Surface-Penetrating Radar for Mars Exploration

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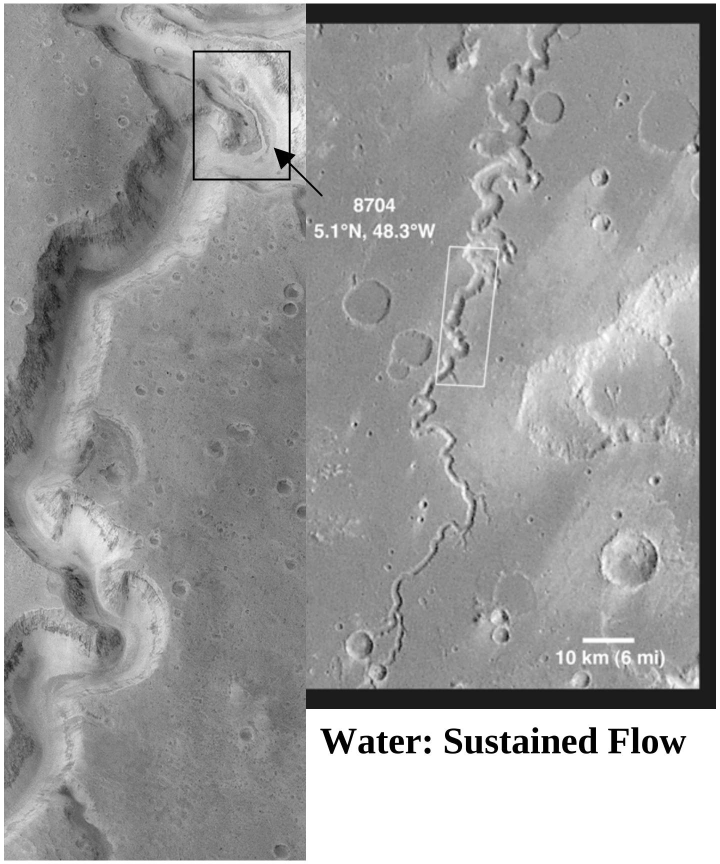
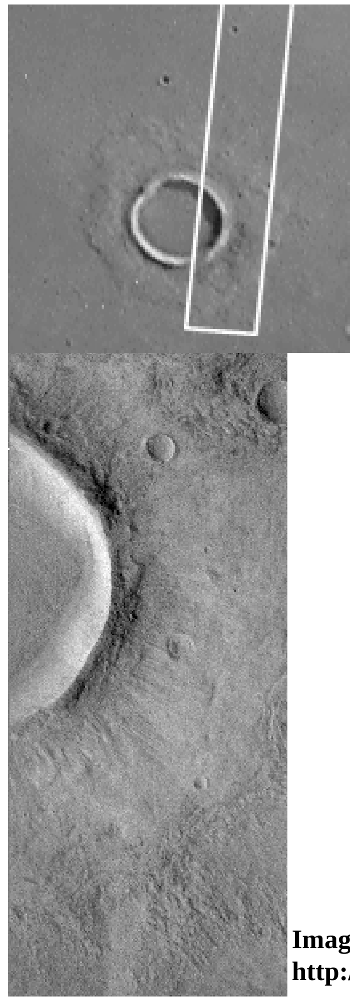
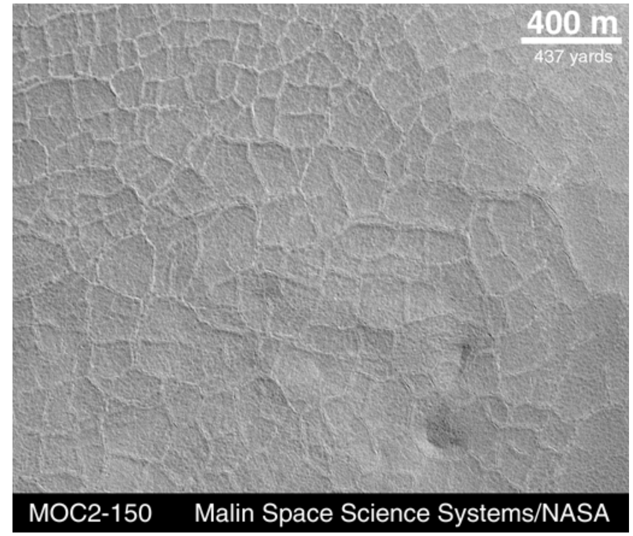
Indicators of Water/Ice



Water: Sustained Flow

Fluidized Ejecta





Freeze-Thaw?

Is there water on Mars?
If so, where is the water now?
How do we find this water?
Why is water so important?
"White Mars" Carbon Dioxide?

Images from Mars Global Surveyor.
http://mars3.jpl.nasa.gov/mgs/

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Why is water so important?

Mars Exploration Program Analysis Group (MEPAG).

Goal - detection of water within the subsurface of the planet.

Knowledge of the 3-dimensional distribution and state of water.

- a better understanding the geological history of the planet.
- guidance in the search for evidence of past or present life.
- crucial resources for future manned exploration.

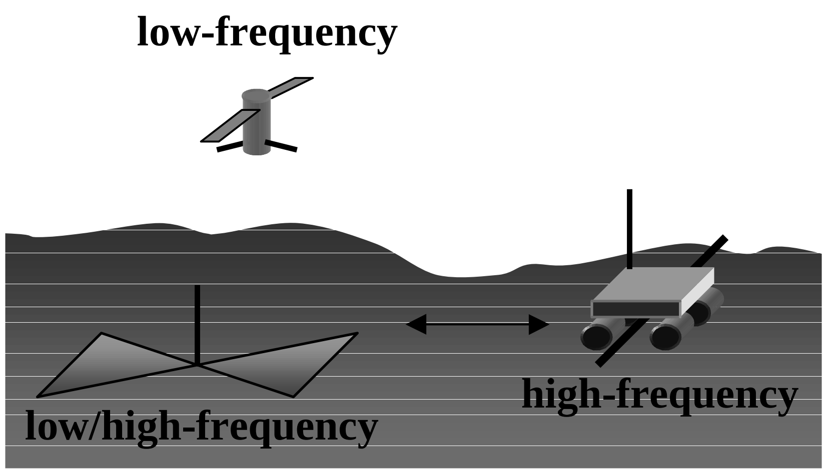
Both orbital- and lander/rover-based systems will be used.

- global coverage.
- high-resolution stratigraphy mapping.

How do we find this water?
Surface-Penetrating Radar

Surface-Penetrating Radar

- Been used on earth in many environments.
- Non-intrusive, there is no direct contact with the ground surface.
- Remote operation.



Considerations

- Composition of the soil.
- Electromagnetic Attenuation.
- Penetration depth.
- Unambiguous Detection.

Surface Penetrating Radar is one of many geophysical methods that could be used. (Low-Frequency EM, Seismic, Drilling, Gravity, …)

Research Goals

- Develop a complete SPR simulator and generate responses over a variety of geological locations.
- Construct a compact, lightweight, low-power radar system.
- Test the system over locations containing subsurface deposits of ice and water.
- Provide a description for a proposed system.

Development of a SPR
OUTLINE

Simulations
Determine radar capabilities and optimize parameters.

Radar System
Prototype - off-the-shelf components and evaluation boards.
evaluate antenna configurations.

Experiments
Lawrence, Kansas and Fairbanks, Alaska.
Locations containing deposits of ice and water.

Signal Processing
Reduce sidelobe clutter and interpret data.

Conclusions and Future Work

Simulations

Literature shows little information of radar performance on Mars.

- Only show zero-order models.
- General plots of attenuation, clutter.

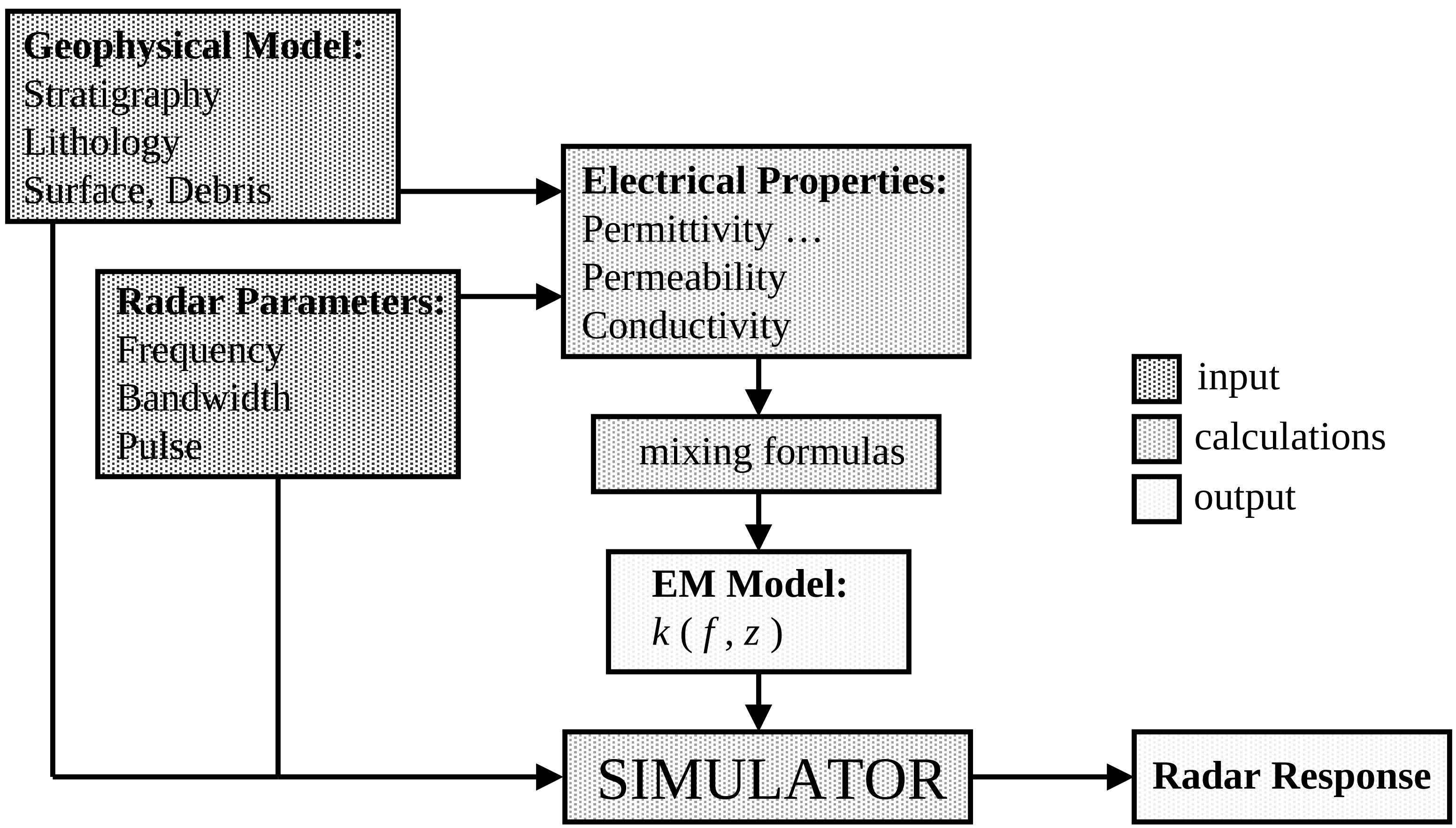
The response of a surface-penetrating radar is more complicated.

There is a need to asses radar performance using more realistic models including:

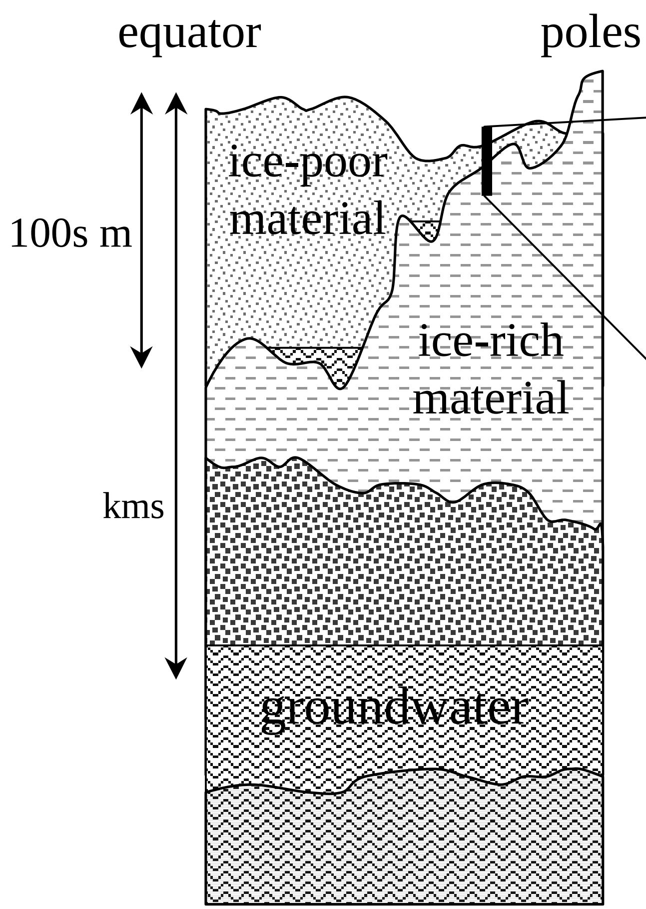
- Surface roughness (clutter).
- Volume debris.
- Fine-scale layering.

Simulations

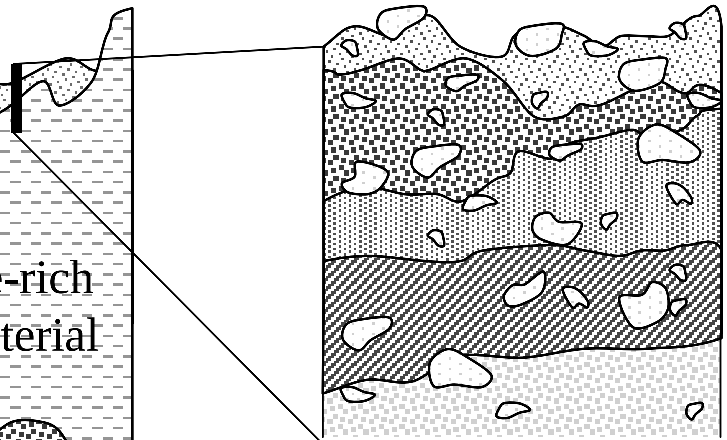
Simulation Flow Chart



Geophysical Model
Stratigraphy



Global Stratigraphy



Local Stratigraphy

Local Scale:

highly resurfaced and inter-bedded with debris (rocks).

