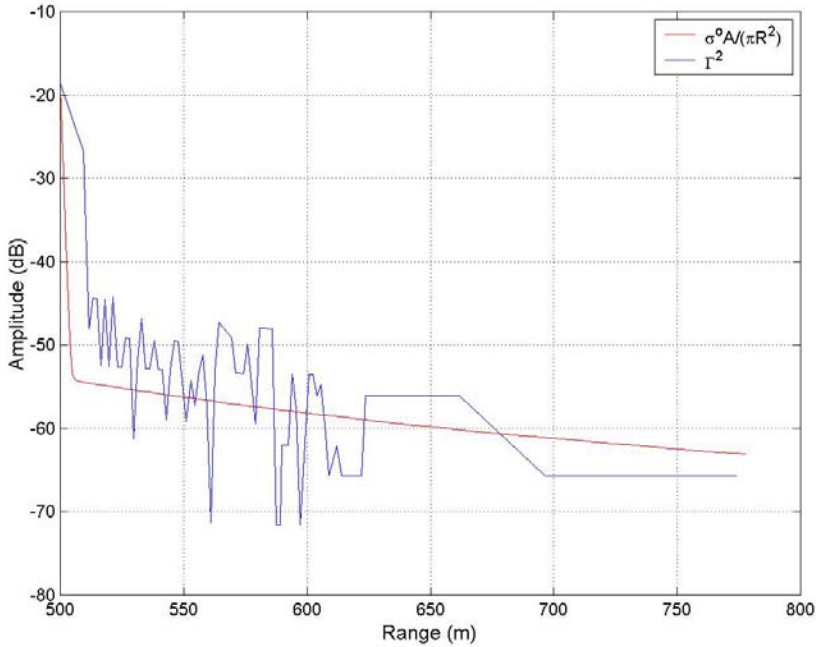
$$S = \frac{P_t \lambda^2 G^2 \Gamma^2}{(4\pi)^2 (2R)^2}$$

Modeling Results—Surface Scattering

600 MHz



900 MHz



PROTOTYPE AIRBORNE SYSTEM

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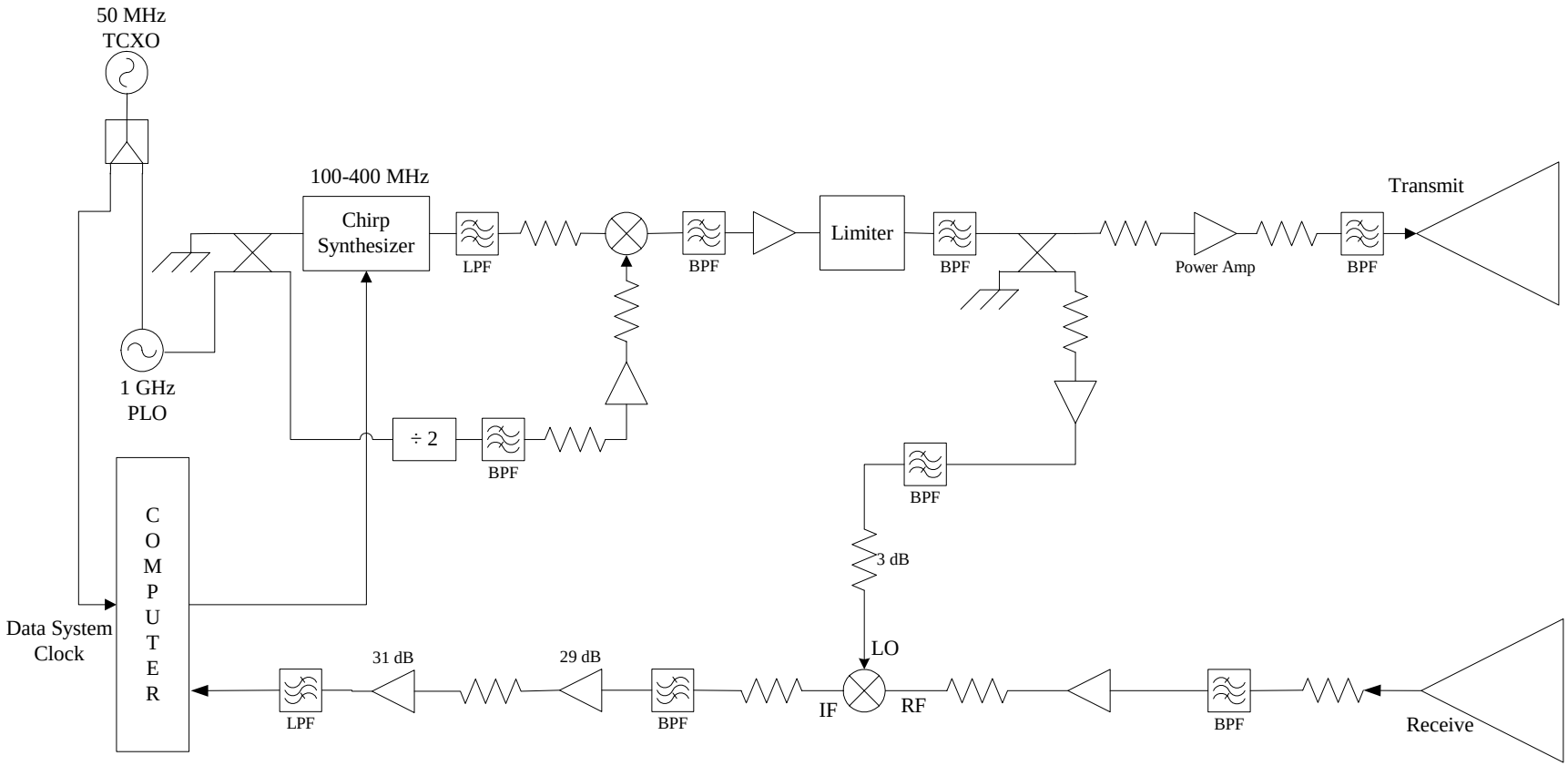
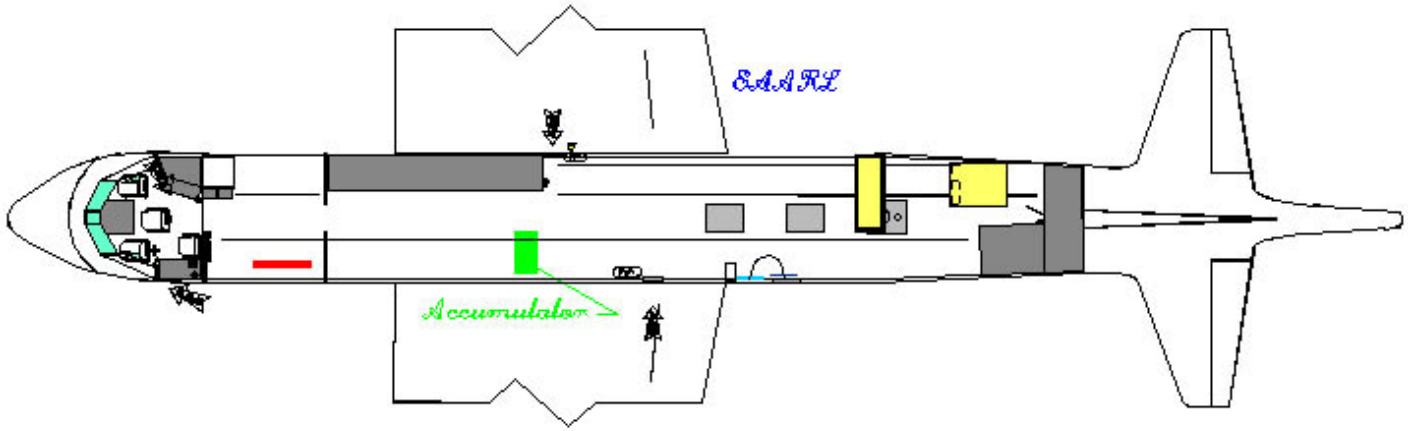
Prototype Airborne System

