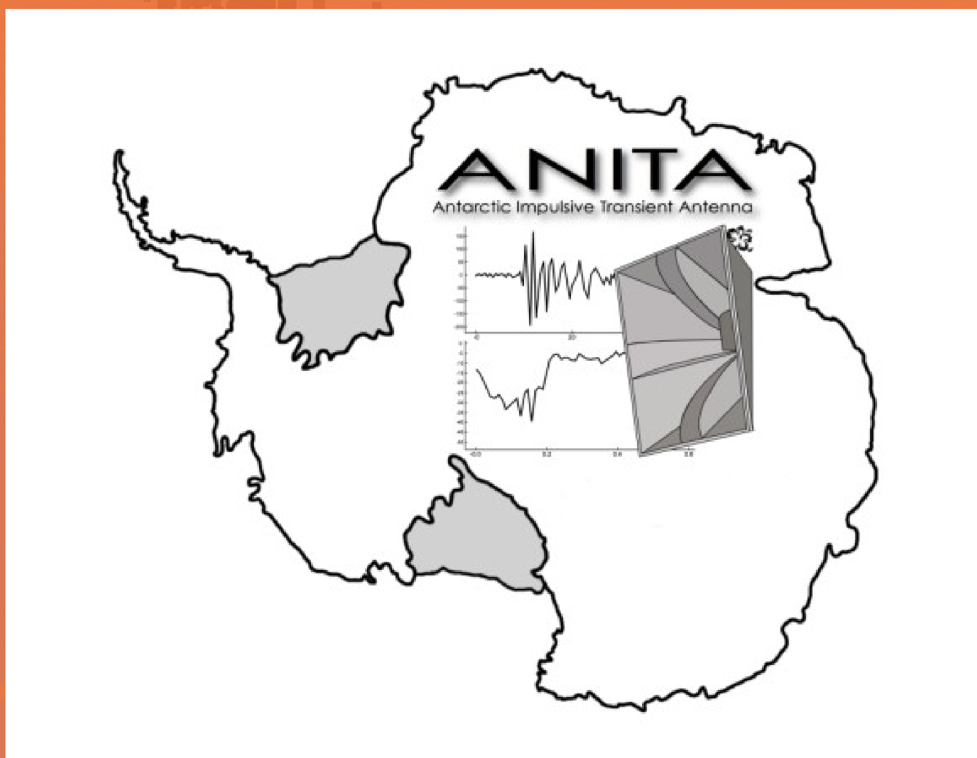
Use of Radar Depth Sounding Data to Estimate Radio Frequency Attenuation in Greenlandic and Antarctic Ice



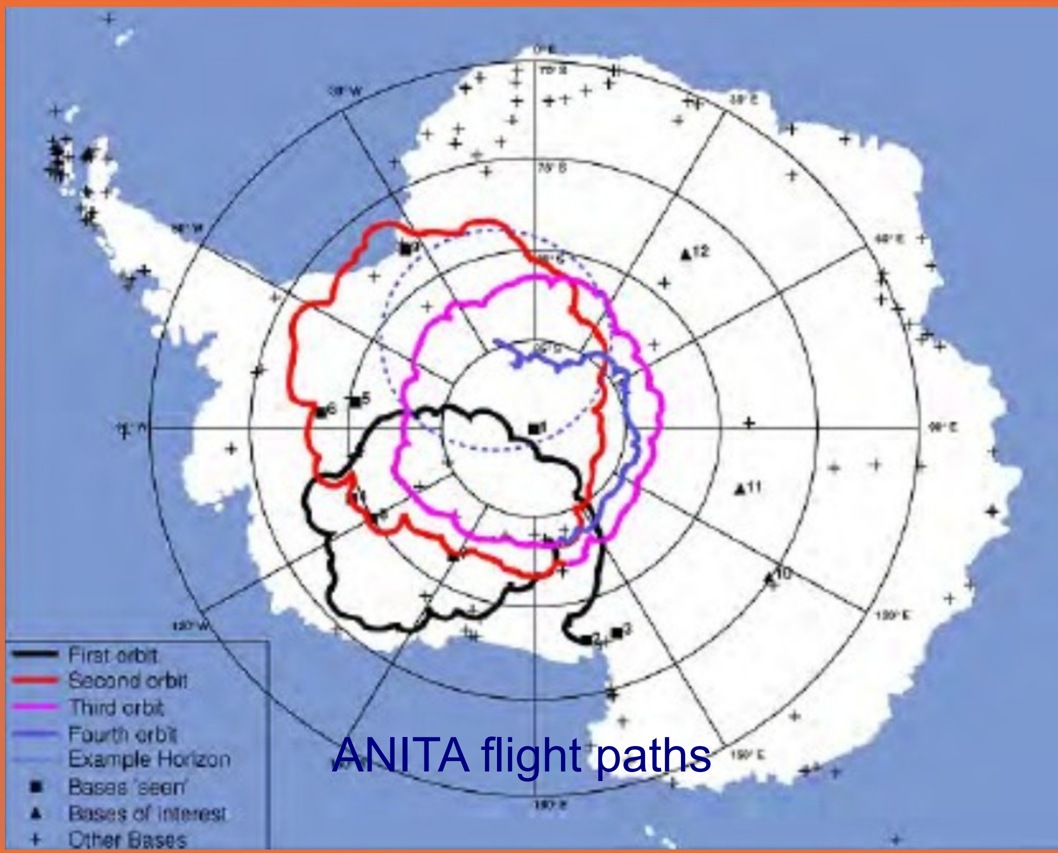
Mark Stockham
University of Kansas
for the ANITA Collaboration

Importance

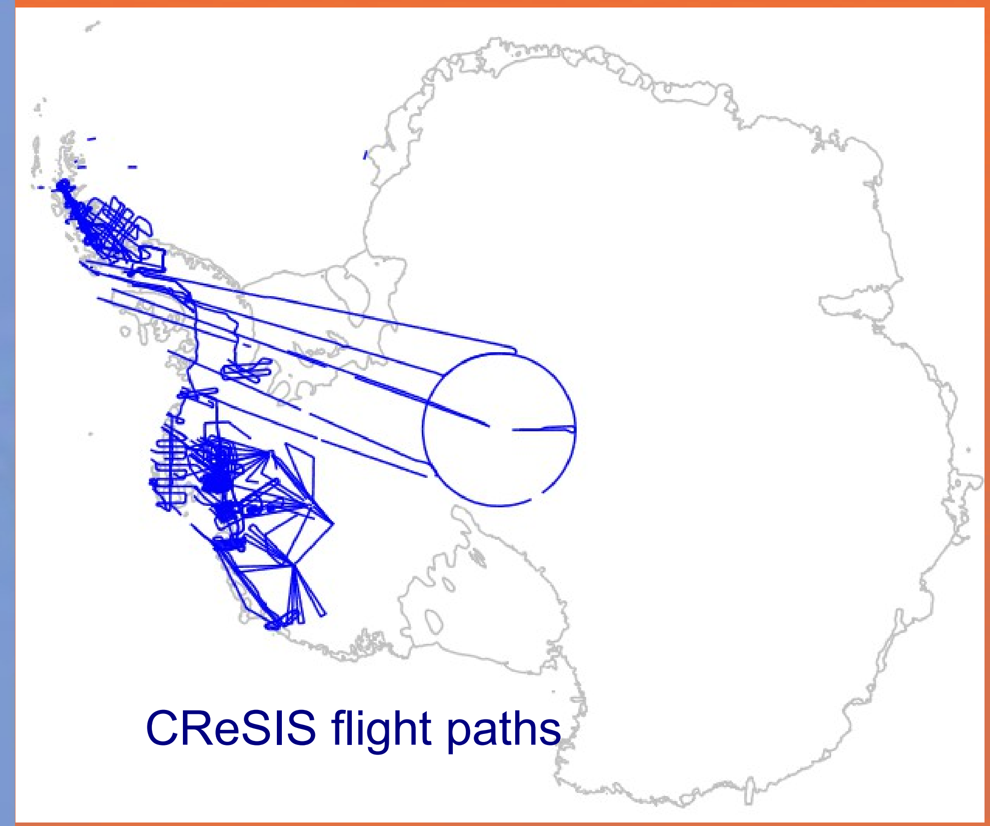
- ANITA is a suite of antennas that rides on a balloon "around the world," looking at in-ice neutrino events
- As radio signals produced by the Askaryan effect from neutrino-ice interaction propagate through the ice they are attenuated (fall off by more than geometric amount)
- After accounting for attenuation, the neutrino energy can be estimated
  - UHE neutrinos are of most importance because of their relation to unexplained UHE CRs, and offer a better chance at directional reconstruction
- Needed for MC effective volume estimate

Current State

- We currently have a model from Amir Javaid (University of Delaware), but continent-wide tests have not been done
- Center for Remote Sensing of Ice Sheets (CReSIS) has database of radar depth sounding (RDS) with good coverage in West Antarctica
  - Can potentially use these data to test our model
- Unfortunately for us, Greenland data is better (higher sampling rate) so use it for technique development



ANITA flight paths



CReSIS flight paths

Goals

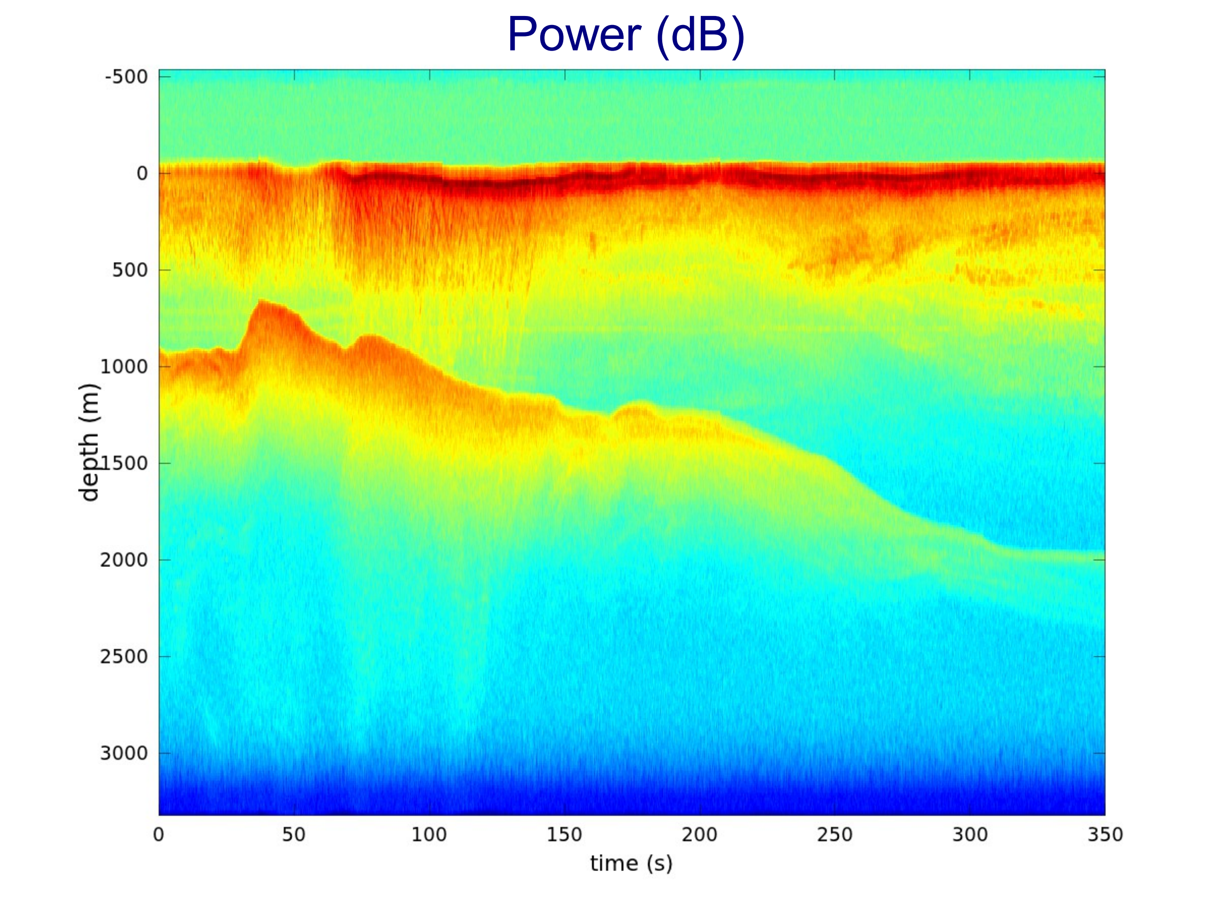
Estimate depth-dependent attenuation length from RDS data