- volcanoes
- wind blown
- impact craters
- debris flows
- water

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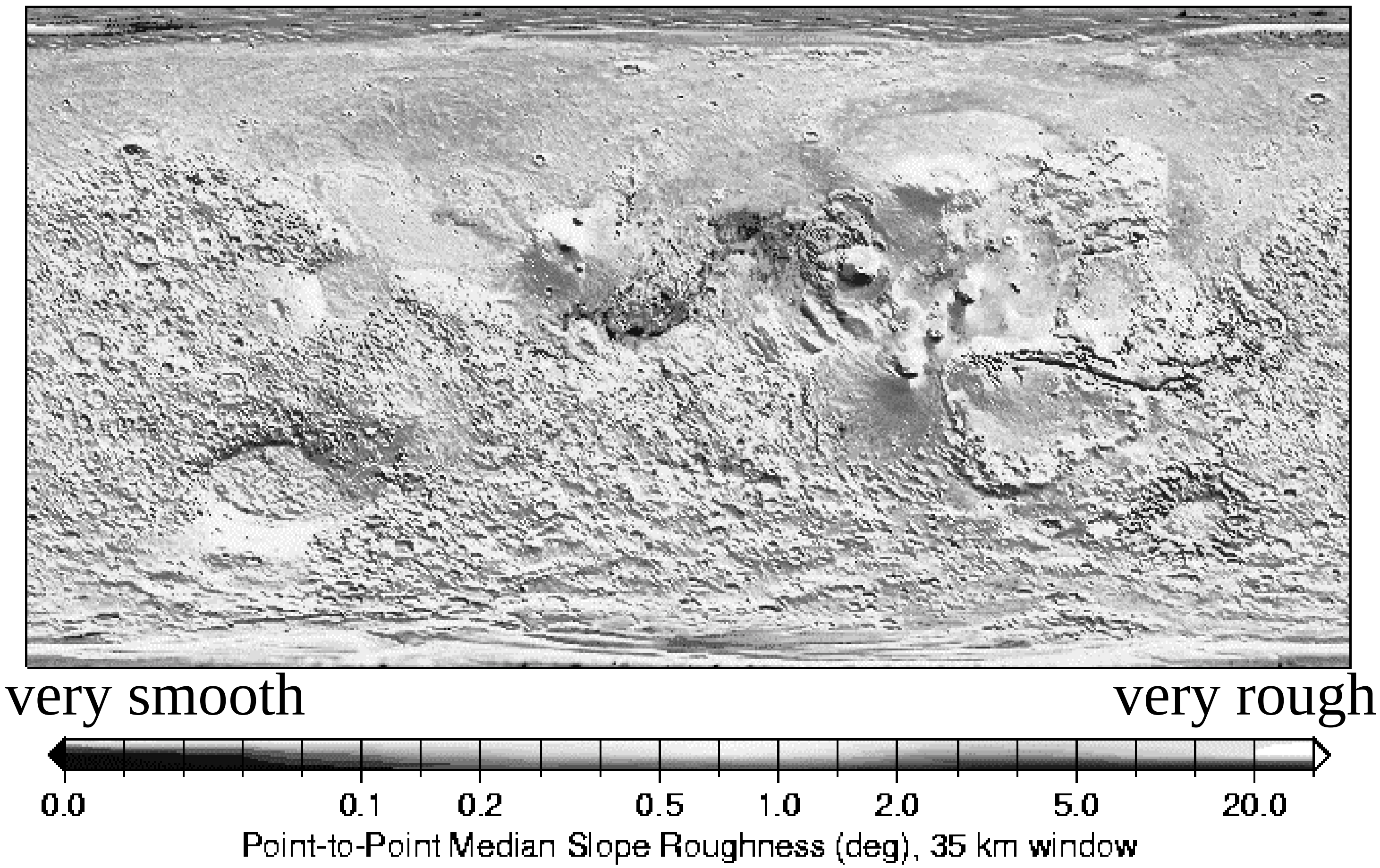
Geophysical Model
Random Surface and Debris

Mars Pathfinder Image

Rocks	
Size	1 cm – 7 m
Distribution	< 30 %

Rough Surface Parameters		
	Large Scale	Small Scale
rms height: σ		0.1 – 1 m
corr. length: l	200 m – 20 km	
rms slope: s	< 0.02 rad	0.1 – .5 rad

Geophysical Model
Global Surface Roughness



From the Mars Orbiter Laser Altimeter (MOLA) website

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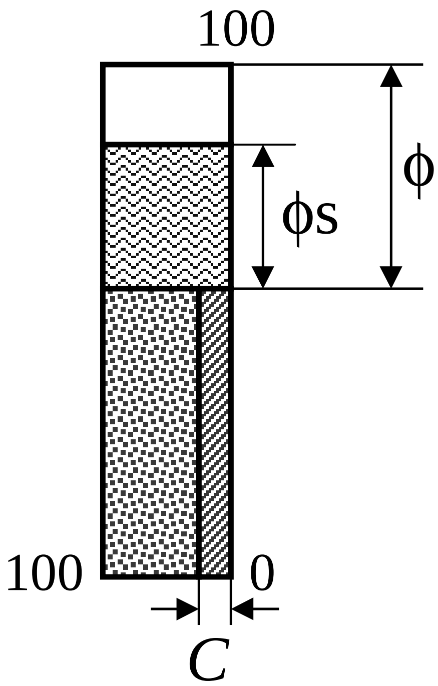
Simulations
Electrical Properties



air:

water/ice, saturation (S):

$$\varepsilon_w = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau} - j\frac{\sigma}{\varepsilon_0\omega}$$

Soil, porosity (ϕ), iron concentration (C):

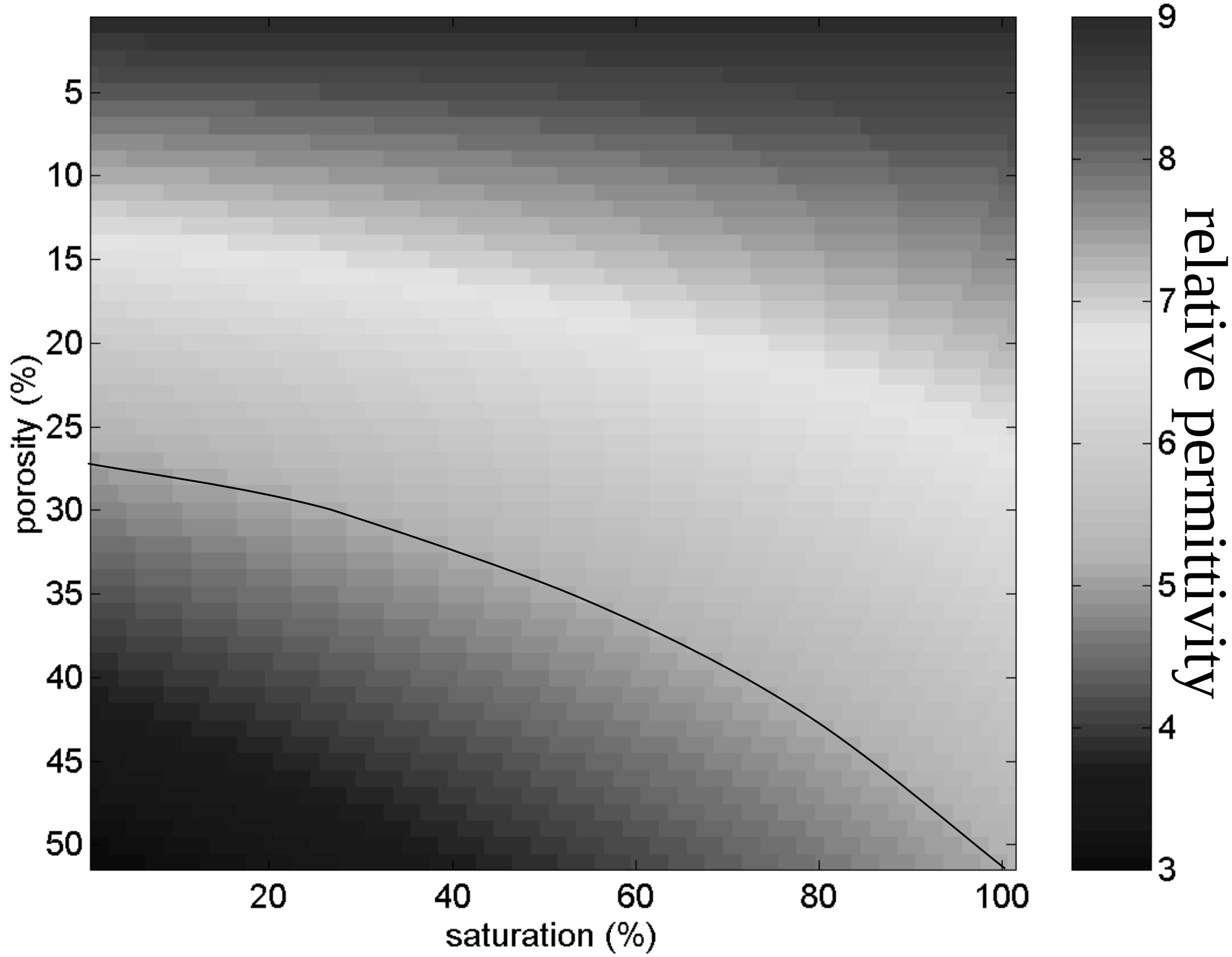
$$\varepsilon_s' \cong 9.0$$

$$\tan(\delta_s) = \varepsilon_s'' / \varepsilon_s' \cong (1.75 + 82.5C) \cdot 10^{-3}$$

Geometric Mean Mixing Formula

$$\varepsilon_m = \varepsilon_a^{\phi(1-s)} \varepsilon_w^{\phi s} \varepsilon_s^{(1-\phi)}$$

Electrical Properties
Air/Ice/Soil Mixture



Simulations
One-Dimensional Simulator

Subsurface is modeled as a layered media.

For each layer:

$$k_n(f) = \omega\sqrt{\varepsilon_n(f)\mu_n(f)}$$ **EM profile**

$$u_n(z) = A_n^+ \exp(-jk_{zn}z) + A_n^- \exp(jk_{zn}z)$$

$$H(f) = \Gamma(f) = A_0^+ / A_0^-$$

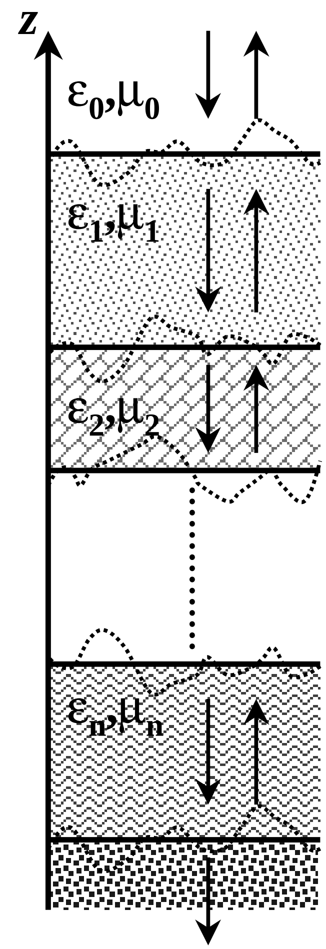
Transmitted Field:

$$P(f) = F\{p(t)\}$$

Received Field:

$$R(f) = H(f)P(f)$$

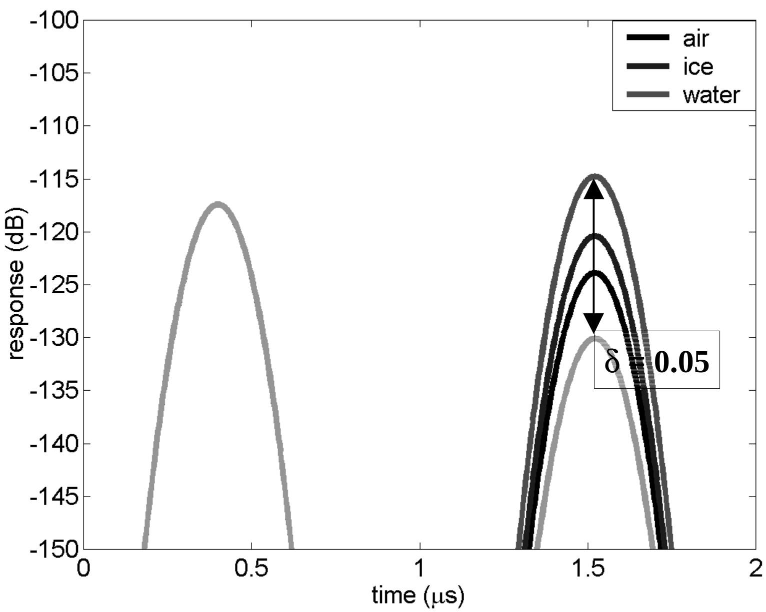
$$p(t) = F^{-1}\{P(f)\}$$



Simulations
Simple 1D Model

Two Layer Model, 20 MHz fc/5MHz BW

Depth	Lithology	ϕ%	s%	fill	ε_r
400km	air	100	-	-	1.0
100m	eolian sediment	50	0	air	2.8
-	layered basalt	25	0 90 90	air ice water	4.8 6.2 13.3



Link Budget for Two Layer Model

Transmit Power	Normalized	0 dB
Antenna Effective Area	$4\pi\lambda$	34.5 dB
Antenna Gain	dipole	0 dB
Spherical Spreading	$1/(8\pi R)^2$	-140 dB
Reflection (Surface)	Γ_0^2	-12 dB
Total (Surface)		**-117.5 dB**
Transmission (Surface)	$(1-\Gamma_0^2)^2$	-0.5 dB
Reflection (air) (ice) (water)	Γ_1^2	-18 dB -14 dB -8.5 dB
Total (air) (ice) (water)		**-124 dB** **-120 dB** **-114.5 dB**

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Simulation Models

List of Simulation Models

NS-1 **Equatorial Site**
NS-2 **"Shallow Seep" Site**
NS-3 **Northern Plains Site**
NS-4 **Simple Massive Ice Lens**
NS-5 **Simple Near Surface Aquifer**
NS-6 **Simple Deep Aquifer**
DS-1 **"Shallow " Global Aquifer**
DS-2 **"Perched and Deep" Global Aquifer**
P-1 **Polar Basil Melting**
P-2 **Deep Polar Aquifer**

NS-5 simple near surface aquifer

depth	Lithology	ϕ%	s%	fill
400km	air	100	-	-
1	eolian sediment	50	0	air
3	indurated sediment	15	0	air
5	sediment-filled basalt	50	100	ice
50	layered basalt	10	100	ice
55	eolian sediment	50	100	ice
205	layered basalt	10	100	water
225	fluvial sediment	20	100	water
1000	layered basalt	10	100	water

