Software Defined Radio and Space Physics

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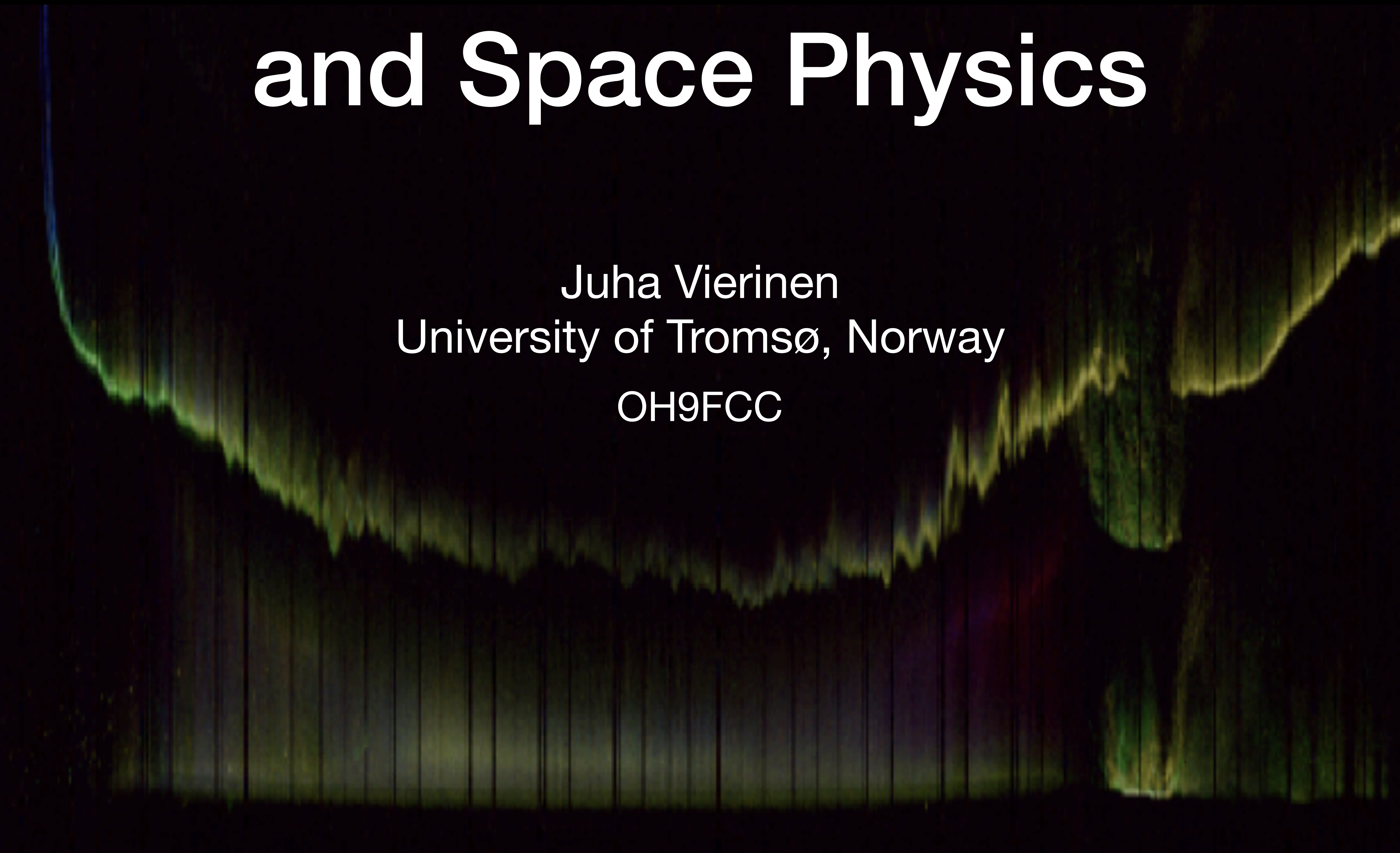
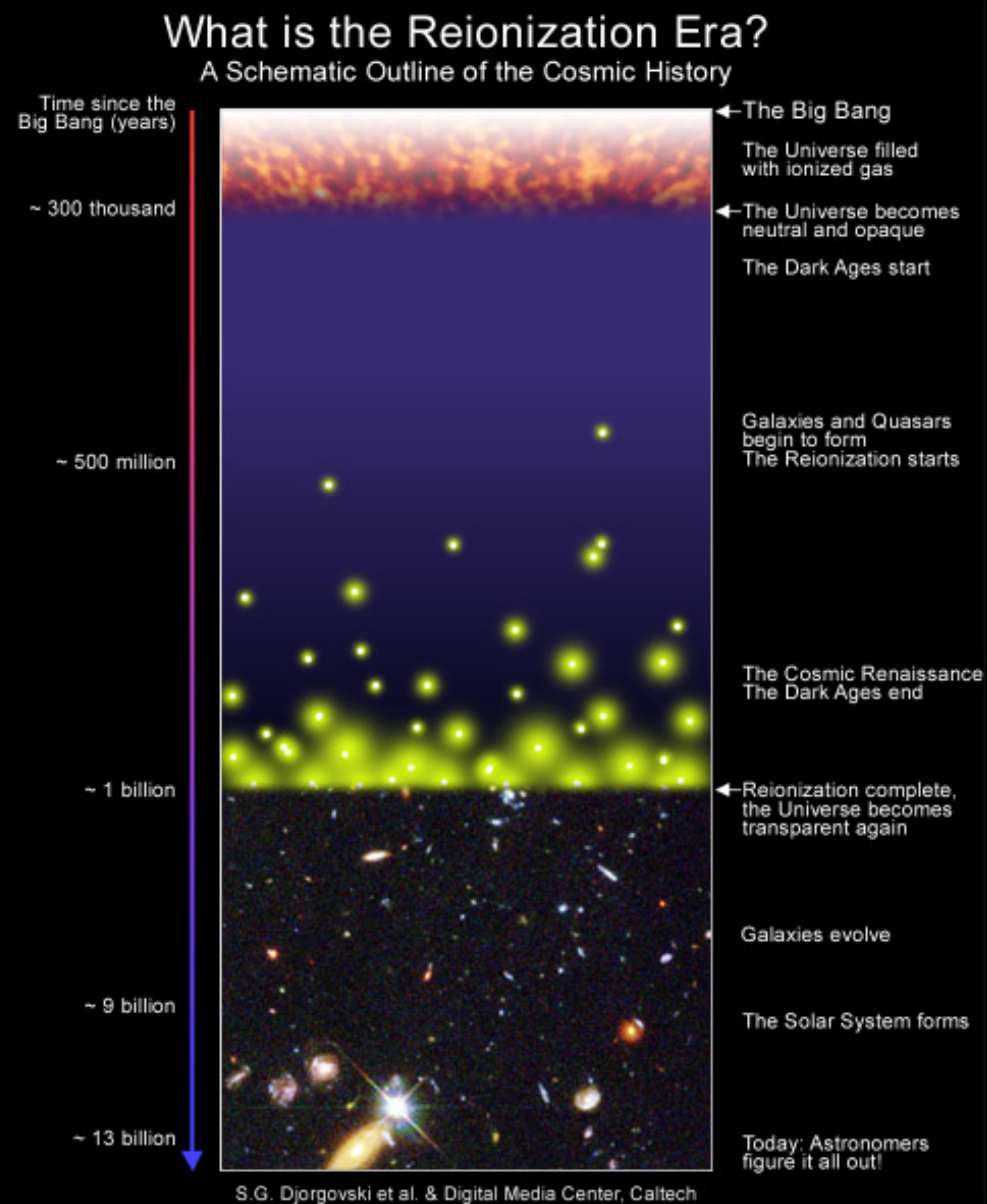
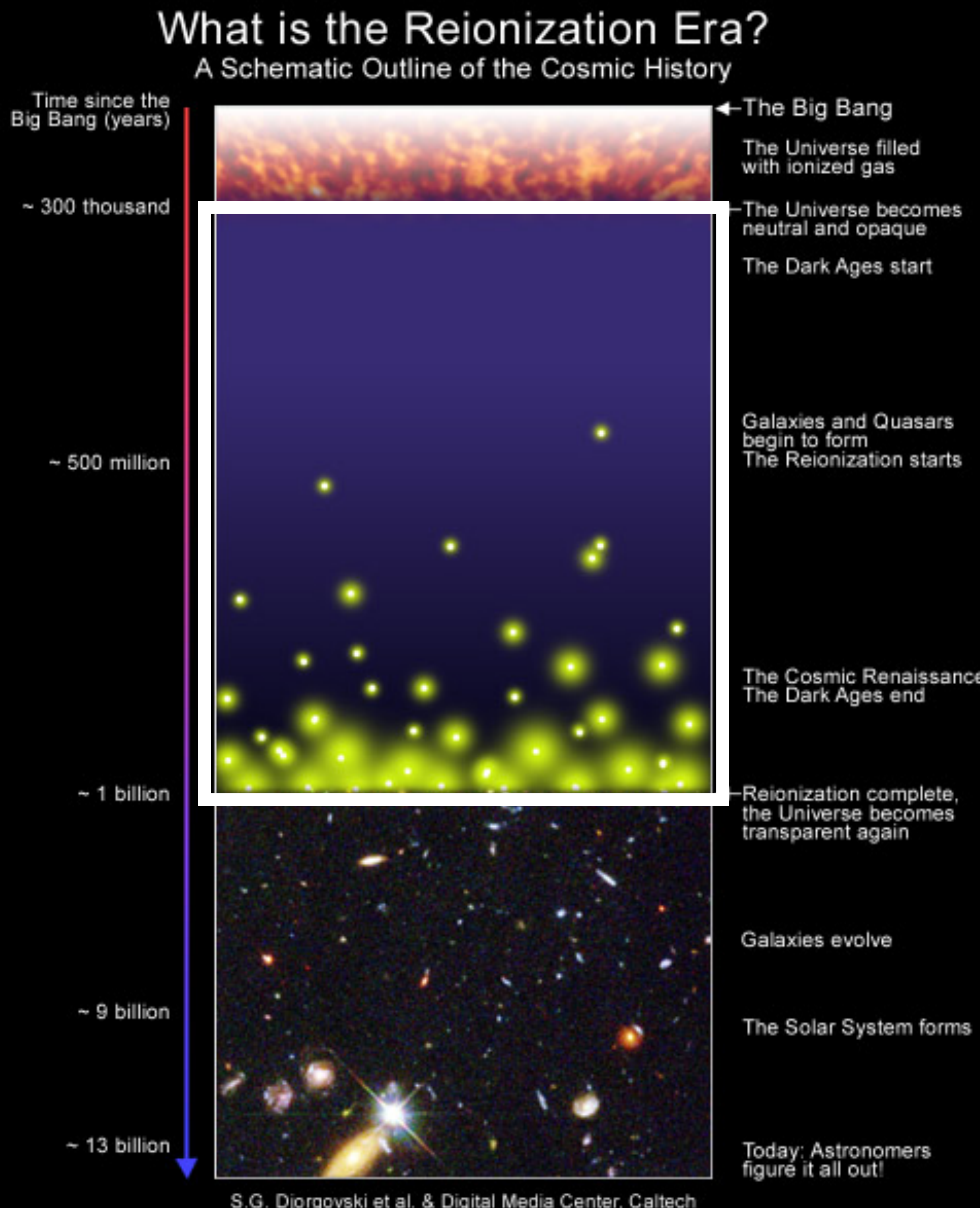
OH9FCC





Q: What is the origin of the universe?

Q: What is the evolution of the universe?