Match estimate from echogram close to a core with prediction from that core

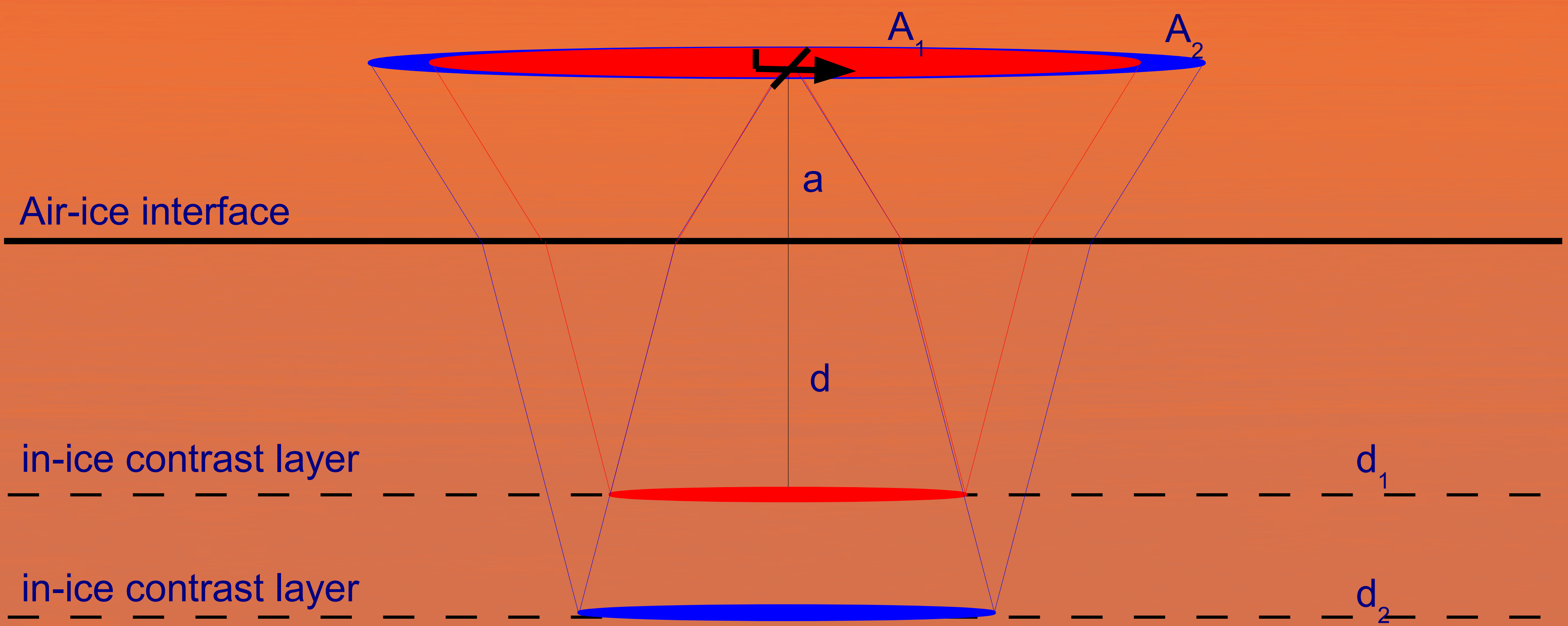
Determine if modeled attenuation length profiles are reasonable compared to estimates from RDS data

Data – CReSIS MCoRDS

- Flyover w/ radar pulsing ~195MHz (BW ~10MHz)
- 2 channels
  - Low gain for surface bounce
  - High gain for bottom bounce
- Put through bounce detection algorithm and stitched together (accounting for gain mismatch)



RDS cartoon



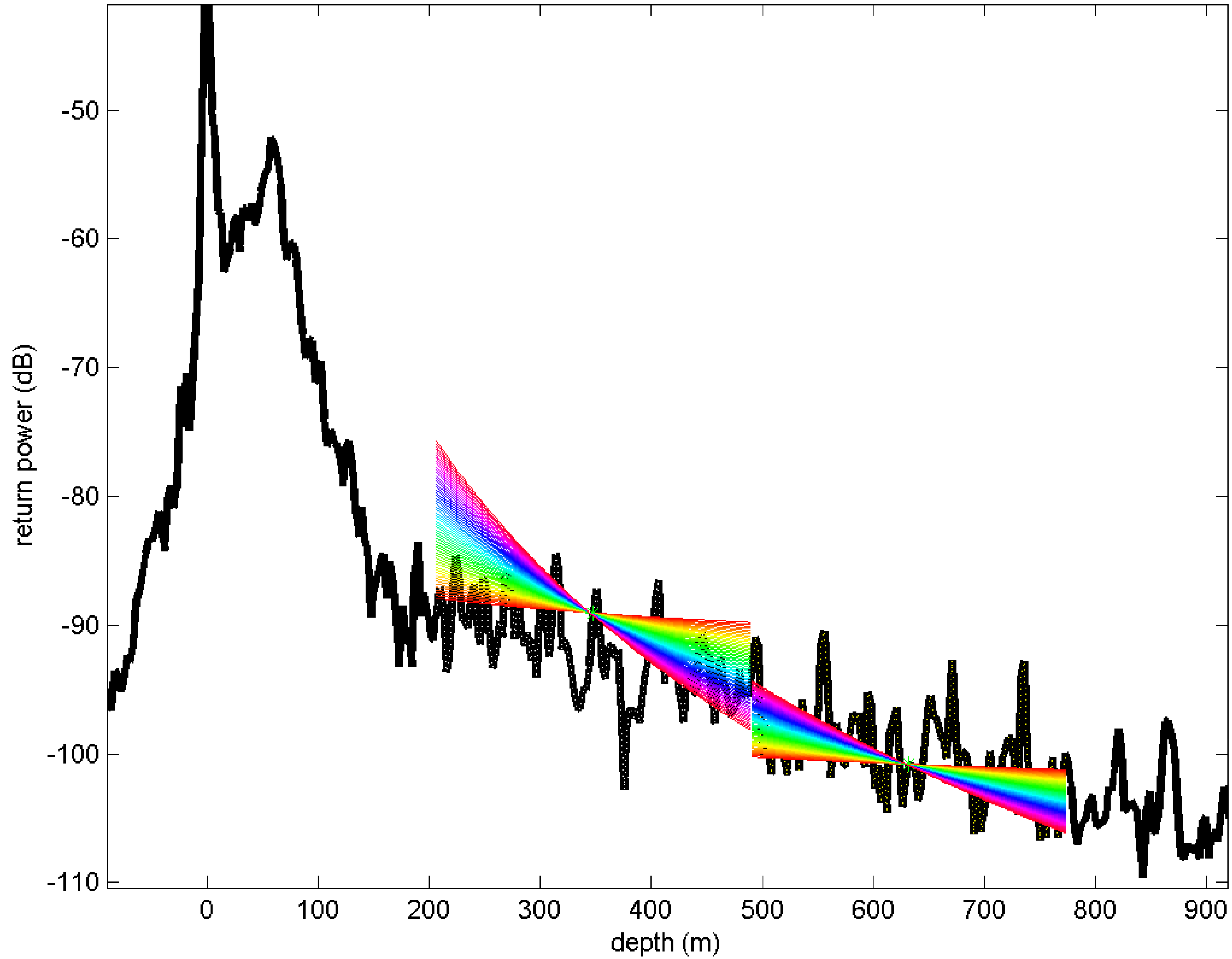
A1
A2
a
Air-ice interface
d
in-ice contrast layer
d1
in-ice contrast layer
d2

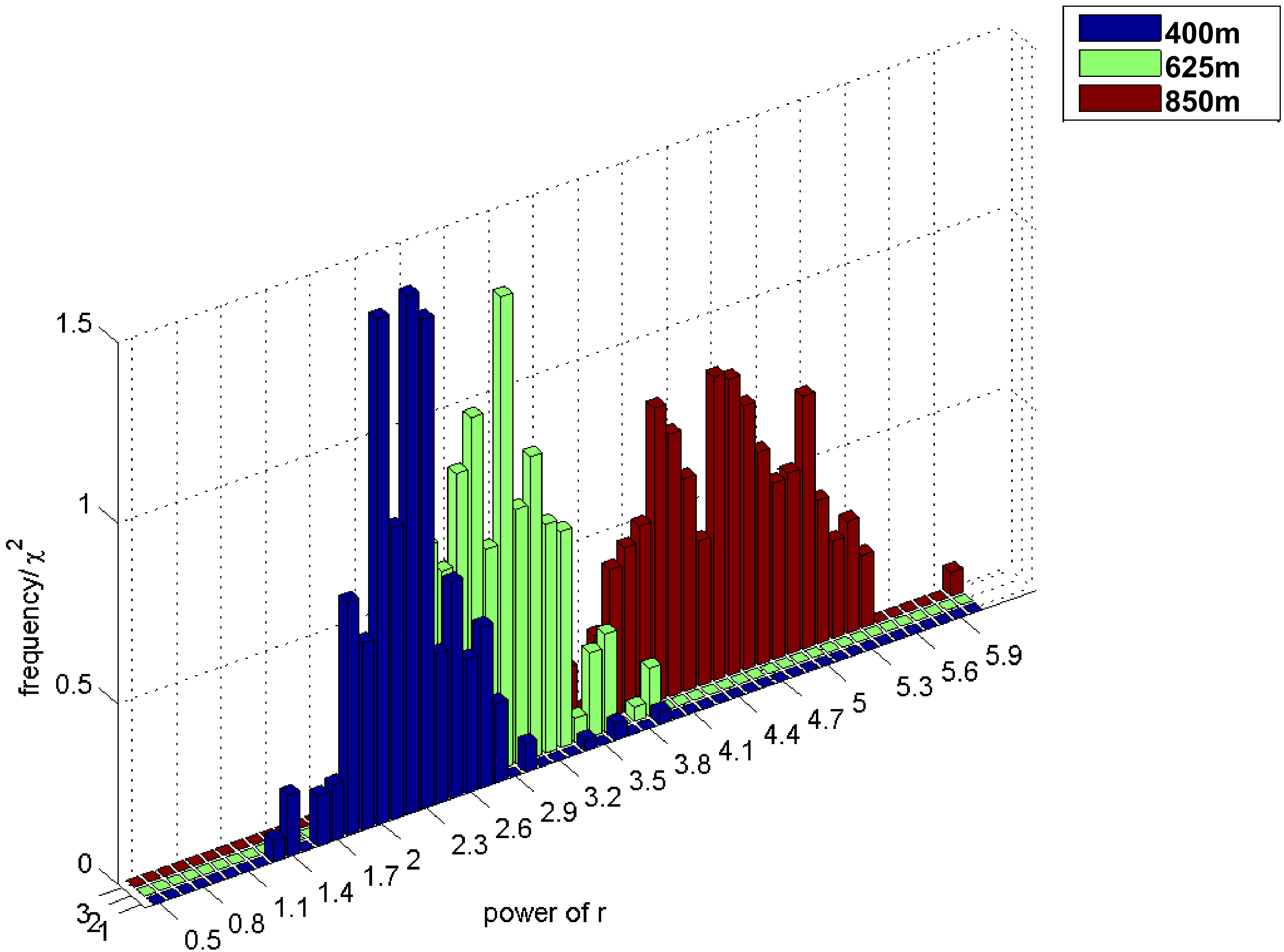
Attenuation Length

- Wish to solve for the attenuation length – the distance over which the amplitude decreases by a factor of *e*
- The expected form of the data should be a power law multiplied by an exponential decay representing geometrical spreading and attenuation, respectively

$$A \propto A_0 \frac{1}{\left(2\mathrm{a}+2\mathrm{d}\right)^n} \exp\left(\frac{-2\mathrm{d}}{L_\alpha}\right)$$

Determining Appropriate Power Law

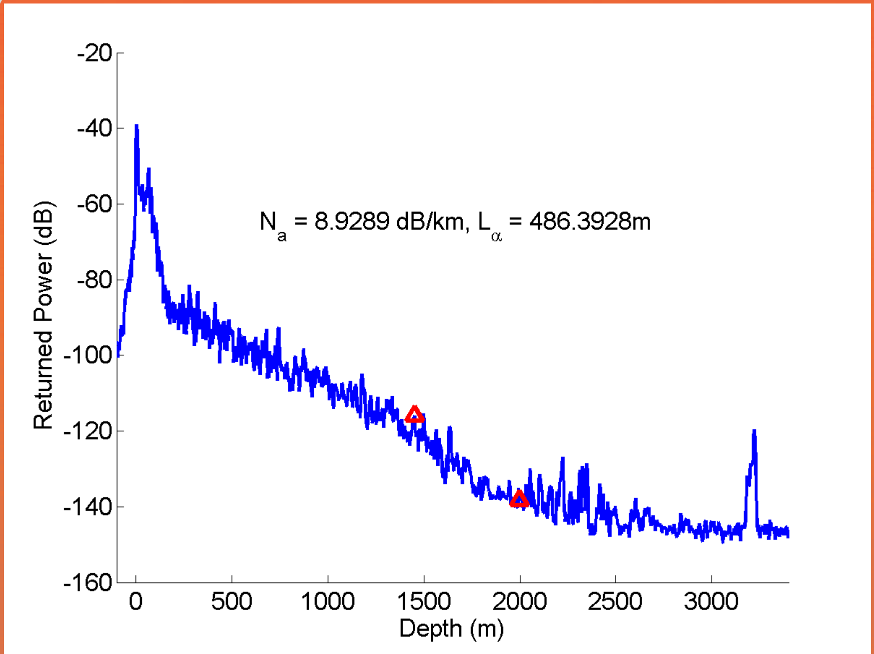



400m
625m
850m
frequency/ χ^2
1.5
1
0.5
0
3
2
1
0.5
0.8
1.1
1.4
1.7
2
2.3
2.6
2.9
3.2
3.5
3.8
4.1
4.4
4.7
5
5.3
5.6
5.9
power of r