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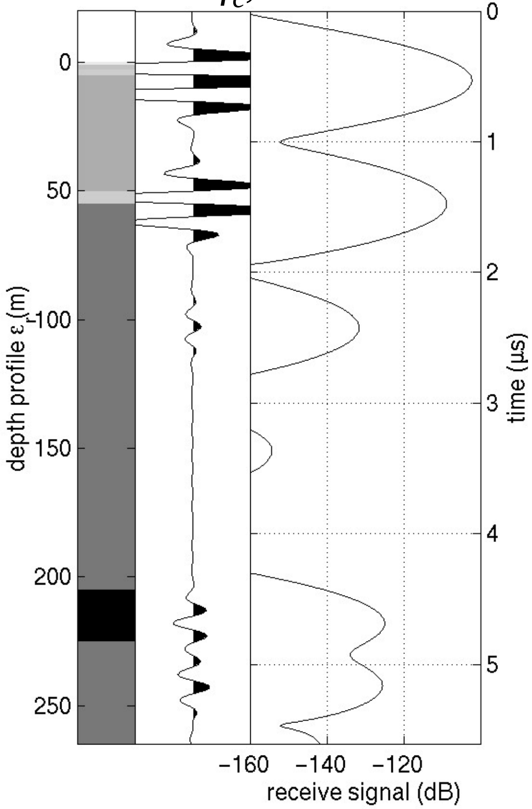
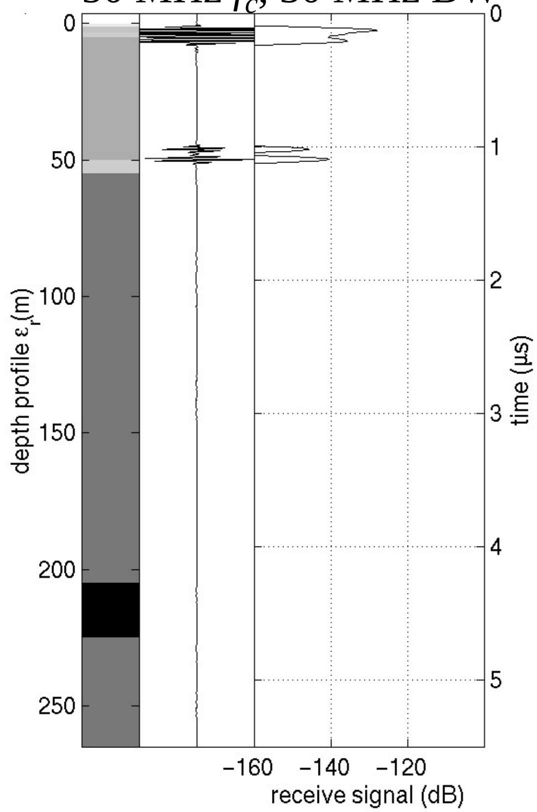
Simulations
Model NS-5

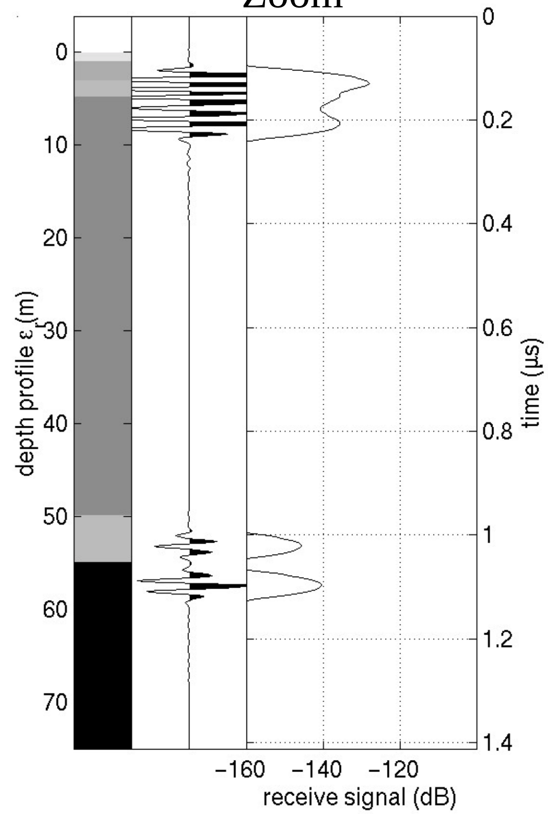
5 MHz f_c, 3 MHz BW



50 MHz f_c, 30 MHz BW



Zoom



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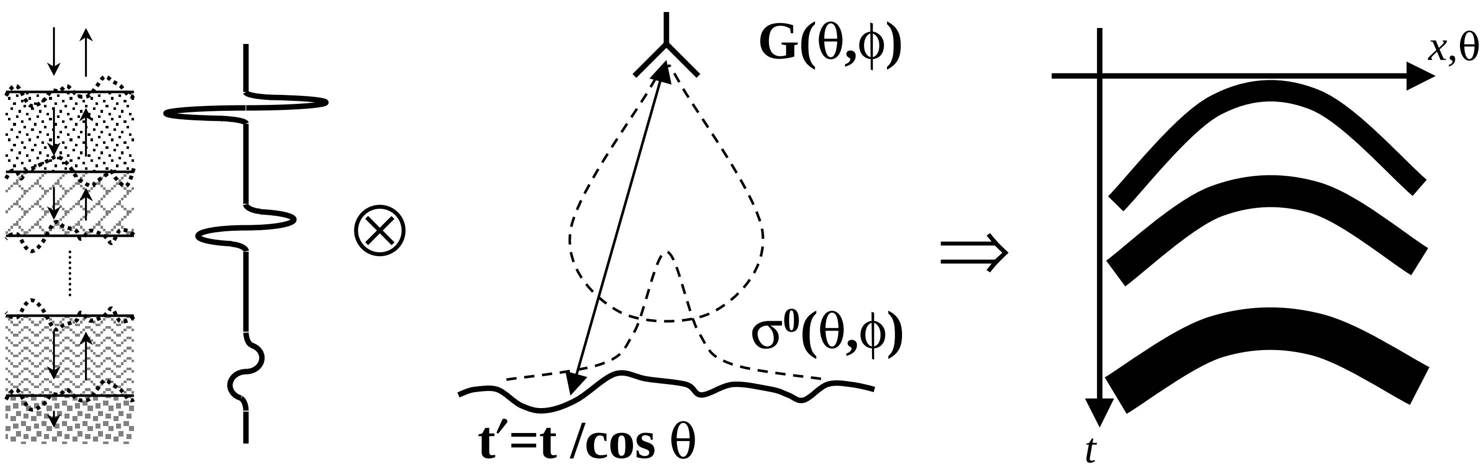
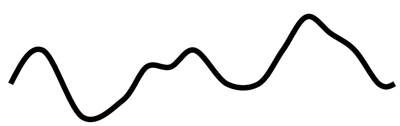
Three-Dimensional Simulator

Rough Surface Response



1d simulation ⊗ rough-surface scattering ⇒ point response



⊗ surface random variable ⇒ **Radar Response**

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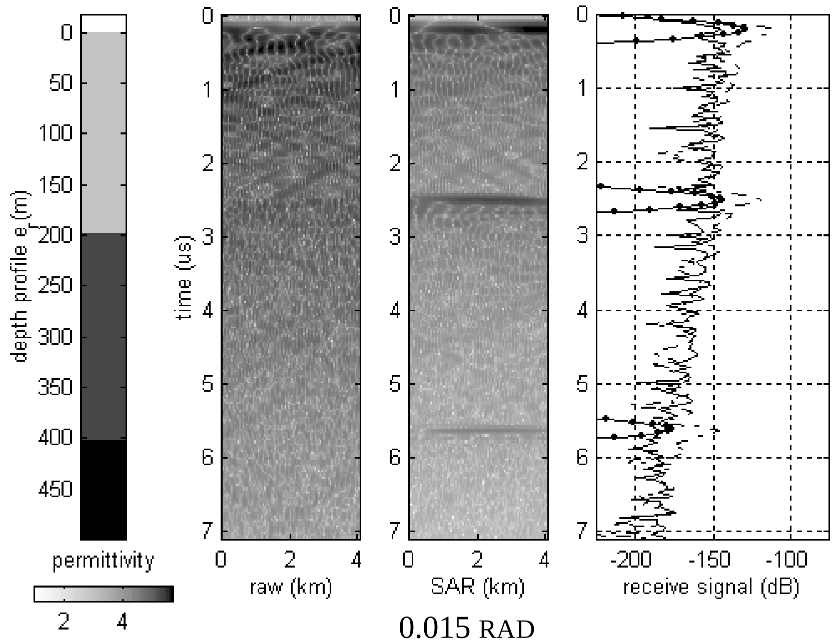
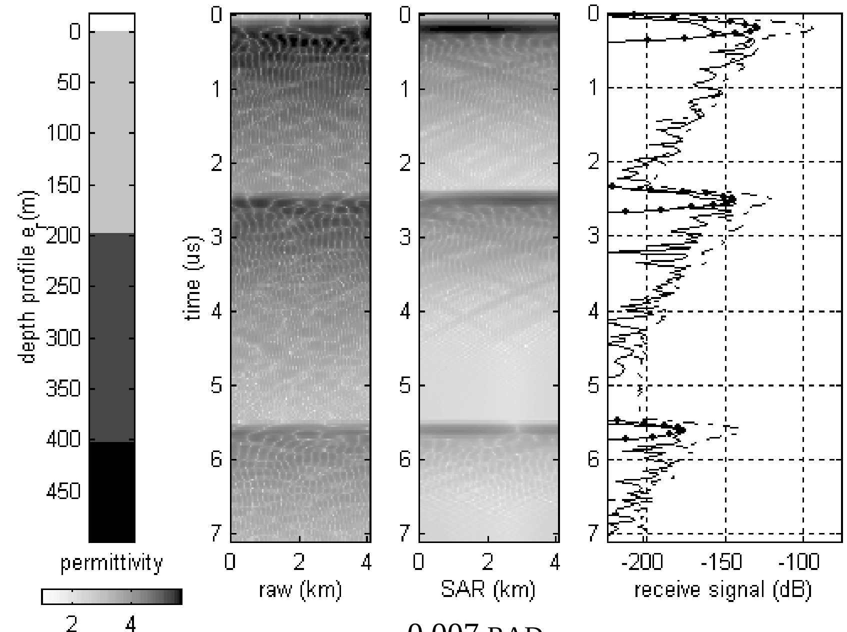
3D Sample Simulations

20 MHz Center Frequency, 10 MHz Bandwidth Incident Pulse
R.M.S. Surface Slope of 0.015 and 0.007 rad.

Depth	ϕ%	S%	Fill	ε_r'	ε_r''
400km	100	0	air	1	0
200	50	0	air	3	0.02
200	30	80	ice	5.4	0.05
100	20	0	air	5.8	0.07



0.015 rad



0.007 rad

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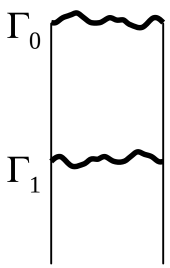
Simulations
Summary

Dielectric Contrast	Reflection, Γ	$\dfrac{\sqrt{\varepsilon_1}-\sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1}+\sqrt{\varepsilon_2}}$
Ohmic Loss	Attenuation, α (Np/m)	$\dfrac{\pi f}{v}\delta$
Fine Scale Layering*	Attenuation/Clutter	$\propto (l/\lambda)^n$
Volume Scattering	Attenuation, δ Clutter, σ	$\propto (a/\lambda)^3$ $\pi a^2 9(2\pi a/\lambda)^4$
Surface Roughness**	Reflection/Clutter, $A\sigma^0$	$2\pi Hc\tau \dfrac{\lvert\Gamma\rvert^2 \exp\left(-ct/2Hs^2\right)}{2s^2}$

* general trend, no equation.

** For an orbital system where H is much greater than the penetration depth.

Trade-off Example
Ohmic Loss vs. Surface Clutter



Ohmic Loss

$$\exp\left(-2\pi f \tan(\delta) t\right)$$

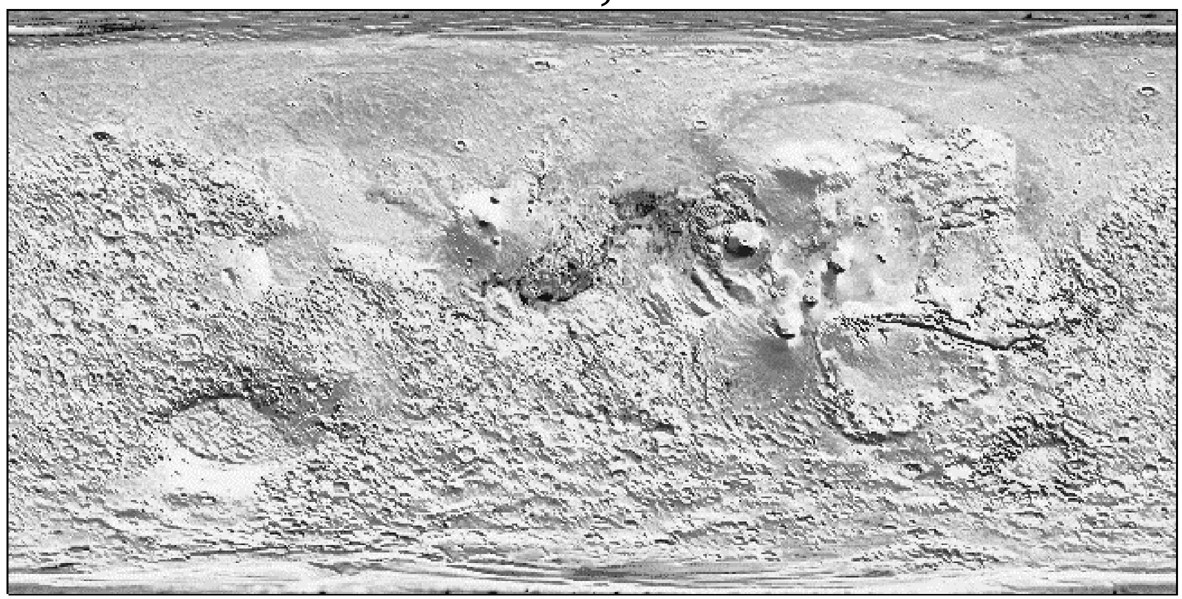
Surface Clutter

$$\exp\left(-ct/2Hs^2\right)$$

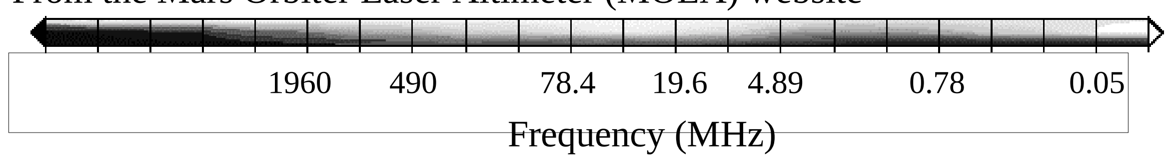
$$f < \frac{c}{4\pi \tan(\delta) H s^2}$$

$$\lambda > 4\pi \tan(\delta) H s^2$$

tan δ = 0.01, H = 400 km



From the Mars Orbiter Laser Altimeter (MOLA) website



-simple 2-layer model, no volume debris or layering.

-volume scattering will be significant for higher frequencies.

Radar System

Commercial GPRs are heavy, high-power, "impulse"-type radar.

- Not a real impulse, antennas limit bandwidth.
- Oscilloscope sampling techniques.
- Difficulties concerning timing precision.

Develop a compact, light-weight, low-power system.

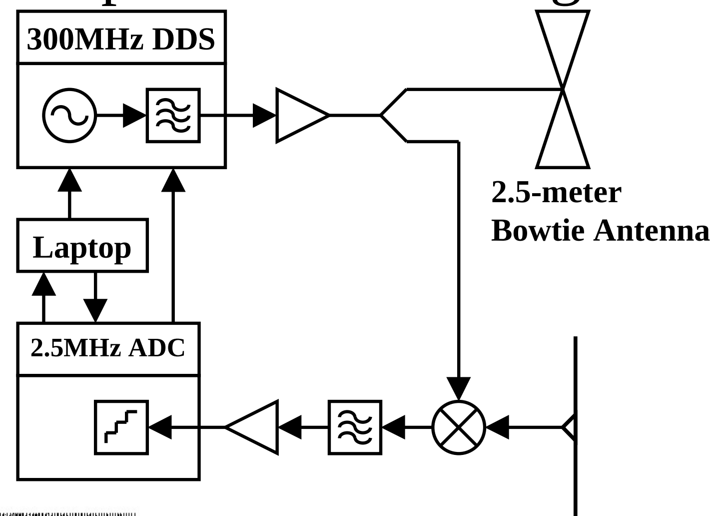
- Chirp compression.
- Connectorized components and evaluation boards.
- Wide bandwidth.
- Deep penetration.
- Fine, near-surface resolution.