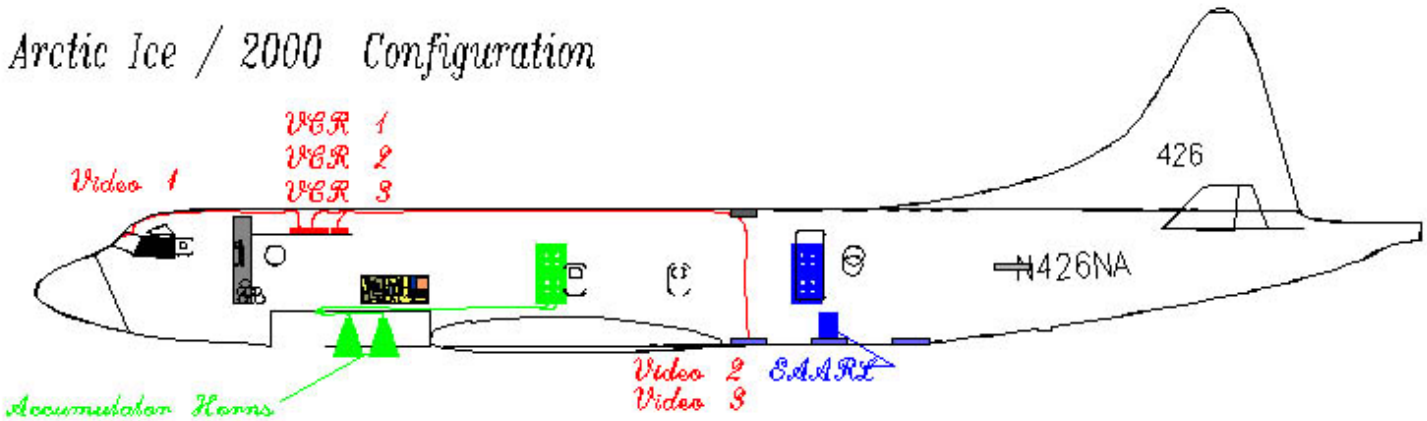
Frequency	600 – 900 MHz
Sweep Time	100 μs
PRF	2 kHz
Transmit Power	1 Watt
Number of Coherent Integrations	100
Antennas	TEM Horn
A/D Dynamic Range	12-bit, 72 dB
Sampling Rate	50 MHz