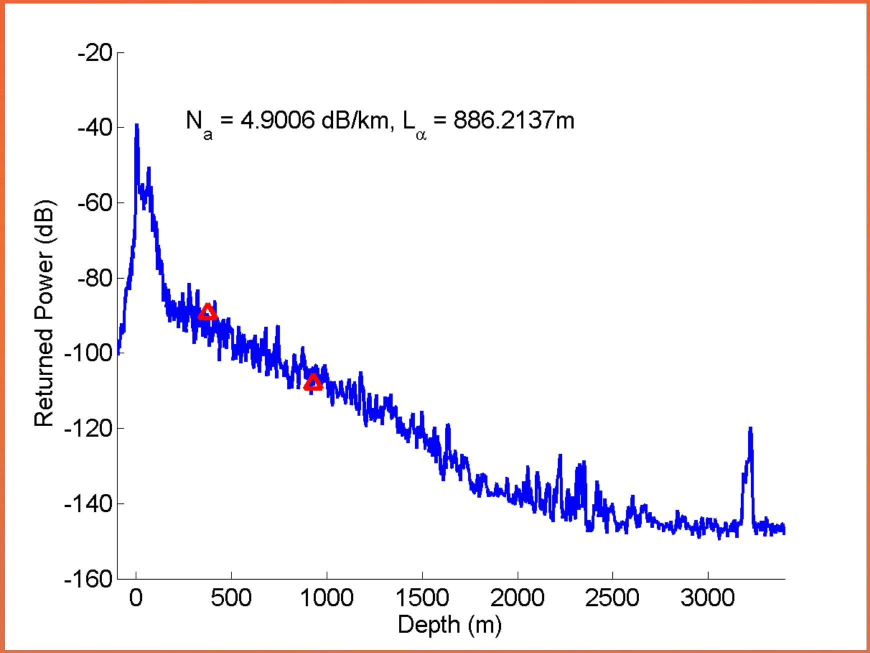
2-point Method

- Picks a random segment from a ping that is between 400-600m long at a random starting point (endpoint must be before thermal noise plateau)
- Calculates change in power due to $1/r^2$, whatever remains is attributed to attenuation
- $$N_a = \frac{1000}{2(r_2 - r_1)}\left(P_1 - P_2 + 20\log\left(\frac{r_1 + a_1}{r_2 + a_2}\right)\right)$$
- Does this large number of times to diminish effects of "bad" pairs
- Statistical fit in log space is converted to attenuation length
- Assumptions:
    - The mechanism that produces the backscattering falls off as 1/r in amplitude and is constant function of depth
        - Many layers with very small and approx equal reflection coefficients would satisfy this
    - Slowly varying attenuation length profile
- Does NOT assume any temperature information or have any fitted offset

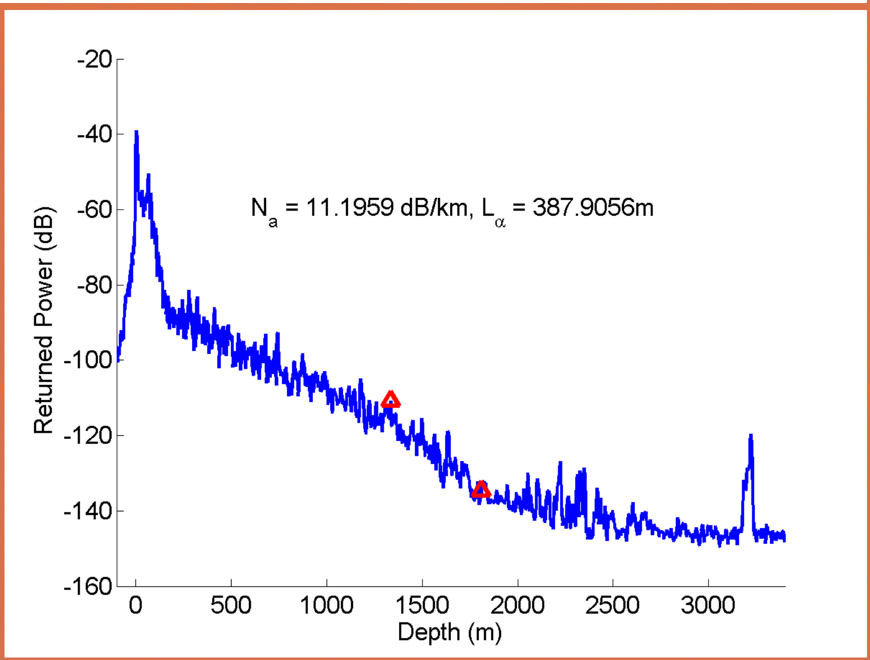
Examples



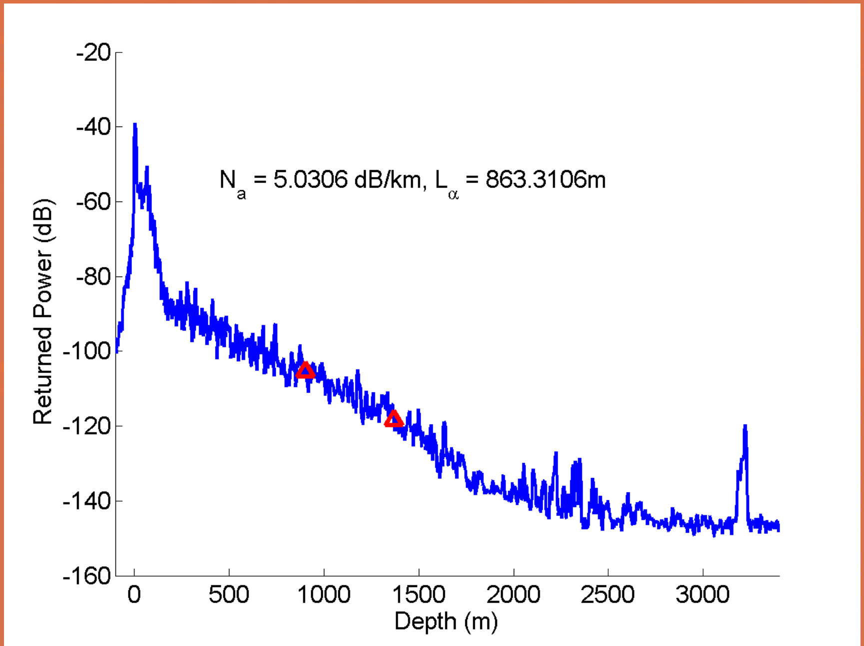
Returned Power (dB)
Depth (m)
N_a = 8.9289 dB/km, L_α = 486.3928m



