HIGH RESOLUTION RADAR BACKSCATTER FROM SEA ICE

&

RANGE-GATED STEP-FREQUENCY RADAR USING FM-CW CONCEPT

Master’s Thesis Defense

by

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Overview - Sea Ice

- Introduction
- Objectives
- Approach
- Experiments
- Data Processing
- Results
- Conclusion

Overview - Radar

- Objective
- FM-CW concepts
- Principles of operation
- Simulation
- System Description
- Results
- Conclusion

Introduction to sea ice remote sensing

- Sea ice plays a major role in the global climate system
  - Surface radiation balance
    - sea ice reflects 90% of solar energy
    - open water absorbs 85-90% of solar energy
    - reduction in sea ice --> global warming
  - Heat flux
    - Ice sheet serves as insulation between cold polar air & the warm ocean
- Operations
  - Navigation and offshore exploration

Objectives

- To determine sources of scattering from saline ice
- To determine relative contributions of coherent and incoherent terms at nadir

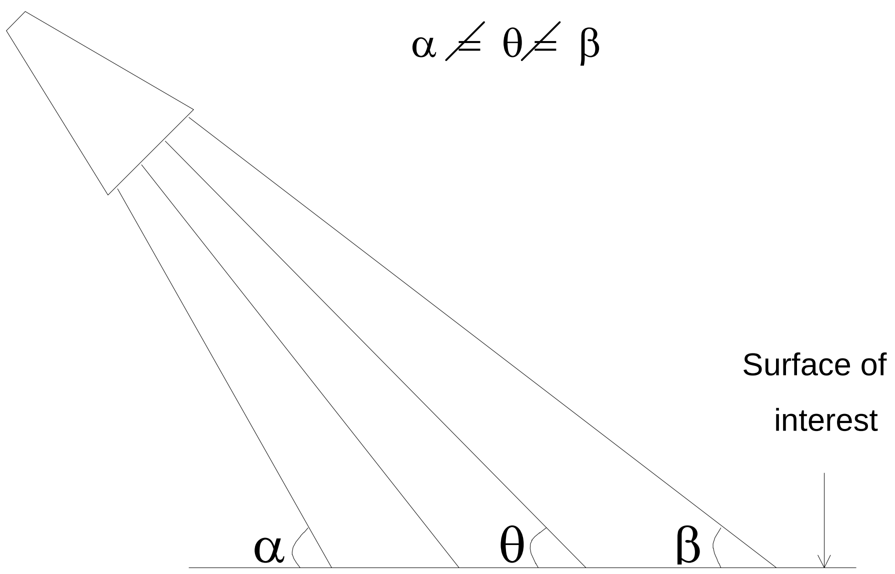
Approach

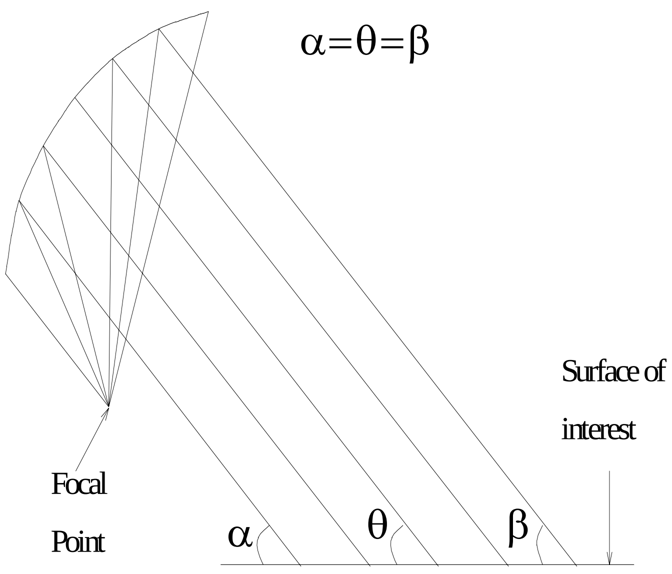
- Determine experimentally by performing high resolution measurements
- Developed an ultra wideband radar using the concept of compact antenna range to generate plane wave

Why Plane Wave Illumination ?

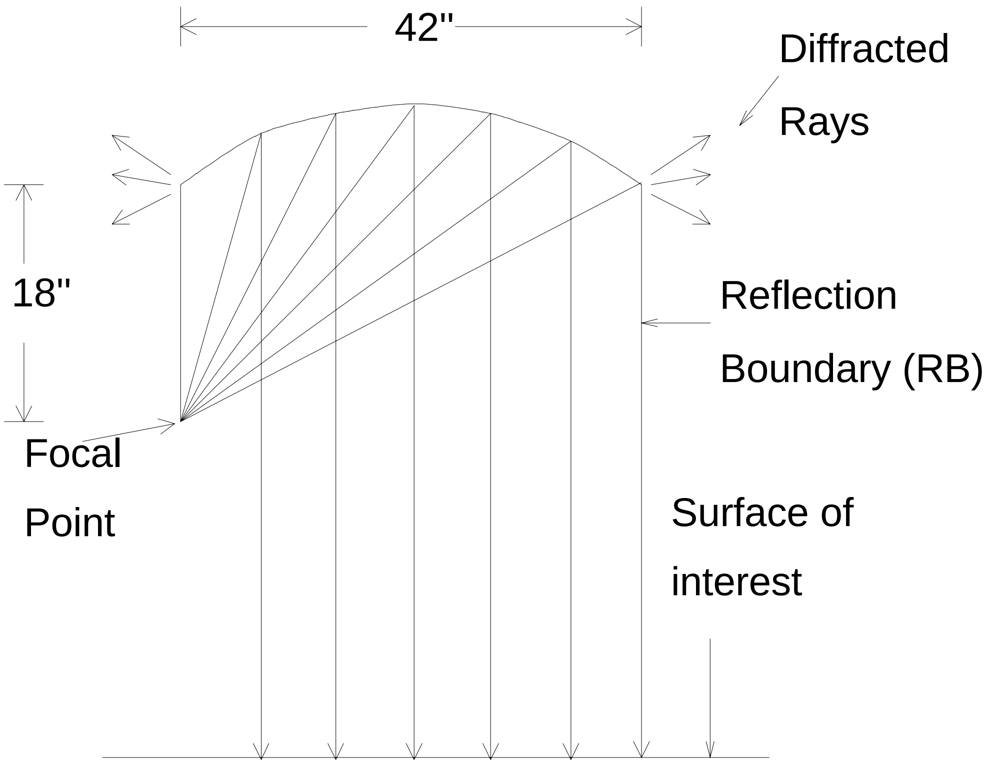
- Radar systems used to generate ground truth data are operated in the near zone region
- Illumination of distributed targets using conventional antennas contain a wide range of incidence angle
- This problem can be overcome by using a parabolic reflector with an offset feed which propagates a plane wave of uniform phase

Comparison between Conventional Antenna and Plane Wave Antenna





Geometry of Parabolic Reflector



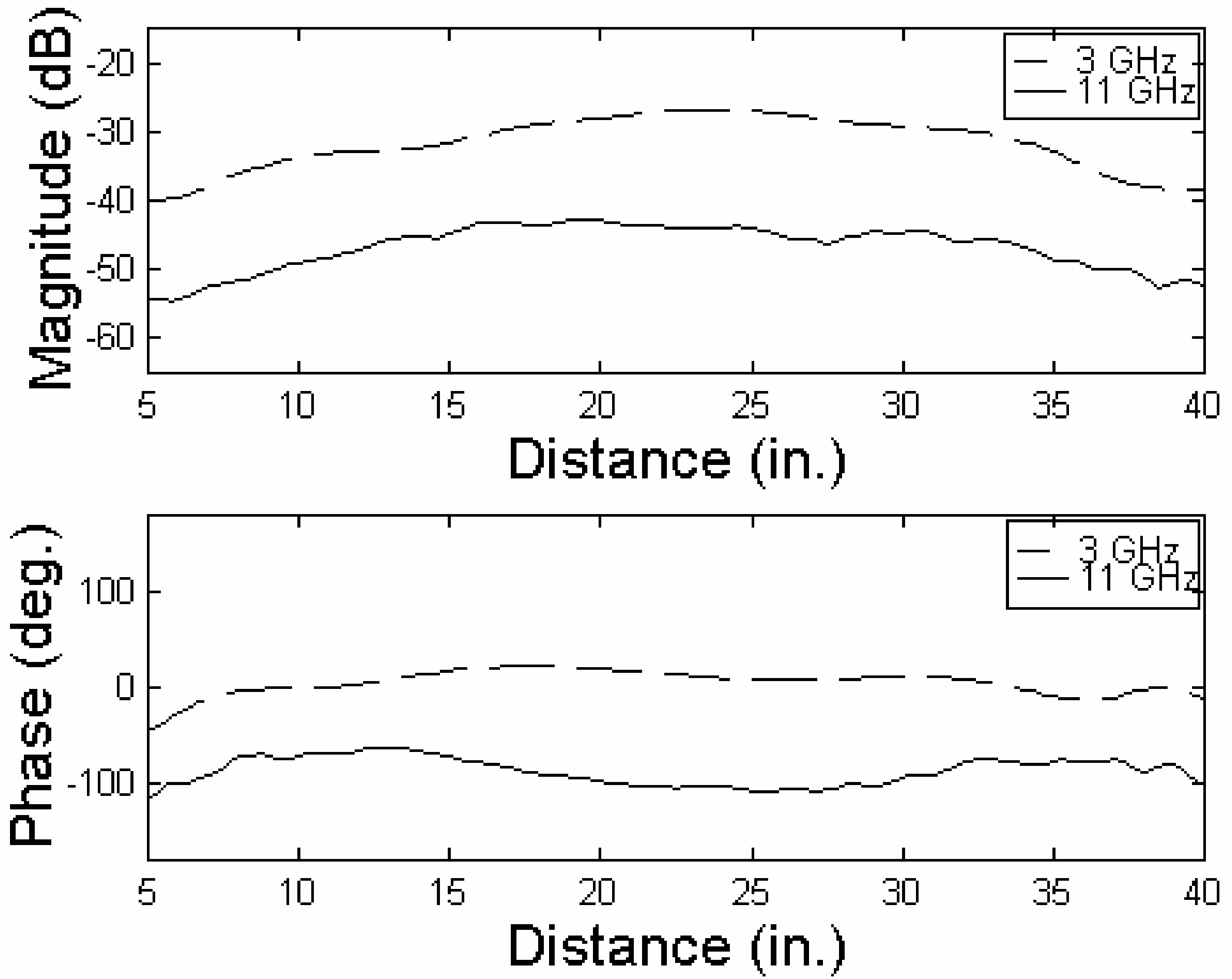
Generation of Plane Wave

- Rays emanating from a spherical source at the focal point of a parabolic reflector are reflected in the form of parallel rays
- Surface normal to these parallel rays will have a constant incidence angle
- In the vicinity of the reflection boundary diffracted rays are planar and they do not decay as a function of range
- Diffracted rays are spherical and their amplitude decays as 1/r far from the antenna
- Diffracted rays can be minimized by edge shaping or the use of absorbing material

Generation of Plane Wave

- Plane wave has uniform phase over an area equal to the area of the reflector
- The range of propagation is about $0.5*D^2/\lambda$
- Ideally the diameter of the reflector should be 10 wavelengths at the lowest frequency to be effective in the compact range

Magnitude and Phase of the field 6 feet away from the antenna shown for vertical polarization



Step-frequency radar principles

- Transmitted signal

$$V_t(f) = E_o$$

- Received signal

$$V_r(f) = E_o \Gamma \exp(j2\beta d)$$

where $\beta=2\pi/\lambda$

d is the distance to the target

- When frequency is stepped uniformly N times we have

$$V_r(f_n) = E_o \Gamma \exp j\left(\frac{4\pi(f_o + n\Delta f)d}{c}\right)$$

n=0:N-1

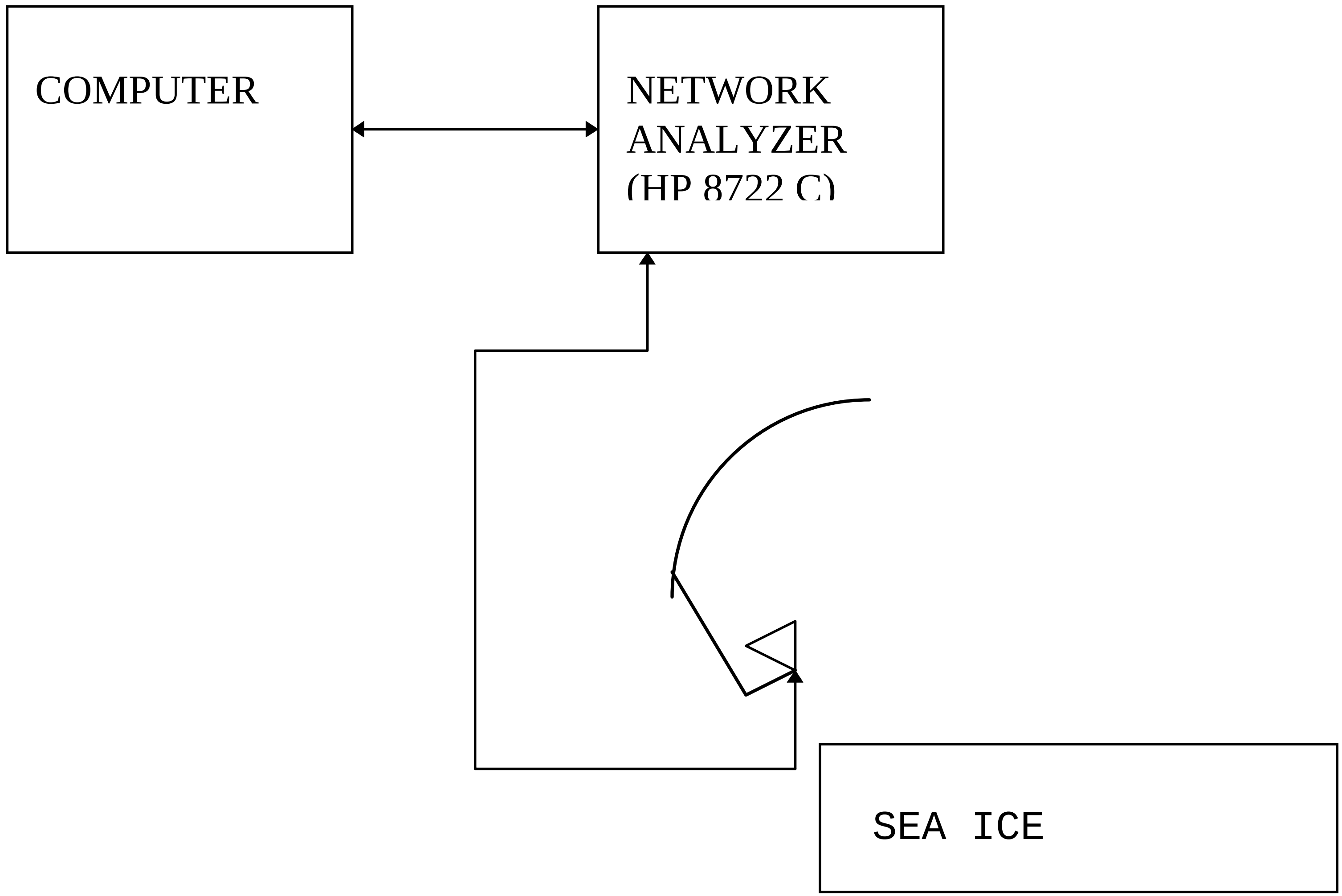
f_o is the start frequency

Δf is the frequency step size

US Army Cold Regions Research & Engineering Laboratory (CRREL) Experiment Description

- Measurements were made at CRREL in the winter of ‘94 and ‘95 using the plane wave system
  - In ‘94 data were collected primarily from bare saline ice and snow covered saline ice
  - In ‘95 data were collected primarily from pancake ice
- The plane wave antenna was used with a network analyzer based radar and operated from 2-18 GHz in ‘94 and 0.5-16.5 GHz in ‘95
- Data were collected at a variety of incidence angles from 0 to 60 degrees and at different spots on the ice

System Setup During CRREL Experiment



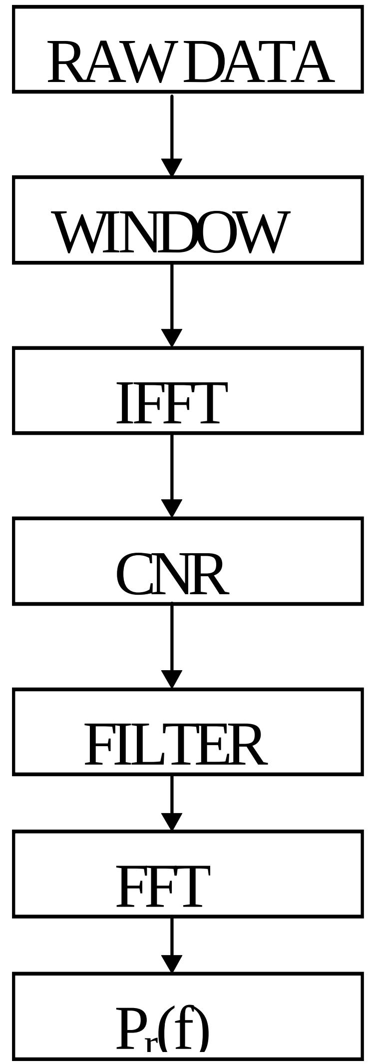
Data Processing

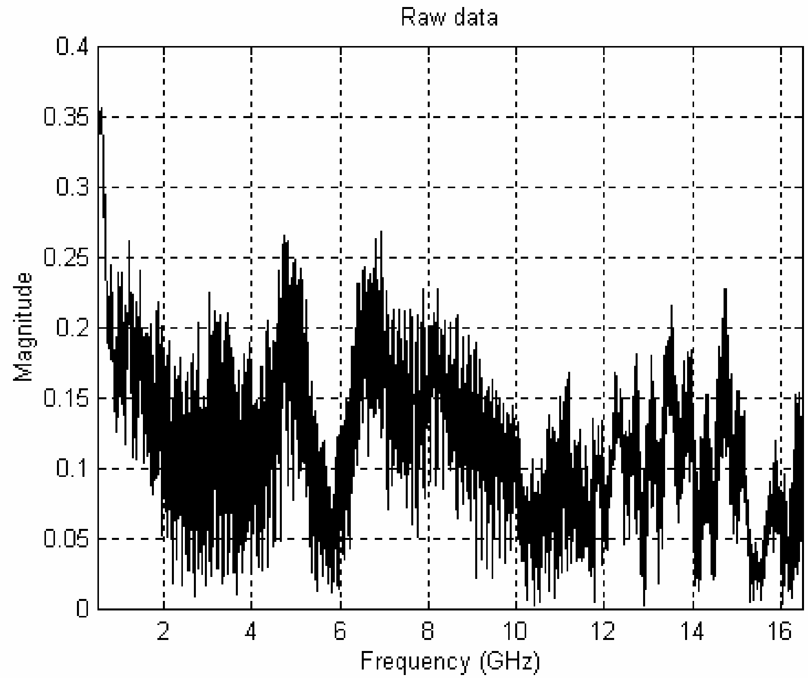
- Important parameter of interest is the backscattering coefficient (σ^o)