Block Diagram

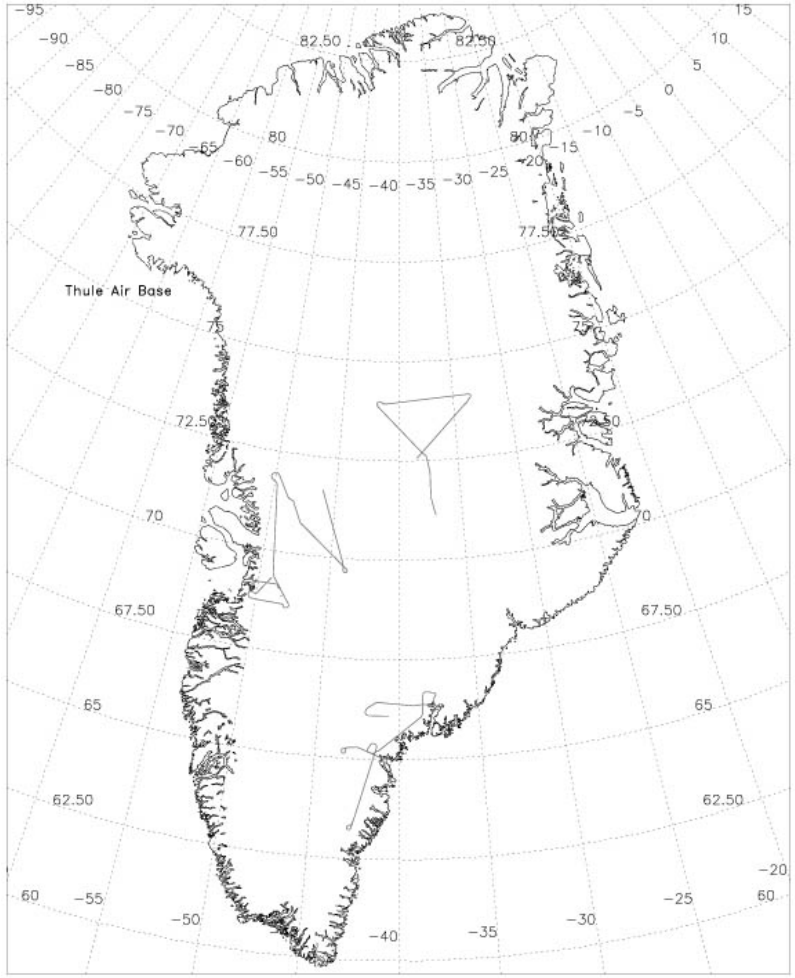


Installation

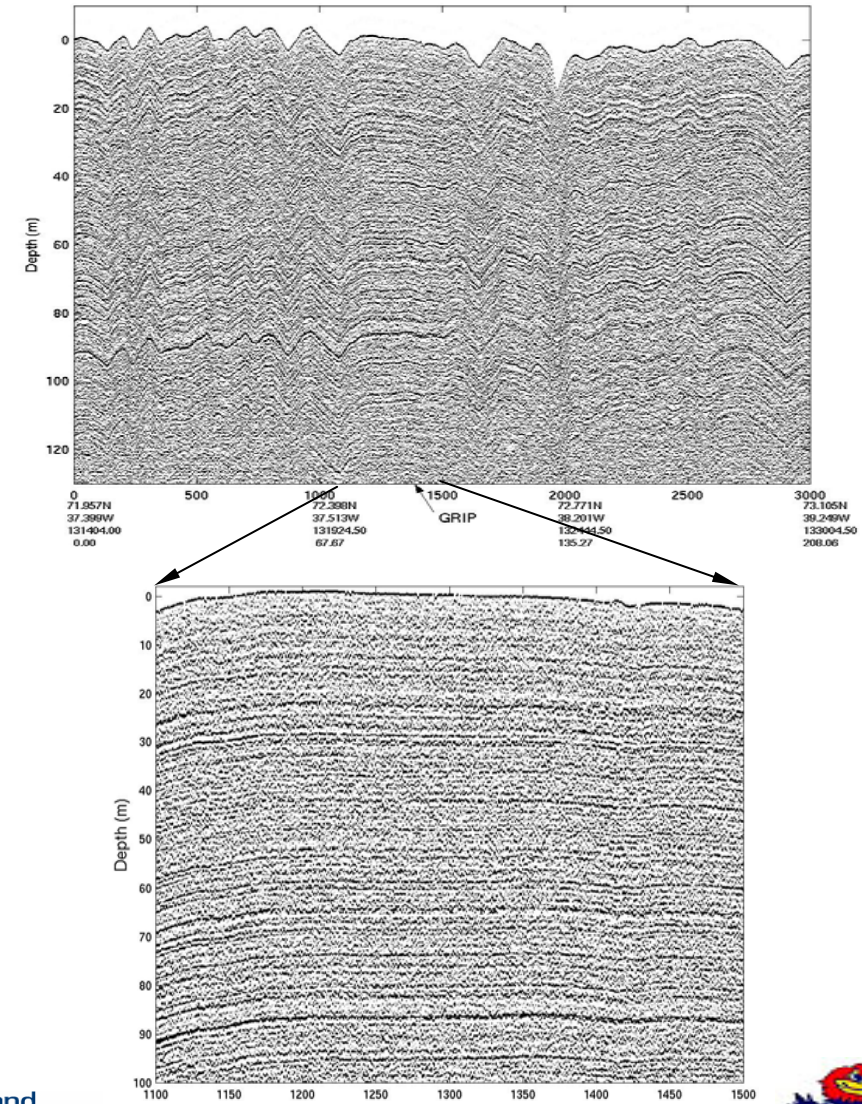




Flight Lines



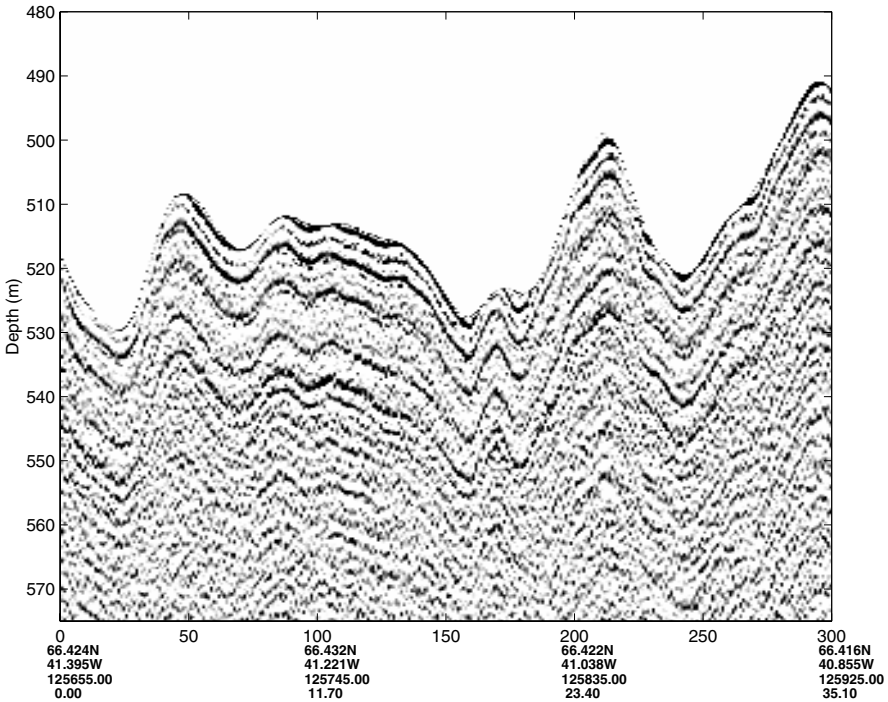
Results



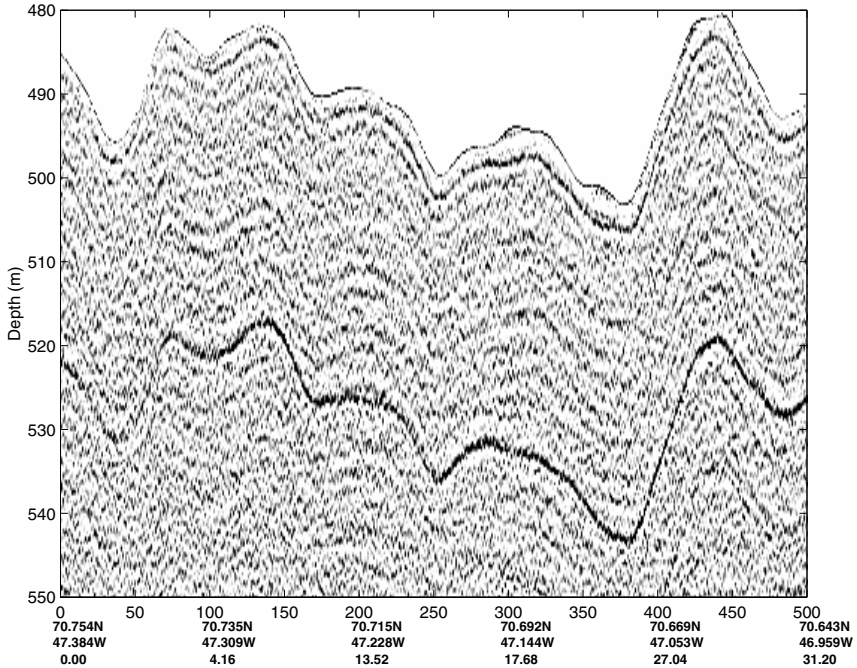
Dry Snow Zone

Results (II)

Percolation Zone



Wet Snow Zone



Problems with Prototype

1. Transient response of the band-pass filter following the mixer was not optimized to minimize ringing.
2. Inadequate isolation between transmitter and receiver sections of the radar.
3. Insufficient receiver dynamic range.
4. Inadequate knowledge of the level of antenna feed through signal.