Returned Power (dB)
Depth (m)
N_a = 4.9006 dB/km, L_α = 886.2137m

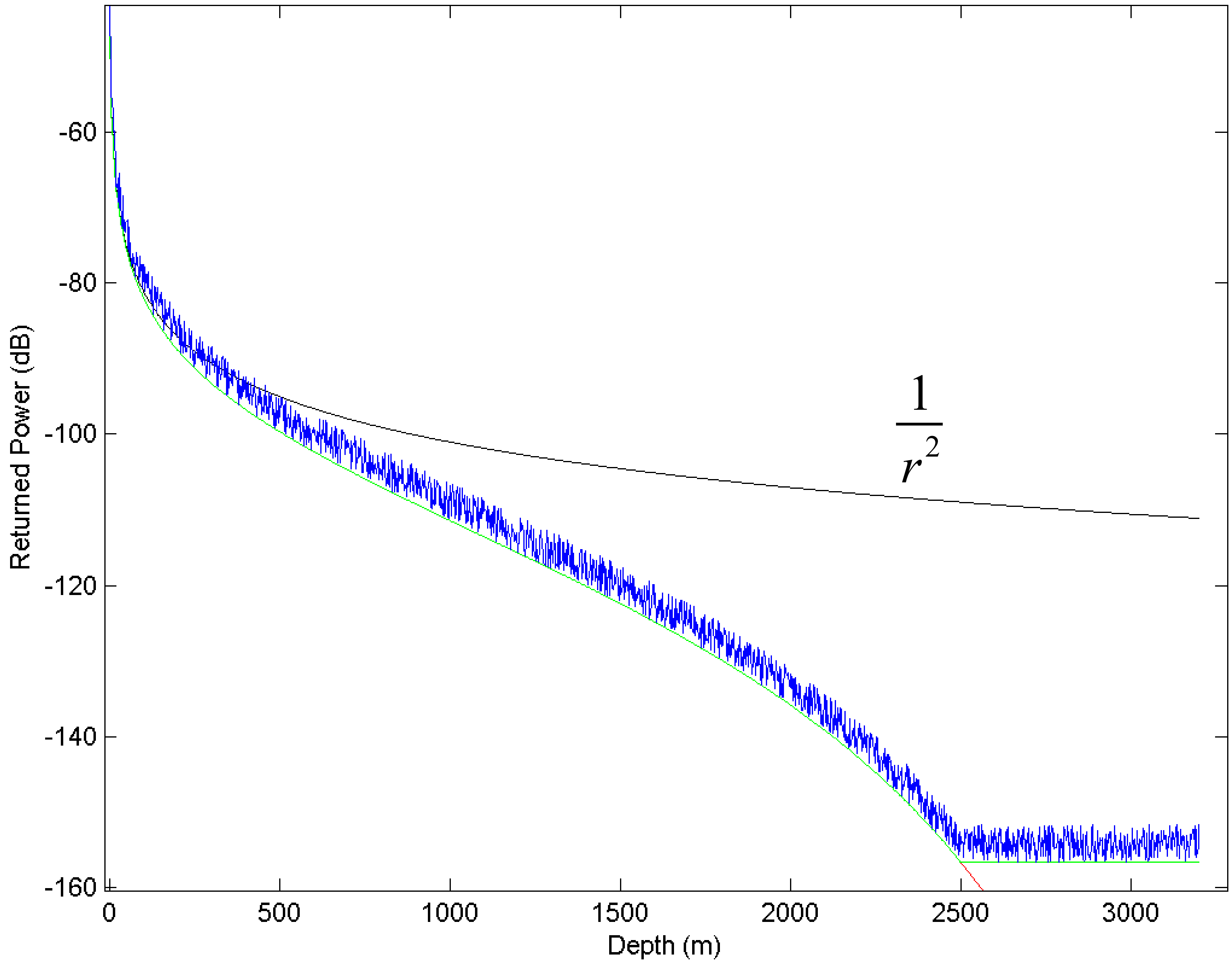


Returned Power (dB)
Depth (m)
N_a = 11.1959 dB/km, L_α = 387.9056m

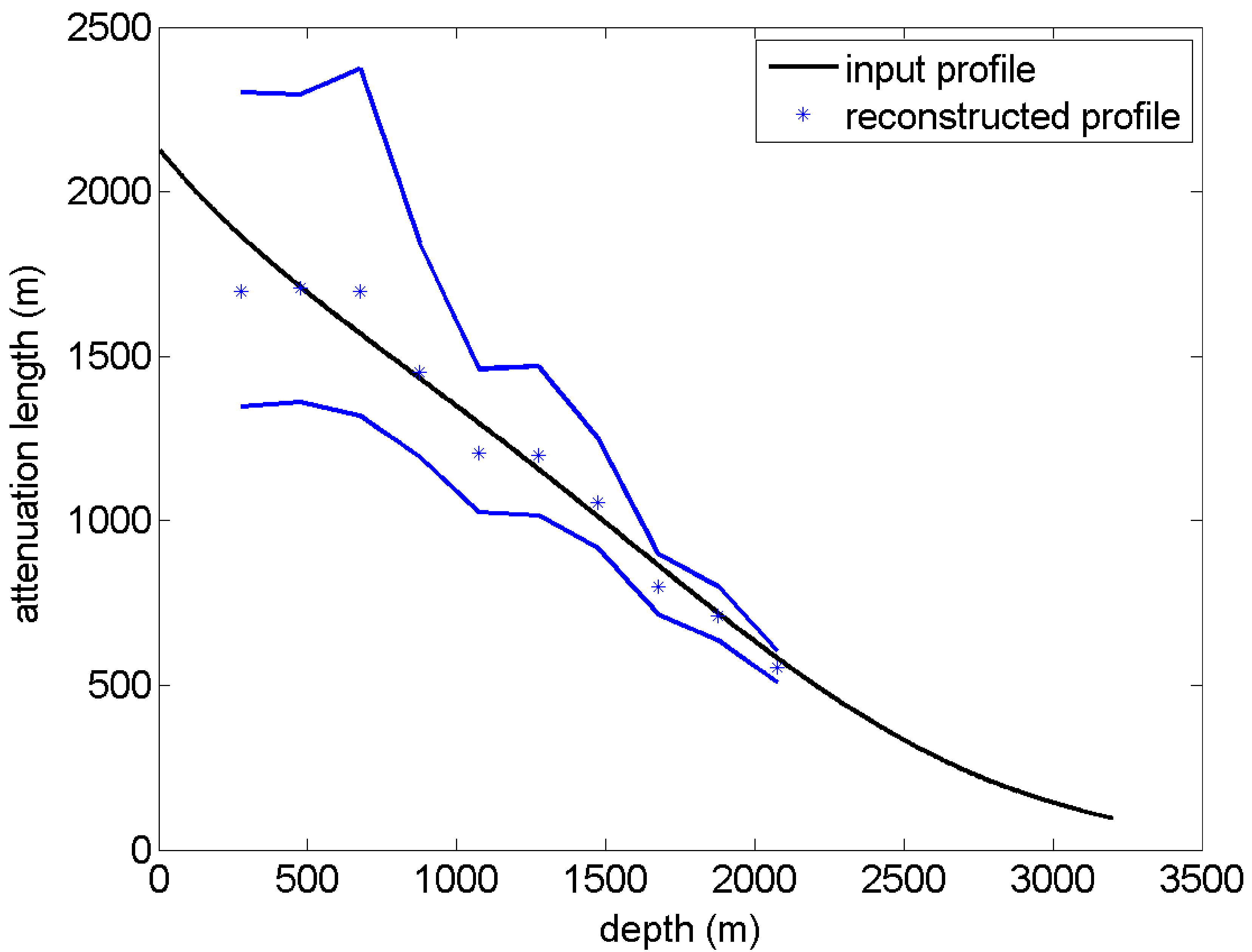


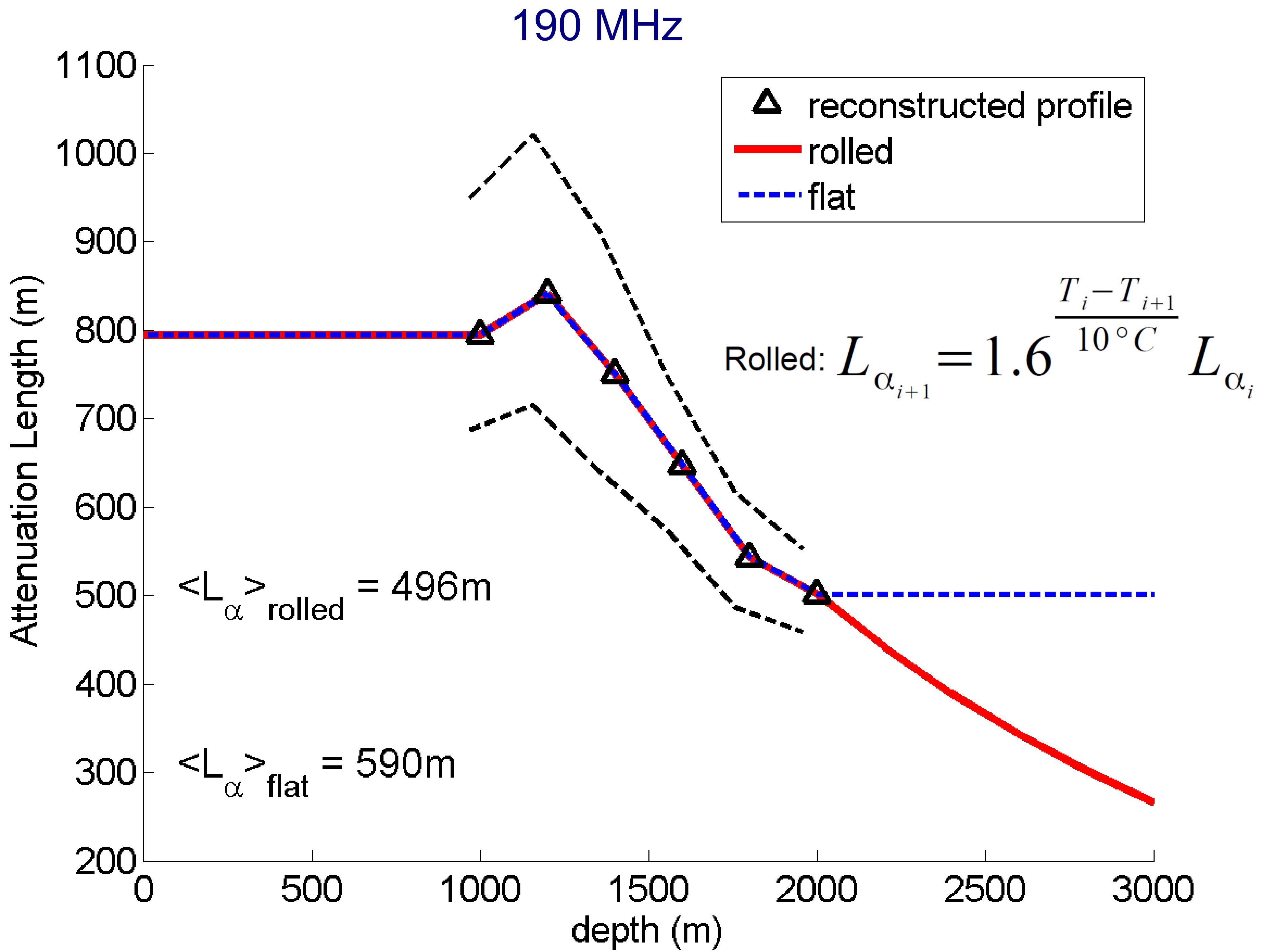
Returned Power (dB)
Depth (m)
N_a = 5.0306 dB/km, L_α = 863.3106m

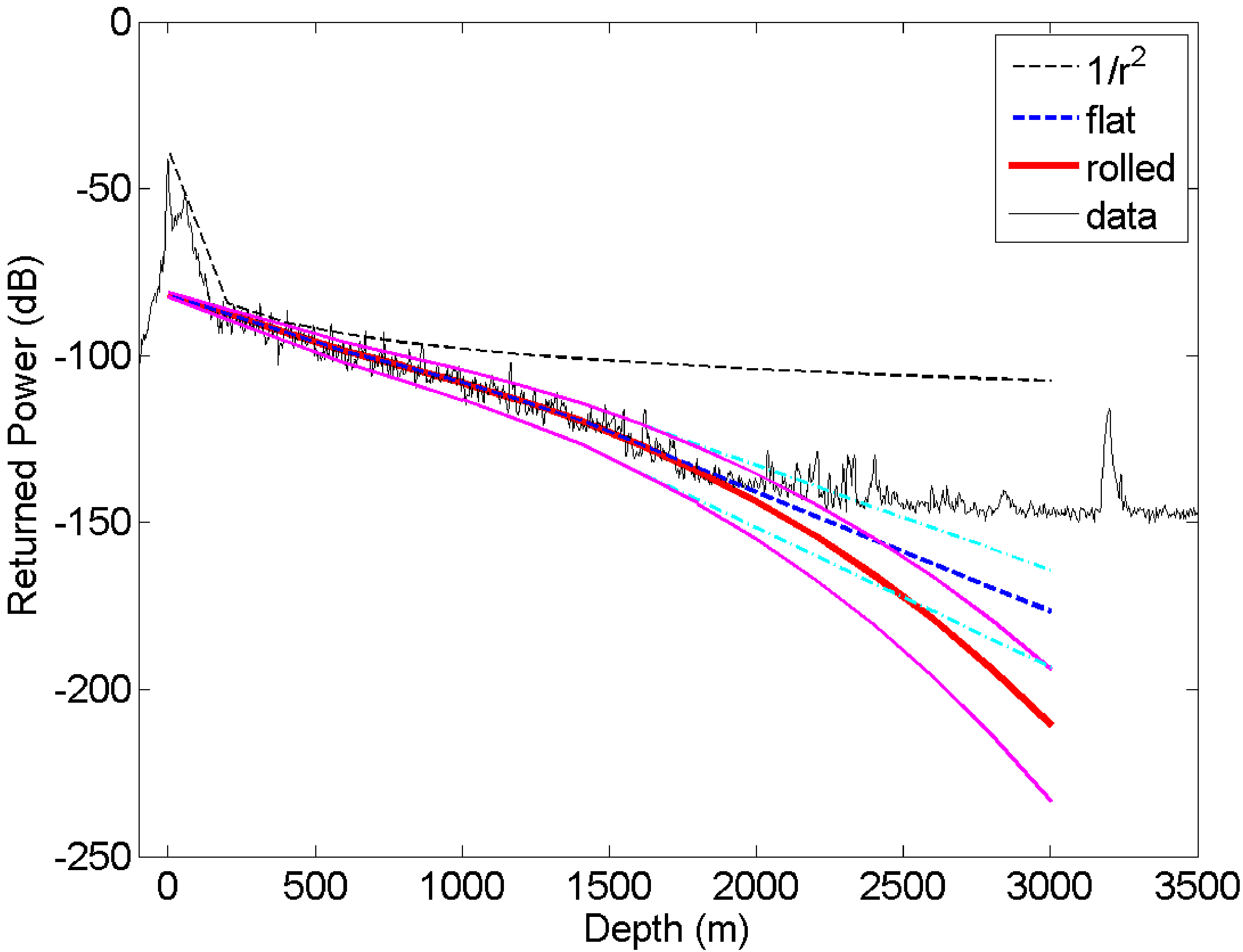
Synthetic Example



Fit to Synthetic Data

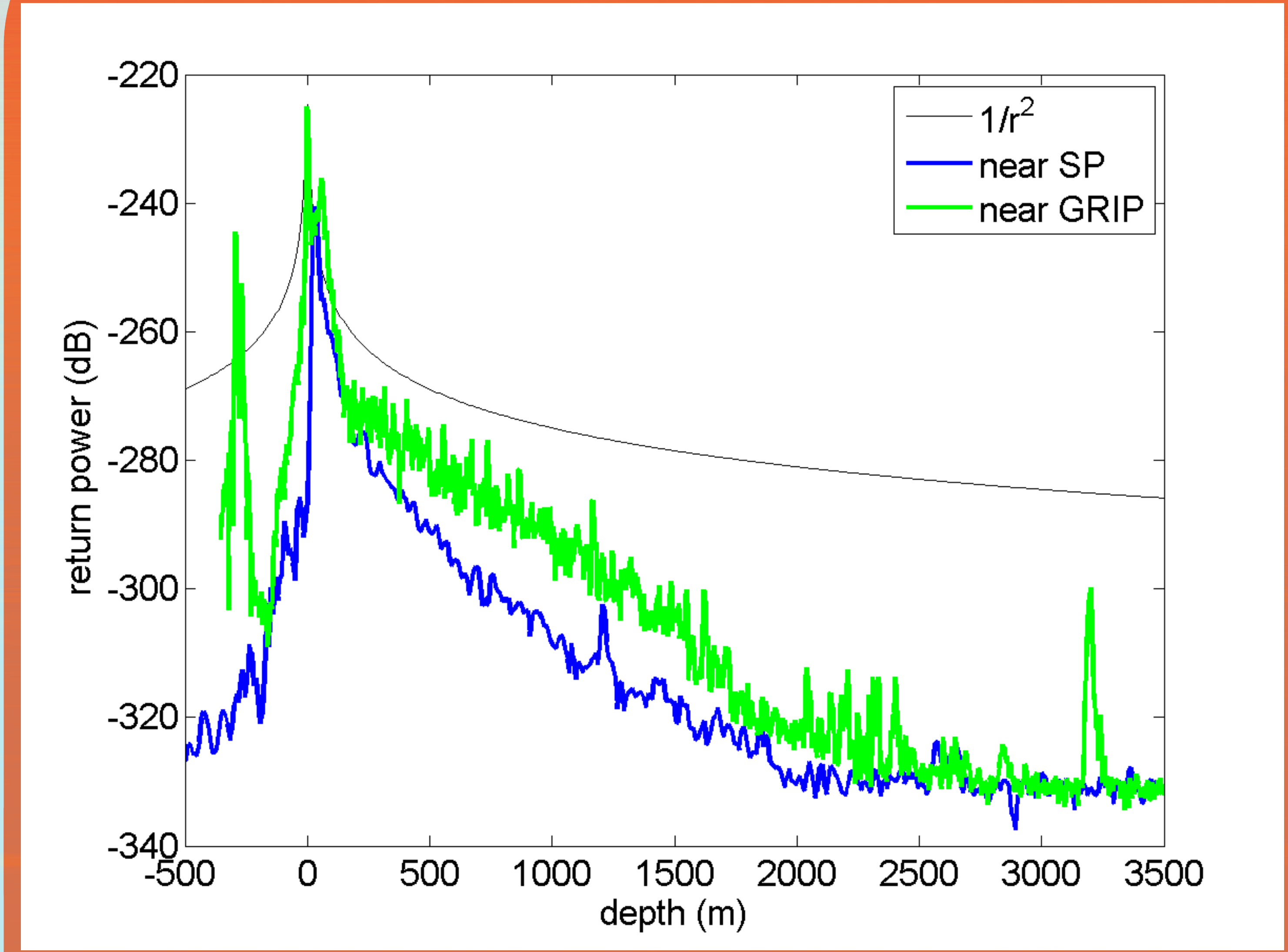



190 MHz
reconstructed profile
rolled
flat
Rolled: $L_{\alpha_{i+1}} = 1.6^{\frac{T_i - T_{i+1}}{10°C}} L_{\alpha_i}$
$\langle L_\alpha \rangle_{rolled}$ = 496m
$\langle L_\alpha \rangle_{flat}$ = 590m
Attenuation Length (m)
depth (m)
1100
1000
900
800
700
600
500
400
300
200
0
500
1000
1500
2000
2500
3000