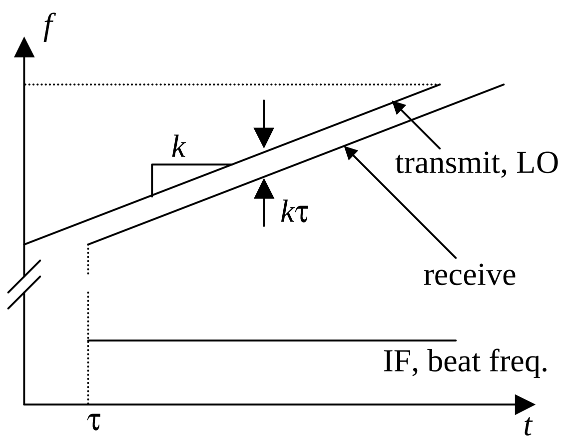
Radar System

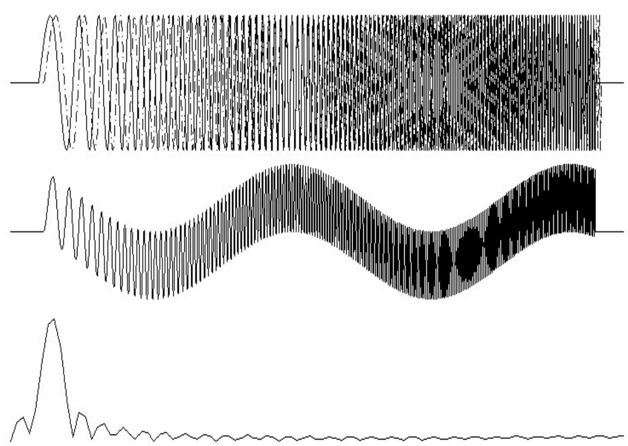
Radar Parameters

Modulation	Pulsed, FMCW, Chirp
Frequency	5 – 120 MHz
Sweep Time (Pulse width)	Adjustable
Power Output	10 dBm
ADC Resolution, Dynamic Range	16 bit
ADC Sampling Rate	2.5 MSPS
Size	7.5 × 15 × 12 cm
Weight	< 5 lbs.

Simplified Block-Diagram







$$u(t) = A\cos\left(2\pi f_0 t + \pi k t^2\right)$$

$$r(t) = A\cos\left(2\pi f_0 (t-\tau) + \pi k (t-\tau)^2\right)$$

$$m(t) = A^2 \cos\left(2\pi k \tau t - \pi k \tau^2 - 2\pi f_0 \tau\right)$$

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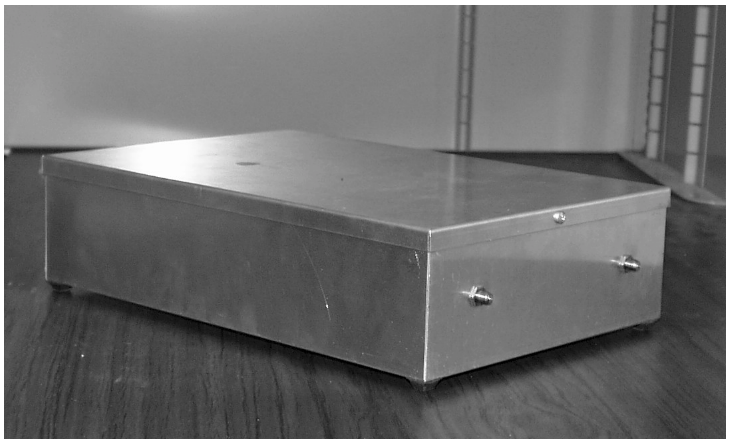
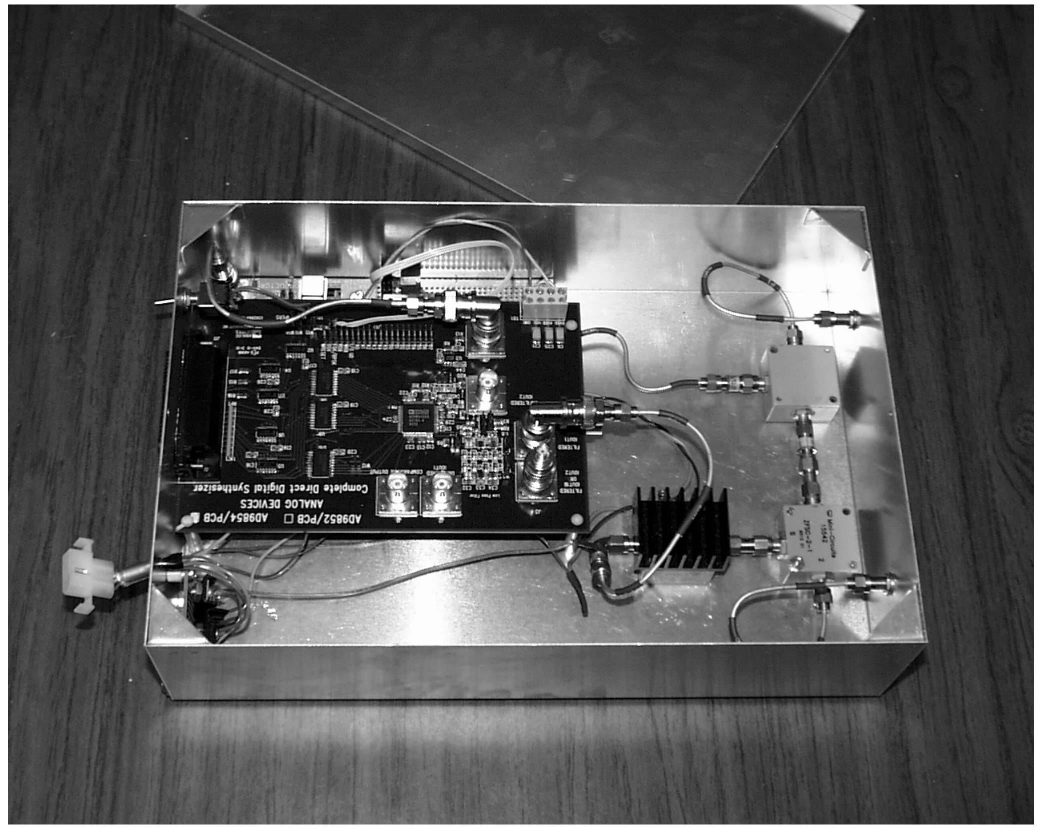
Radar System

Digital, RF, and IF Subsystems





Radar System
Antenna Subsystems

Antenna on a dielectric half-space

Increase effective length.
Lower frequency response.
Increase bandwidth (lossy ground).

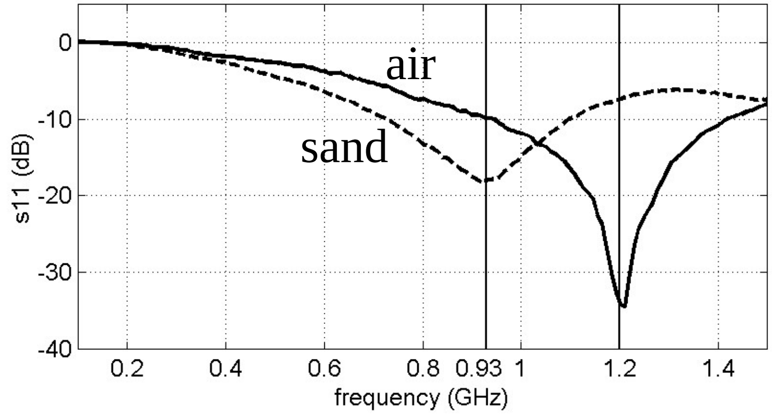
17 cm bowtie

Frequency reduction: (0.93/1.2) = 0.775.
Sand permittivity (dielectric probe): 2.4-2.65.
Effective permittivity: $(1/0.775)^2 = 1.66$.

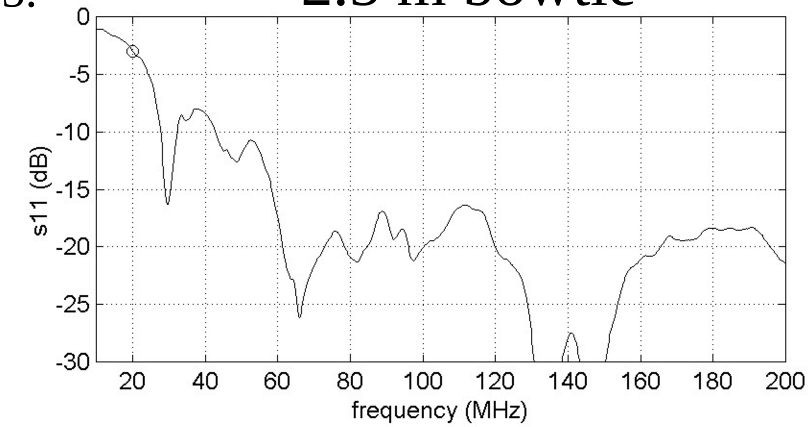
2.5 m bowtie

Shows greater than 3 octaves of bandwidth.

17 cm bowtie



2.5 m bowtie



Antenna Subsystems

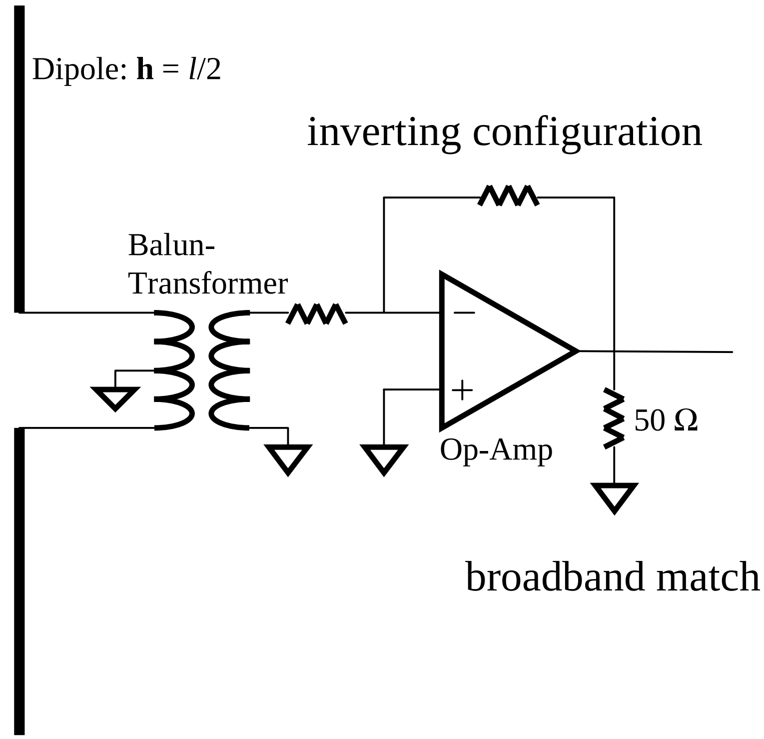
Transmit Antenna

Radiate power into the ground.
Must match for efficient power transfer.

Receive Antenna

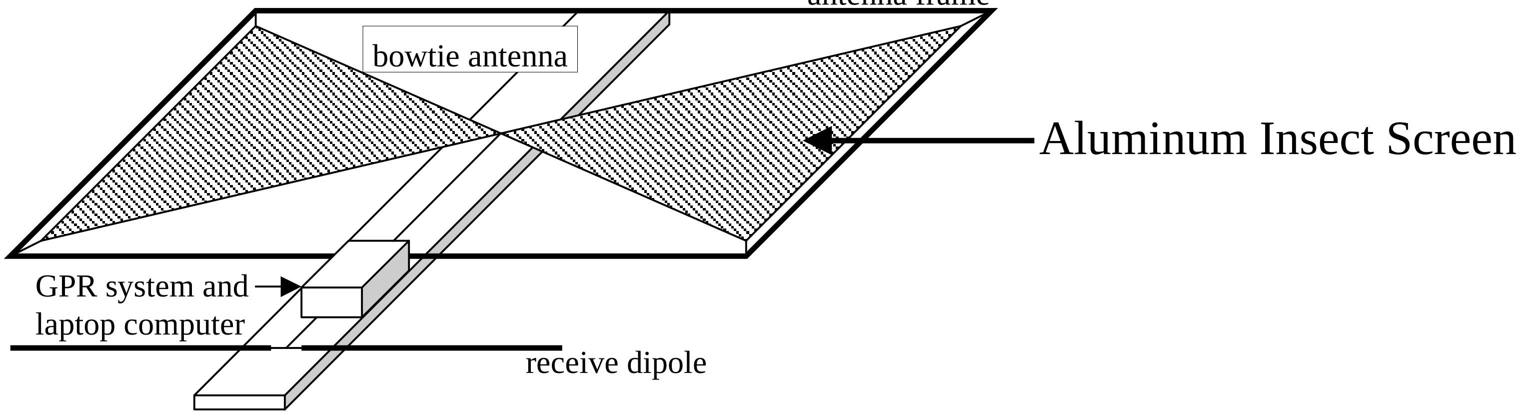
Measure the reflected electric field.
No need for a broadband match.
Effective length: $V_{oc} = \mathbf{E} \cdot \mathbf{h}$

Bowtie Transmit, Dipole Receive



Radar System

Complete System in Alaska



Experiments

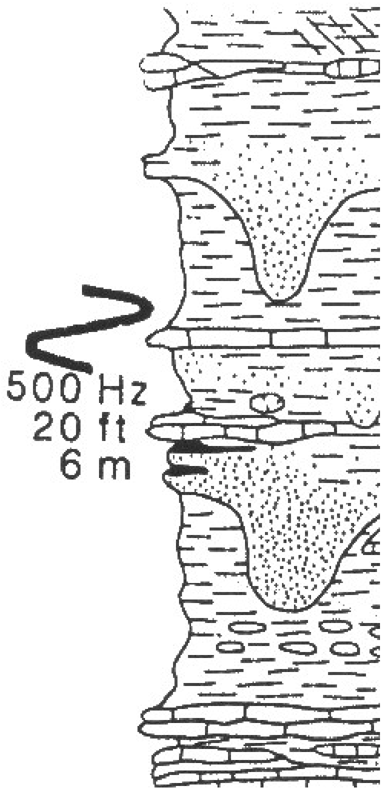
Test the performance of the prototype system.

Compare results with a commercial GPR.