IMPROVED AIRBORNE SYSTEM

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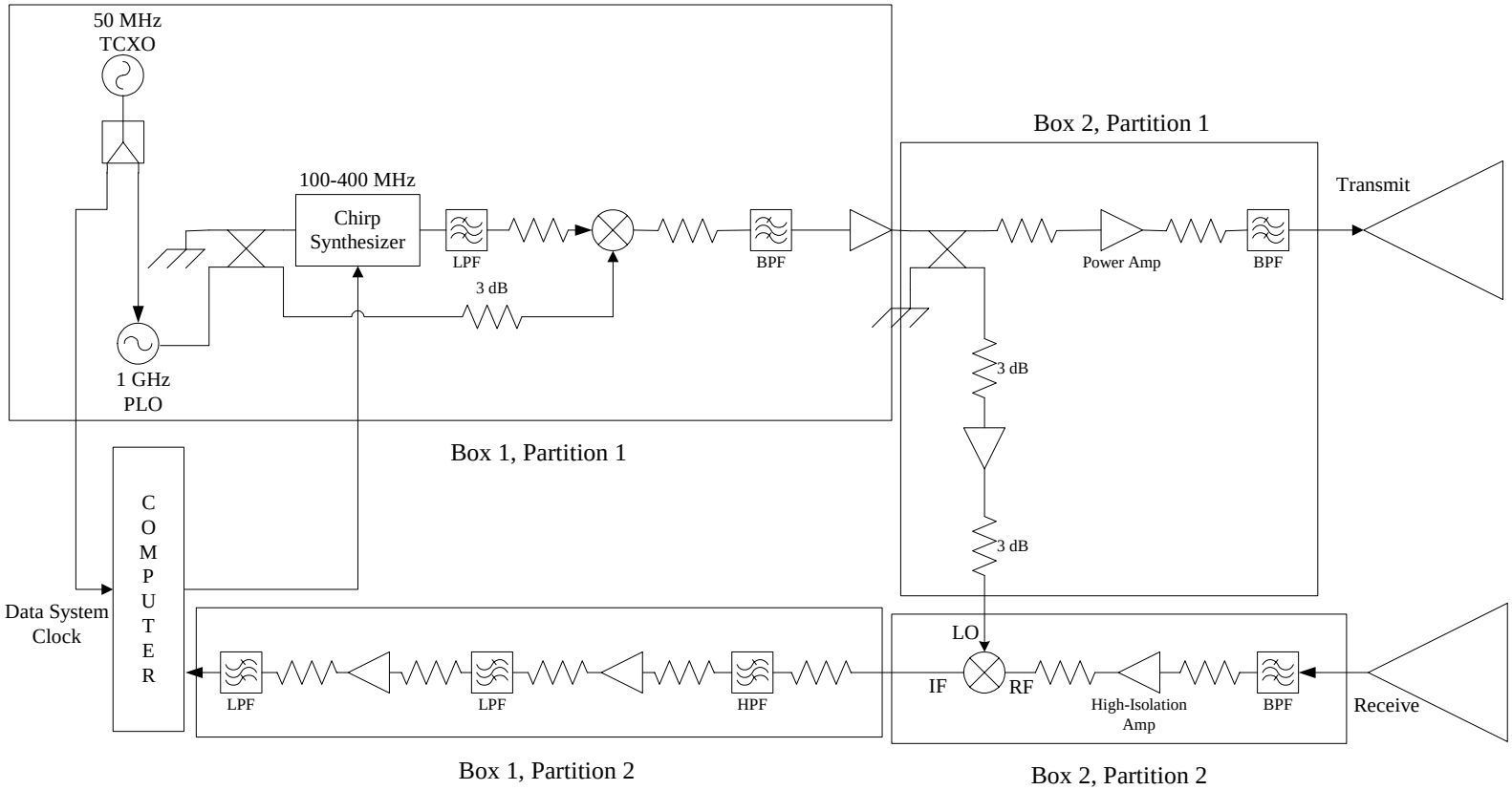
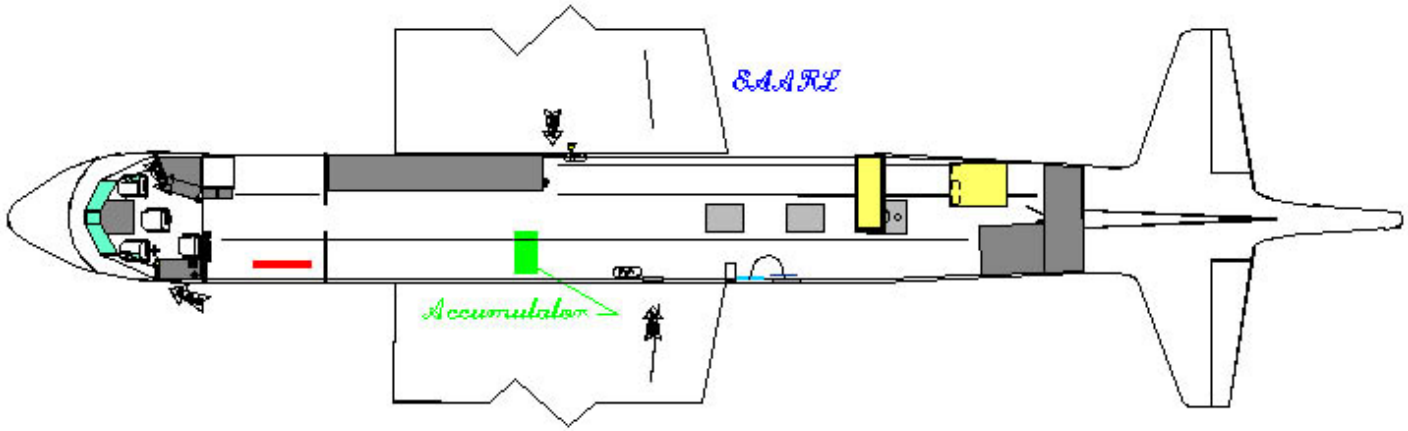
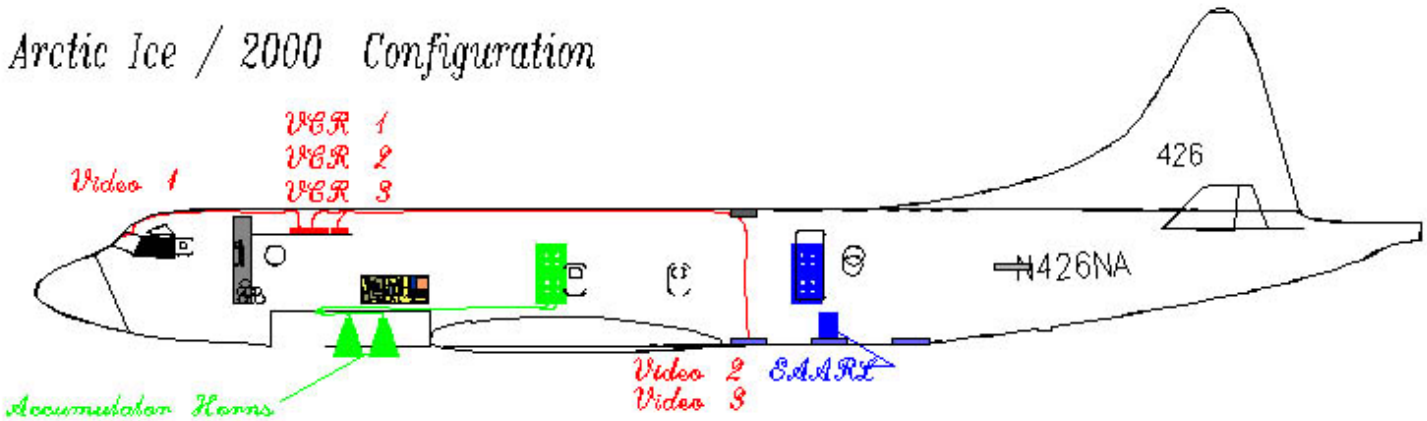
Improved Airborne Design