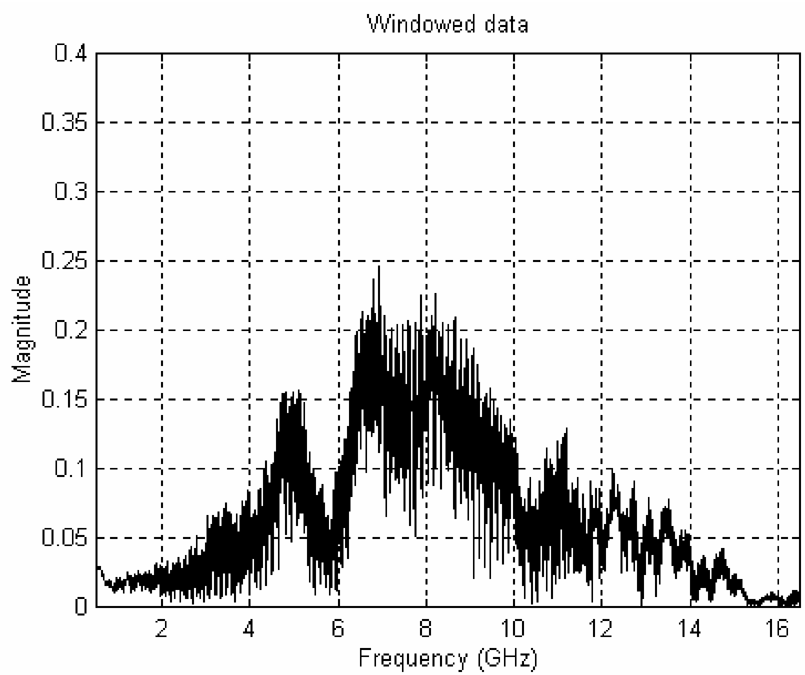
$$\sigma^o = \frac{P_r \sigma_{cal}}{P_{cal} A_{ill}}$$

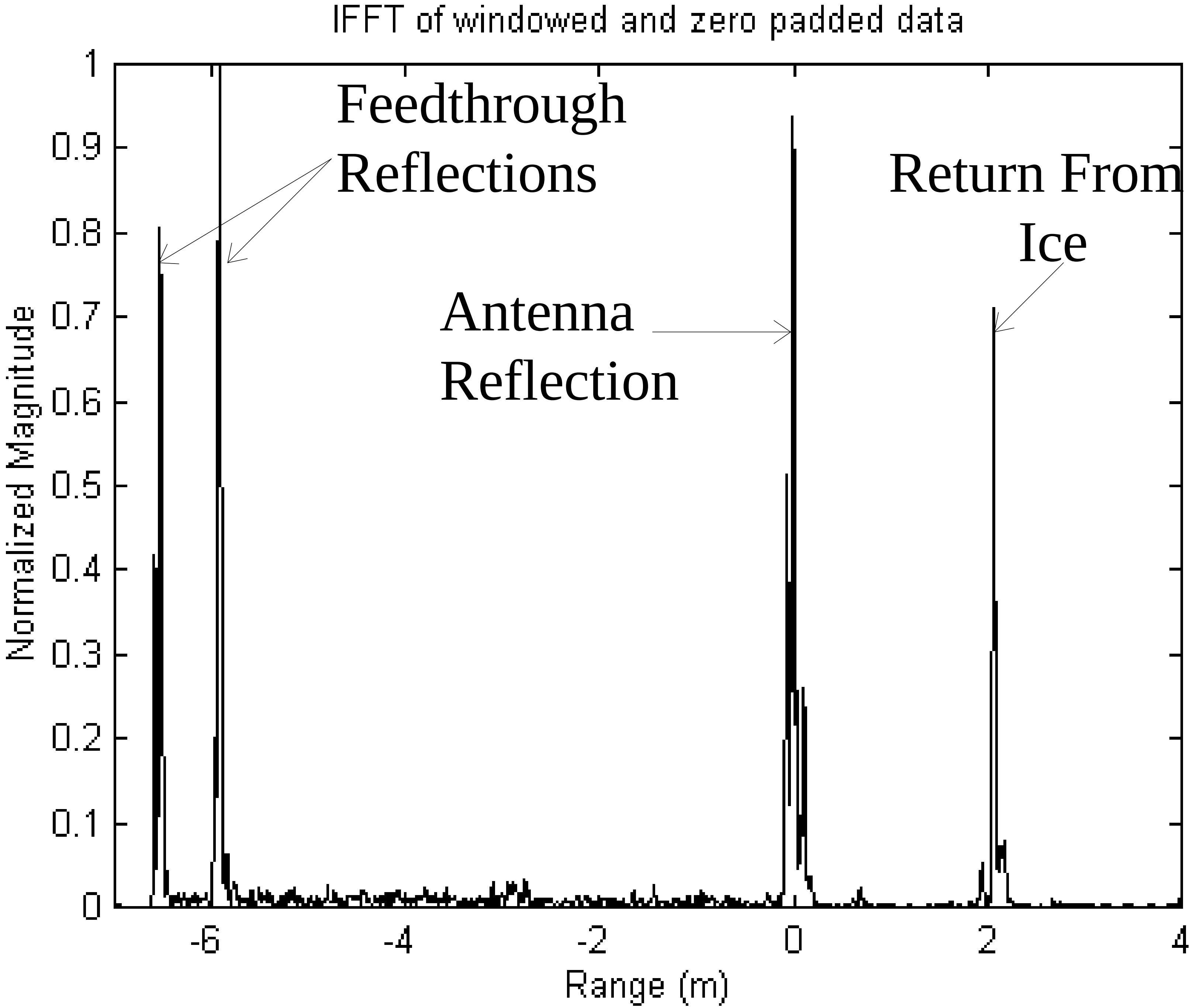
P_r is the power returned from ice
P_{cal} is the return power from a target of known radar cross section, σ_{cal} and
A_{ill} is the area illuminated by the antenna

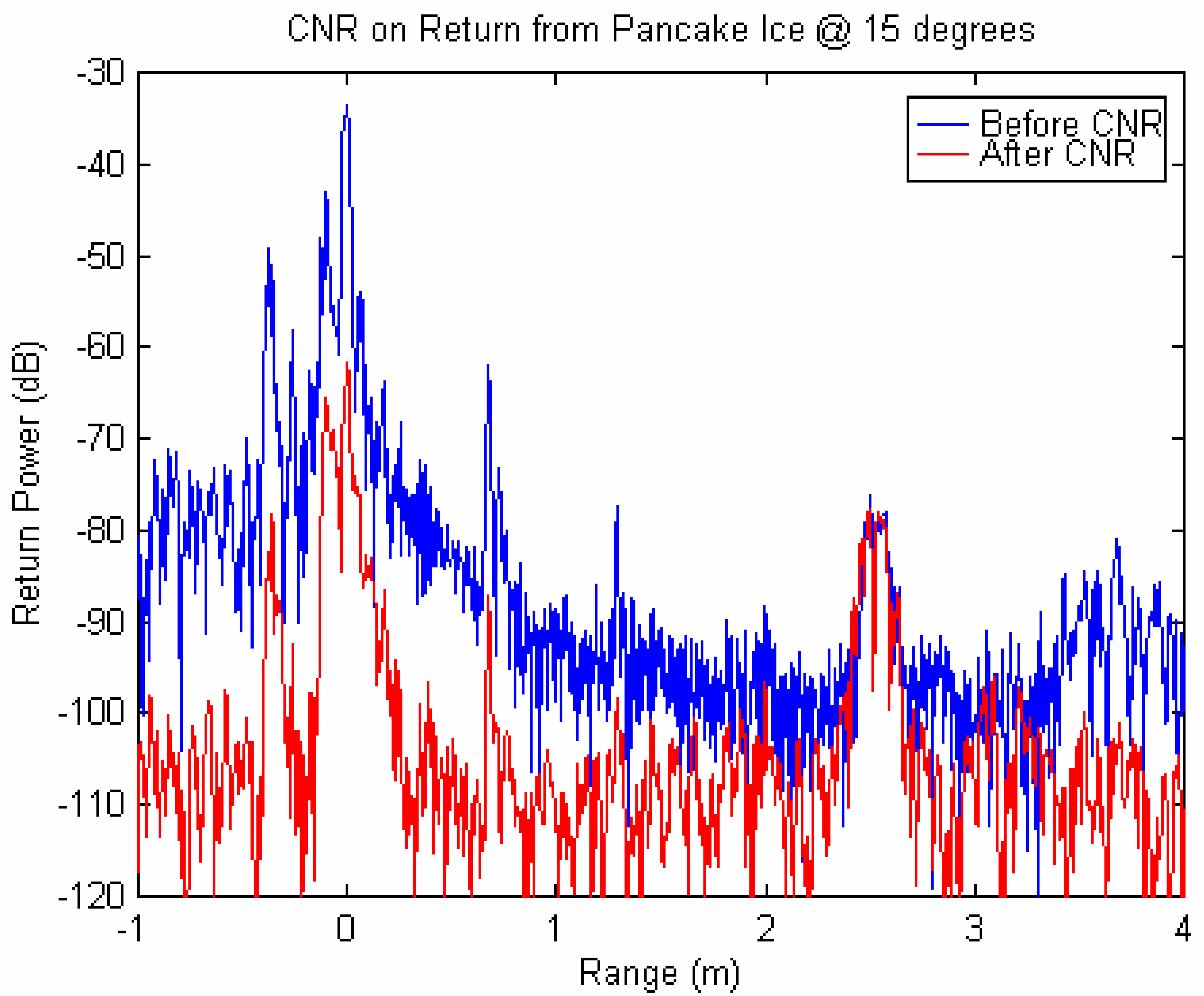
Frequency Response Computation of $P_r(f)$



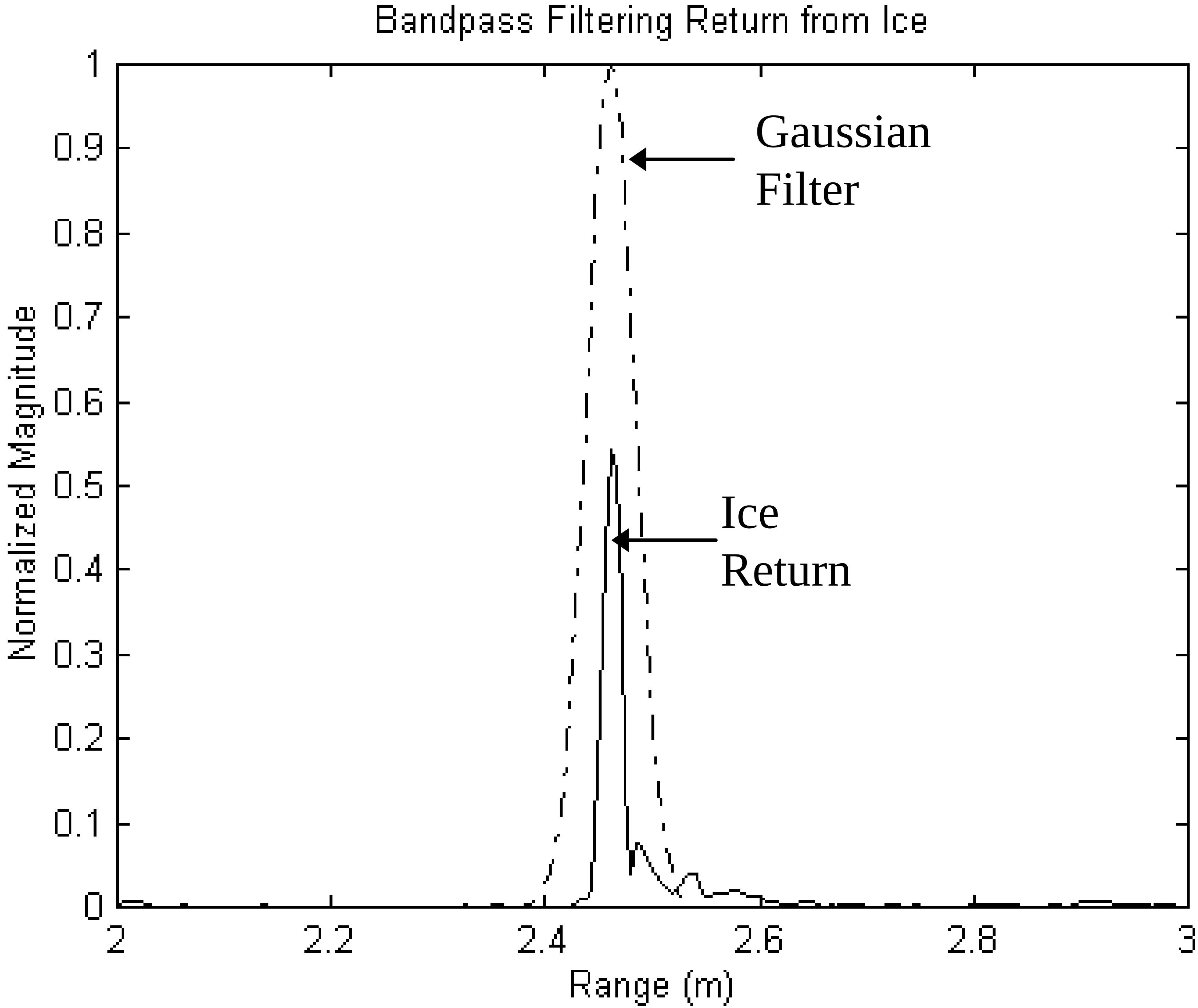

Raw data
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Magnitude
2
4
6
8
10
12
14
16
Frequency (GHz)


Windowed data
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Magnitude
2
4
6
8
10
12
14
16
Frequency (GHz)


IFFT of windowed and zero padded data
Feedthrough
Reflections
Antenna
Reflection
Return From
Ice
Normalized Magnitude
Range (m)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-6
-4
-2
0
2
4