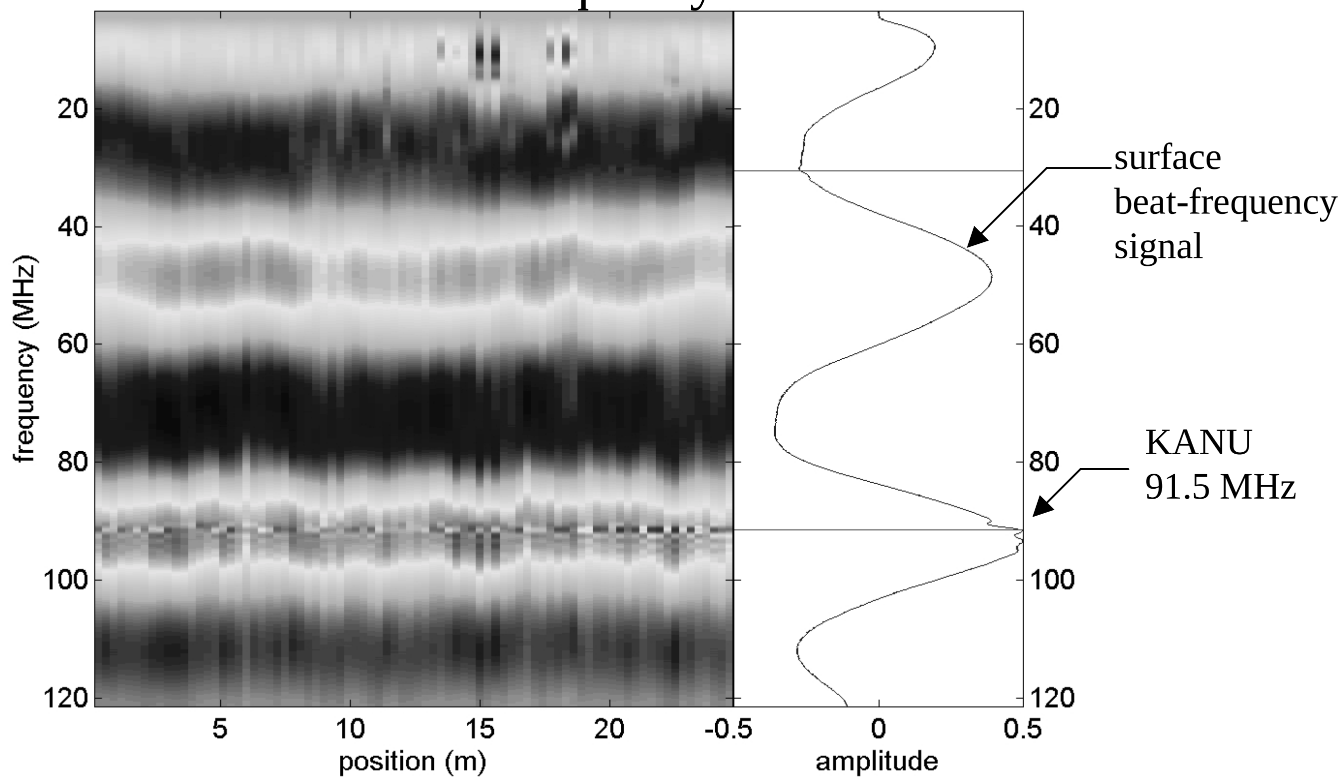
- Common belief “impulse”-type system are best for GPR applications.*
- Show FM-CW radars can perform as well as “impulse”-type system.

Experiments
Lawrence, Kansas

Measurement collected outside Moore Hall (KGS).



Raw Data – Frequency Domain



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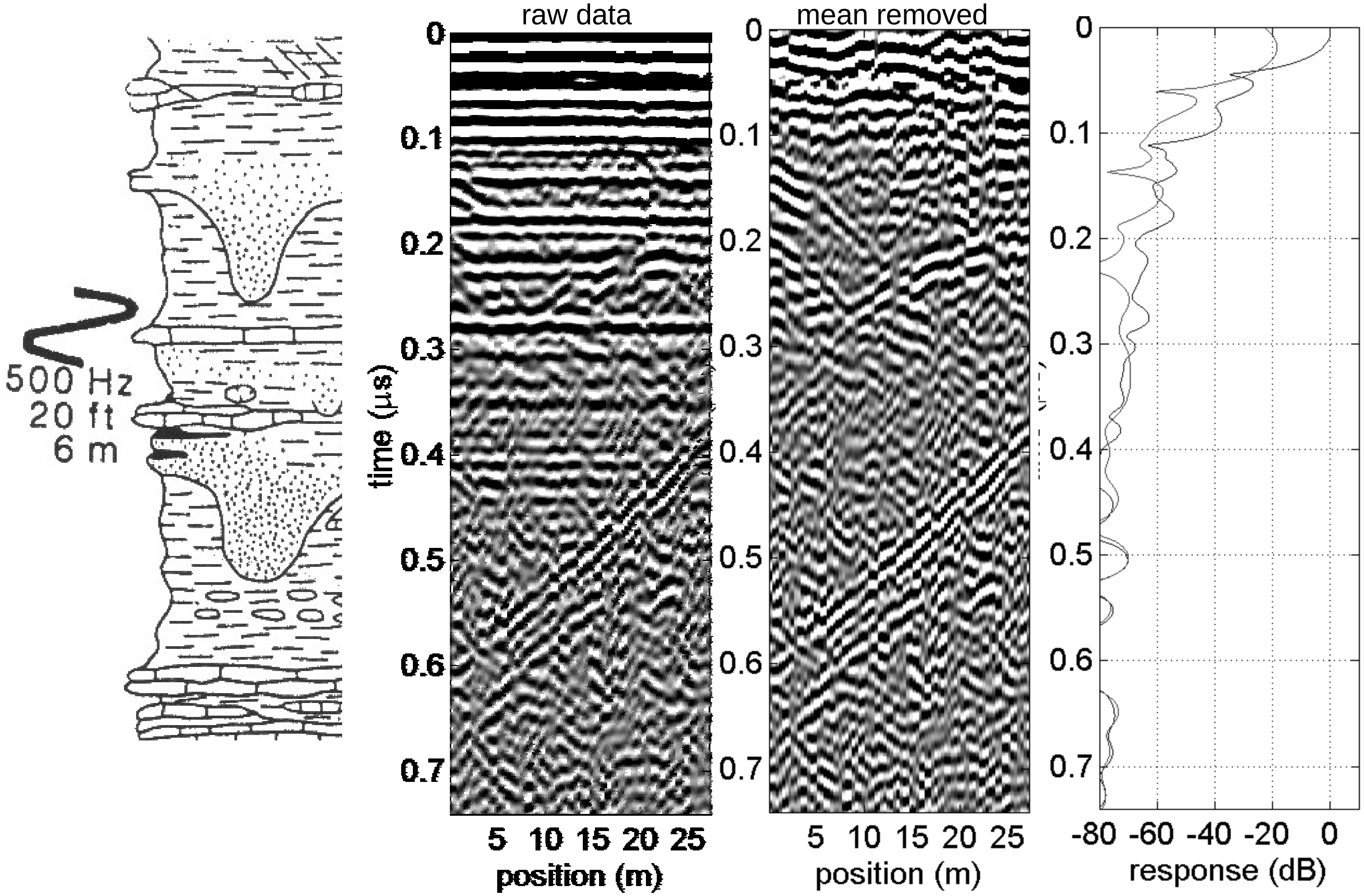
Data Processing

Raw Data

1. Choose FFT limits.
2. Apply windowing function.
3. Transform Data.
4. Differentiate/Dewow/High Pass Filter.
5. Average/Stack/Integrate.
6. Apply Gain.

Processed Data

Lawrence, Kansas
Processed Image



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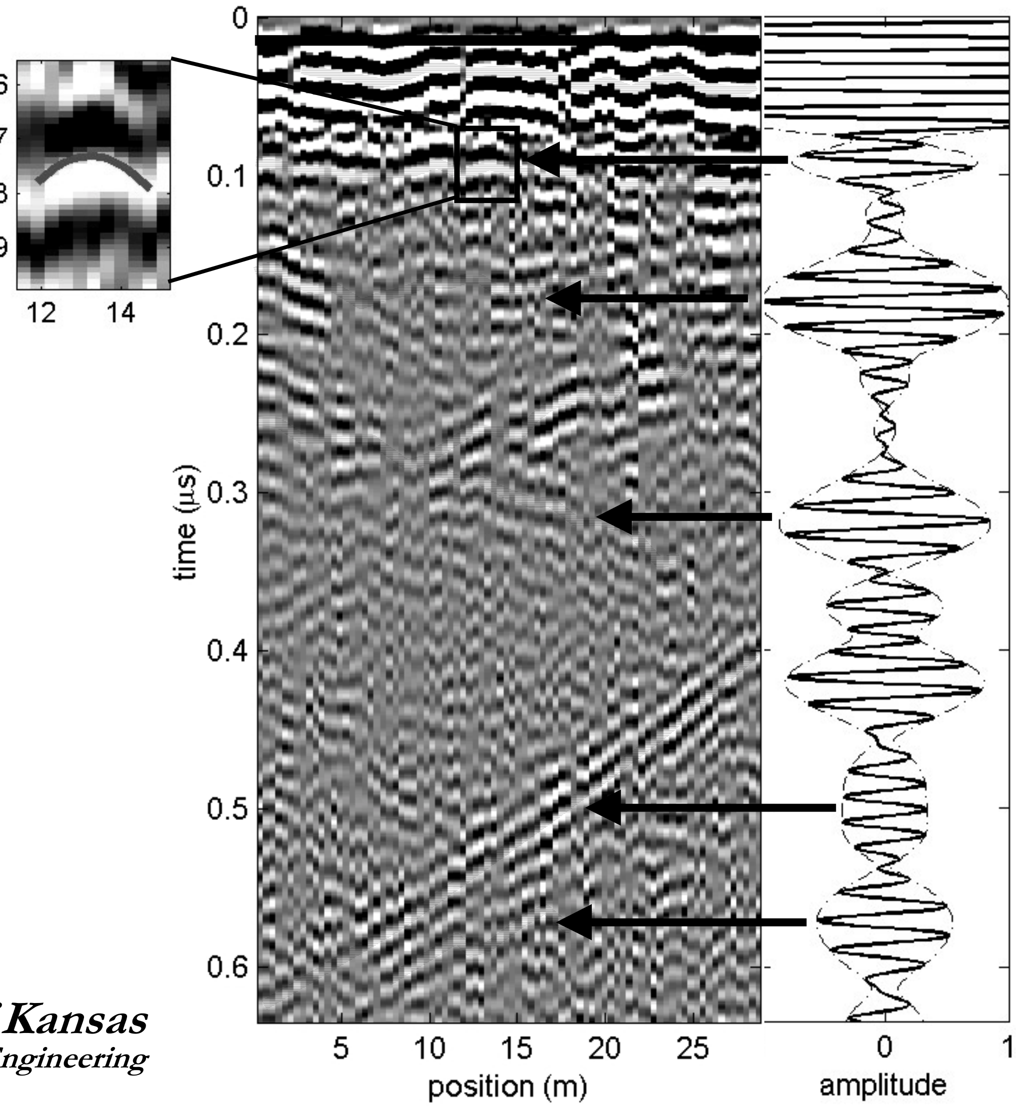
Lawrence, Kansas
Processed Image

Depth: 5m

ε_r: 4.7



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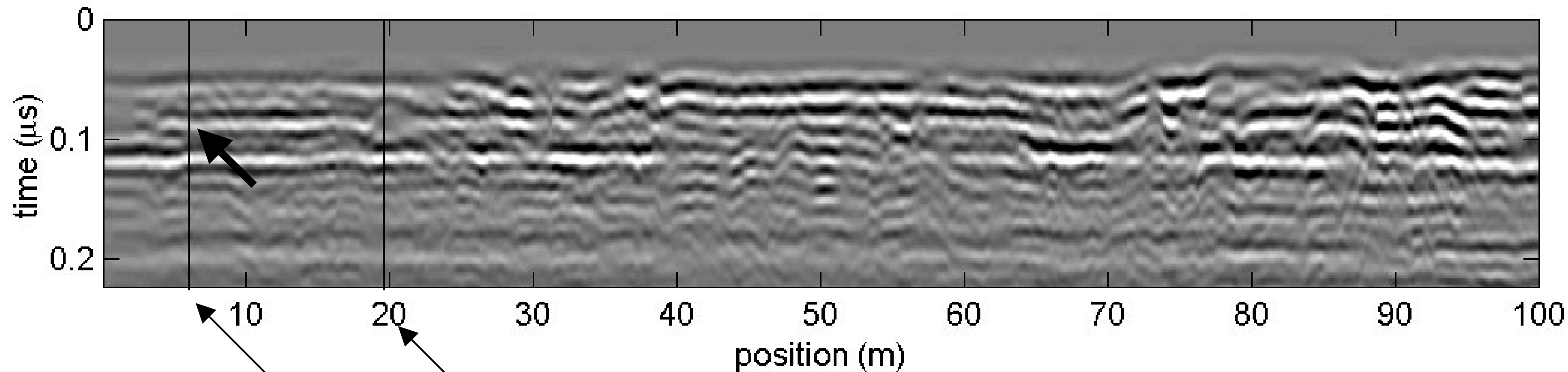
Experiments
Delta Junction, Alaska

Estimated Subsurface Structure.

depth	Lithology	ϕ%	s%	fill
1 m	silt-thaw (eolian deposit)	30	70	water
2 m	silt-frozen (eolian deposit)	20	80	ice
-	gravel (out wash)	30	0	



Where does the layer go at 20 m?
Simulate the response at these locations.

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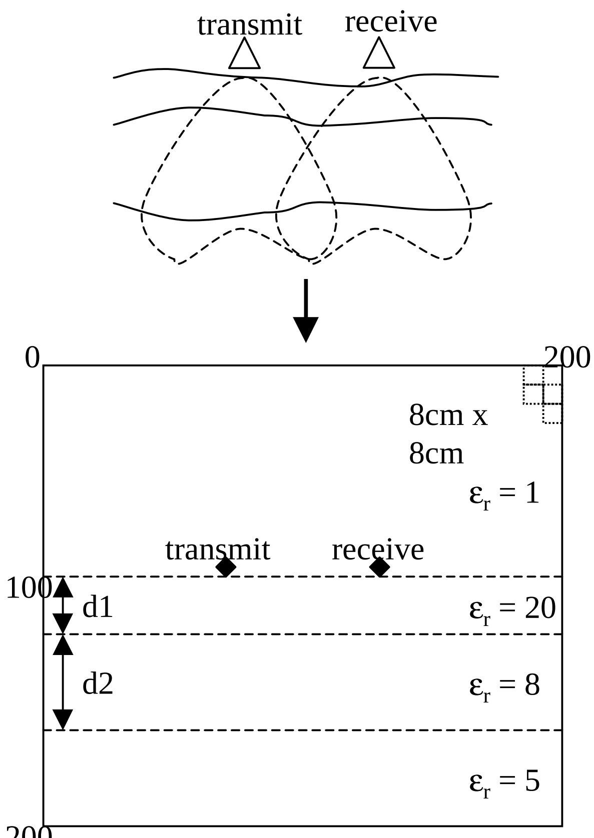
Delta Junction, Alaska
Simulated Responses



FDTD Grid

6 m position.