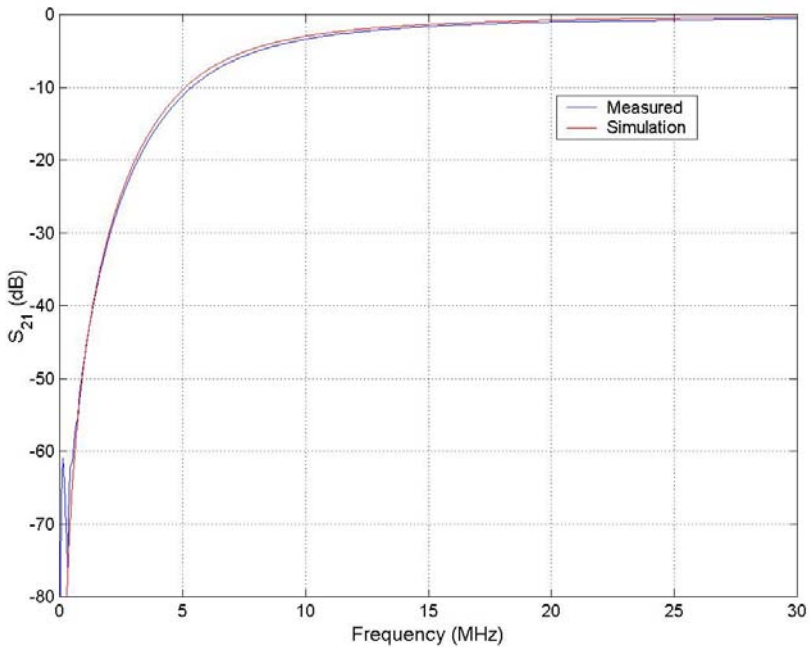
Installation

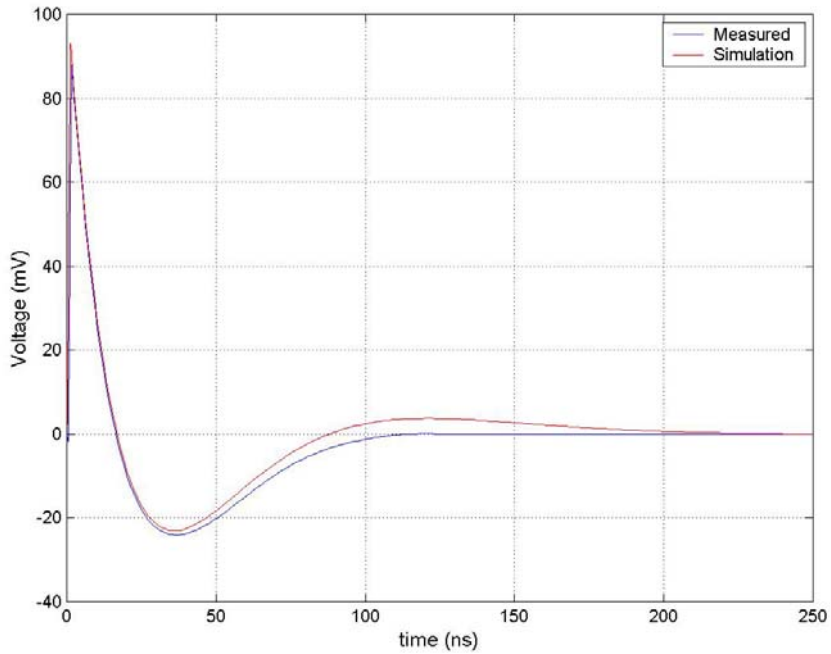




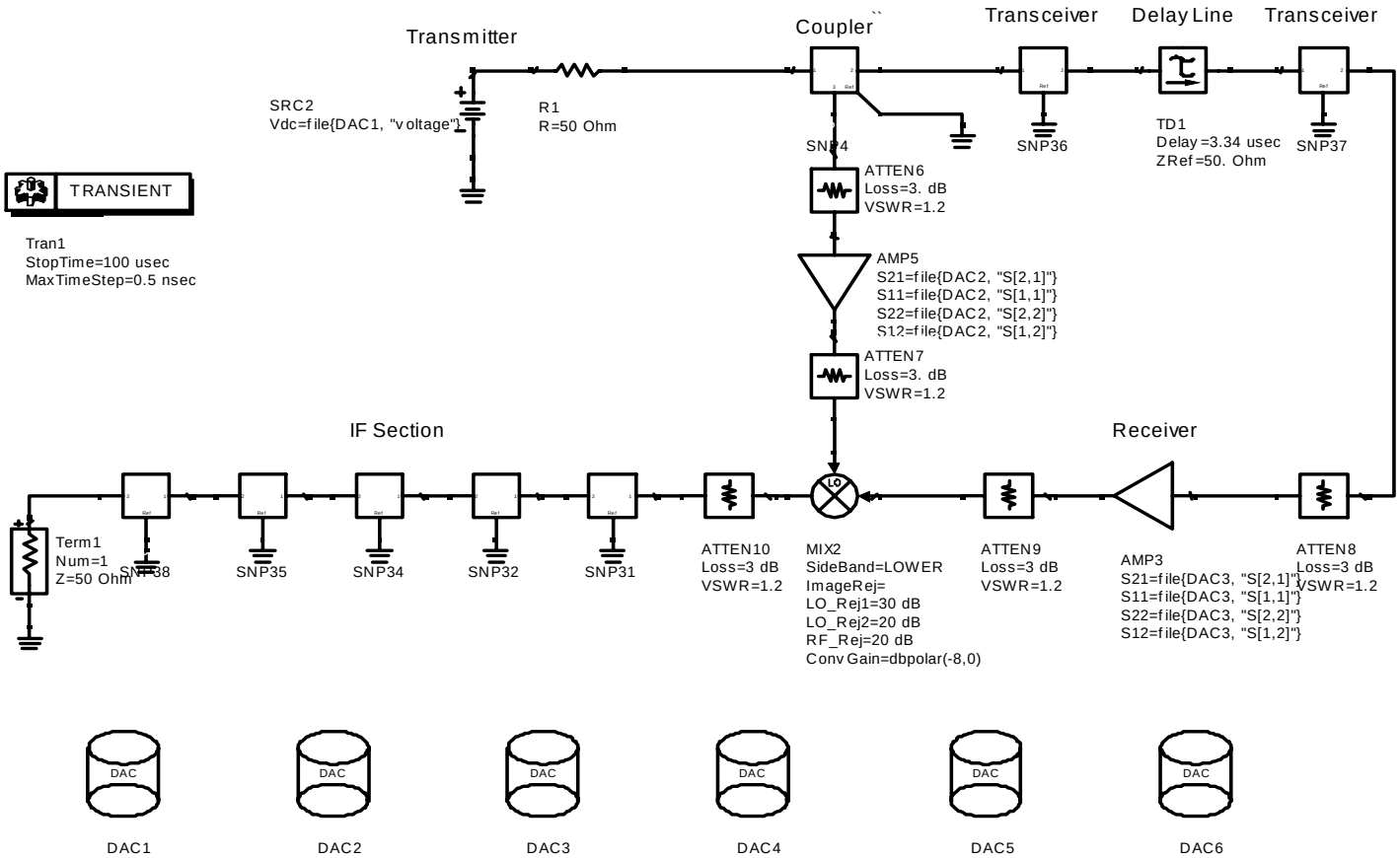
Improved High Pass Filter

- Gaussian filter design to minimize ringing

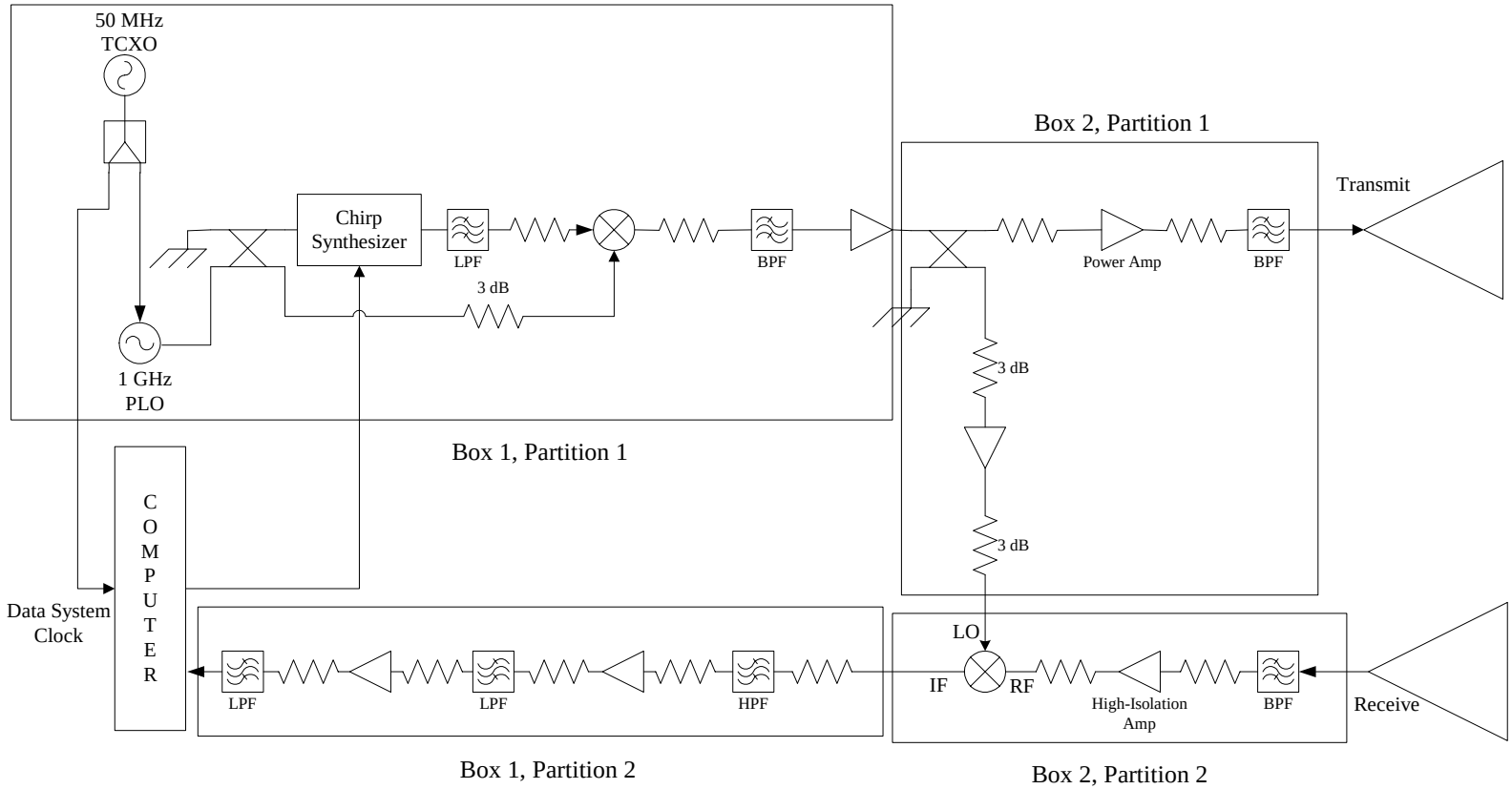




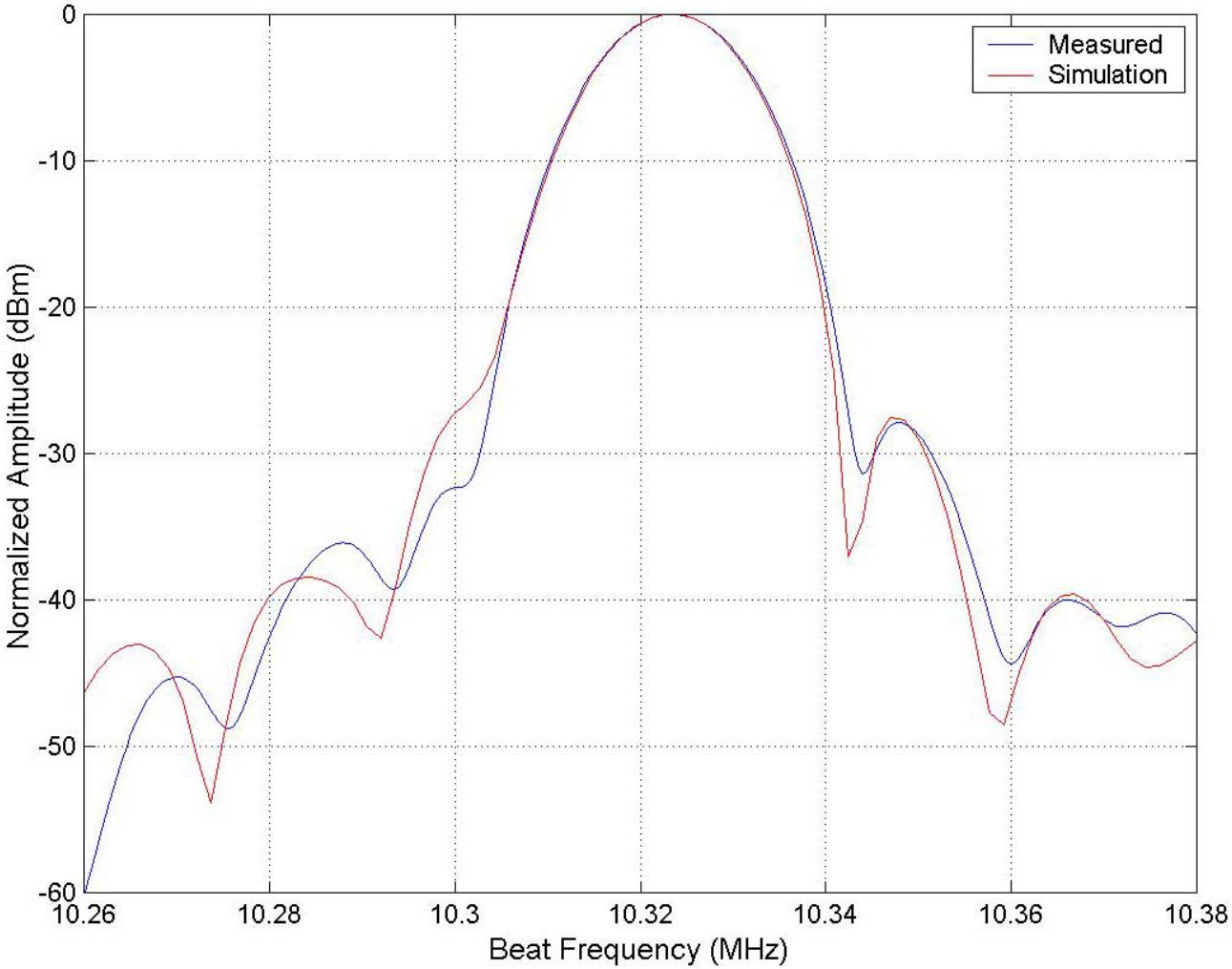
EEsof® Simulation