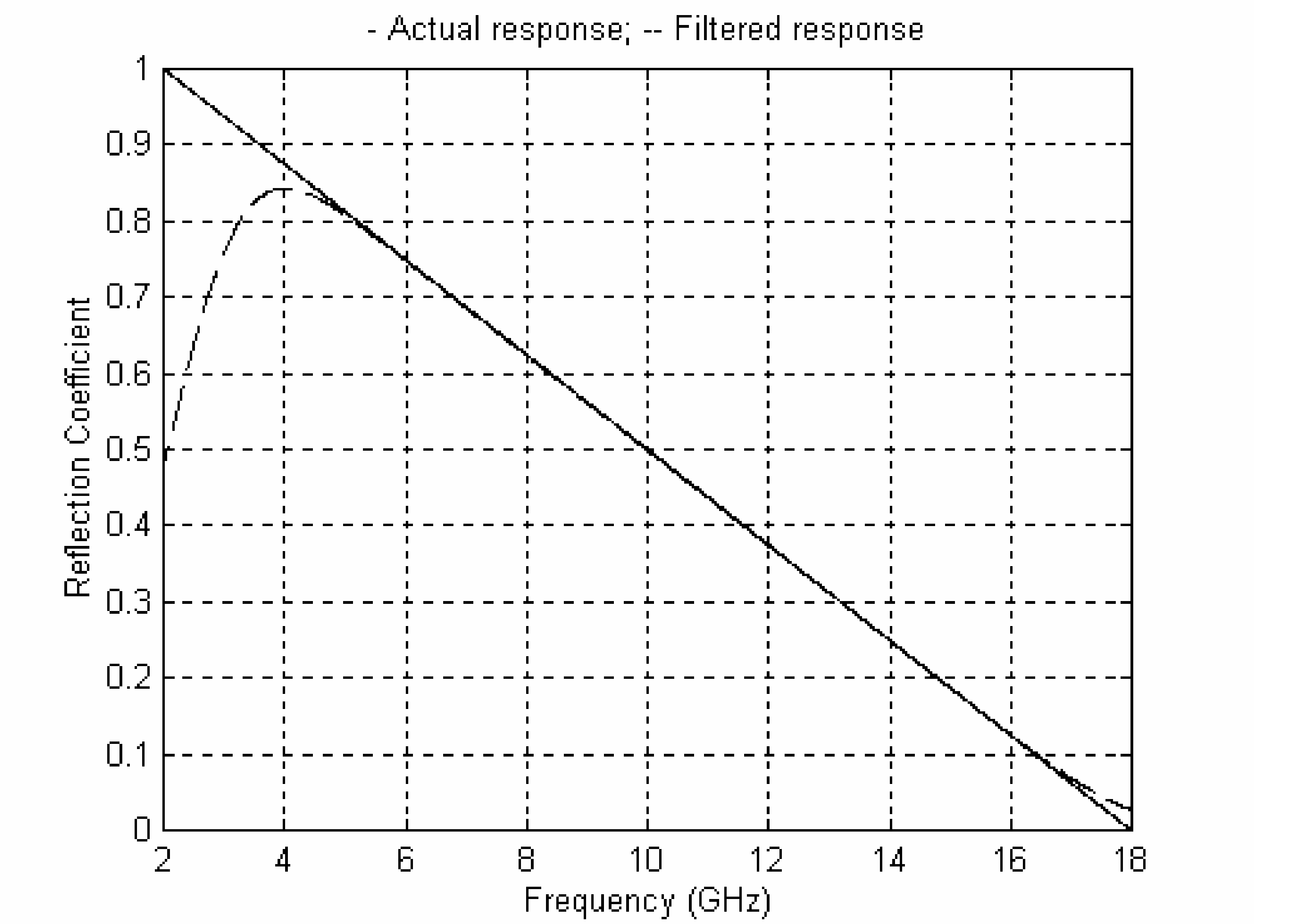


$$V_{1CNR} = V_1 - \frac{1}{N}\sum_{i=1}^{N} V_i$$

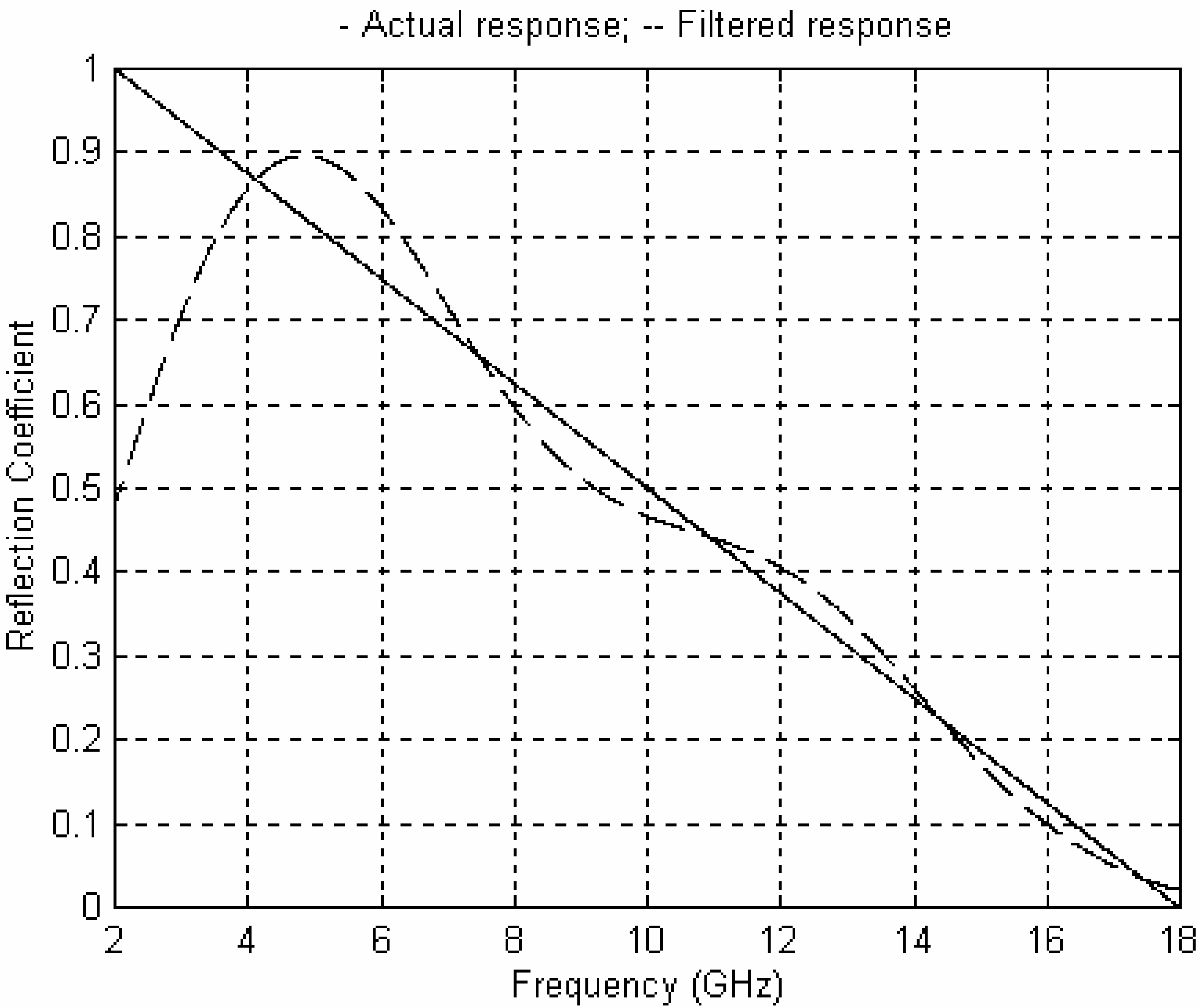


Bandpass Filtering Return from Ice
Gaussian Filter
Ice Return
Normalized Magnitude
Range (m)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
2
2.2
2.4
2.6
2.8
3

Gibb's Effect Using Gausian Filter

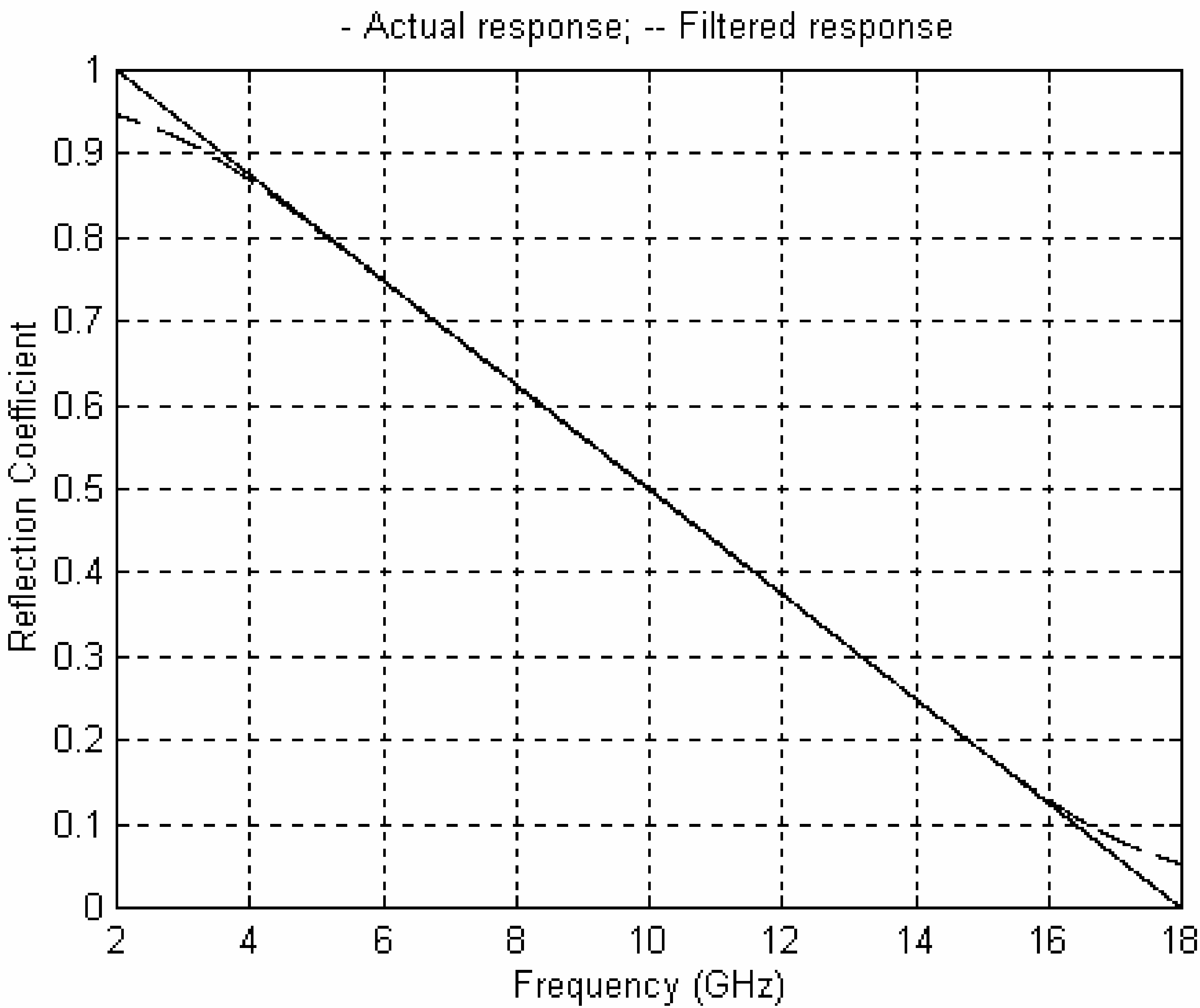


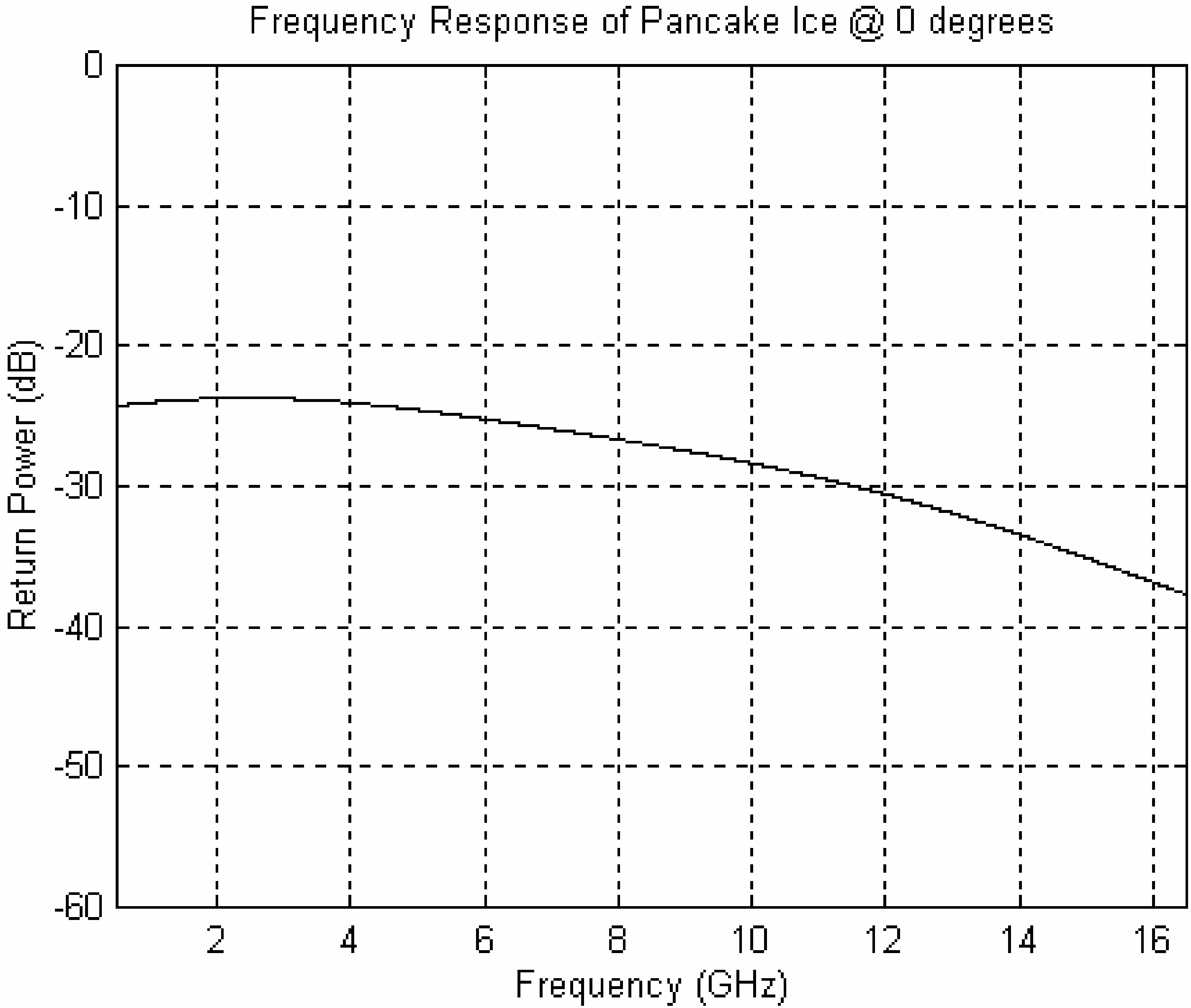
Gibb's Effect Using Rectangular Filter



Reducing the Gibb's effect

- To reduce the Gibb's effect,
  -Simulate the step-frequency data with a reflection coefficient of one at the same range as the target
  -Use the same window on the simulated data, zero pad and take the IFFT
  -Use the same filter that is used on the ice return for the simulated data.
  -FFT of this filtered signal is the correction factor which is divided by the frequency response of the target.


- Actual response; -- Filtered response
Reflection Coefficient
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2
4
6
8
10
12
14
16
18
Frequency (GHz)


Frequency Response of Pancake Ice @ 0 degrees
0
-10
-20
-30
-40
-50
-60
Return Power (dB)
2
4
6
8
10
12
14
16
Frequency (GHz)