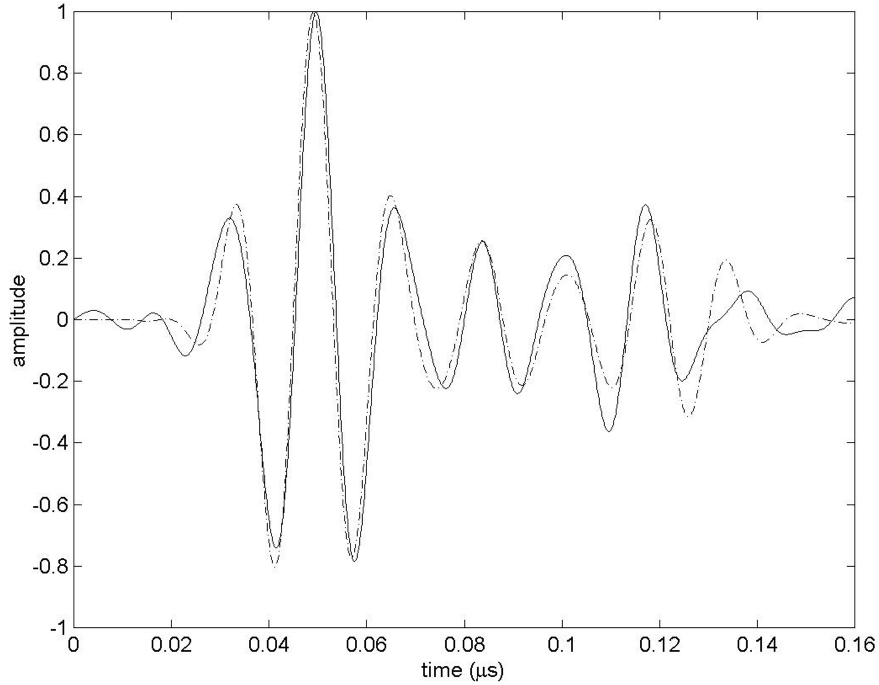
Depth	Lithology	ε_r	loss
1.2 m	silt-thaw	18	0.02
2 m	silt-frozen	9	0.001
-	gravel	3	-

20 m position.

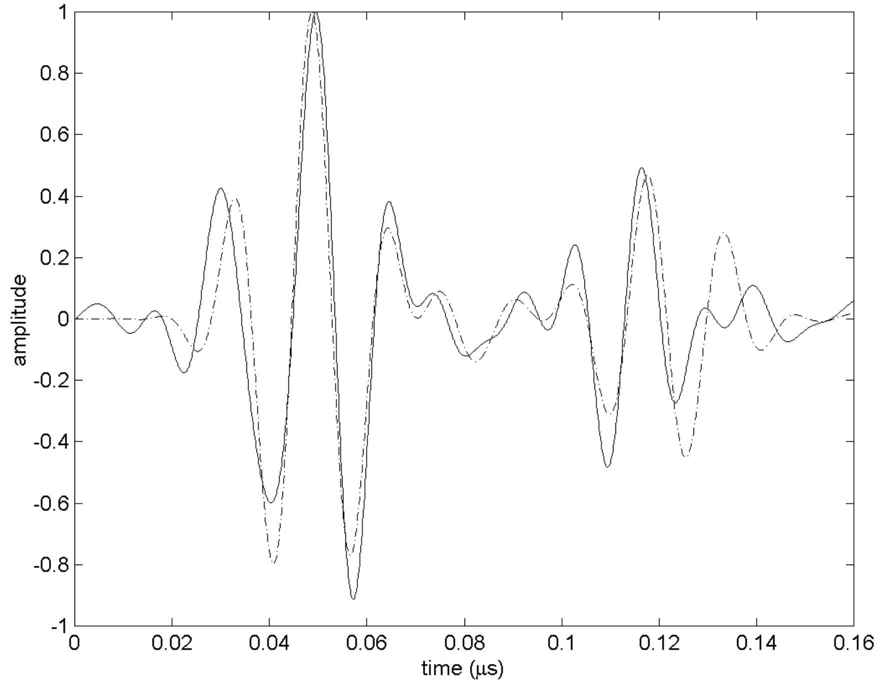
Depth	Lithology	ε_r	loss
0.5 m	silt-thaw	18	0.02
2.4 m	silt-frozen	9	0.001
-	gravel	3	-

Delta Junction, Alaska
Simulation Comparisons

6 m position.

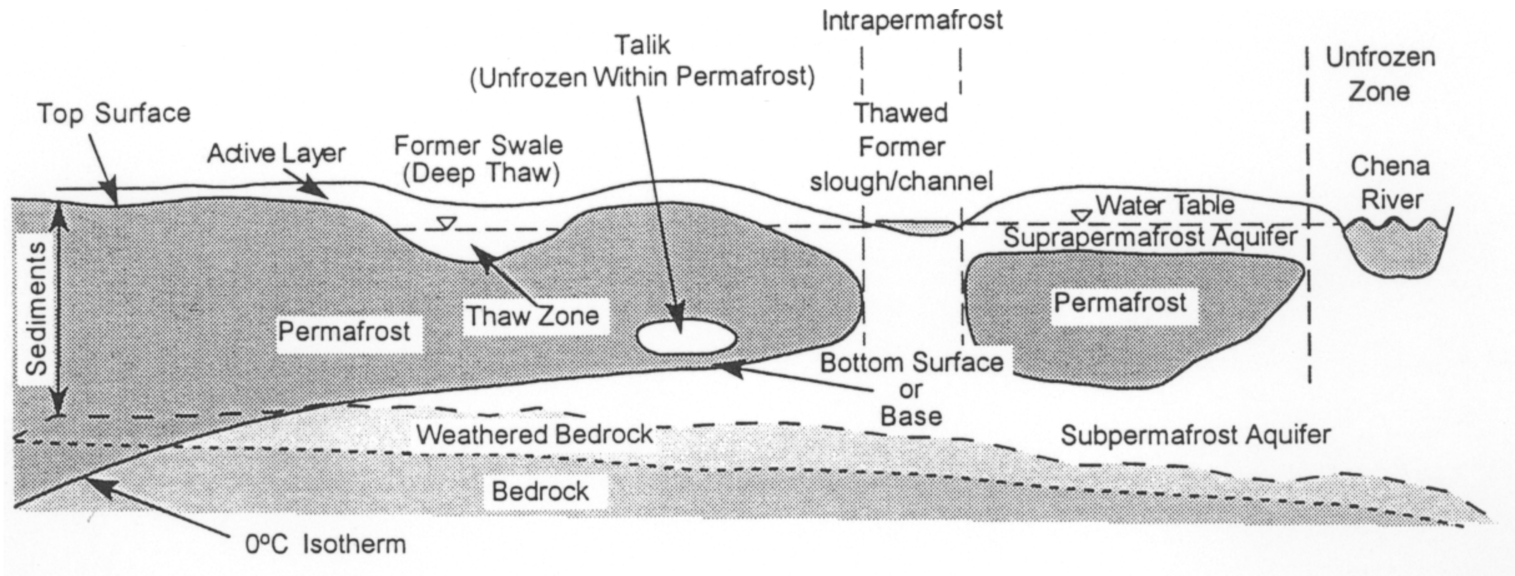


20 m position.

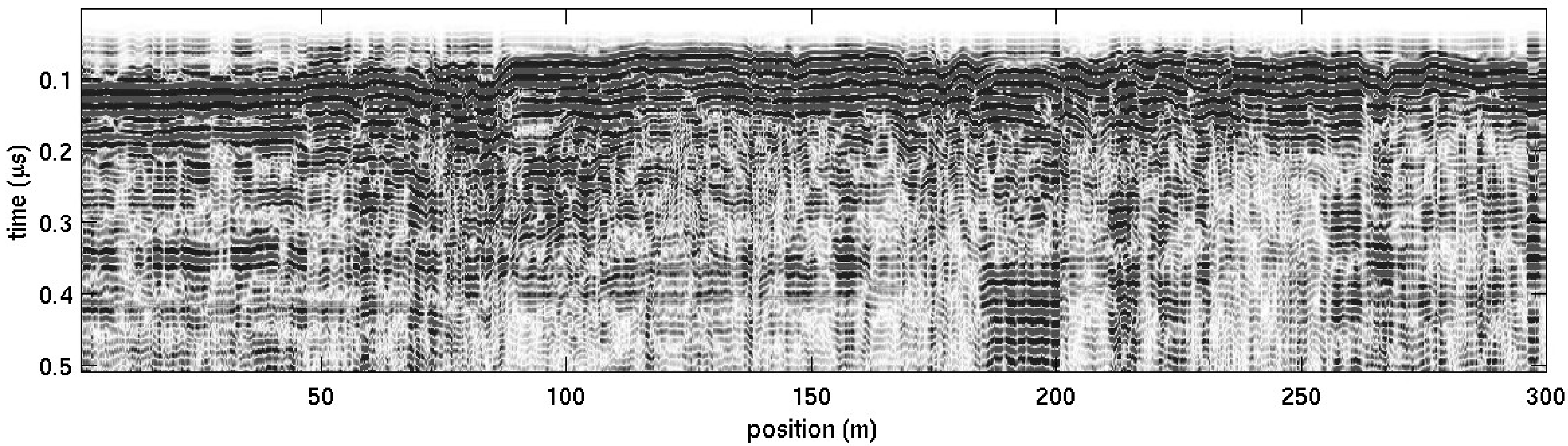


Experiments
Fort Wainwright, Alaska

Discontinuous Permafrost over Water-Table and Bedrock



Fort Wainwright, Alaska
Radar Image



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Fort Wainwright, Alaska
Commercial GPR

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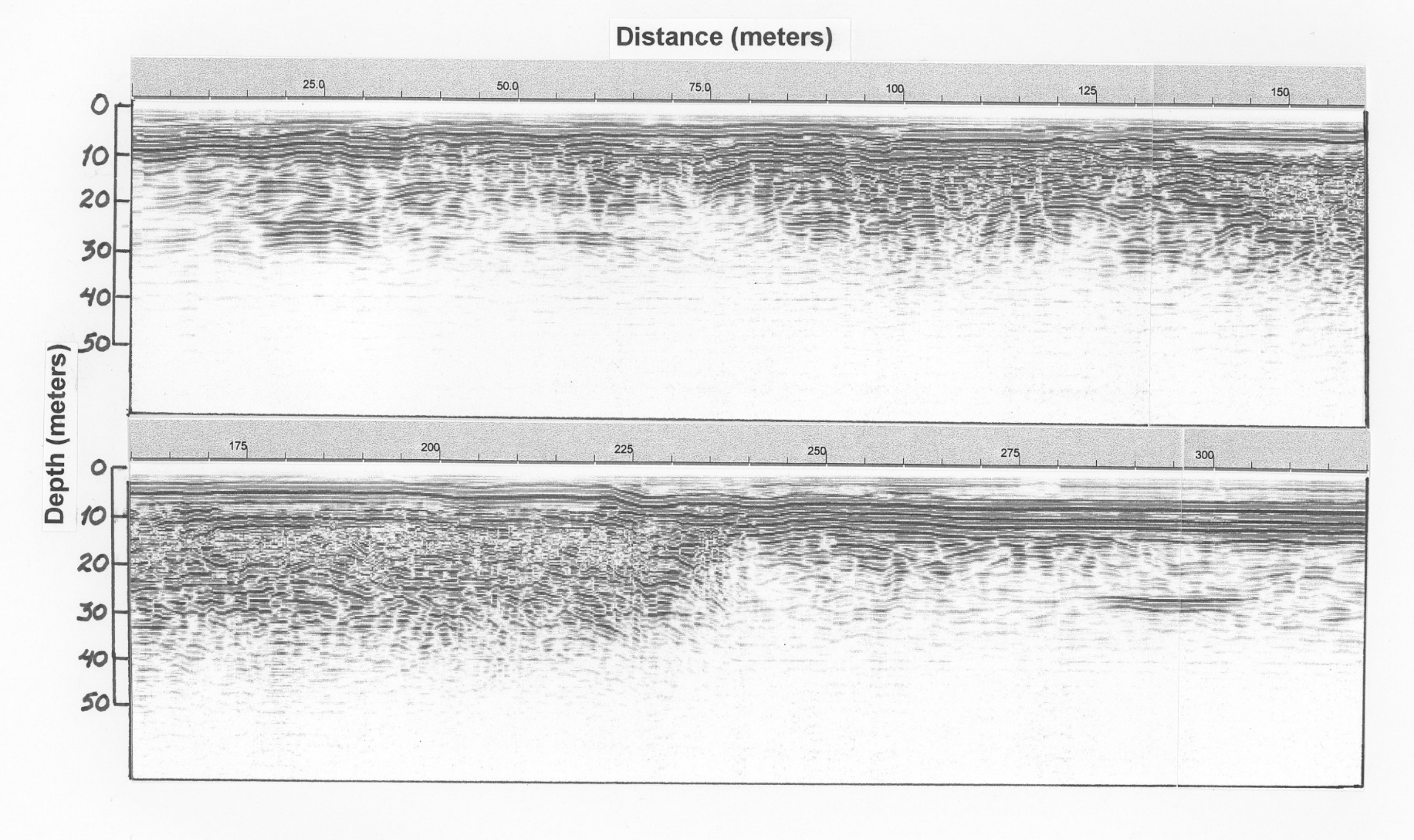
Fort Wainwright, Alaska
Commercial GPR Image



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Signal Processing

Sidelobes are a major problem with FM-CW radars.

- Mask weaker reflections.
- Careful calibration to eliminate.

SPR is difficult to interpret and quantify.

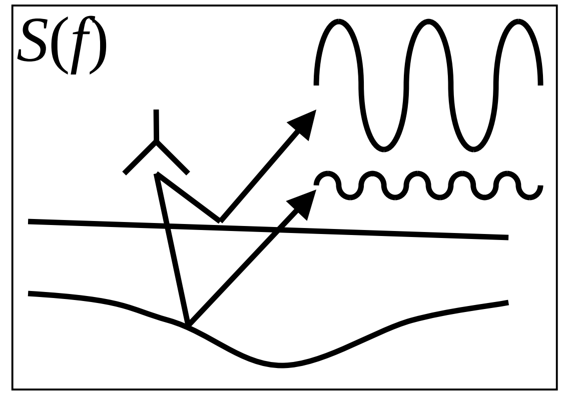
- Interference from neighboring pulses will add/subtract coherently.

Develop a method to extract reflectivity information from a SPR response.

Signal Processing

Signal is a composition of surface and subsurface layers.
For a FM-CW radar (linear chirp),

$$S(f_T) = A_0 \cos(2\pi f_T \tau_0 + \phi_0) + \sum_{n>0} A_n \cos(2\pi f_T \tau_n + \phi_n)$$

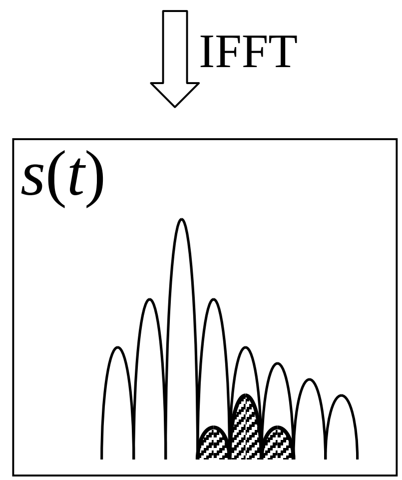


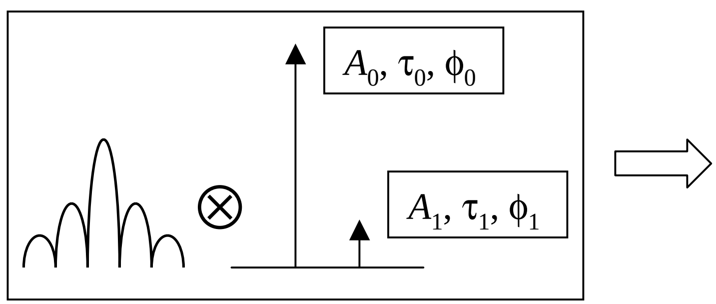
In general, response is convolution,

$$s(t) = \int r(\tau) \cdot u(t-\tau) d\tau = r(t) \otimes u(t)$$

r(t): reflection profile ⇐ this is what we want to know.
u(t): bandlimited radar waveform (sin(x)/x).