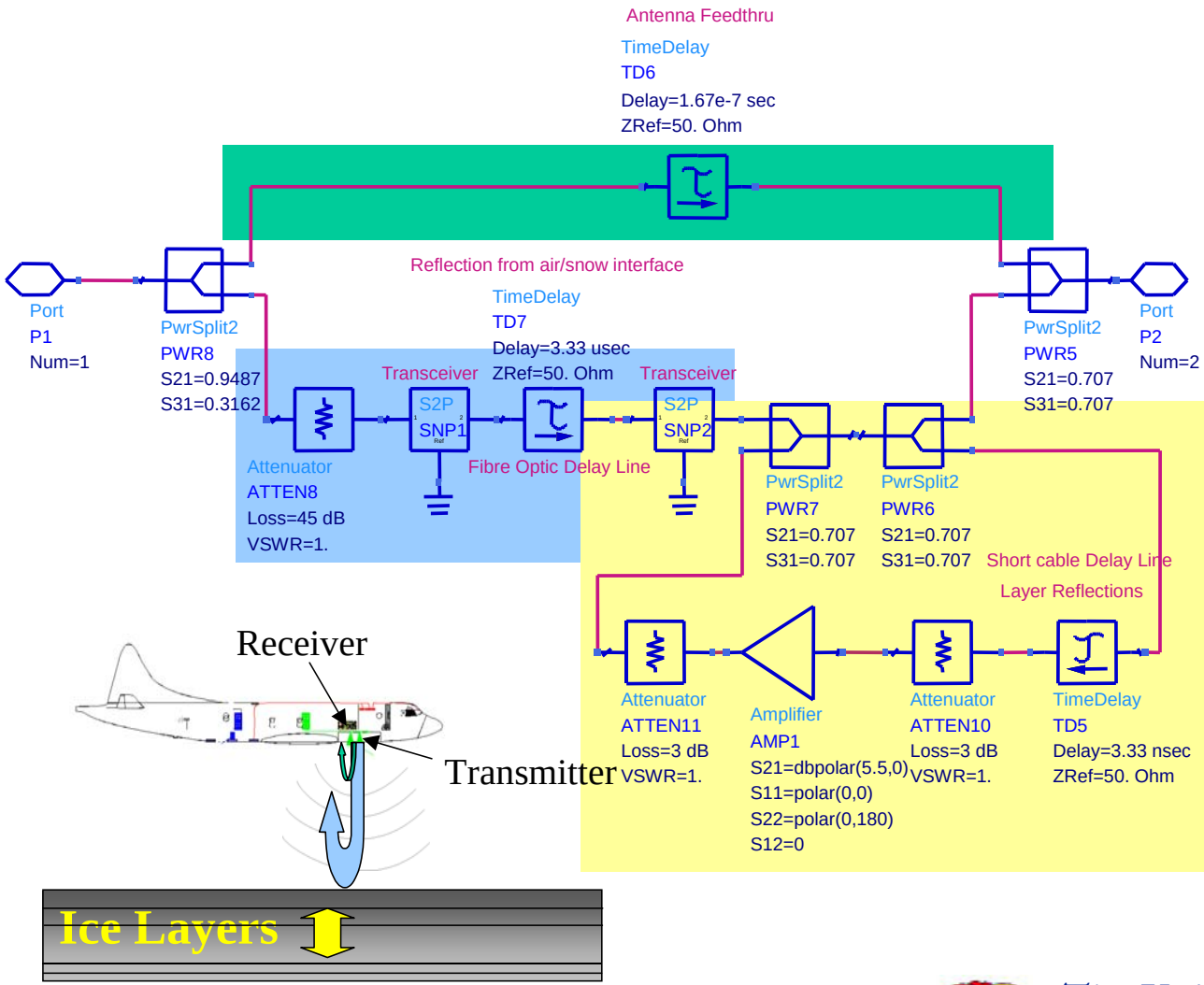
Improved Airborne Design



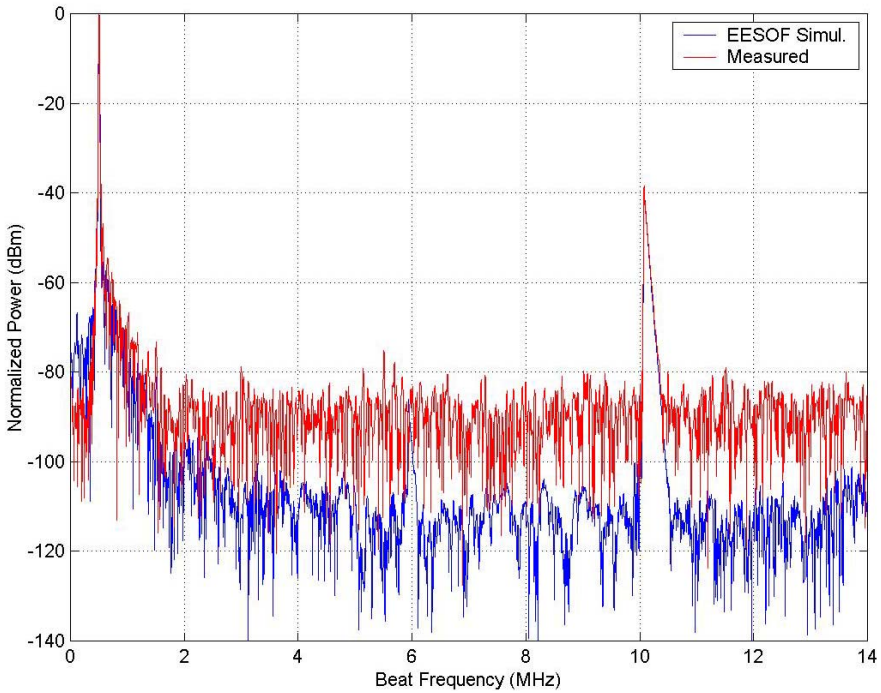
Comparison

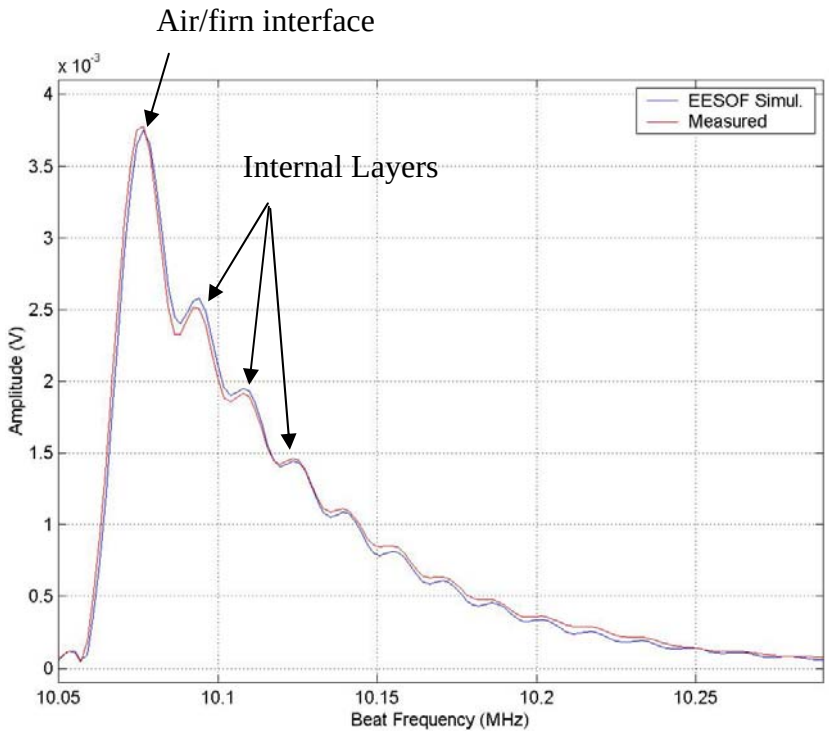

Measured
Simulation
Normalized Amplitude (dBm)
0
-10
-20
-30
-40
-50
-60
10.26
10.28
10.3
10.32
10.34
10.36
10.38
Beat Frequency (MHz)

Target Simulator

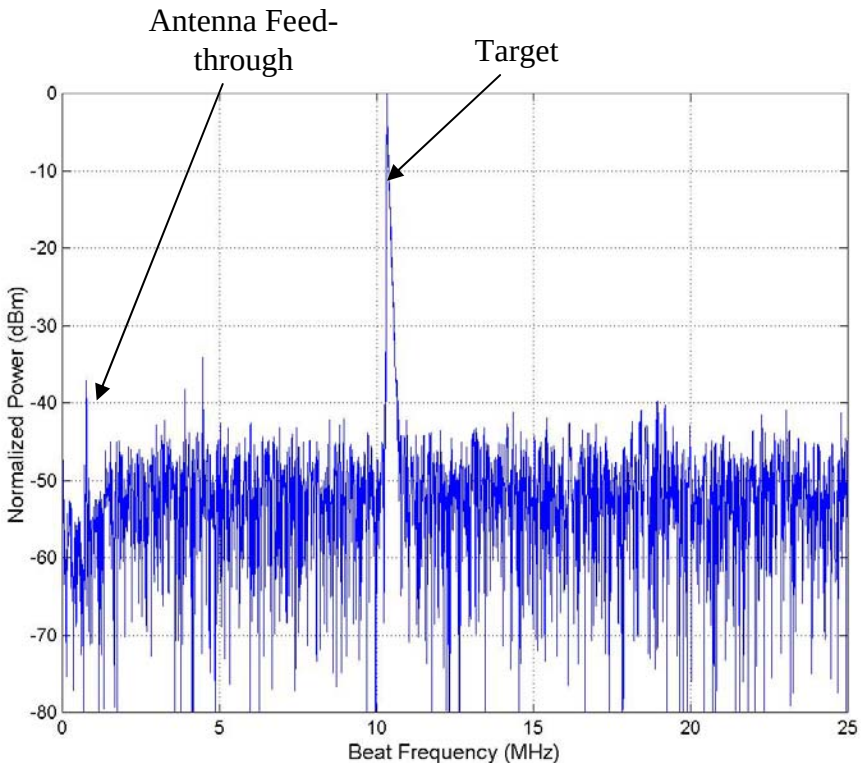