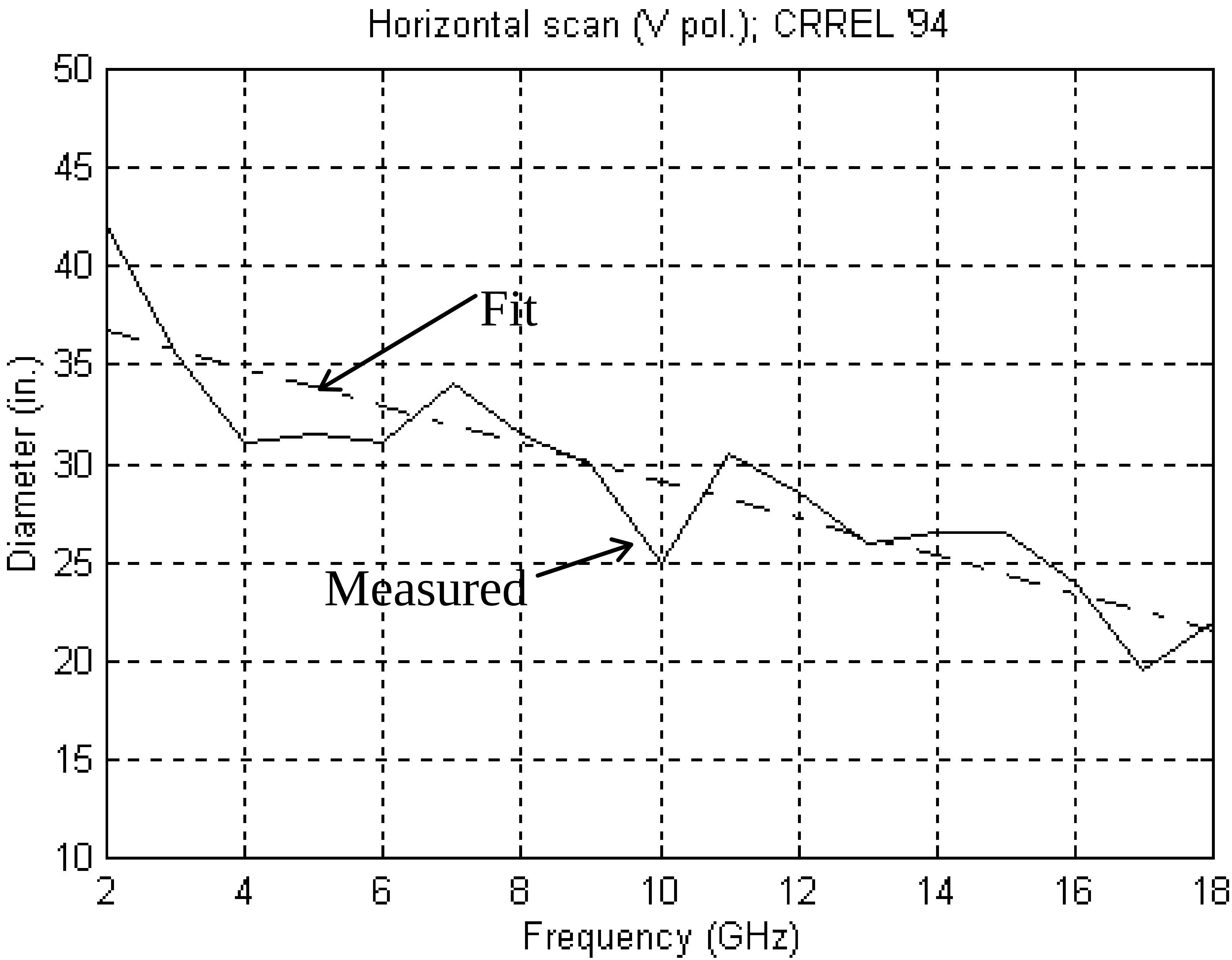
Illuminated Area Calculation

$$A_{ill} = \frac{\pi D_V D_H}{4\cos(\theta)}$$

where D_v is the vertical diameter,

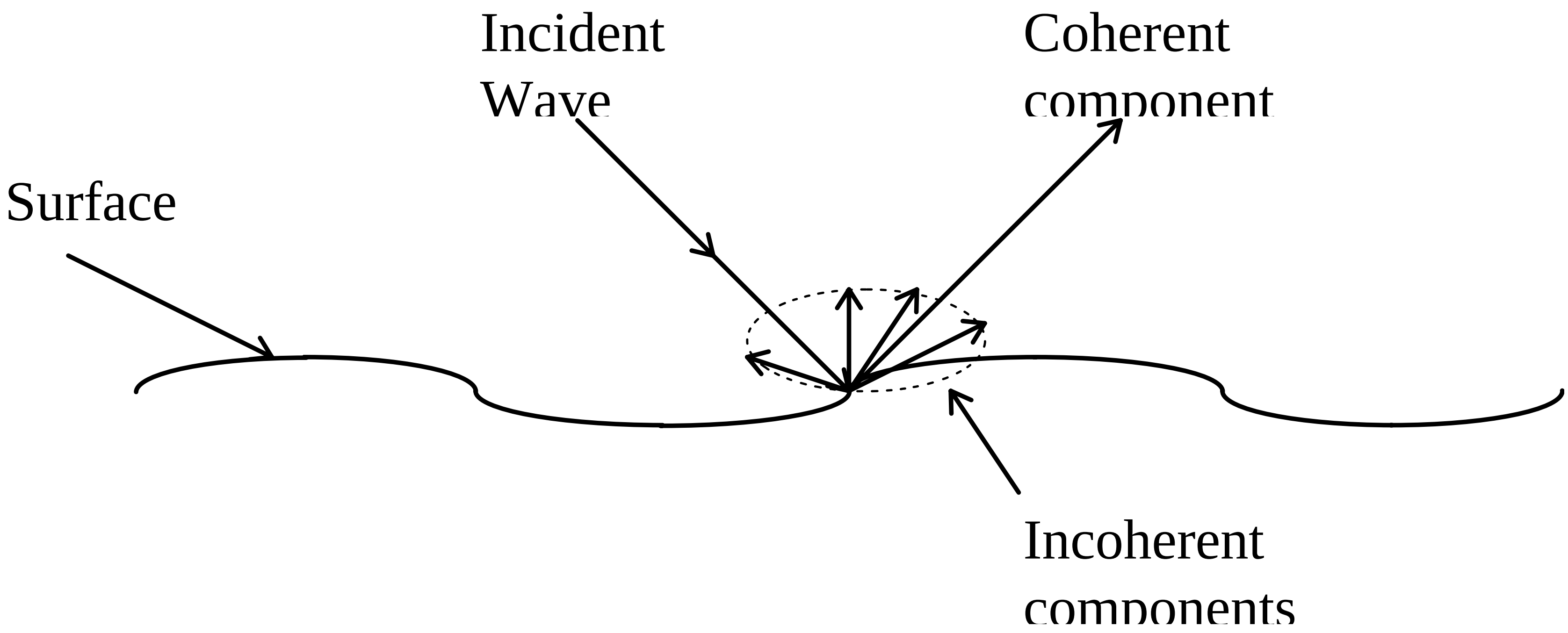
D_H is the horizontal diameter, and

θ is the incidence angle



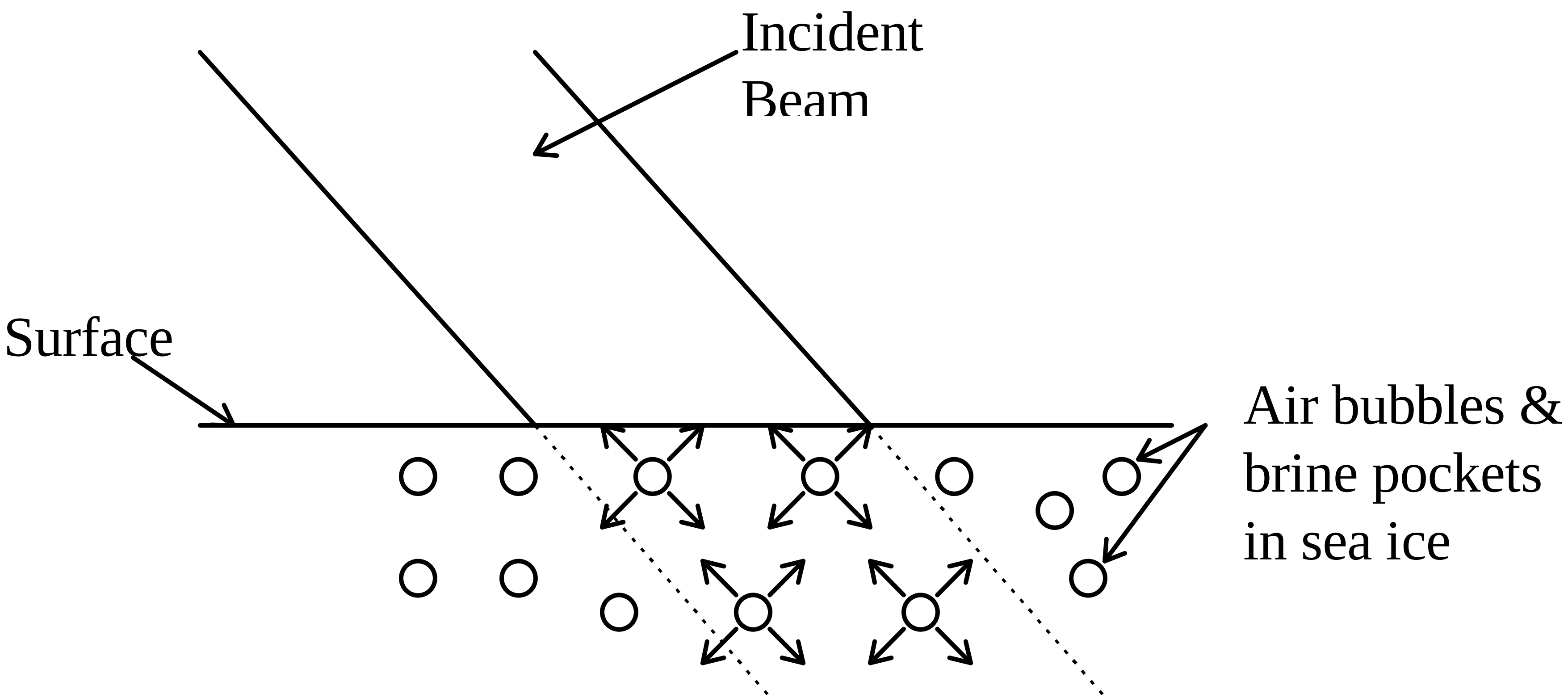
Horizontal scan (V pol.); CRREL '94
Fit
Measured
Diameter (in.)
Frequency (GHz)
50
45
40
35
30
25
20
15
10
2
4
6
8
10
12
14
16
18

Scattering Theory

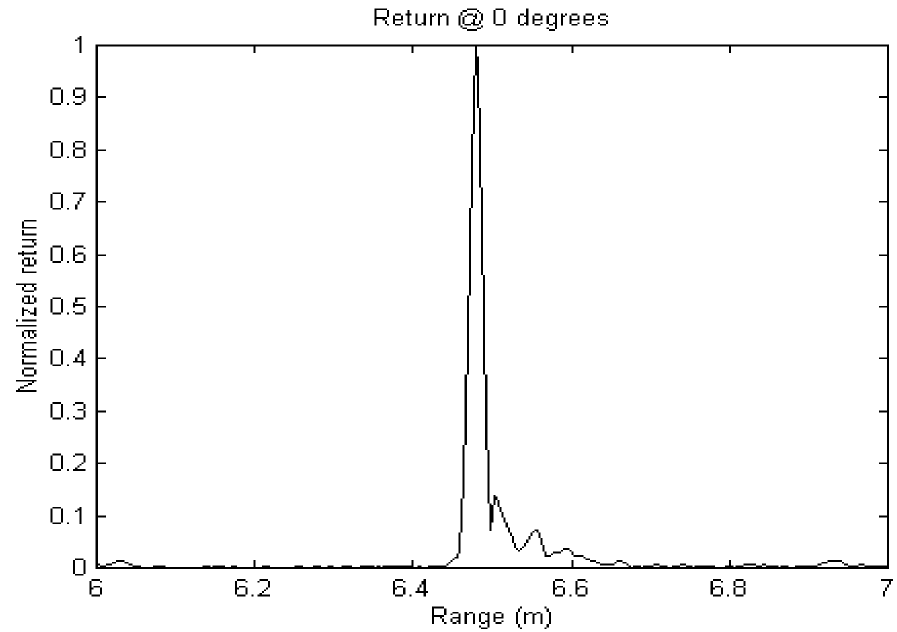


Surface Scattering

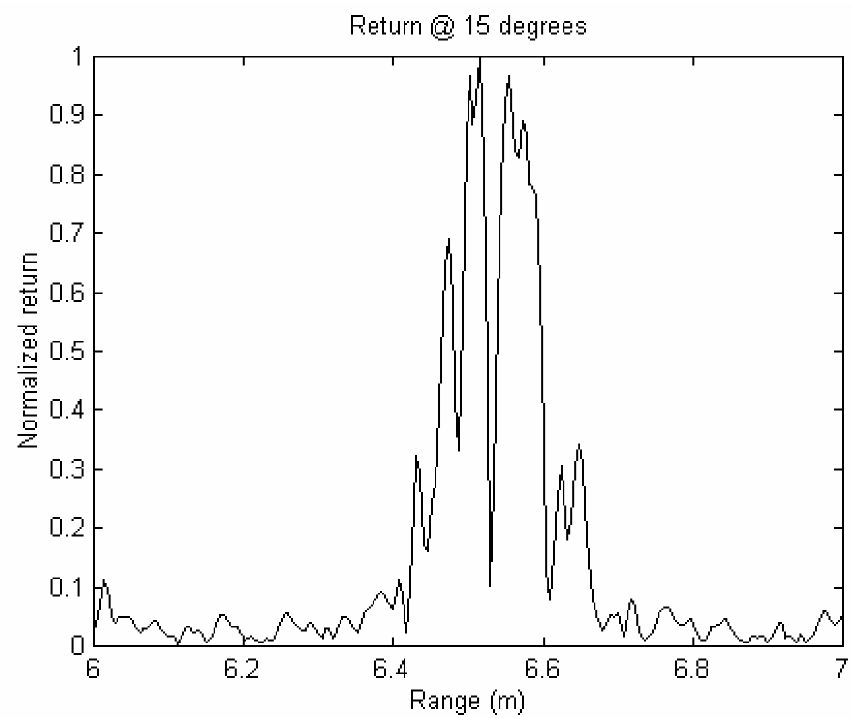
Scattering Theory- con't



Volume Scattering

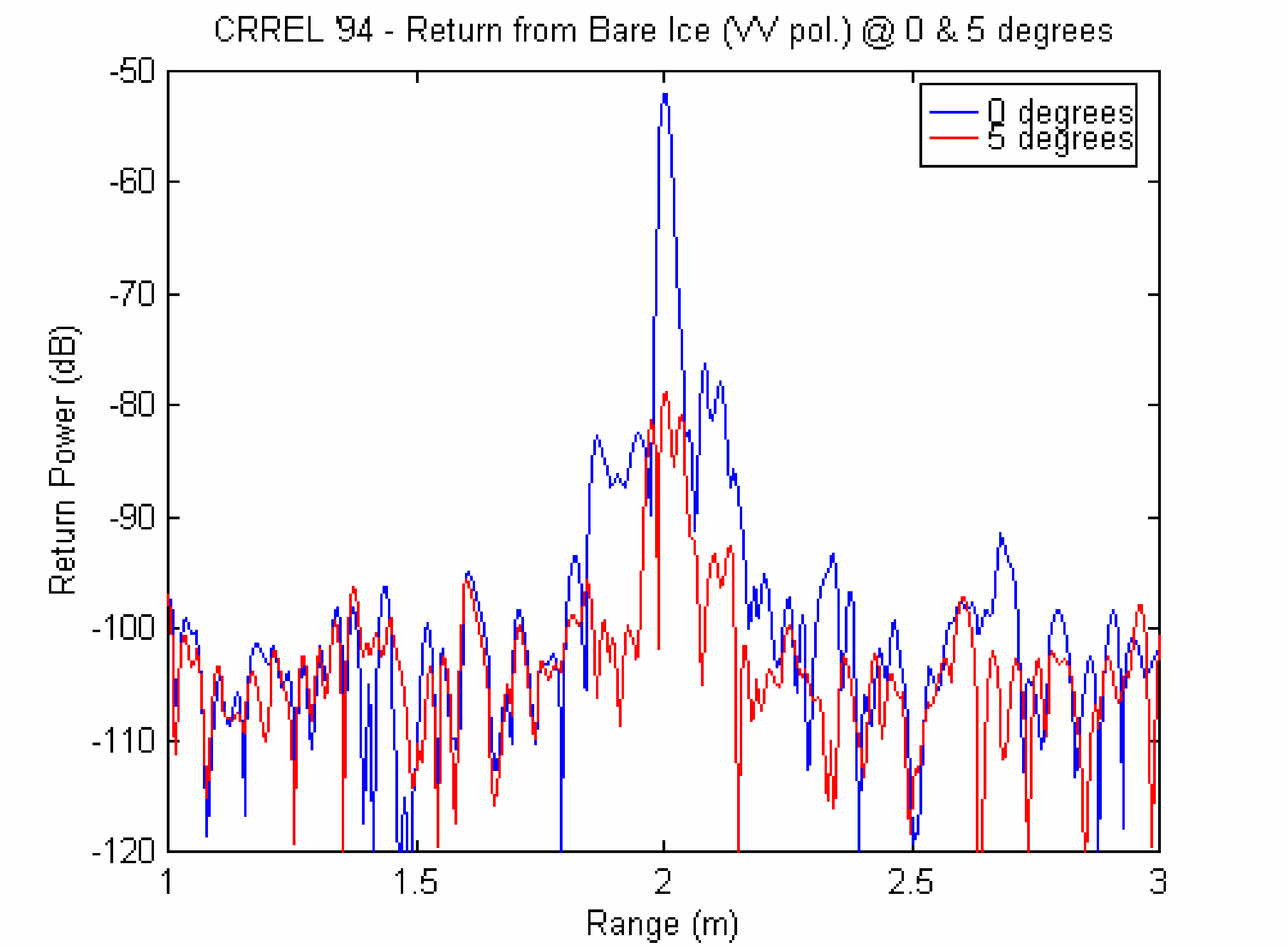


Return @ 0 degrees
Normalized return
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
6
6.2
6.4
6.6
6.8
7
Range (m)

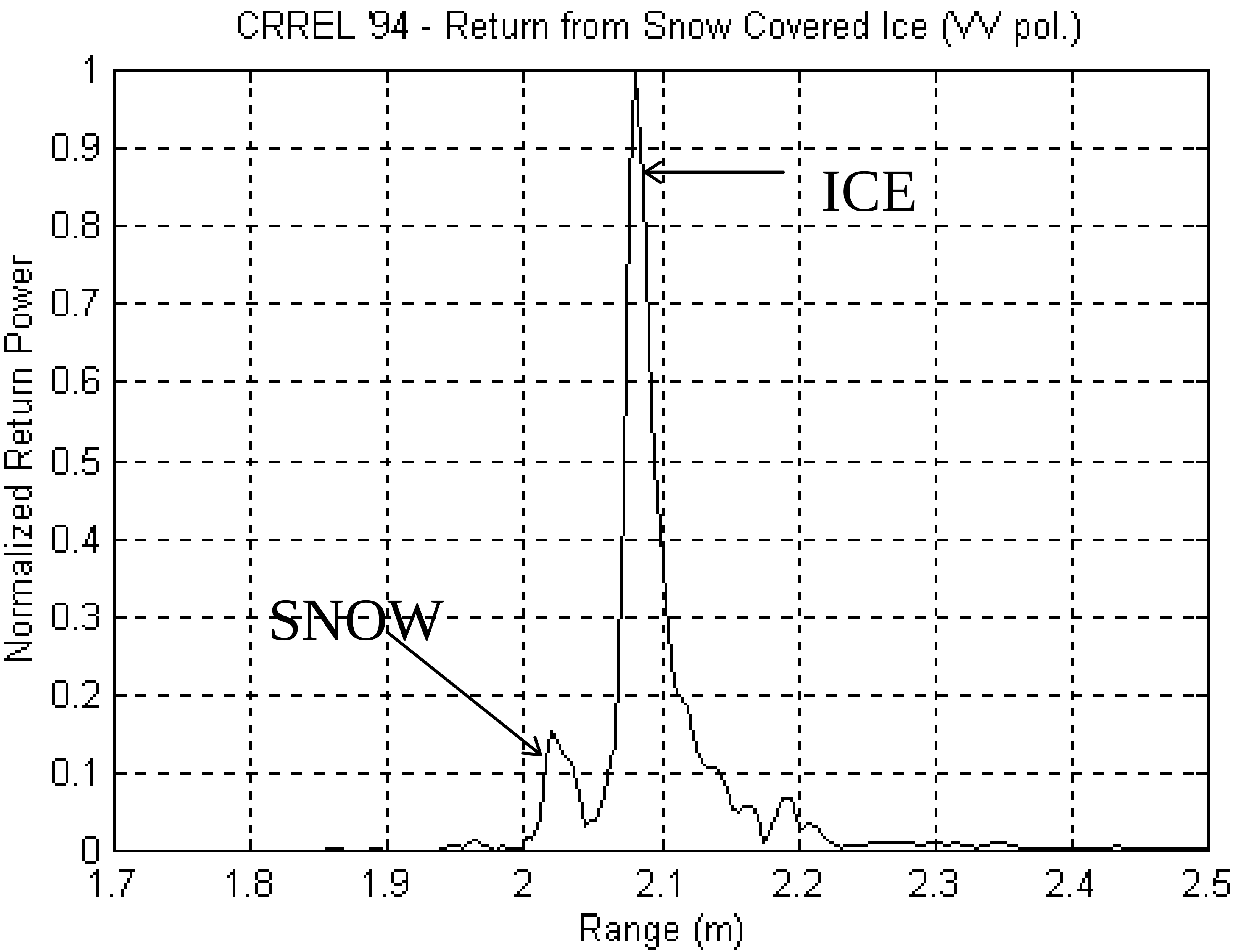


Return @ 15 degrees
Normalized return
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
6
6.2
6.4
6.6
6.8
7
Range (m)