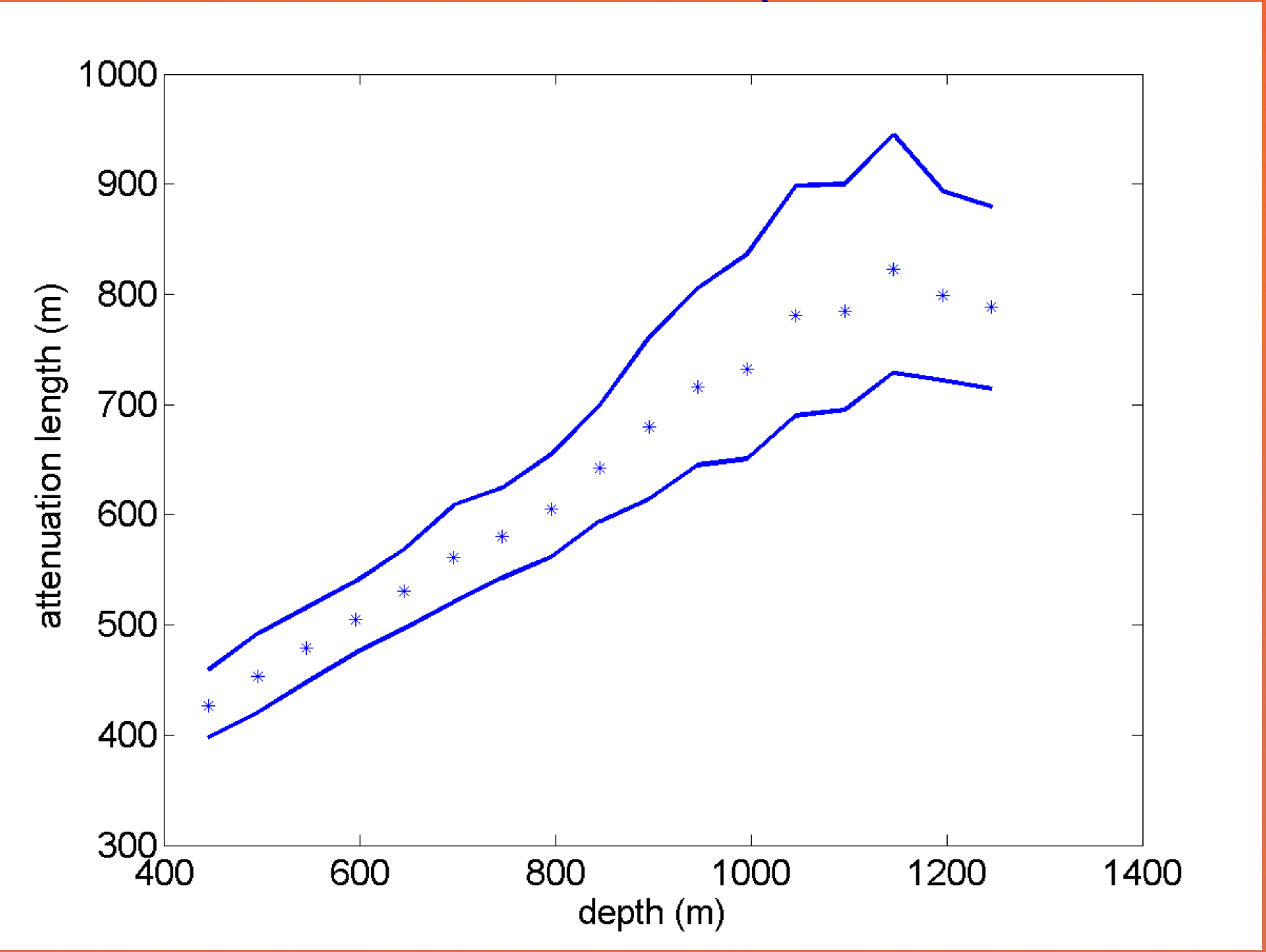
Returned Power (dB)
0
-50
-100
-150
-200
-250
0
500
1000
1500
2000
2500
3000
3500
Depth (m)
1/r^2
flat
rolled
data

Comparison to Antarctic Data



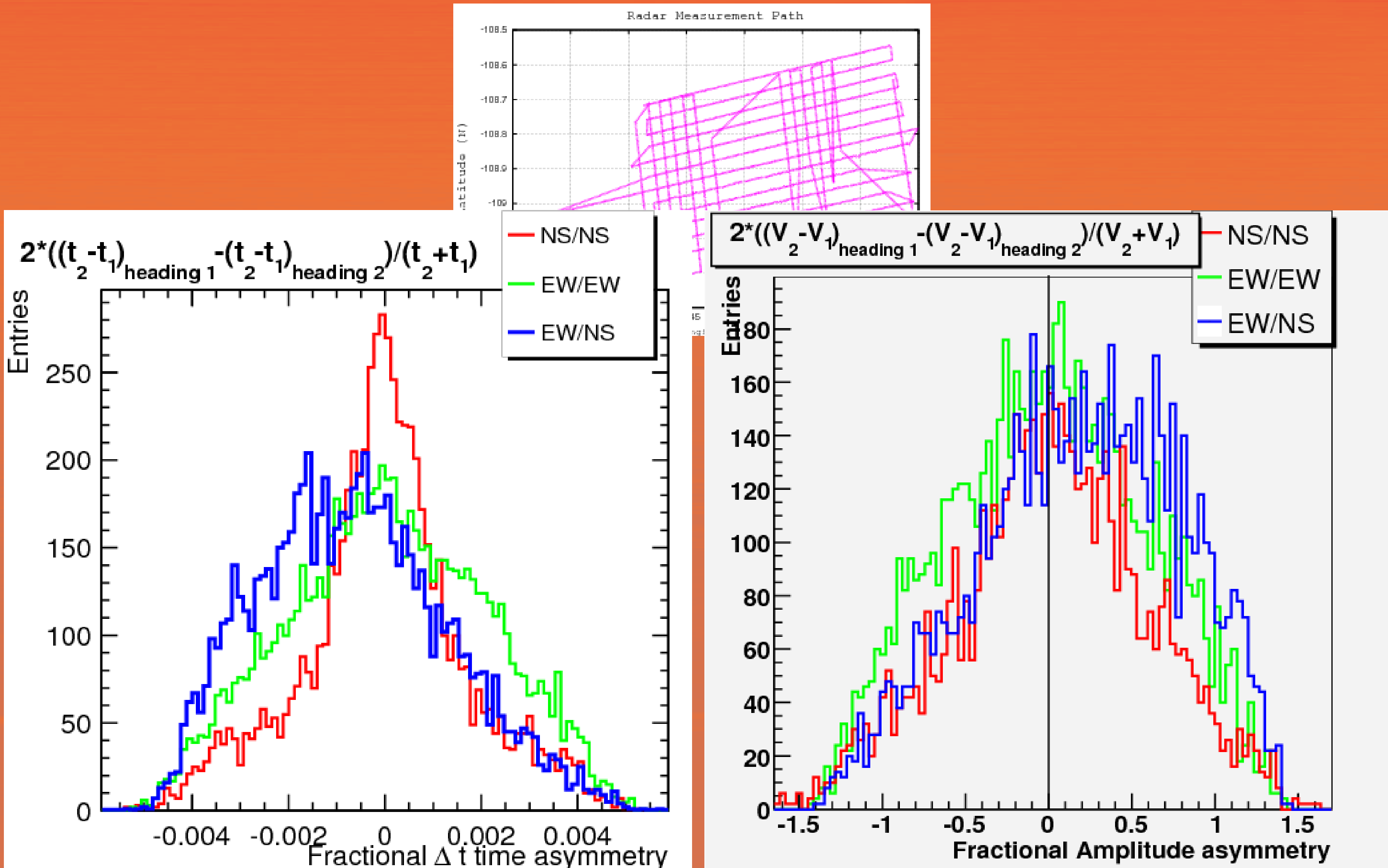
- Antarctic and Greenlandic returns look very different (supposedly same DAQ)
- Speculation: constant reflector assumption that works in Greenland is invalid

Implied South Pole Profile (without correction)



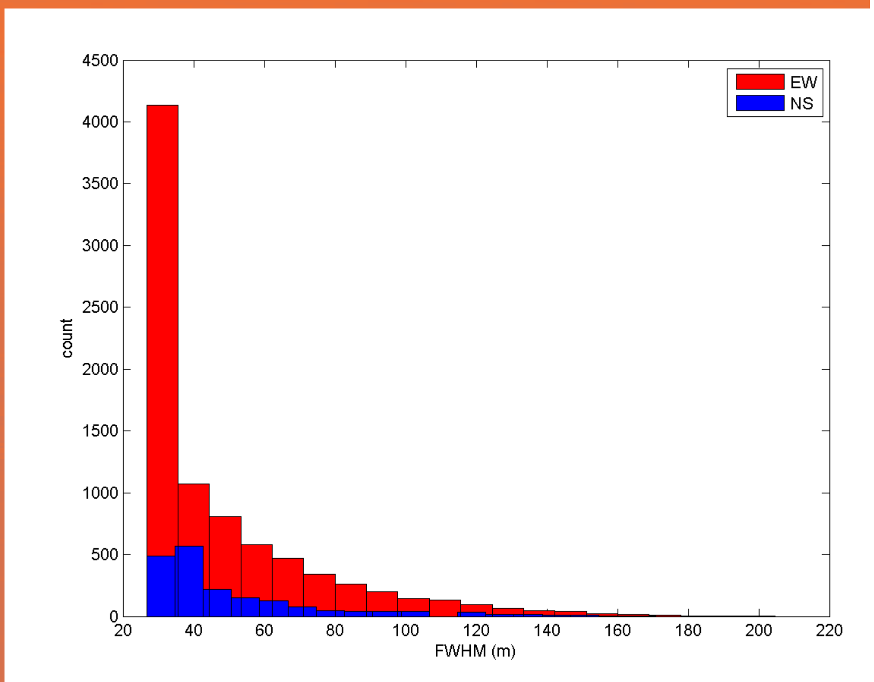
Inverted from what we would expect

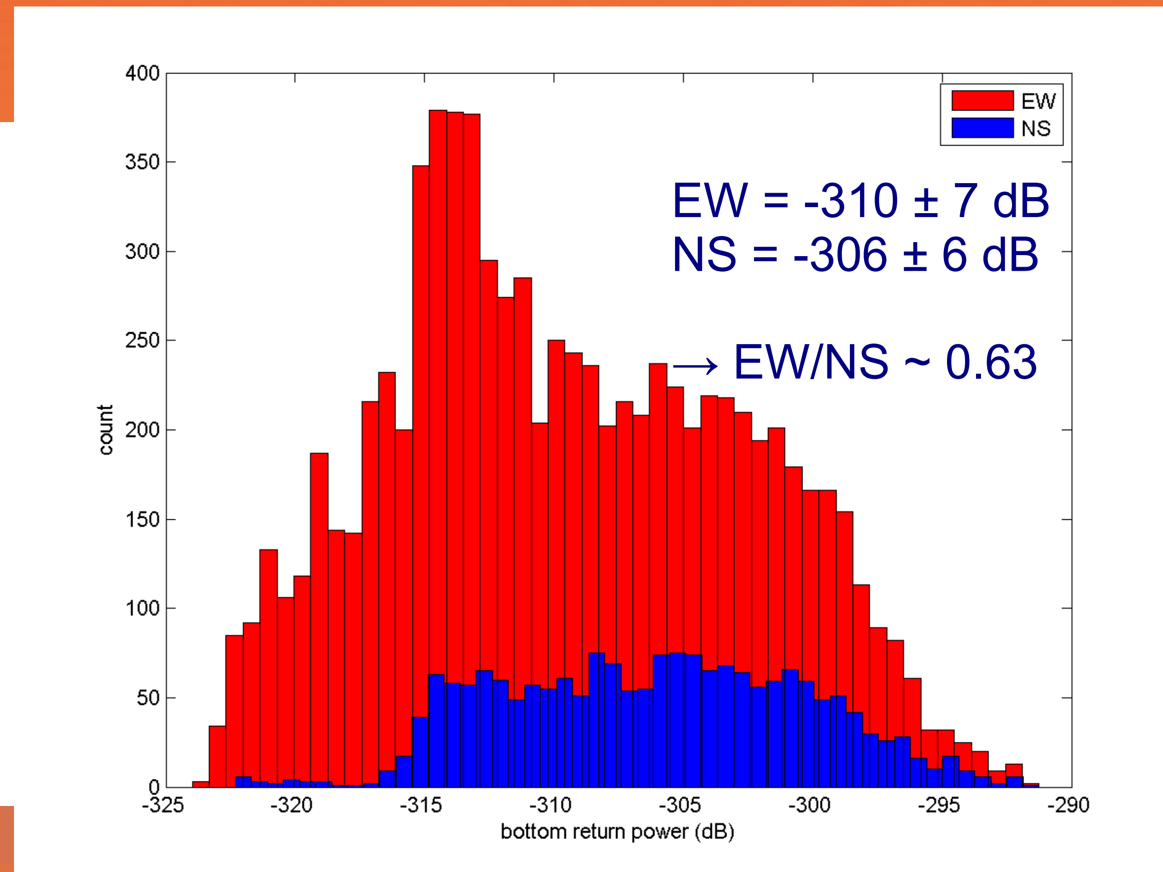
Birefringence (Thwaites)