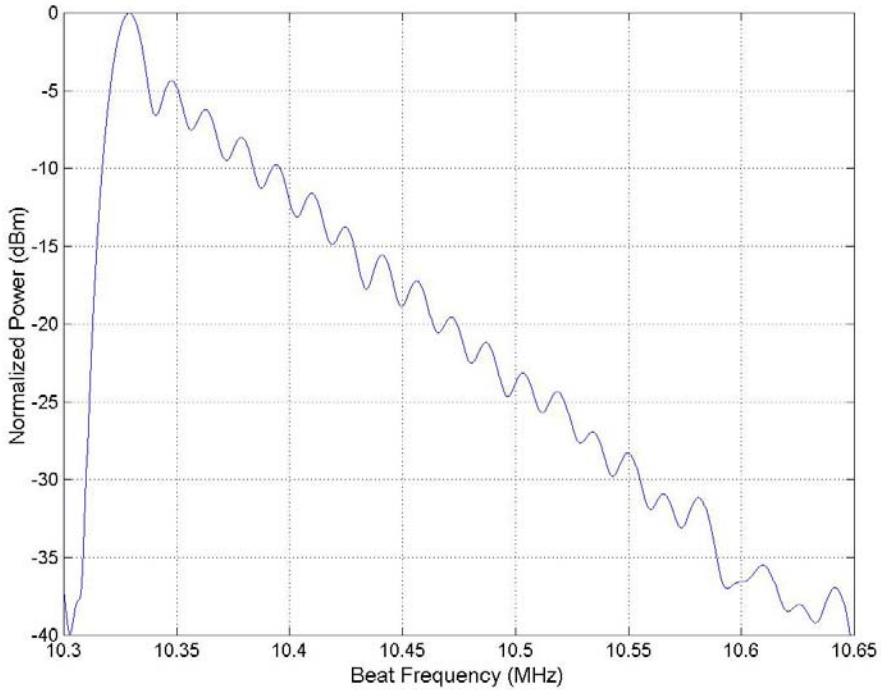
Results


EESOF Simul.
Measured
Normalized Power (dBm)
Beat Frequency (MHz)
0
-20
-40
-60
-80
-100
-120
-140
0
2
4
6
8
10
12
14


Air/firn interface
Internal Layers
x 10^-3
EESOF Simul.
Measured
Amplitude (V)
Beat Frequency (MHz)
4
3.5
3
2.5
2
1.5
1
0.5
0
10.05
10.1
10.15
10.2
10.25