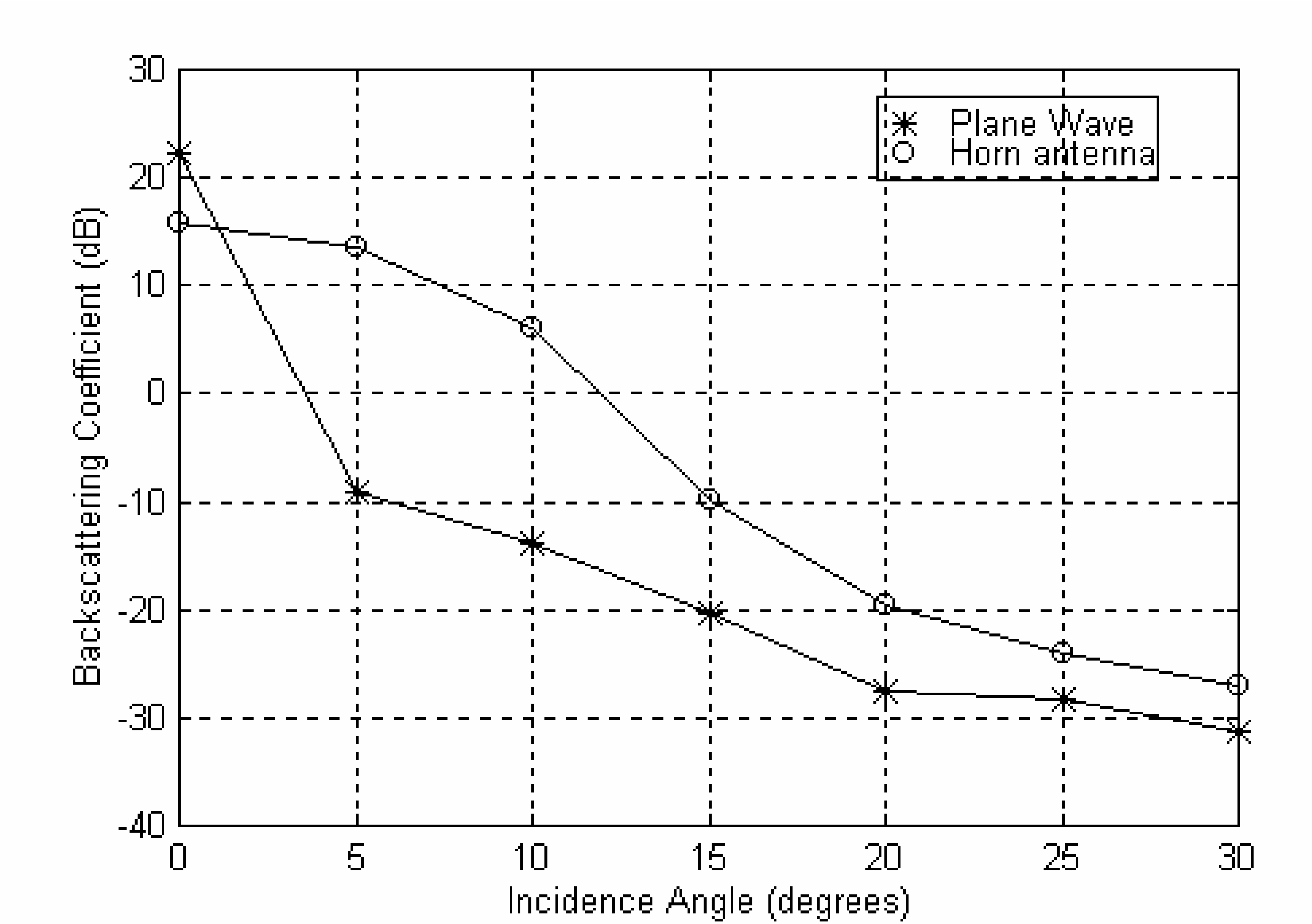
Results - Impulse Response I



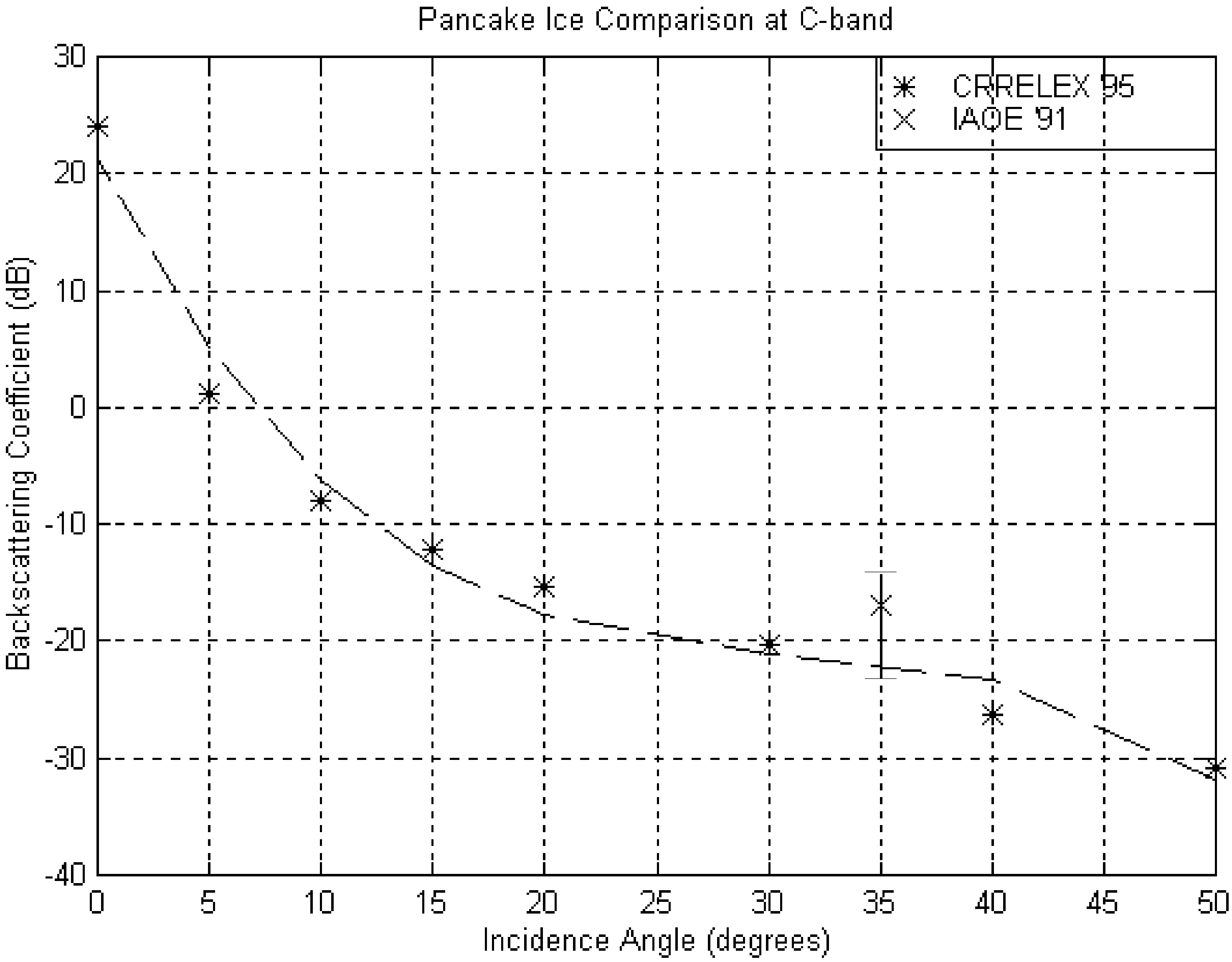
Results - Impulse Response II



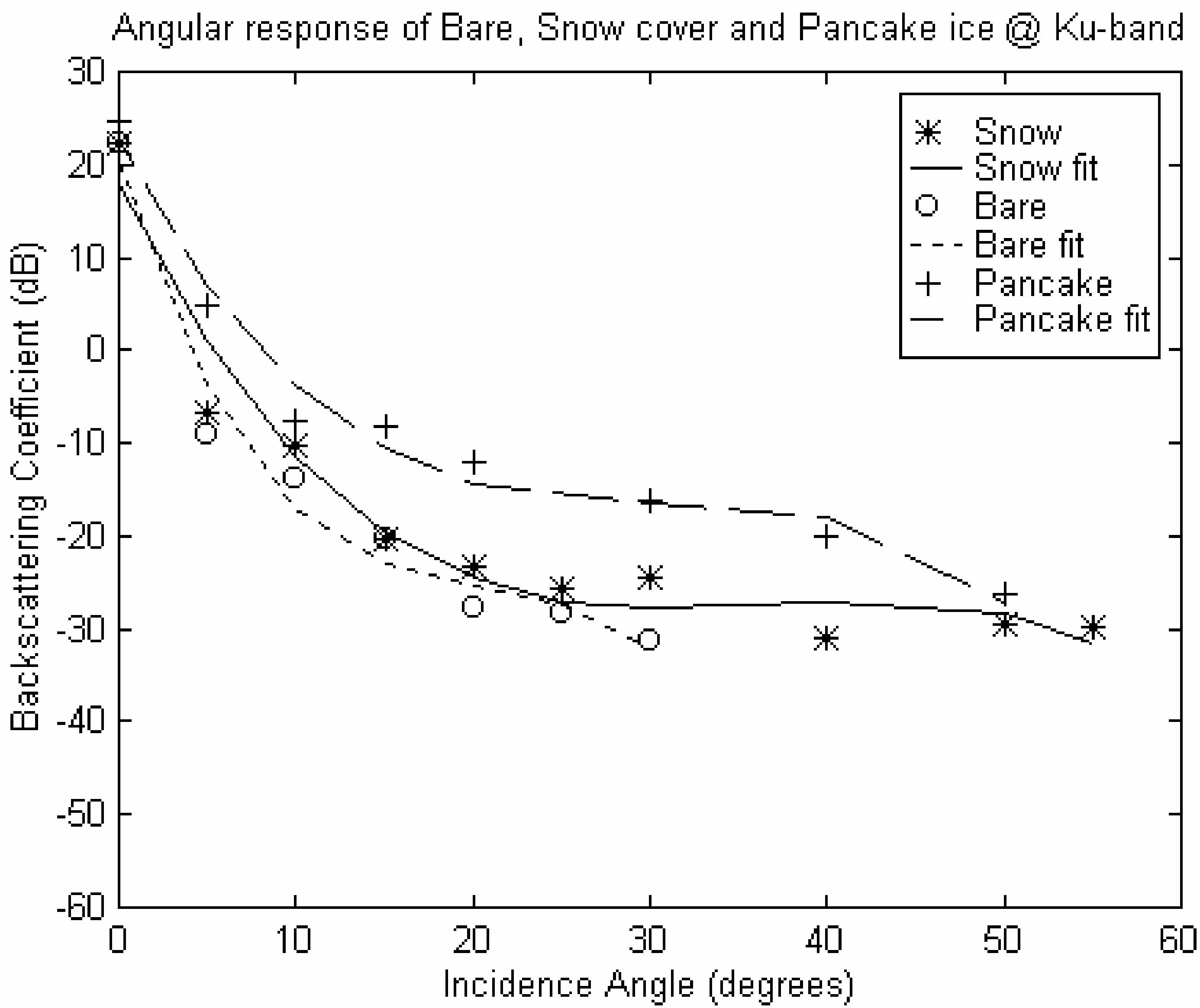
Results - Angular Scattering Response I



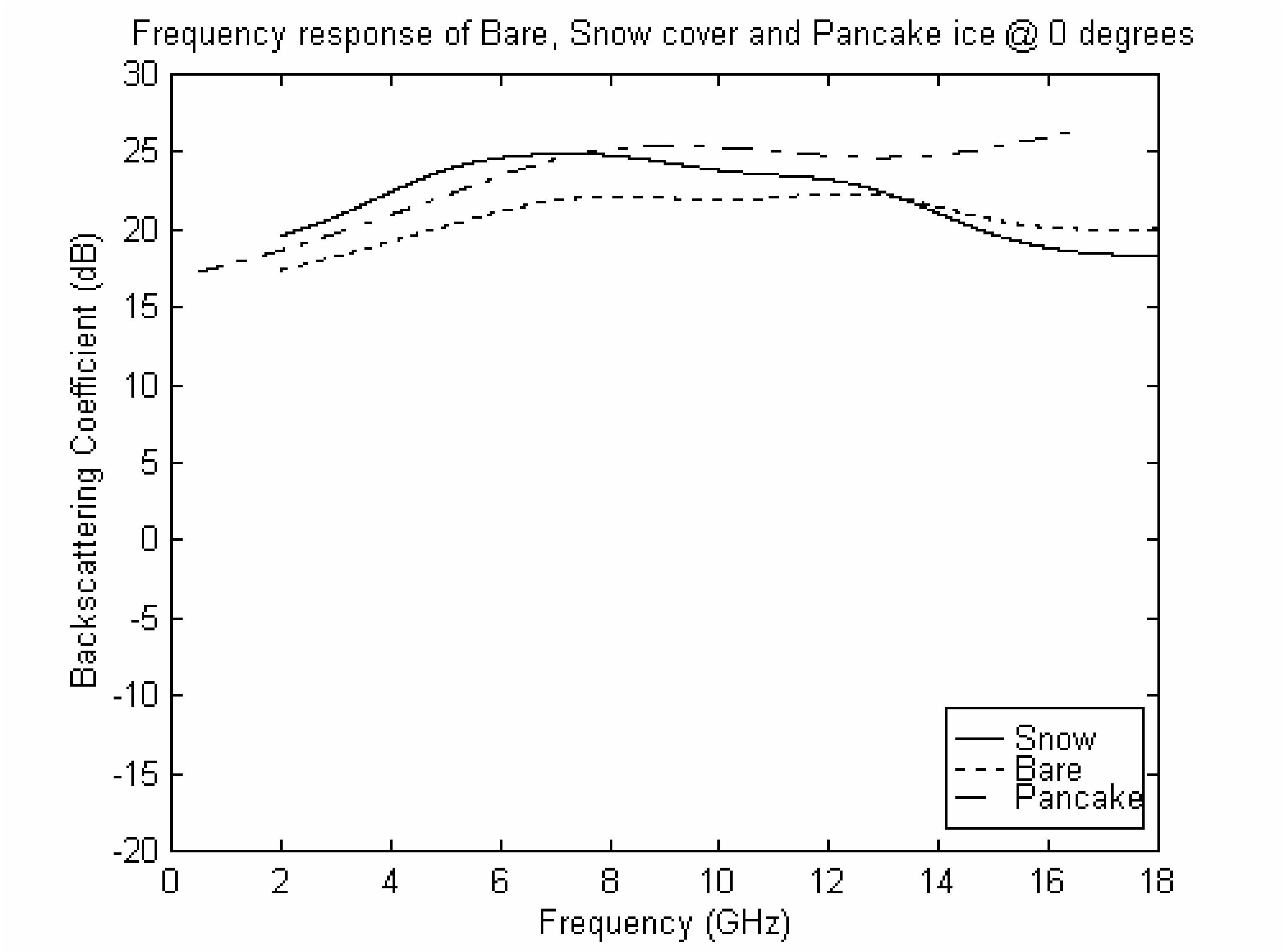
COMPARISON BETWEEN FIELD AND LAB MEASUREMENT OF PANCAKE ICE



ANGULAR RESPONSE OF BARE, SNOW COVER AND PANCAKE ICE



FREQUENCY RESPONSE OF BARE, SNOW COVER AND PANCAKE ICE



Conclusions and Future work

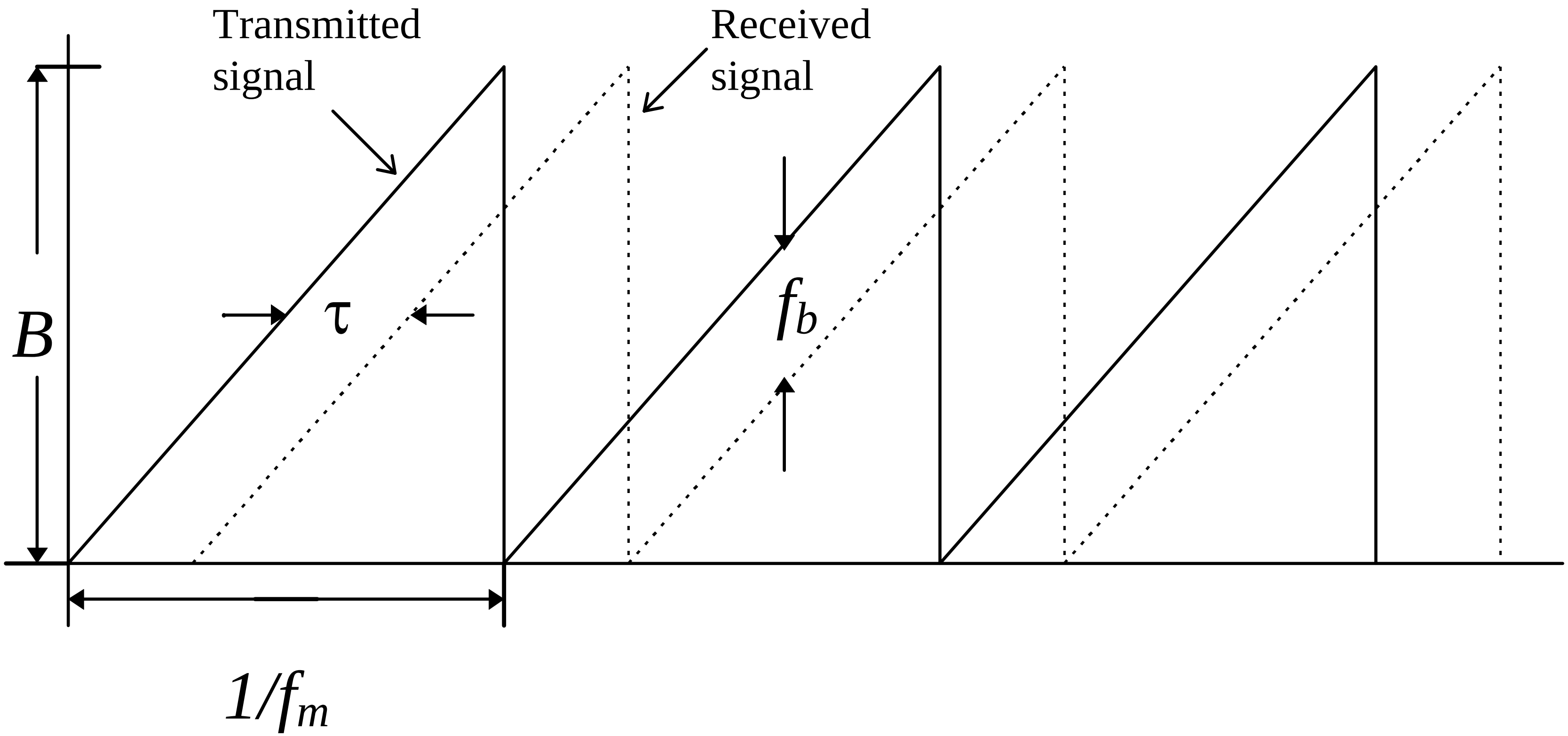
- We have developed an ultra wideband radar and a plane wave antenna to perform high angular and range resolution measurements
- Our results show that surface scattering is the dominant source of scattering for angles less than 30 degrees
- At nadir our results show that for pancake ice we get increasing incoherent contribution with increasing frequency
- Field measurement of pancake ice agree with lab measurement
- Accuracy can be further improved by applying cepstrum techniques to deconvolve the antenna pattern