Analysis and figures by Dave Besson

Near SP





No strong evidence of reflection broadening, but majority of data is on-axis (NS or EW)

Approximately the same voltage asymmetry is observed, but points are not co-located

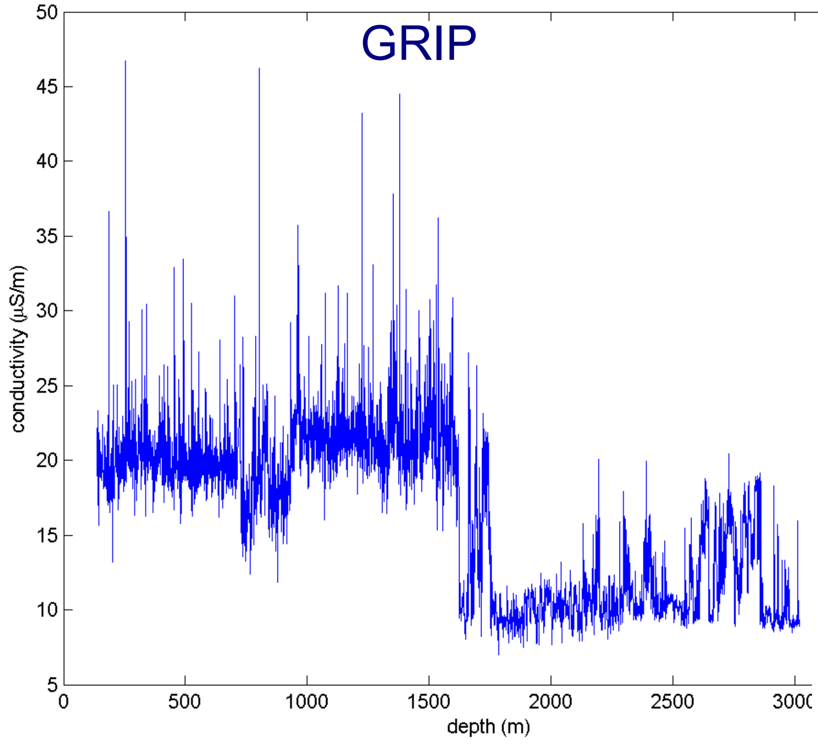
- Conclusions:
  - Good fit with synthetic data (even with large noise values)
  - Hard to compare with GRIP profile (temperature-only attenuation profile from data is a bad fit, Greenland potentially has larger chemical effect)
  - Sampled 2-point method is fairly robust and does not require record by record tuning as did some previous methods
    - Minimum-maximum segment length and vertical bin number responsible for most change
- Need to:
  - Find reliable borehole record with nearby CReSIS data to truly verify method as well as tune those “universal” variables
    - Investigate correcting Antarctic data
  - Compare to values given by Amir's model
  - Other ice properties from CReSIS? More with birefringence, also radar bands of 550-900 MHz, 2-6 GHz, and 13-17 GHz

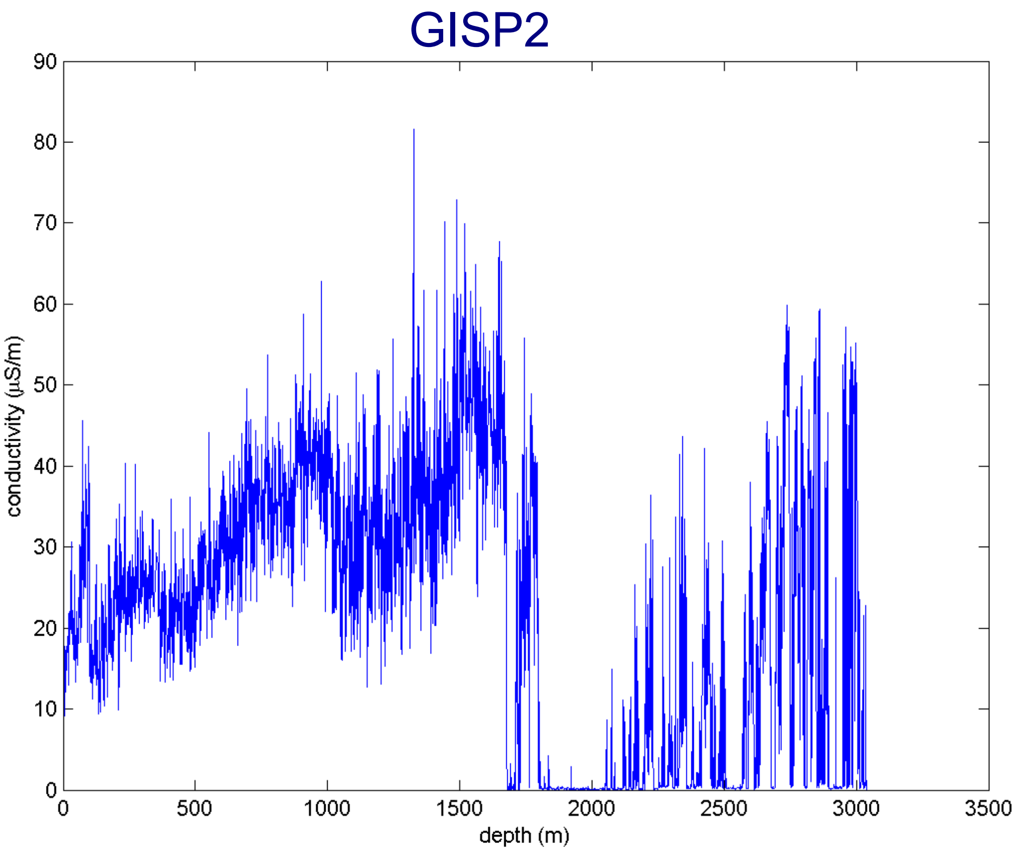
Thank You
Questions?

- Funded by NASA
- Sources
  - CReSIS (data.cresis.ku.edu)
  - John Paden for RDS answers
  - Amir Javaid PhD dissertation, U. of Delaware
  - Joseph A MacGregor “Development and Applications of a Radar-Attenuation Model for Polar Ice Sheets”, PhD Dissertation, 2008, U. of Washington

Extras

Conductivity Near GRIP



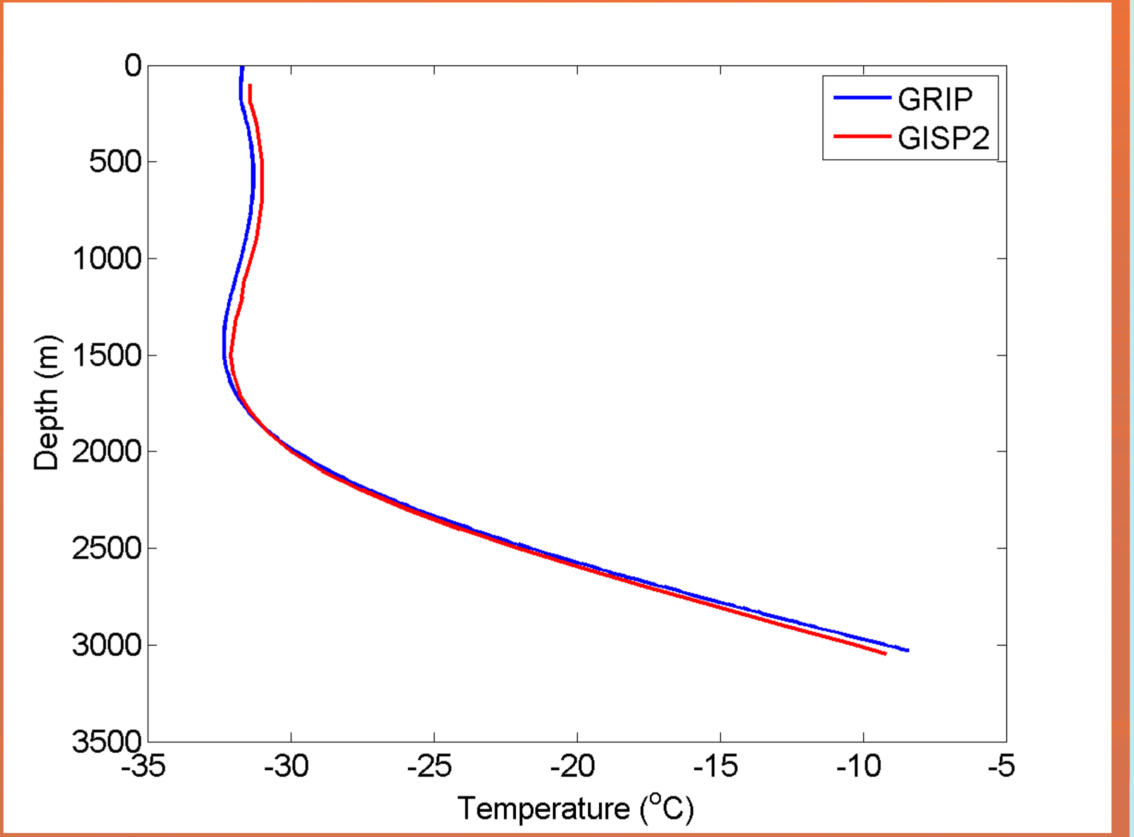


Comparison of GRIP with GISP2

"Several temperature logs and fixed-depth temperature experiments were conducted in the 3-km borehole (GISP-D) at the GISP2 site during 1994, 1995, and 1996. These experiments were conducted using the U.S. Geological Survey's temperature logging system (Clow et al., 1996; Clow and Gundestrup, 1997). The sample spacing for the primary temperature logs is about 20 cm while the accuracy of the temperature measurements is estimated to be 4.5 mK.

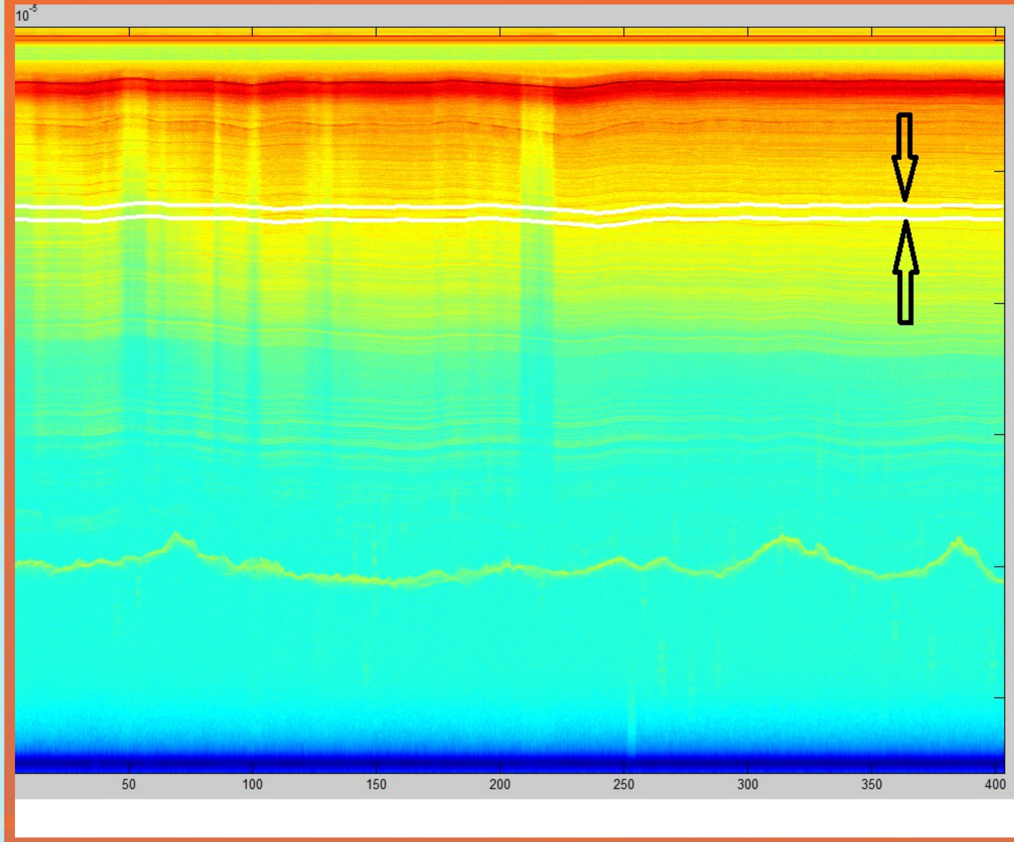
However, the temperature logs must be deconvolved to account for the finite response time of the temperature probe, corrected for the thermal disturbance caused by the drilling process, and corrected for the effects of fluid convection within the borehole. As of this time (SEP 1996), we are still developing the fluid convection and drilling disturbance corrections.