Results from Improved System





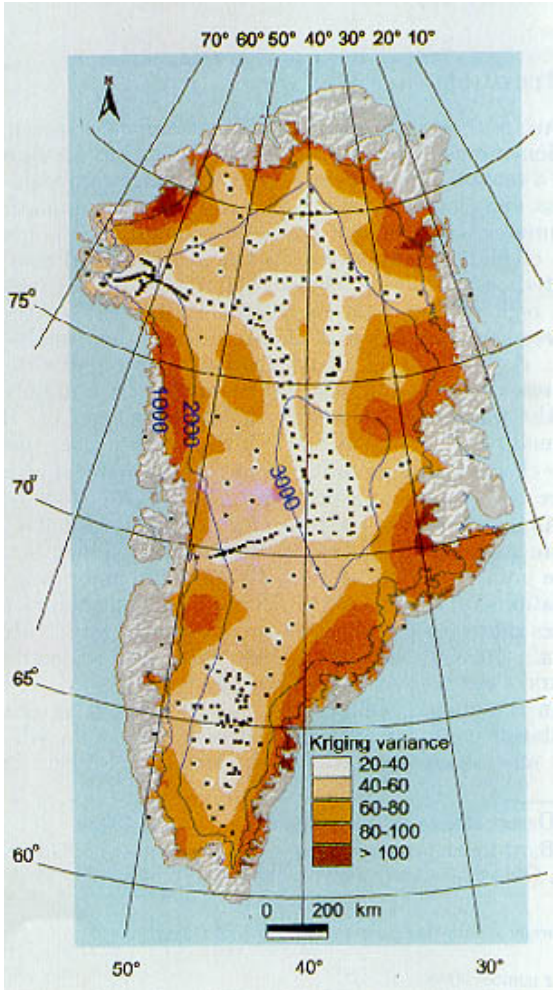
SUMMARY

Summary

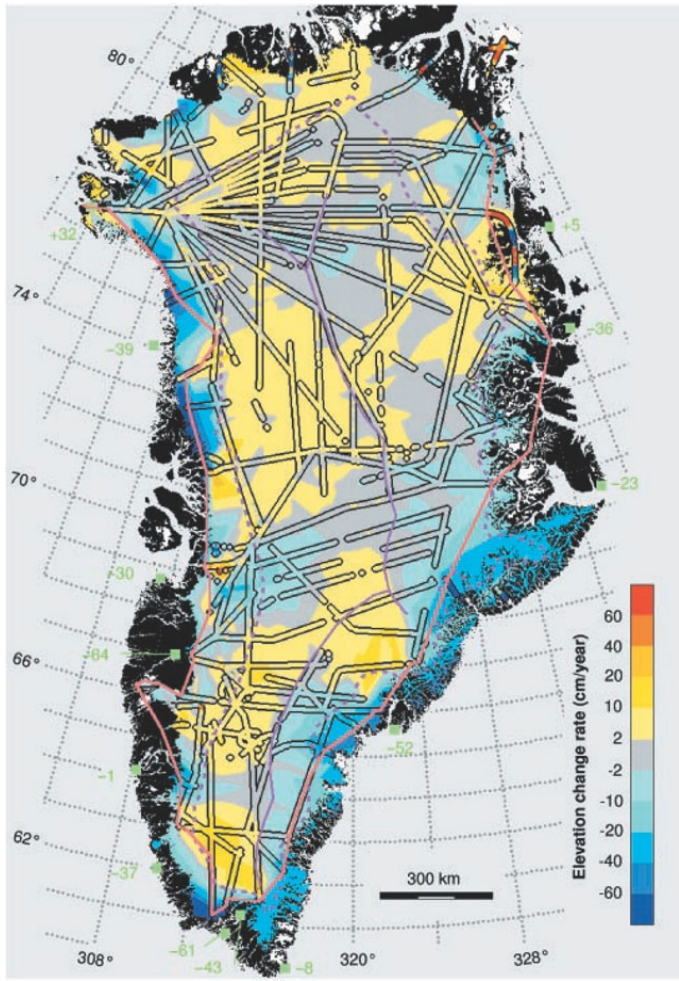
- We developed a 600-900 MHz airborne radar system to map the internal layers of the Greenland ice sheet.
- Will help overcome the limitations of surface based methods in determining the accumulation rate.
- Airborne radar system was developed based on surface-based radar measurements made at NGRIP.
- We successfully mapped the internal layers over the Greenland ice sheet up to a depth of 120 m with better than 1 m resolution.
- We developed a target simulator that can be used to optimize radar performance.

RECOMMENDATIONS

Accumulation Map



Bales et al., 2001



Krabill et al., 2001

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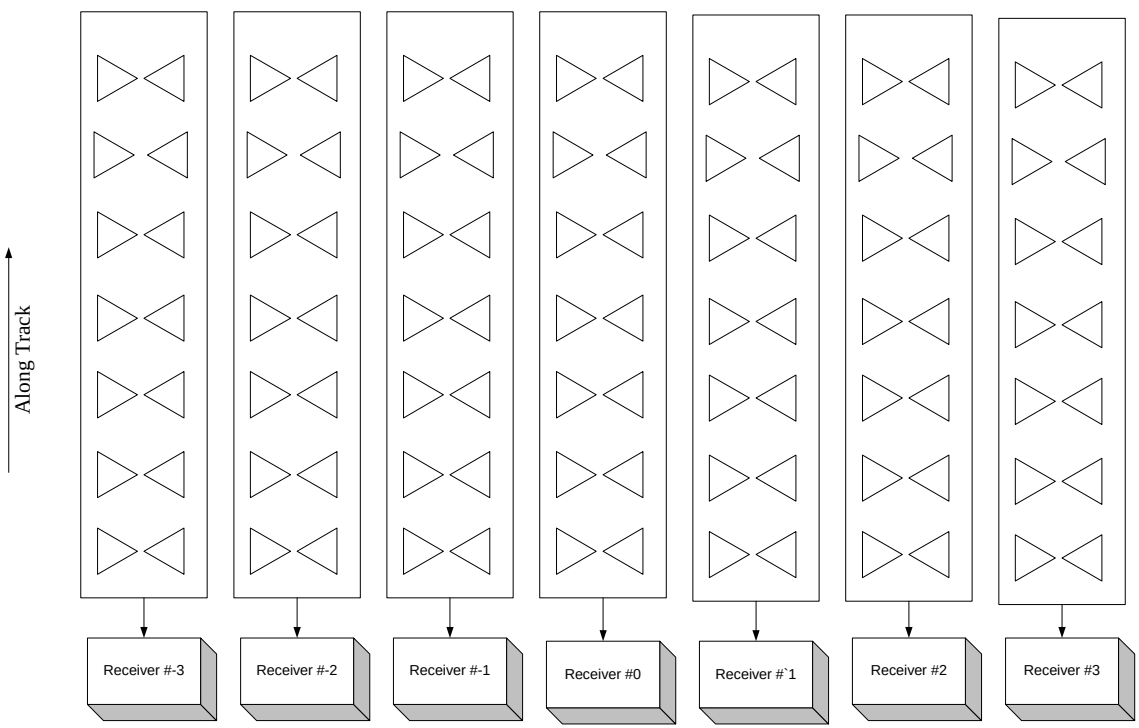
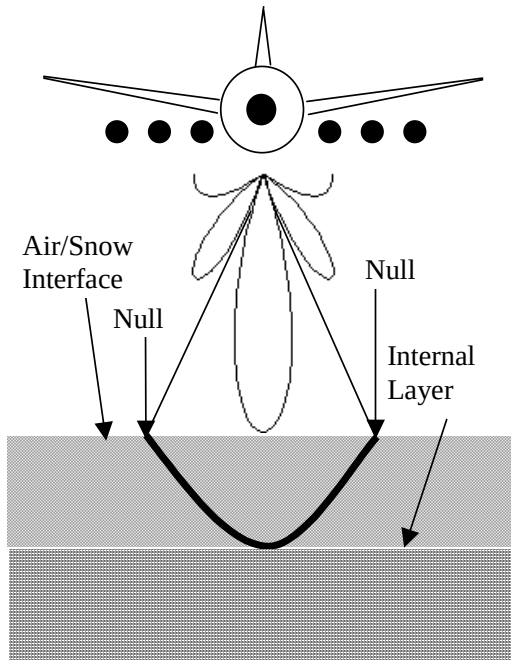
Surface Property

Digital Beamforming





Model-Based Signal Processing