Design of a Range-Gated Step-Frequency Radar using FMCW Concept

Objective

- To design a range-gated step-frequency radar/probe using FMCW concept

FM-CW Concepts



$$\tau = \frac{2R}{c}$$

$$f_b = \frac{2RBf_m}{c}$$

Principles of Operation 1

- Transmitted FM signal

$$v_t(t) = A\cos(2\pi f_c t + \pi B f_m t^2 + \theta_o)$$

where f_c is the center frequency
B is the sweep bandwidth
f_m is the rate of modulation

- Received FM signal

$$v_r(t) = \sum_i |\Gamma_i| A\cos(2\pi f_{bi} t + 2\pi f_c \tau_i + \pi f_{bi} \tau_i + \phi_i)$$

where $|\Gamma_i|$ is the magnitude of the reflection coefficient of the target at location i ϕ_i is the phase of Γ_i

Principles of Operation 2

- FFT of the received signal gives the magnitude and phase of the target at each beat frequency.

$$V_{fft}(f_b) = |\Gamma_{fb}|\exp(j\psi_{fb})$$

  where $\psi_{fb} = 2\pi f_c \tau_{fb} + \phi_{fb}$

- Apply a bandpass filter centered at the beat frequency corresponding to the target to obtain the complex Γ of the target

Principles of Operation 3

- Store the magnitude and phase of target for each center frequency (f_c)
- We now have

$$H(i) = |\Gamma_{tar}| \exp\{ j(2\pi f_i \tau_{tar} + \phi_{tar})\}$$

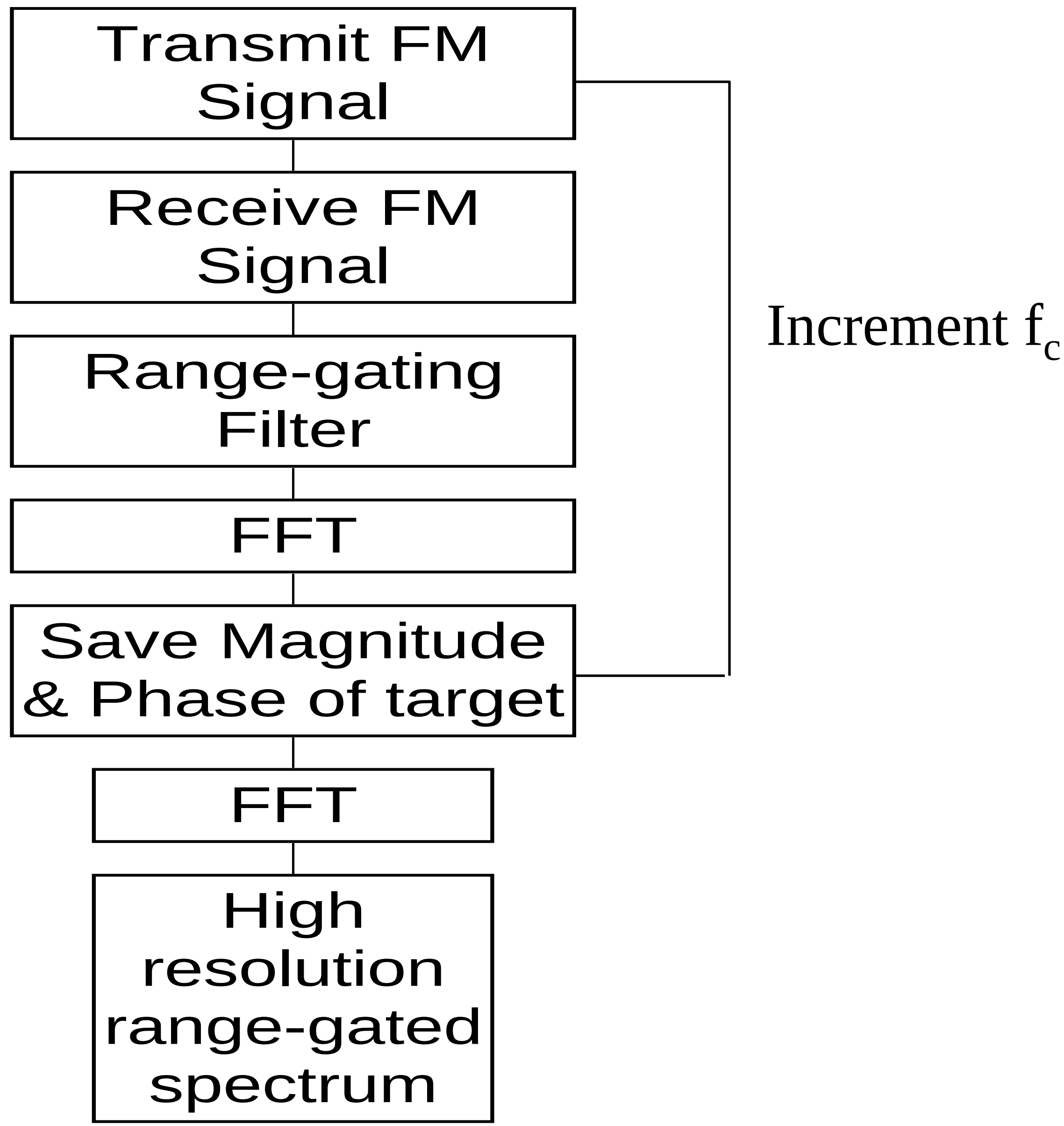
where $f_i = f_o + i\Delta f$

f_o is the start frequency

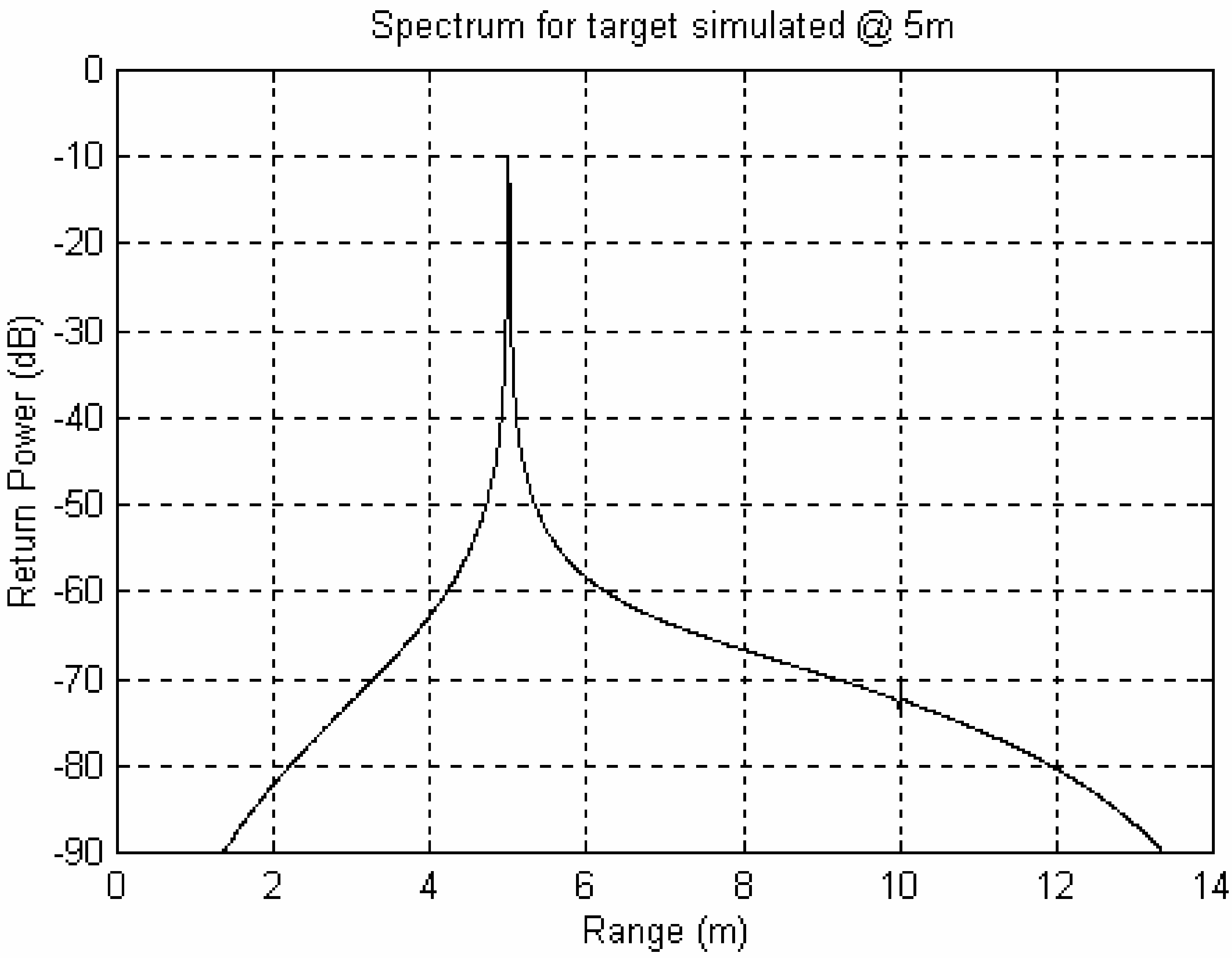
Δf is the frequency step size

- FFT of H(i) with respect to i gives us the high resolution spectrum of the target.