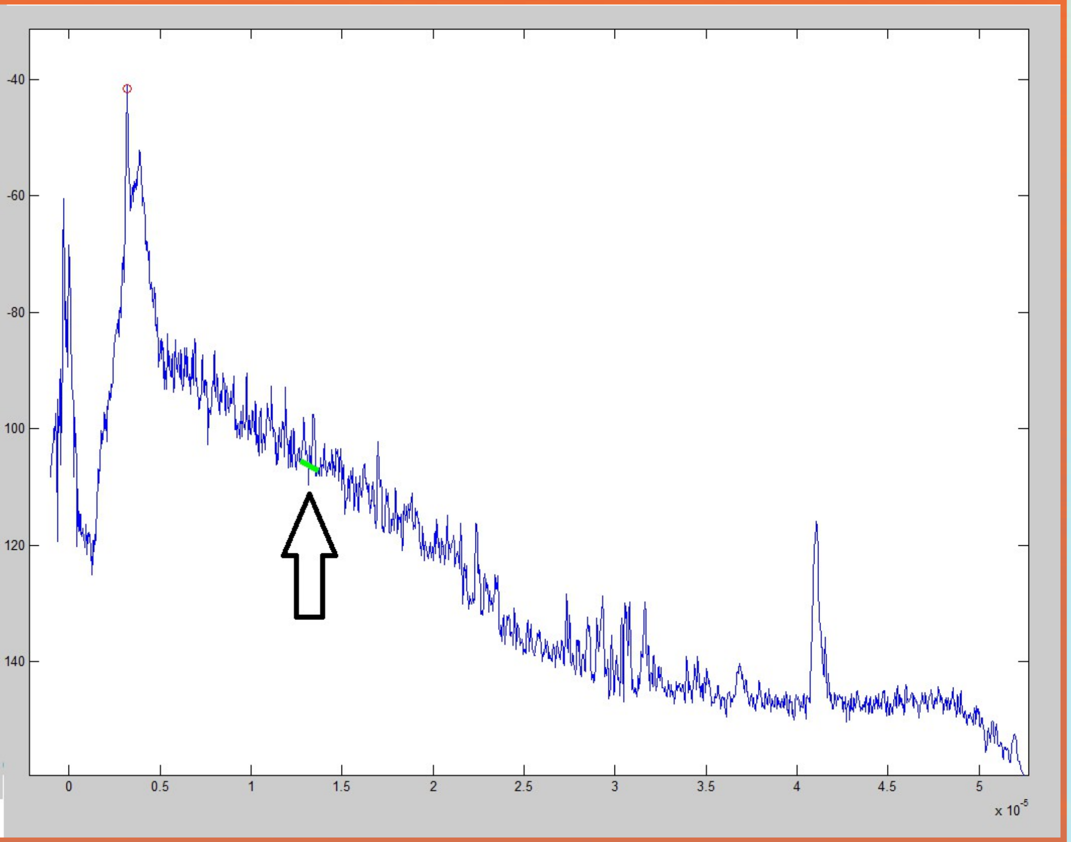
The following "uncorrected" data were obtained on 14 June, 1995. Although the quality is insufficient for borehole thermometry studies, it is probably adequate for many other studies (e.g. constraining ice dynamics models). The fully processed data will become available at a later date." GISP README, ca. 1996



Quick note – stitch time

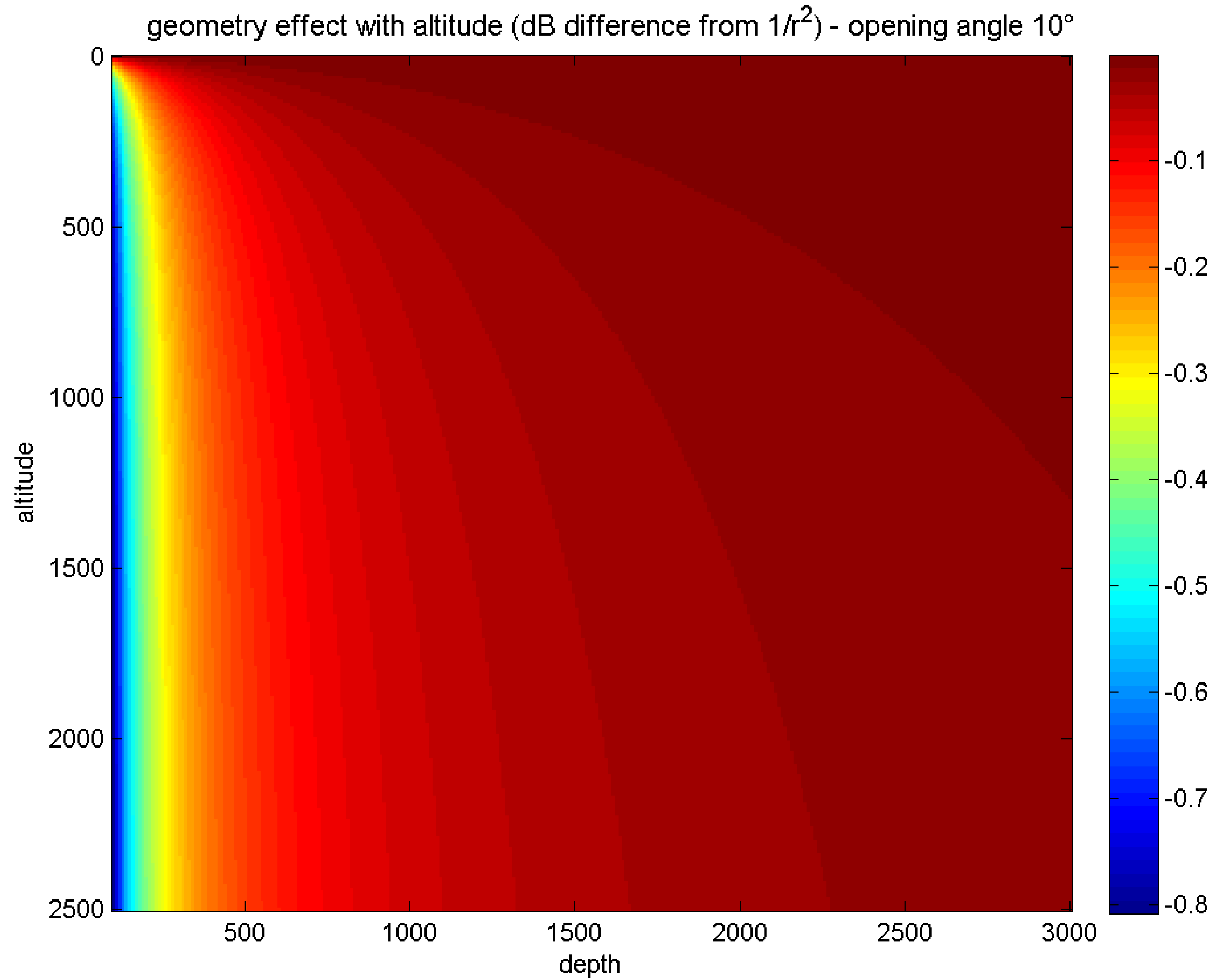
190 MHz



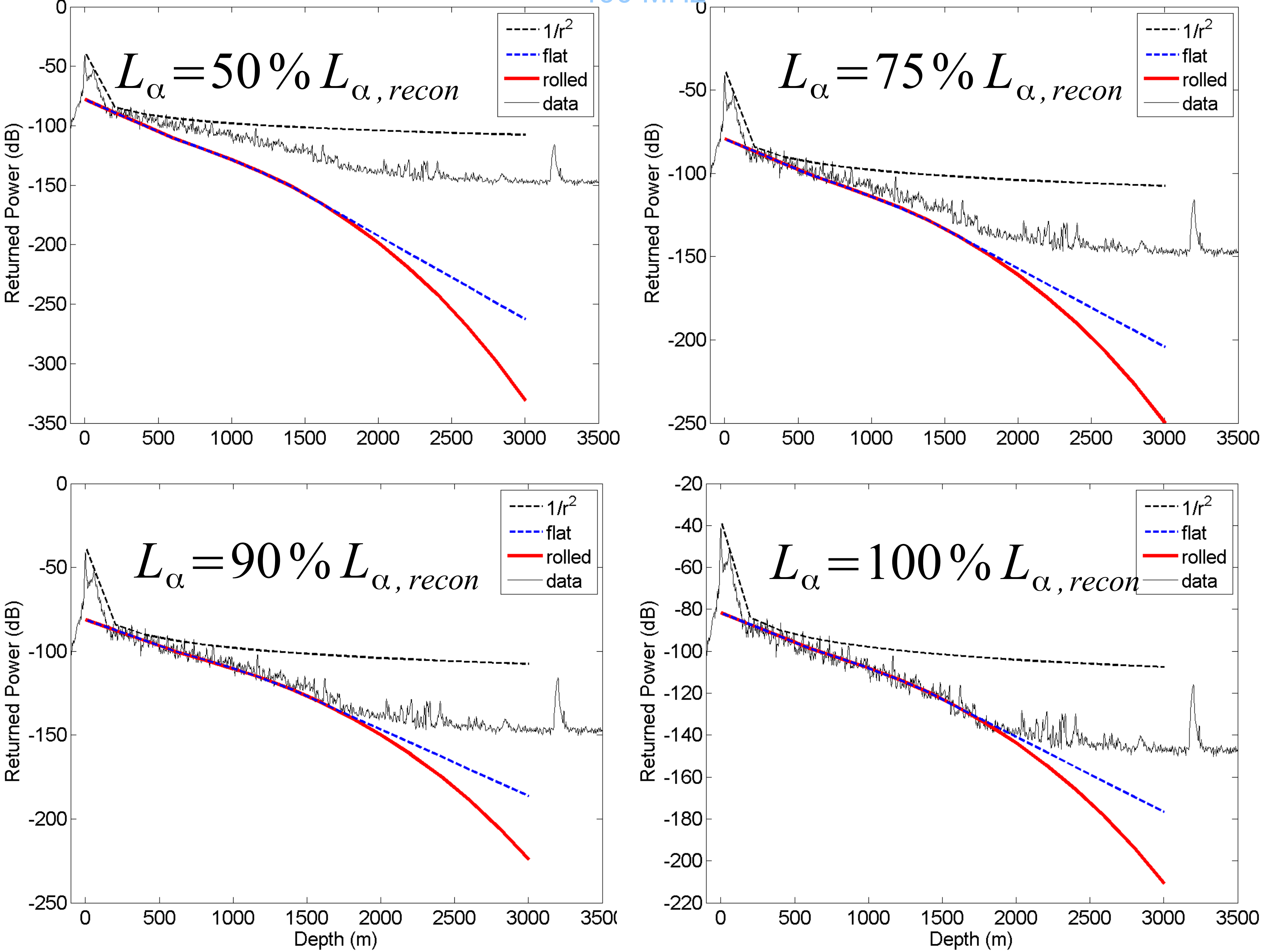


Constraints on the Method

- Needs to compare data that is proximal to have same chemistry and bottom depth (within same echogram ~50km)
- For various DAQ related reasons, more straight-forward approaches to measuring the attenuation (e.g. surface and basal reflection strength) are not possible
- What's left? The continuum signal from each individual ping
  - Not Rayleigh scattering – cross section implies -240dB
  - Small dielectric contrasts could do this (bi-annual layers)