Sidelobes may mask weaker reflections.





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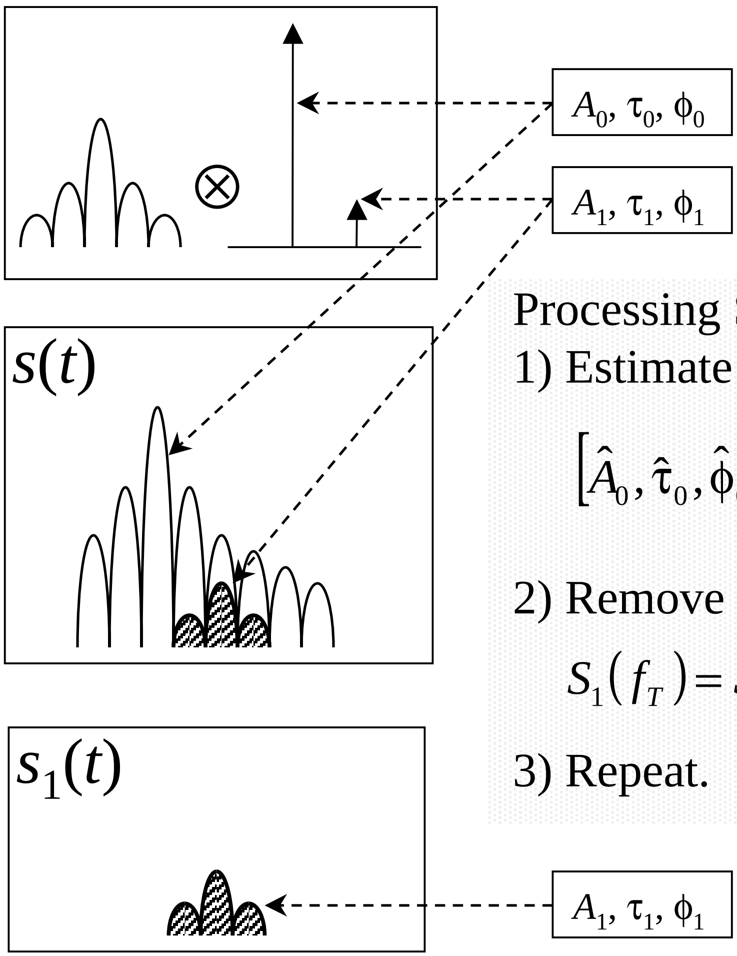
Signal Processing

Signal Decomposition



Easy to detect $\Rightarrow \max\left|\int_{f_1}^{f_2} S(f_T)\exp(j2\pi f_T t)\,df_T\right|$

Hard to detect

Processing Steps:

1) Estimate the main reflection (surface).

$$\left[\hat{A}_0, \hat{\tau}_0, \hat{\phi}_0\right] = \max\left|\int_{f_1}^{f_2} S(f_T)\exp(j2\pi f_T t)\,df_T\right|$$

2) Remove main reflection (and sidelobes).

$$S_1(f_T) = S(f_T) - \hat{A}_0\cos\left(2\pi f_T\hat{\tau}_0 + \hat{\phi}_0\right) \cong \sum_{n>0} A_n\cos(2\pi f_T\tau_n + \phi_n)$$

3) Repeat.

Easy to detect $\Rightarrow \max\left|\int_{f_1}^{f_2} S_1(f_T)\exp(j2\pi f_T t)\,df_T\right|$

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Signal Processing: Reconstruction/Reflection Profile

Reconstruction of the original response – add up all the components.

Frequency domain:

$$S(f_T) = \sum_n \hat{A}_n \cos\left(2\pi f_T \hat{\tau}_n + \hat{\phi}_n\right) + S_e(f_T)$$

Time domain:

$$s(t) = \sum_n \hat{A}_n e^{j\hat{\phi}_n} u(t - \hat{\tau}_n) + s_e(t)$$

similar forms

As a convolution:

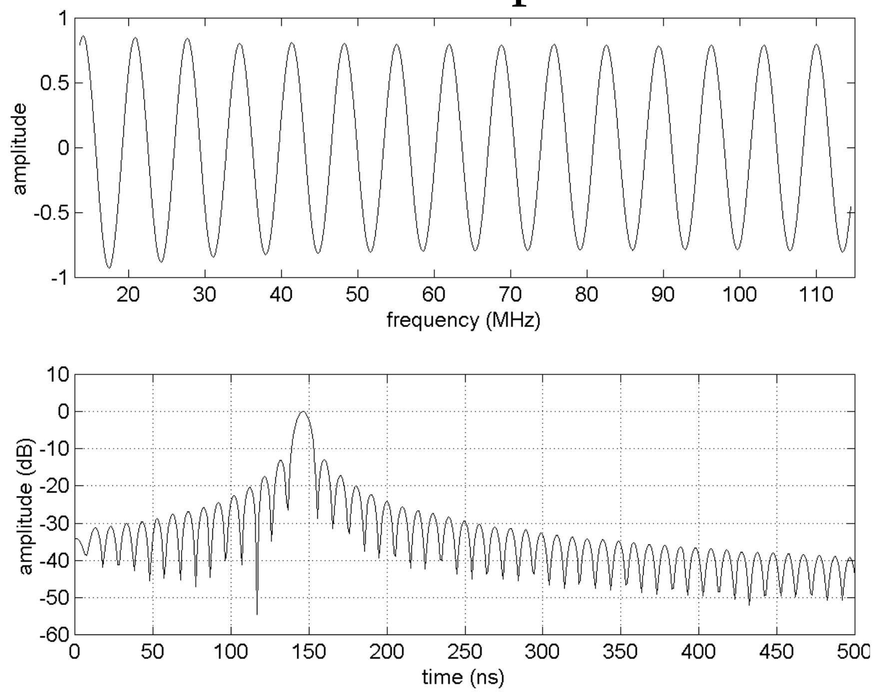
$$s(t) = \left[\sum_n \hat{A}_n e^{j\hat{\phi}_n} \delta(t - \hat{\tau}_n)\right] \otimes u(t) + s_e(t) \iff s(t) = \int r(\tau) \cdot u(t - \tau) d\tau = r(t) \otimes u(t)$$

Estimation of the reflection profile.

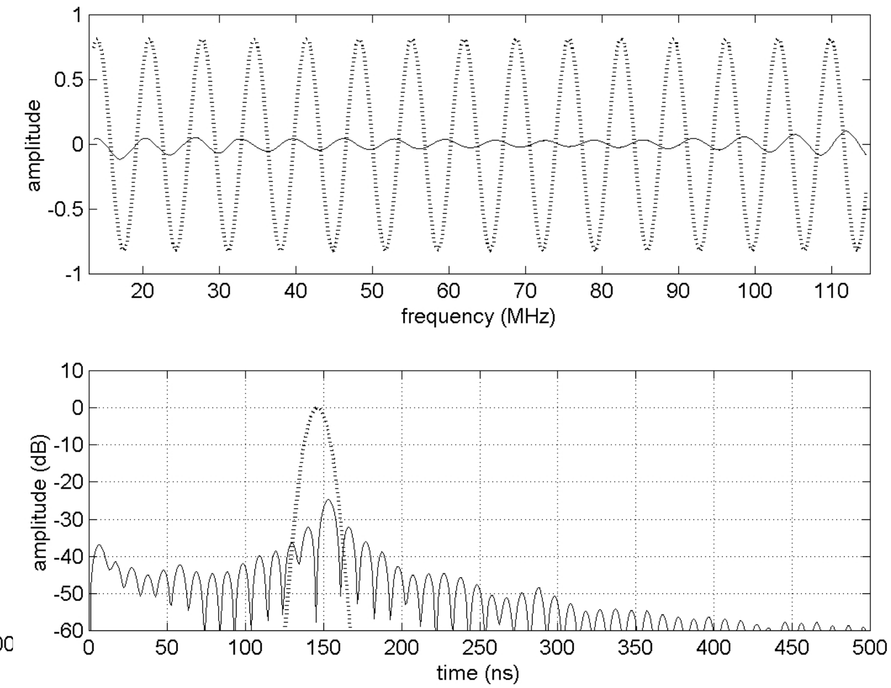
$$\hat{r}(t) = \sum_n \hat{A}_n e^{j\hat{\phi}_n} \delta(t - \hat{\tau}_n)$$

Signal Processing Example: Transmission Line Data

Radar Response



One Iteration



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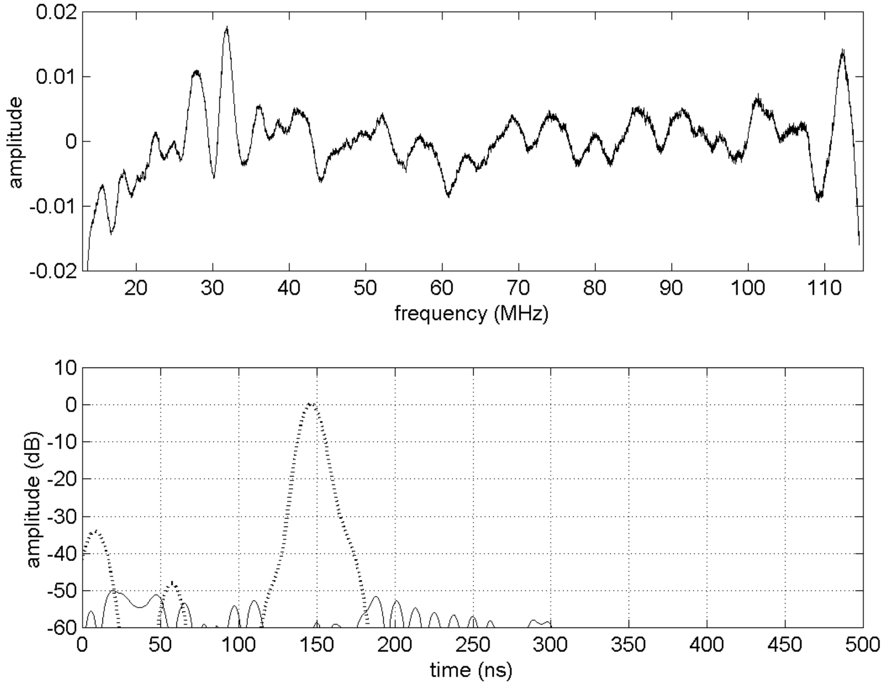
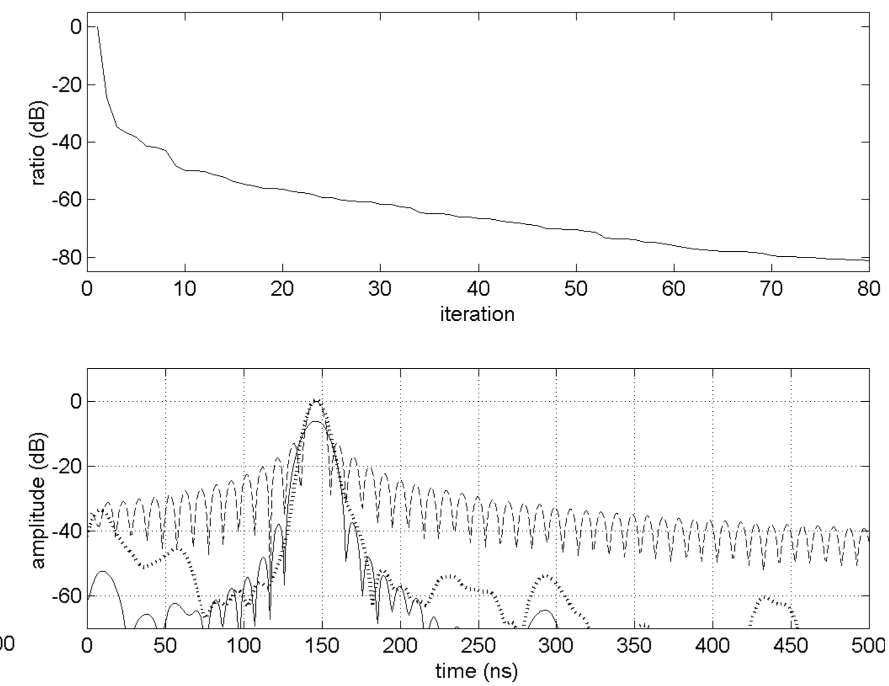
Signal Processing Example:
Transmission Line Data