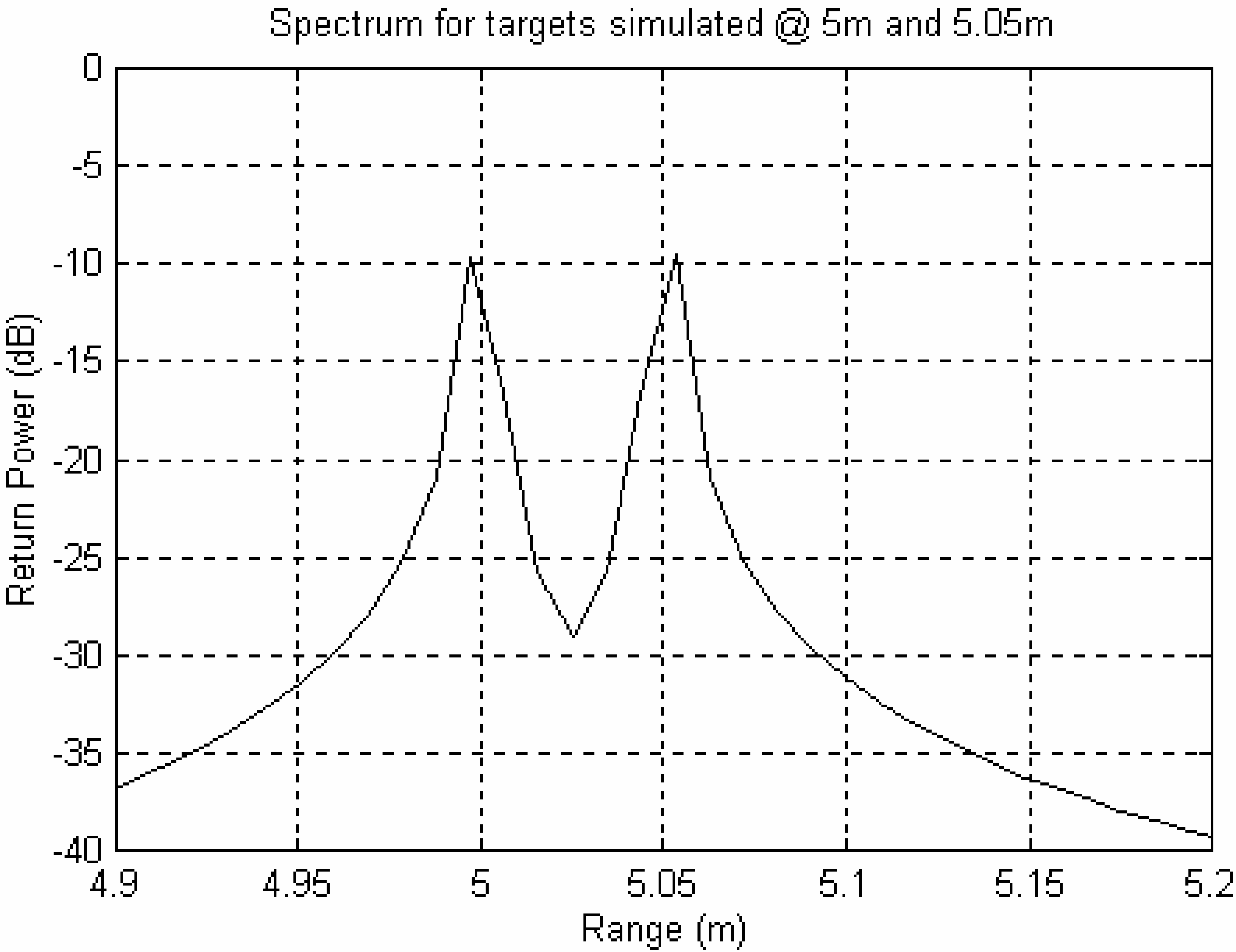
Summary of operation



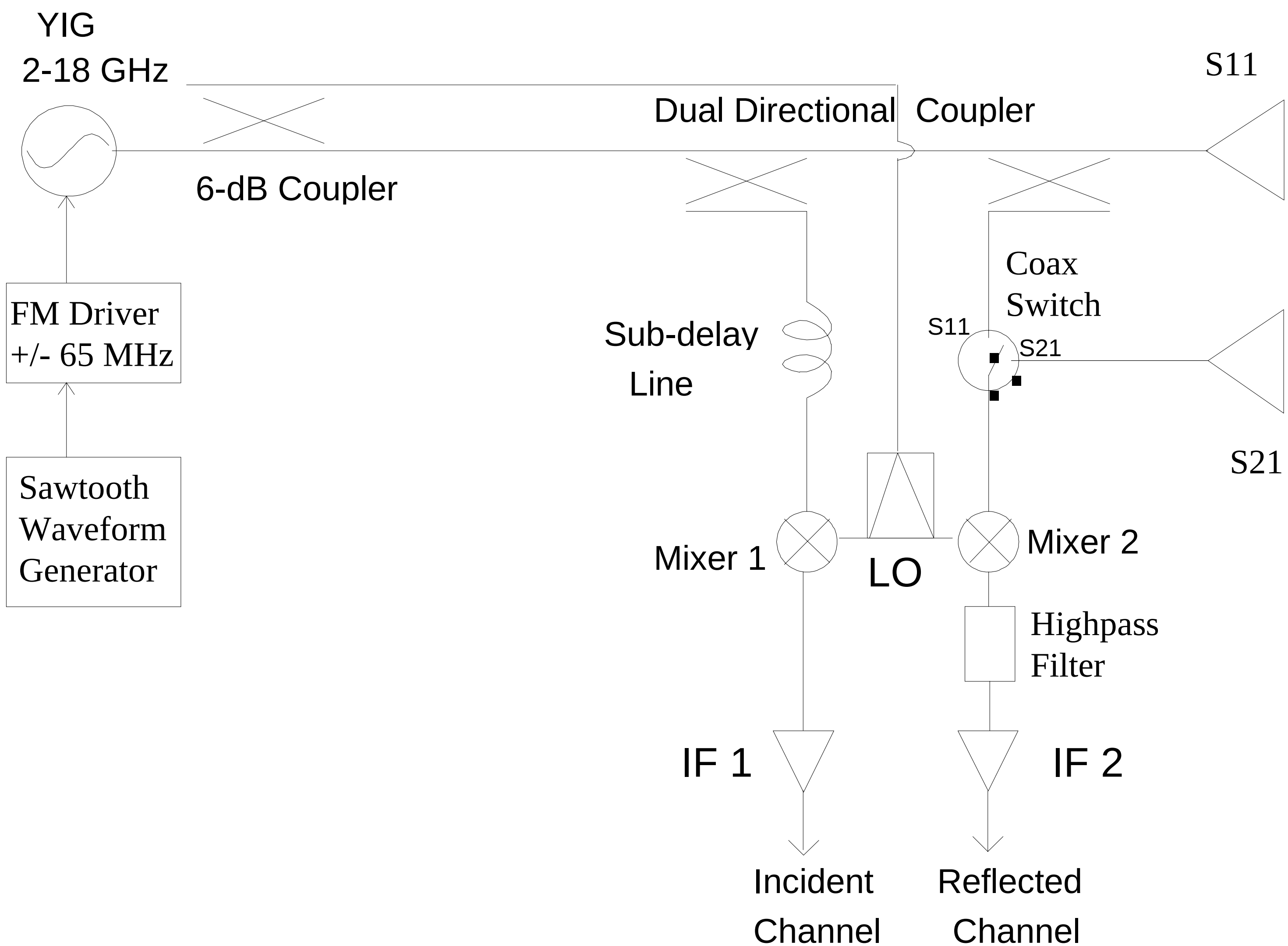
SIMULATION - I



SIMULATION - II



SYSTEM BLOCK DIAGRAM



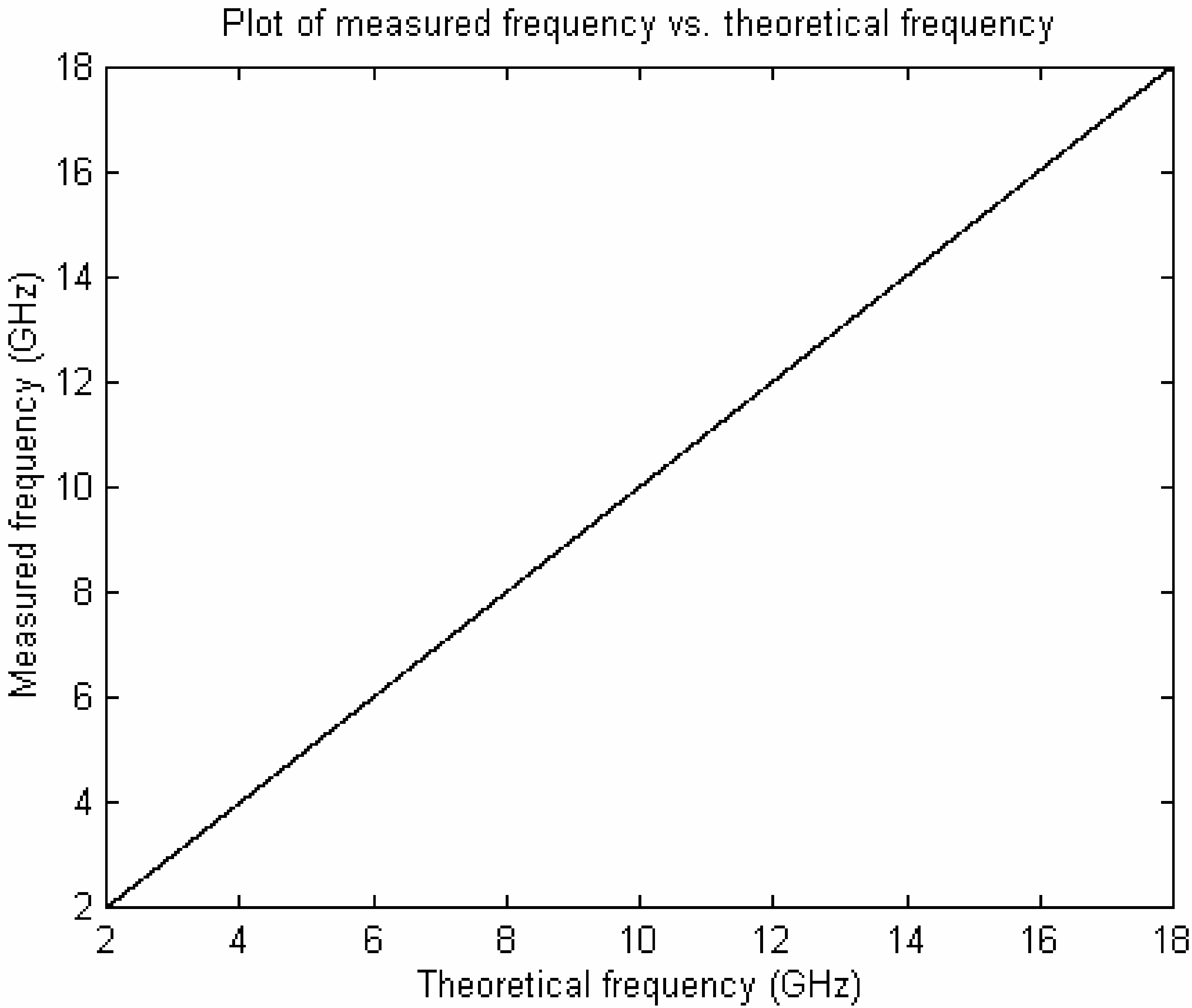
STEP-FREQUENCY RADAR PARAMETERS

Parameter	**Value**
Center Frequency	2.37 - 17.65 GHz
Center Frequency step size	11.7 MHz
Number of Frequency steps	1300
Range resolution	0.98 cm
Max. Unambiguous Range	29 m

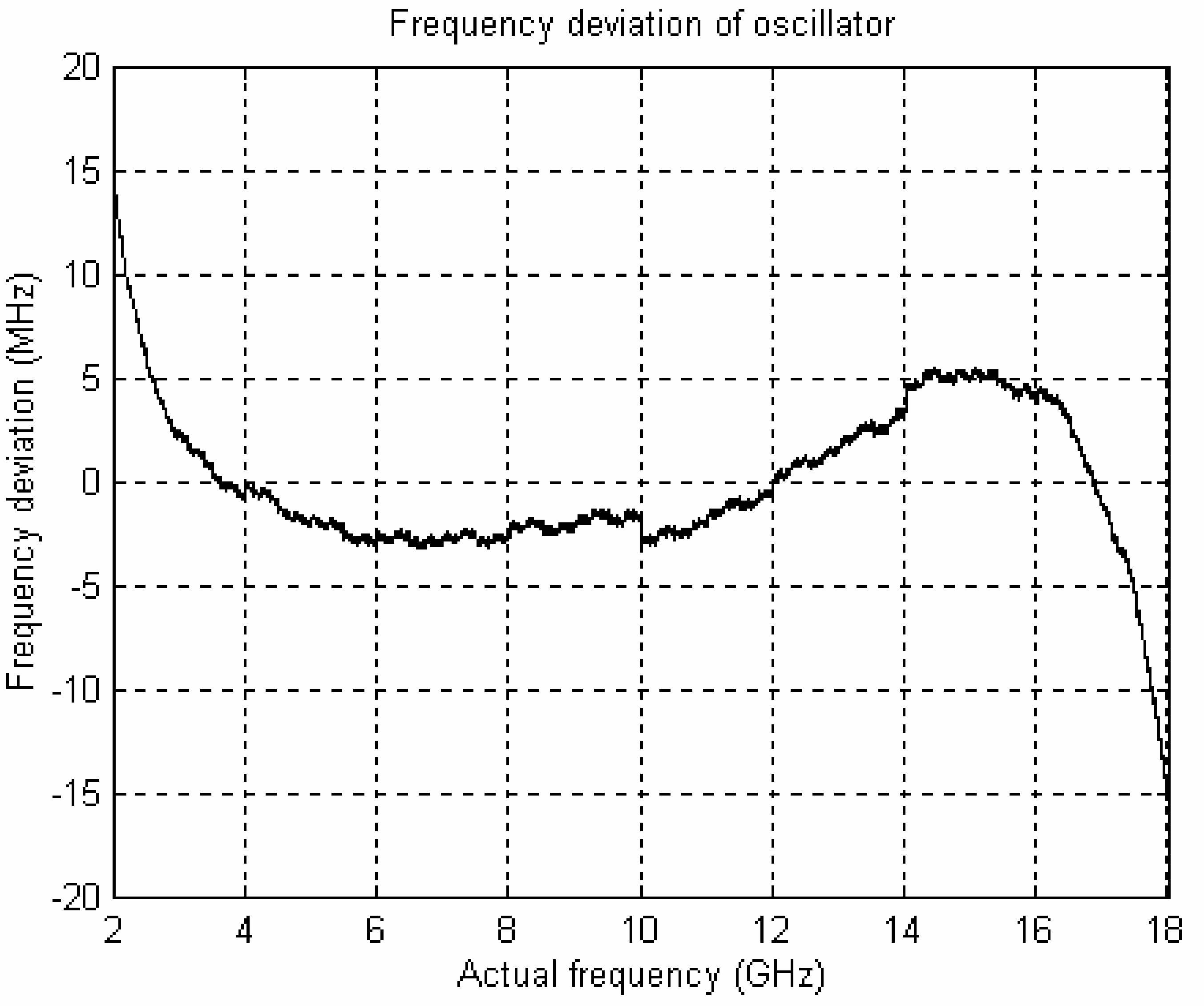
LINEARITY OF OSCILLATOR’S SWEEP

- The performance of the radar is dependent on the linearity of the oscillator’s sweep
- To test the linearity of the oscillator’s sweep, we measured all 4096 of the oscillator’s frequency using a spectrum analyzer

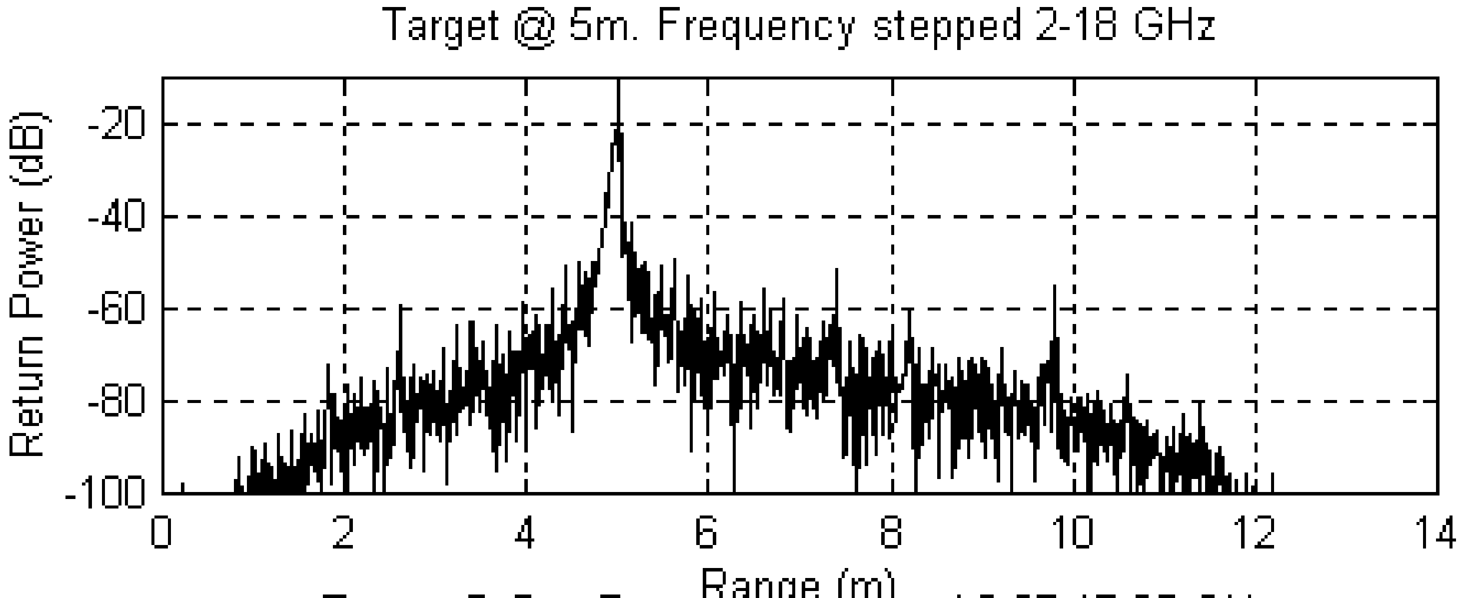
LINEARITY OF OSCILLATOR’S SWEEP - I

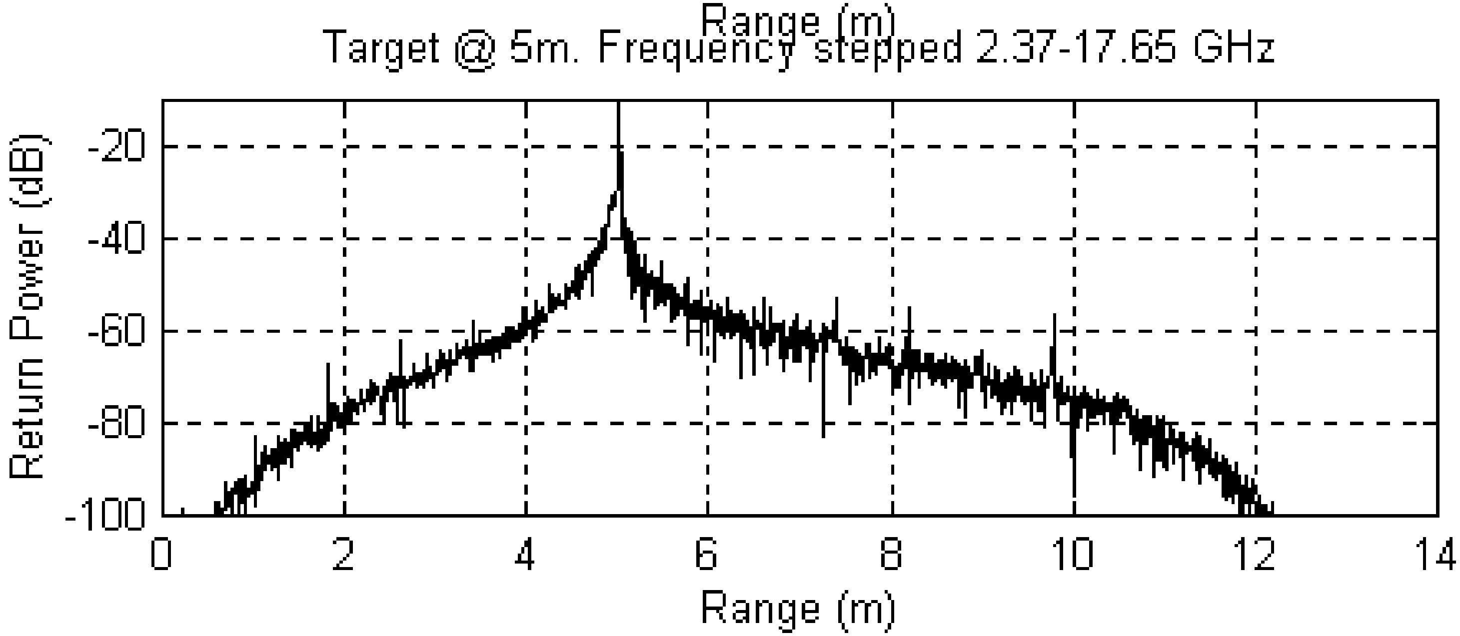


LINEARITY OF OSCILLATOR’S SWEEP -II



SIMULATION WITH OSCILLATOR'S MEASURED FREQUENCY





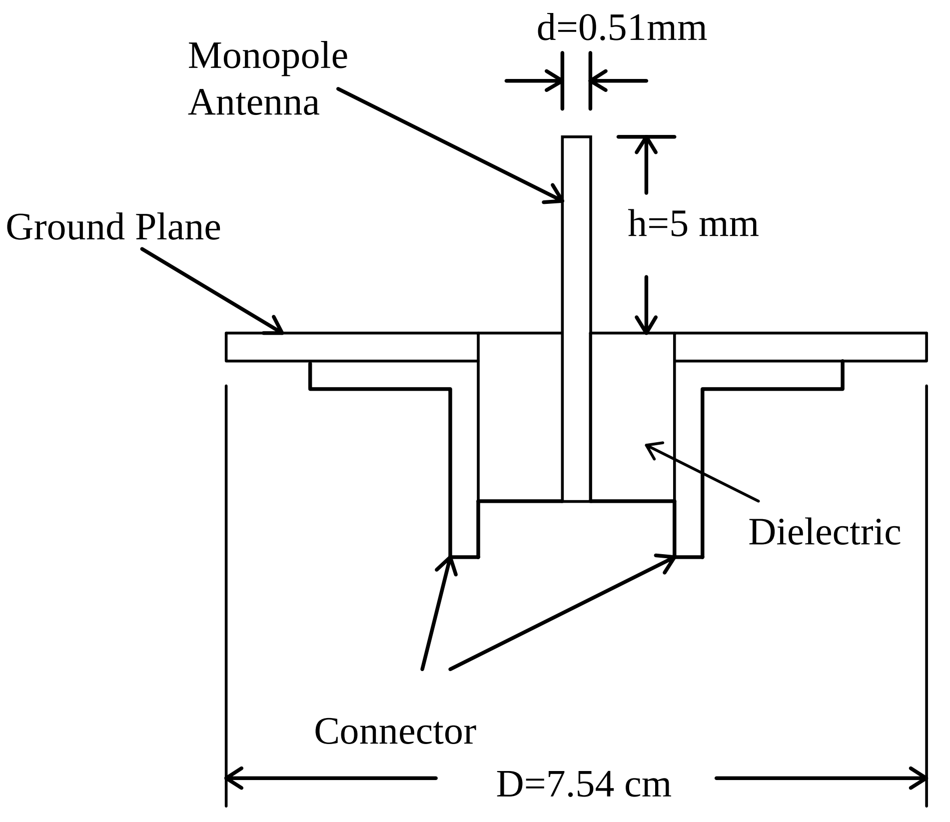
SYSTEM TESTS

- To test the system’s ability to measure the permitivity of materials we developed a cylindrical monopole antenna
- To use the existing models to obtain the relative permittivity of materials, the antenna has to resonate
- To resonate, the ratio of the length to diameter must be greater than 10