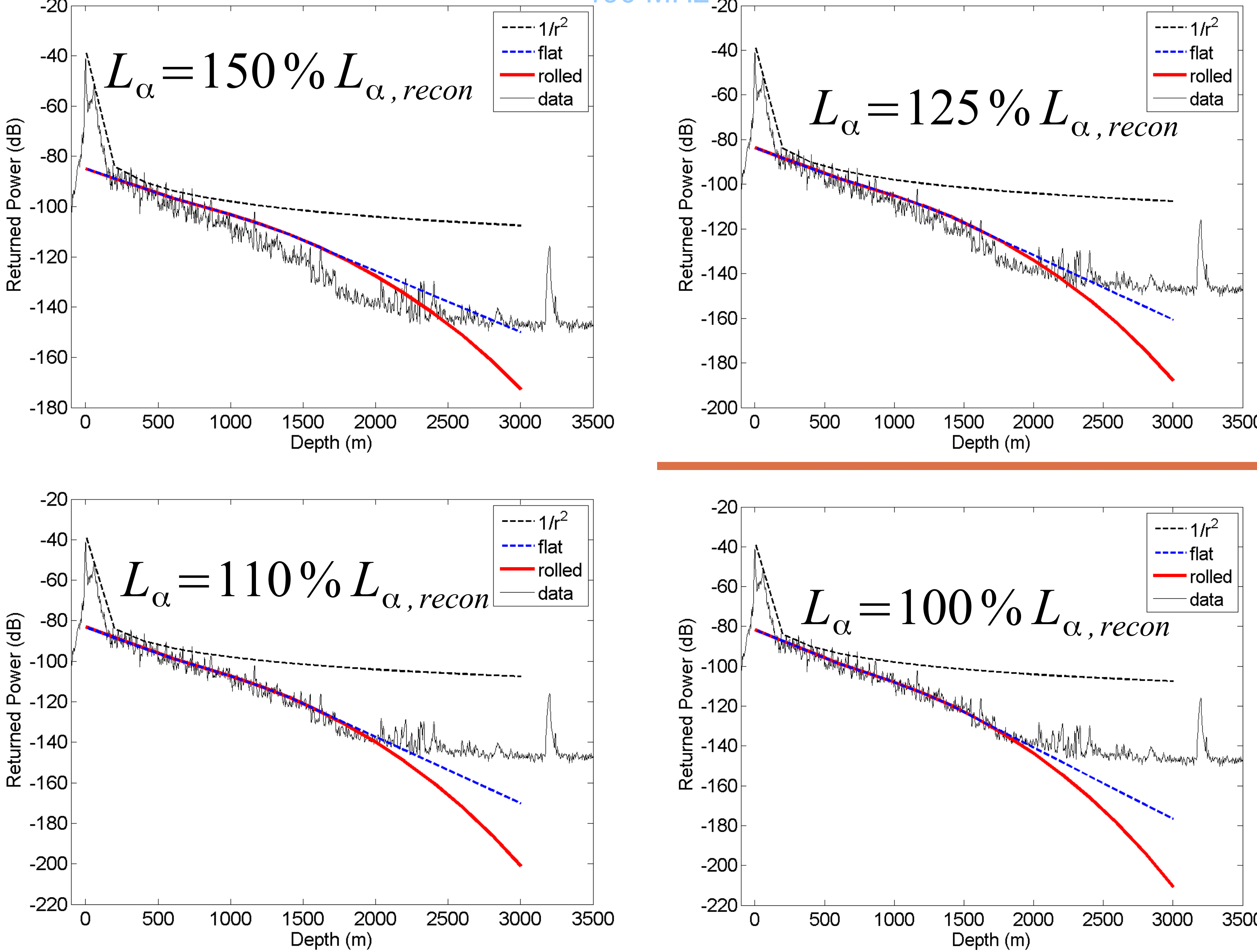

geometry effect with altitude (dB difference from 1/r2) - opening angle 10°
altitude
0
500
1000
1500
2000
2500
depth
500
1000
1500
2000
2500
3000
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8

190 MHz

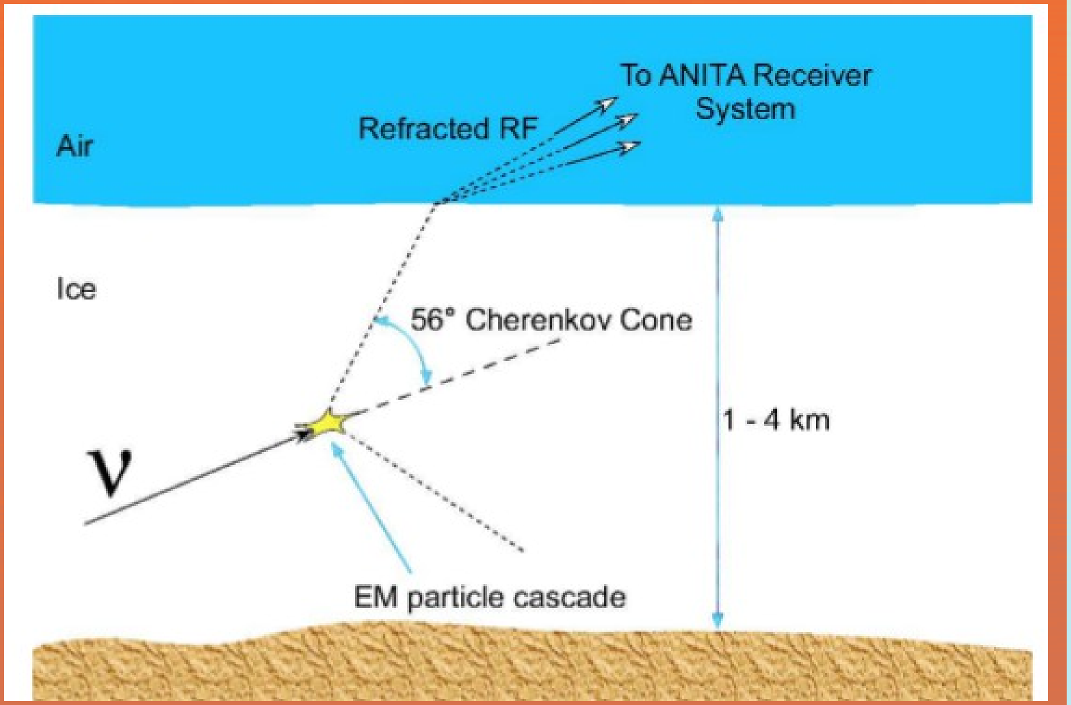


$L_\alpha = 50\% L_{\alpha, recon}$
$L_\alpha = 75\% L_{\alpha, recon}$
$L_\alpha = 90\% L_{\alpha, recon}$
$L_\alpha = 100\% L_{\alpha, recon}$
1/r2
flat
rolled
data
Returned Power (dB)
Depth (m)

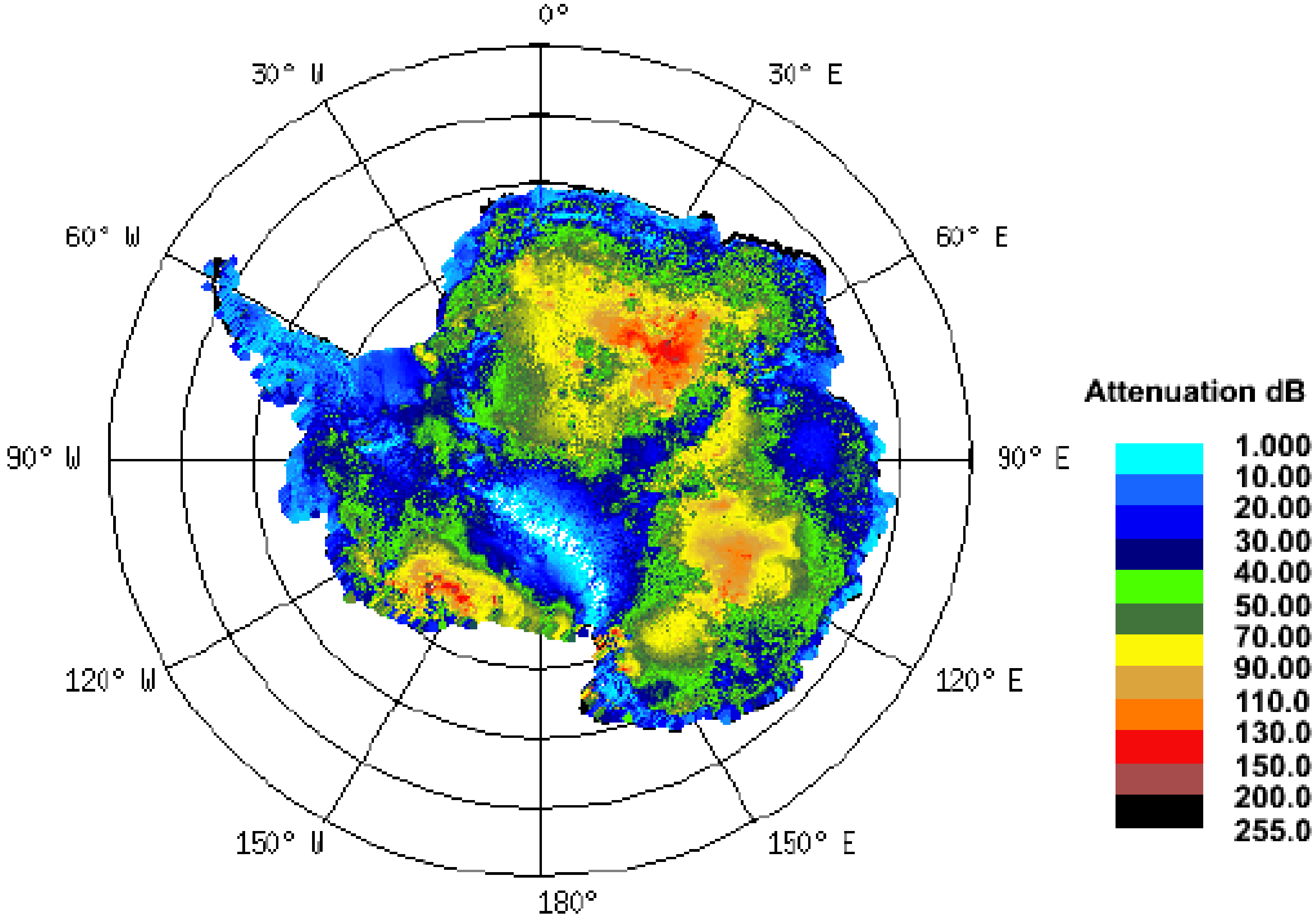
190 MHz



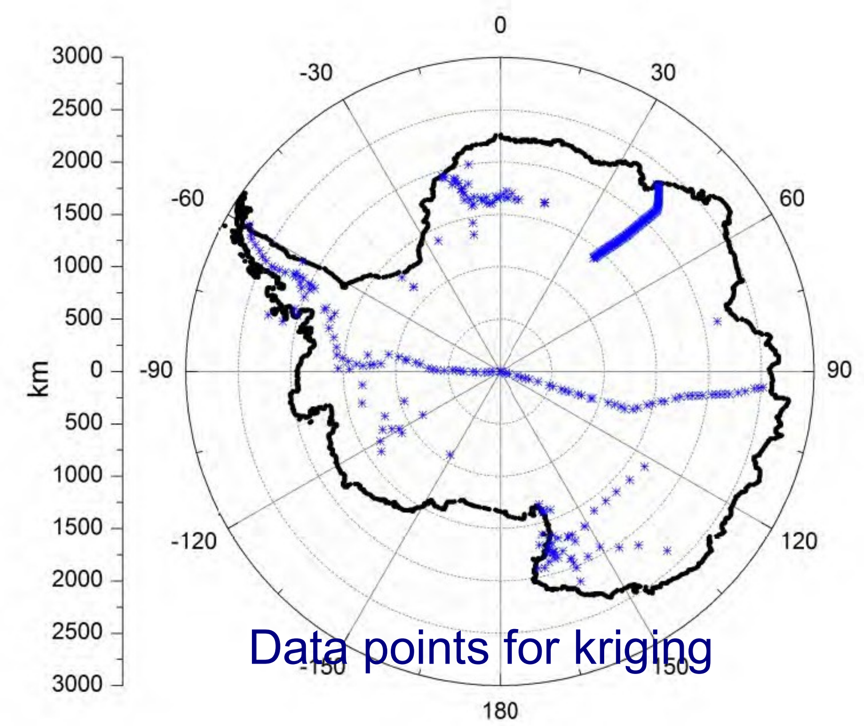
$L_\alpha = 150\,\%\,L_{\alpha,recon}$
$L_\alpha = 125\,\%\,L_{\alpha,recon}$
$L_\alpha = 110\,\%\,L_{\alpha,recon}$
$L_\alpha = 100\,\%\,L_{\alpha,recon}$
1/r^2
flat
rolled
data
Returned Power (dB)
Depth (m)


To ANITA Receiver System
Refracted RF
Air
Ice
56° Cherenkov Cone
1 - 4 km
ν
EM particle cascade

Total Two-Way Attenuation



Based off Amir Javaid model



Data points for kriging