10 Iterations



80 Iterations



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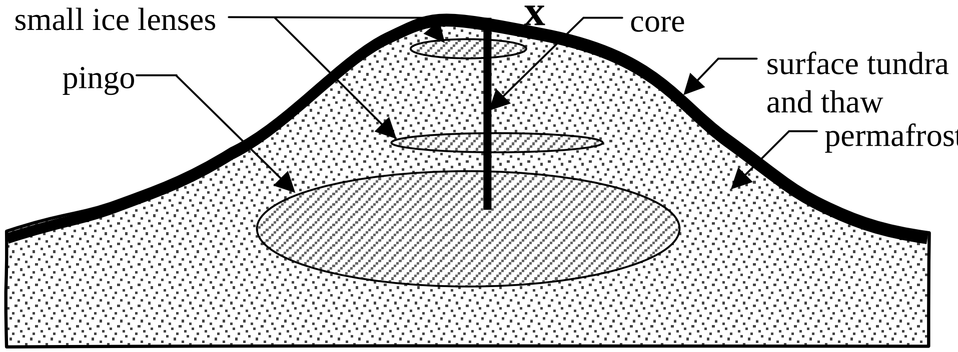
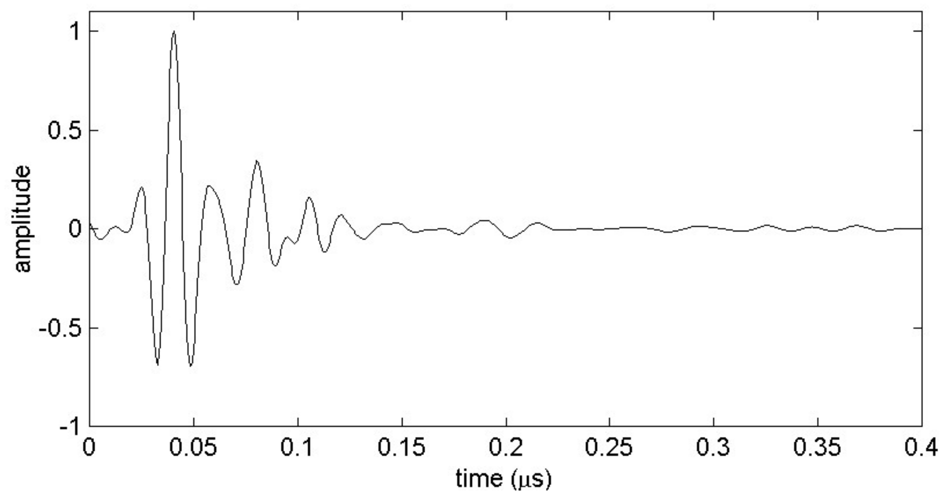
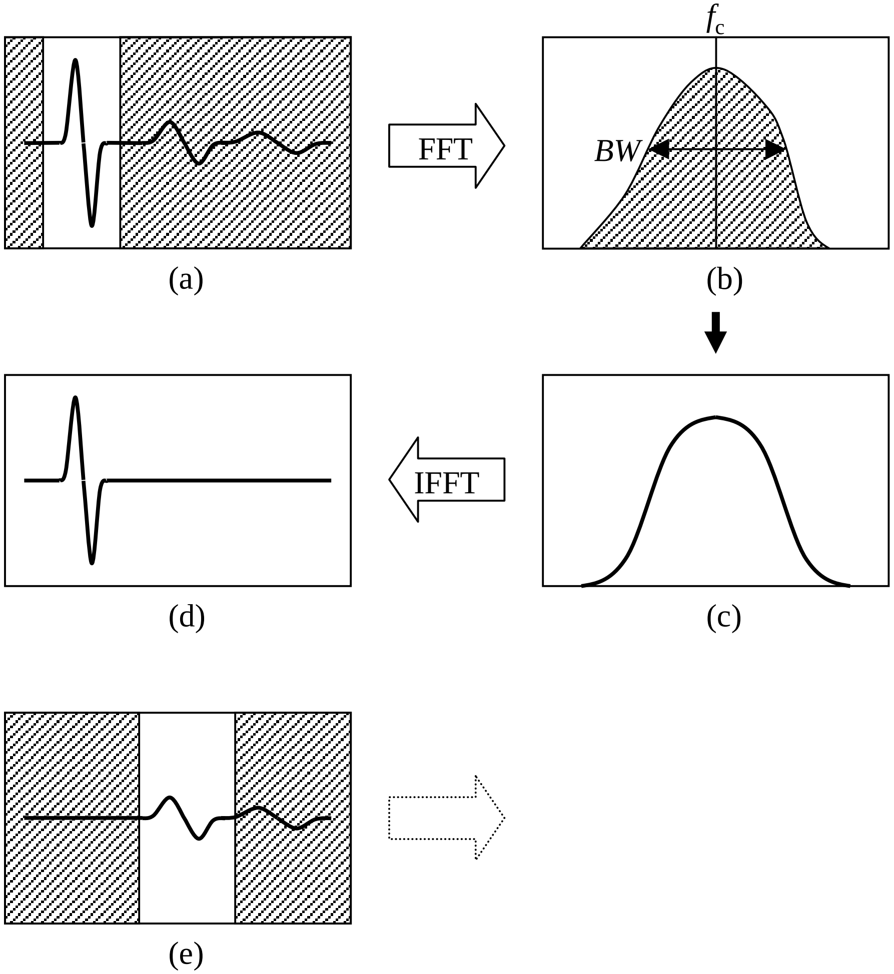
Signal Processing Example:
SPR Data (Pingo Site)



depth	Lithology	ϕ%	s%	Fill
0.3 m	tundra	50	70	water
0.5 m	soil (eolian deposit)	40	70	water
1.0 m	soil	30	90	ice
0.5 m	ice	100	100	ice
4.0 m	soil	30	90	ice
0.5 m	ice	100	100	ice
0.5 m	soil	25	90	ice
?	ice (main pingo ice)	100	100	ice



Signal Processing Modifications



a) Window maximum reflection.
b) Fourier transform and estimate center frequency and bandwidth.

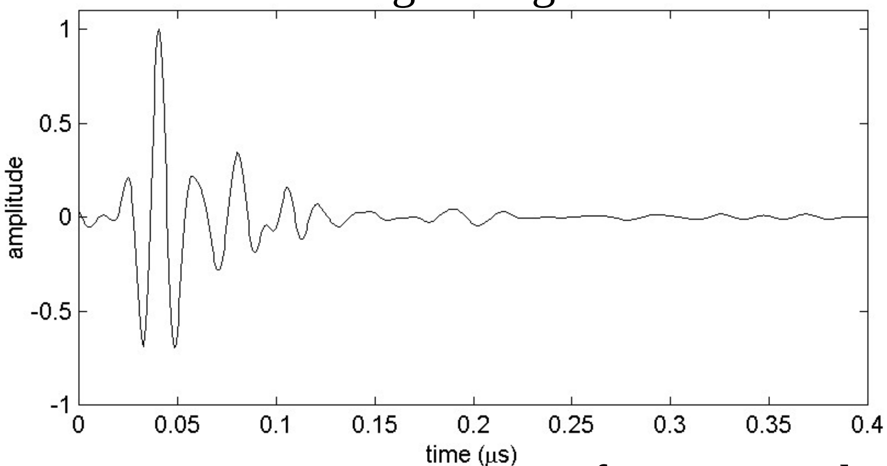
$$f_c = \frac{\int f\left|S(f)\right|df}{\int\left|S(f)\right|df}$$

$$BW = \sqrt{\frac{\int f^2\left|S(f)\right| - df}{\int\left|S(f)\right|df} - f_c^{\,2}}$$

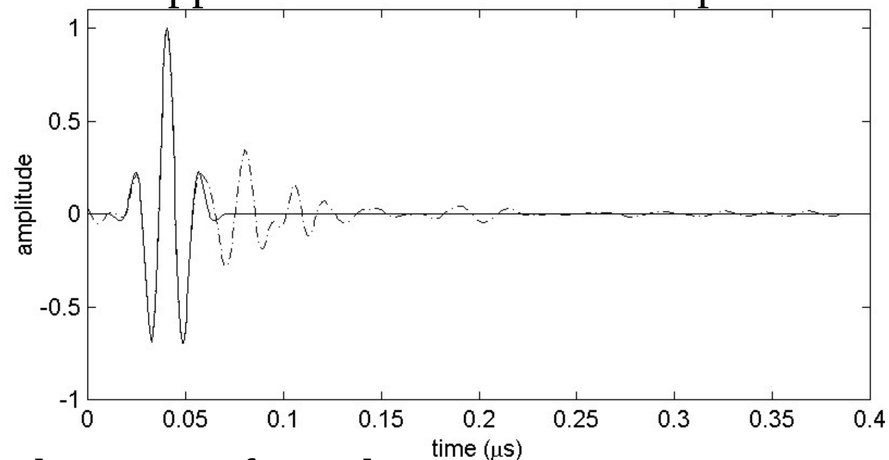
c) Generate spectrum.
d) Inverse transform to generate waveform.
e) Subtract from response and repeat.

Signal Processing Example:
SPR Data (Pingo Site)

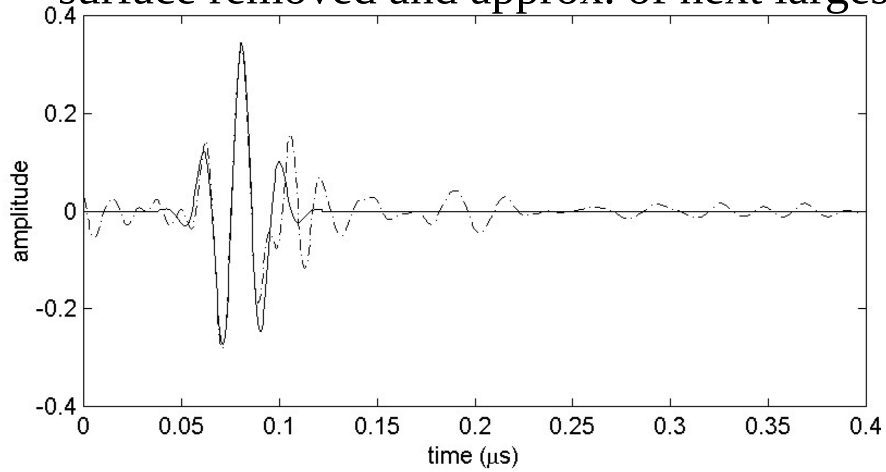
original signal



approximation of surface response



surface removed and approx. of next largest



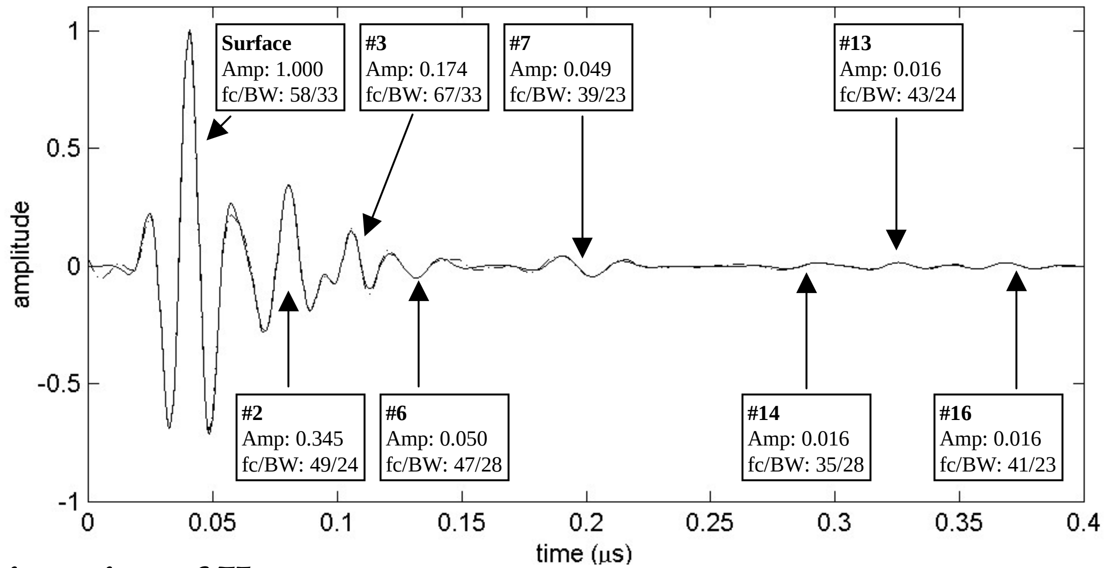
Signal Processing Example: SPR Data (Pingo Site)

Reflection Profile

iteration	time (ns)	amplitude	fc (MHz)	BW (MHz)
1	40	1.000	58	33
2	80	0.345	49	24
3	101	0.174	67	33
6	132	0.050	47	28
7	197	0.049	39	23
13	322	0.016	43	24
14	290	0.016	35	28
16	368	0.016	41	23

Filtered Reflections
4,5,8-12,15

Data Compression
1024 complex
8×6 matrix



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Conclusions and Future Work

Simulations

Accomplishments

1. Developed a detailed simulator to asses radar performance including scattering off rough surfaces, volume debris, and layering.
2. Generated radar responses of a wide variety of geological locations.

Conclusions

1. The performance of a SPR on Mars is dependent on a number of factors that are unknown.
2. Lower frequencies will ensure deeper penetration and increase the probability of detecting water/ice
3. Unambiguous detection is difficult using reflectivity data alone.

System/Experiments

Accomplishments

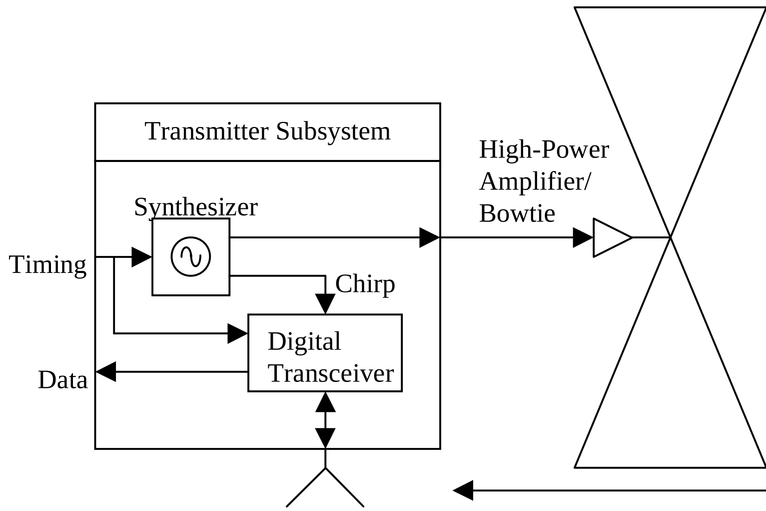
1. Developed a compact, lightweight, low-power prototype system.
2. Tested the system over locations containing subsurface ice and water.
3. Showed similar performance compared to a commercial “impulse”-type system.

Conclusions

1. Frequency modulation (stepped, swept FM) can be used in a low-frequency GPR and produce similar results to a heavy “impulse”-type system.

Proposed System

Showed FM-CW system performs as well as commercial system.



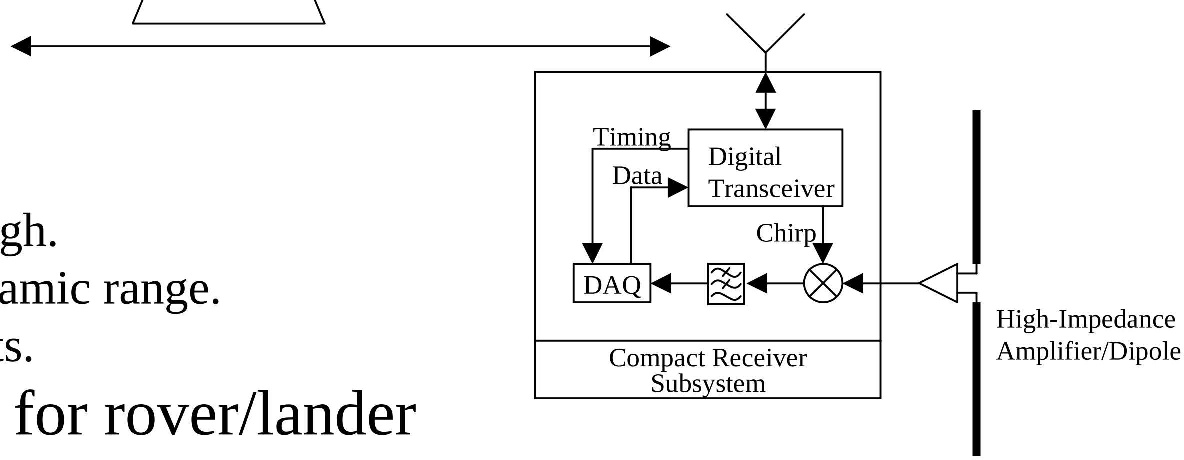
Frequency Range

low: determined by antennas – 5 MHz.

high: determined by DDS – 120 MHz.

Proposed: 5 – few hundred MHz

resolution and penetration depth.



Wireless Link

increased separation.

decreased feed-through.

increased usable dynamic range.

bistatic measurements.

Antennas: modify for rover/lander

THE END

Questions or Comments