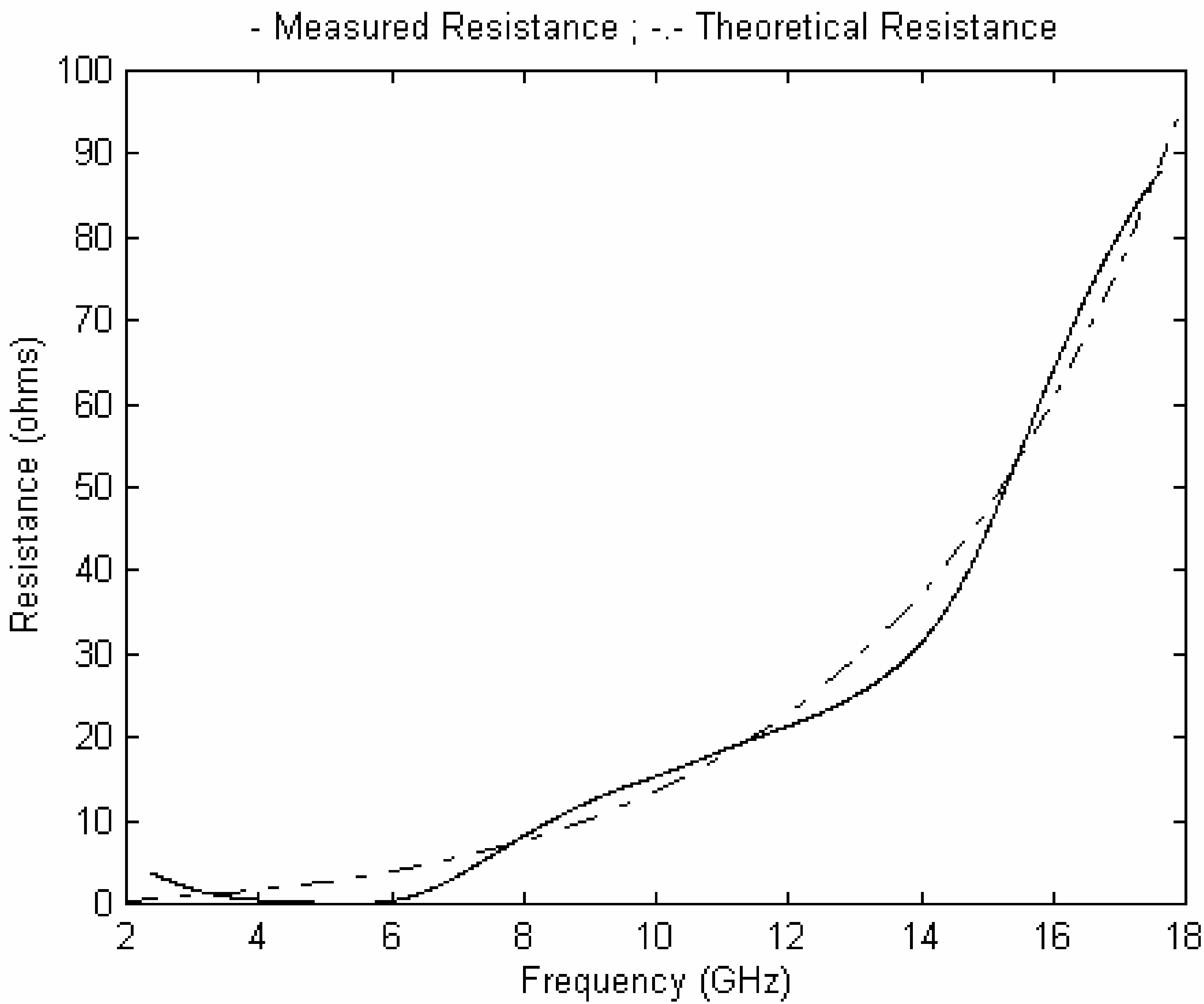
SYSTEM TESTS - II

- The length of the antenna for a given resonant frequency is

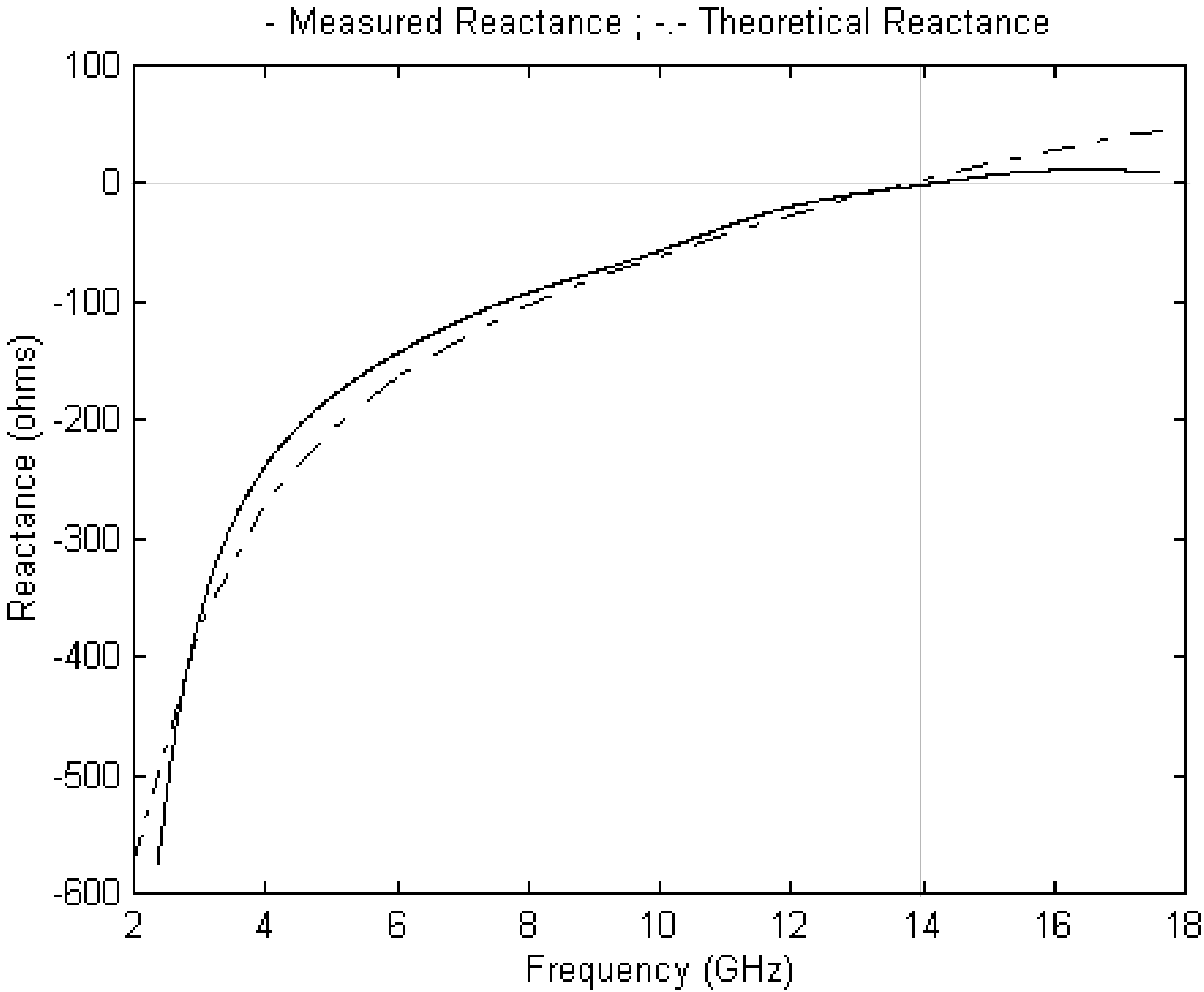
$$h = \frac{0.24c}{f} - \frac{d}{2}$$



REAL PART OF INPUT IMPEDANCE



IMAGINARY PART OF INPUT IMPEDANCE



MODELLING THE INPUT IMPEDANCE

$$Z(\omega,\varepsilon) = Z_o \frac{1+\Gamma(\omega,\varepsilon)}{1-\Gamma(\omega,\varepsilon)}$$

Deschamp's Theorem

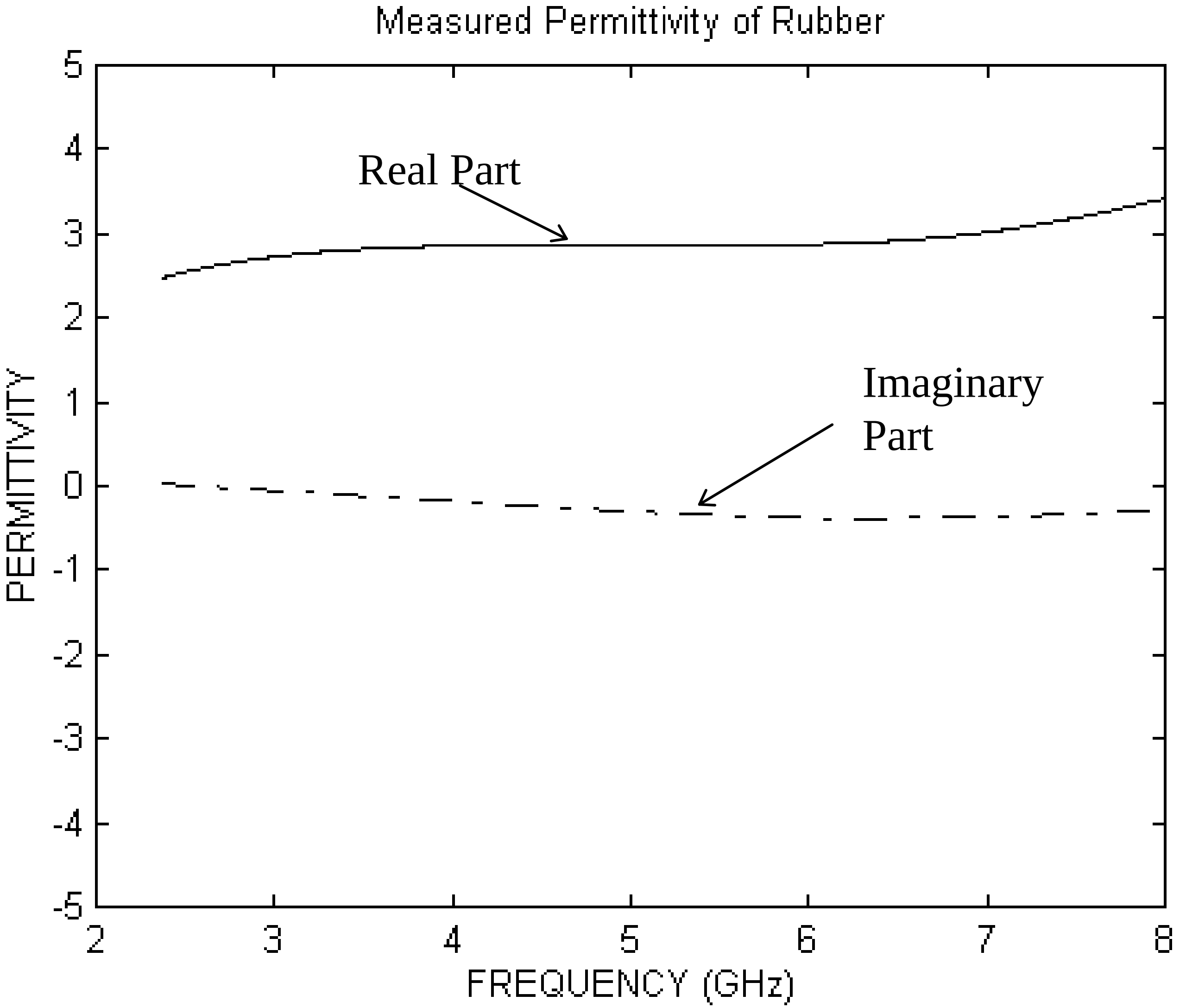
$$\sqrt{\varepsilon_{r1}} Z_1(\omega_1,\varepsilon_{r1}) = \sqrt{\varepsilon_{r2}} Z_2(\omega_2,\varepsilon_{r2})$$

$$Z_n(kh) = \sqrt{\varepsilon_r} Z(\omega,\varepsilon_r) = \frac{kh}{k_o h} Z(\omega,\varepsilon_r)$$

$$Z_n(kh) \approx j\frac{K}{kh}\left[\frac{1+jb_1(kh)+b_2(kh)^2}{1+jb_1(kh)+a_2(kh)^2}\right]$$

$$\varepsilon_r = \left(\frac{kh}{k_o h}\right)^2$$

MEASURED PERMITTIVITY OF RUBBER

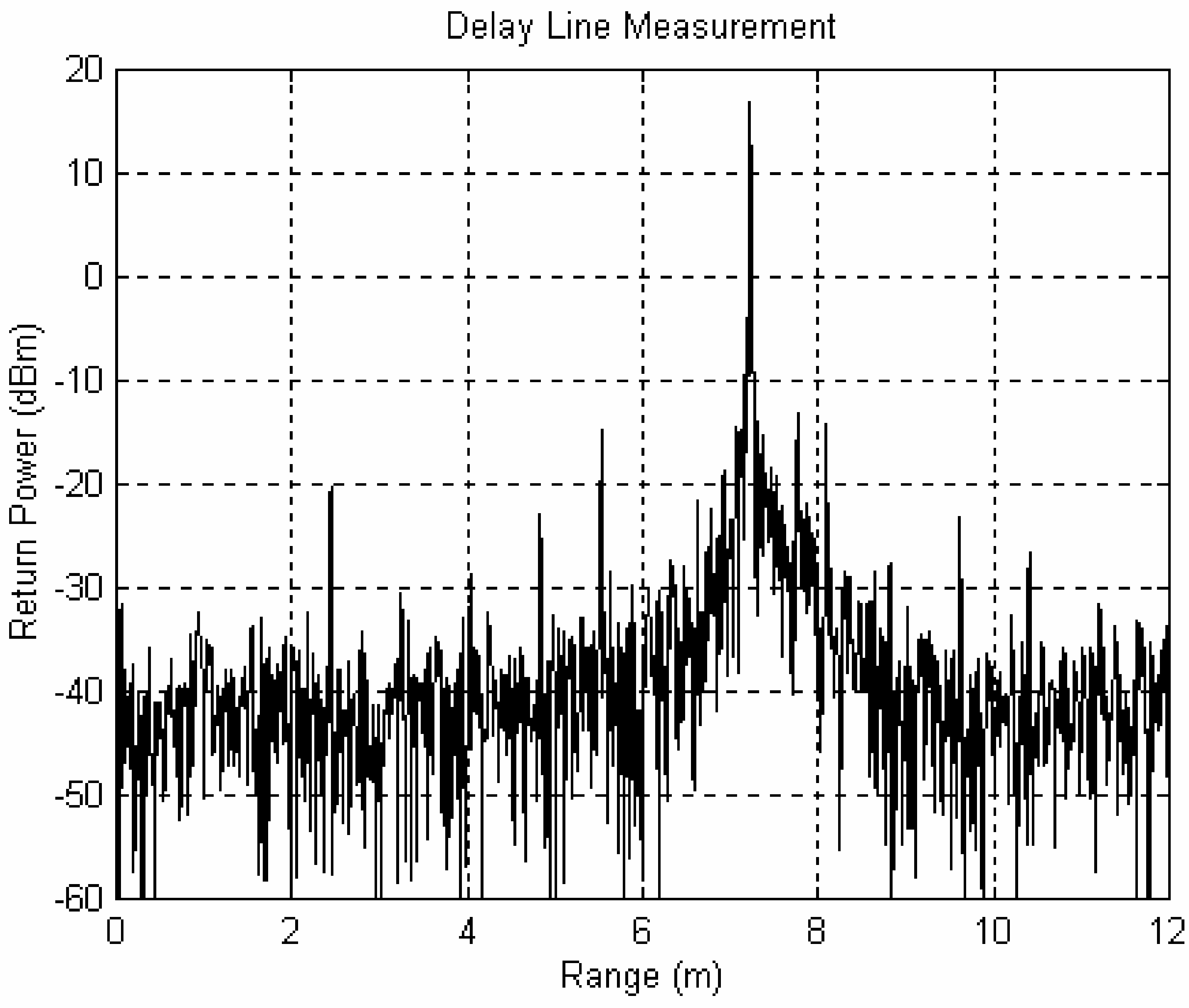


NOTE ON CALIBRATION

- Reflection from the medium did not appear at the plane of calibration
- Applied phase correction term to the reflection coefficient to correct for this lag

$$Z(\omega,\varepsilon) = Z_o \frac{1+\Gamma(\omega,\varepsilon)e^{-2\alpha l - j2\beta l}}{1-\Gamma(\omega,\varepsilon)e^{-2\alpha l - j2\beta l}}$$

DELAY LINE TEST



Radar Comparison

- FMCW Radar
  - Long range
  - Poor resolution
- Step-frequency radar
  - High resolution
  - Very short range
  - Need to use network analyzer for ultra wideband operation
  - Need very fast switches to implement range gate

- Our Radar
  - FMCW radar's range
  - Ultra wideband operation
  -Range gate can be implemented with filters
  - Range-gated spectrum with the resolution of step-frequency radar
  - Can be operated with a single antenna

CONCLUSION & FUTURE WORK

- Shown that the step-frequency radar can be operated and range-gated using the FM-CW concept
- Permittivity measurement using this system agrees with theoretical results
- Radar can be used for high-resolution probing of geophysical surfaces and also for ground-pentration applications
- Performance can be improved using Direct Digital Synthesizer (DDS)