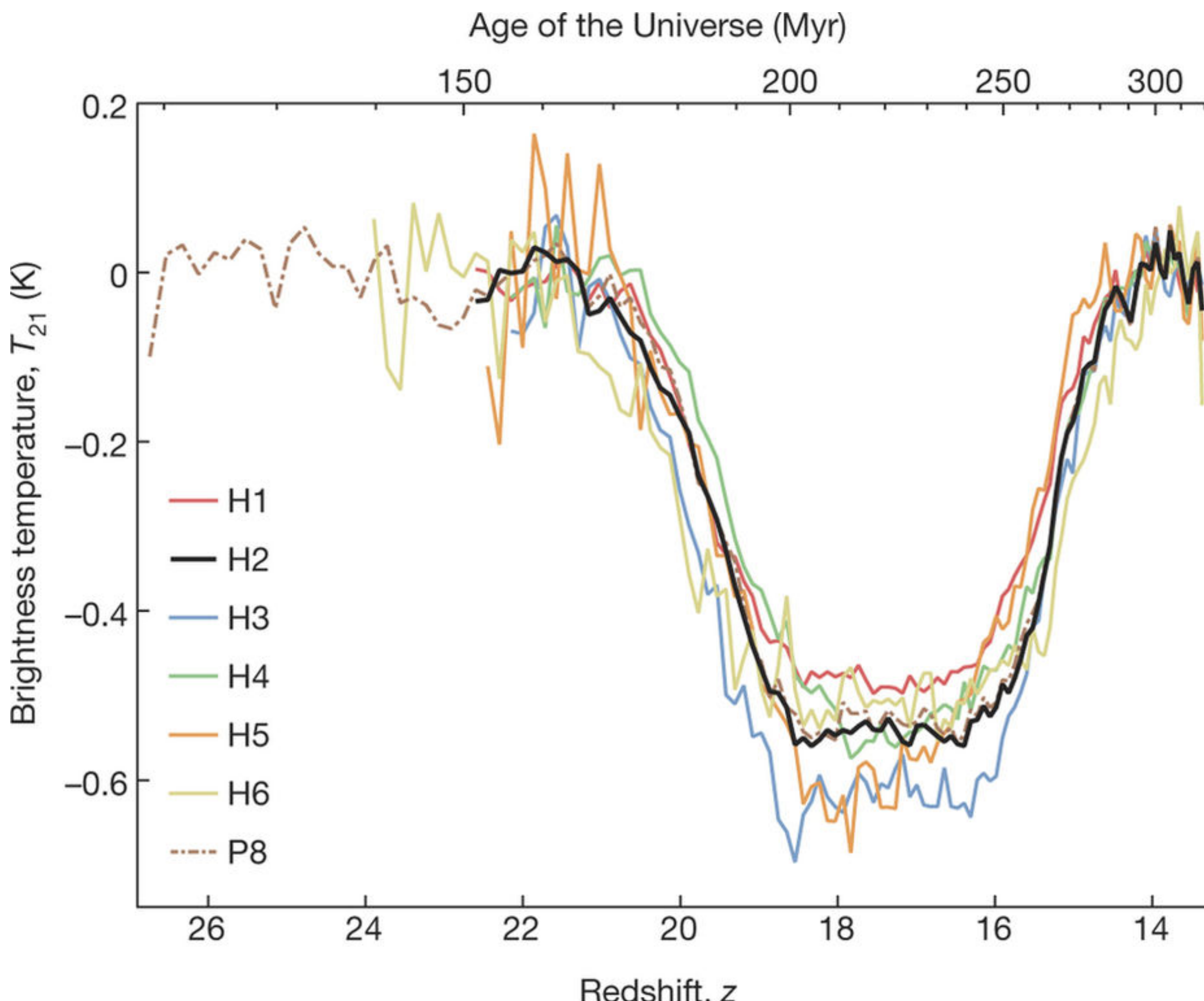


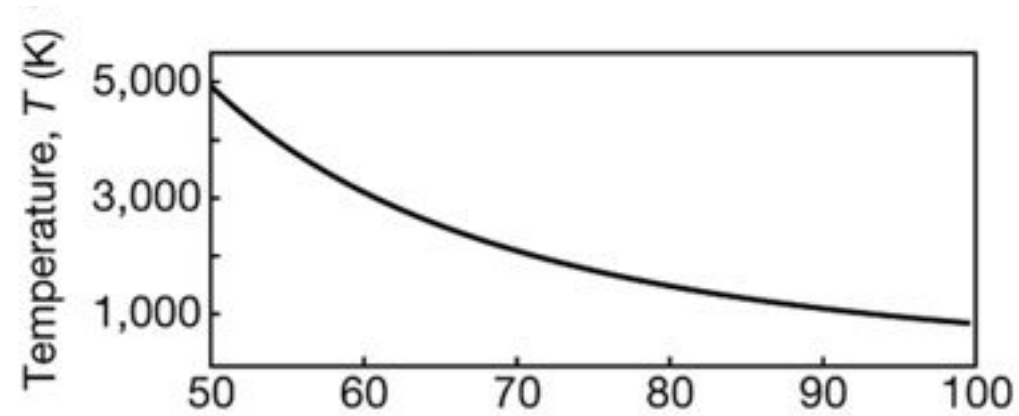
Q: What happened after the universe cooled down to a neutral gas, before the first stars formed?

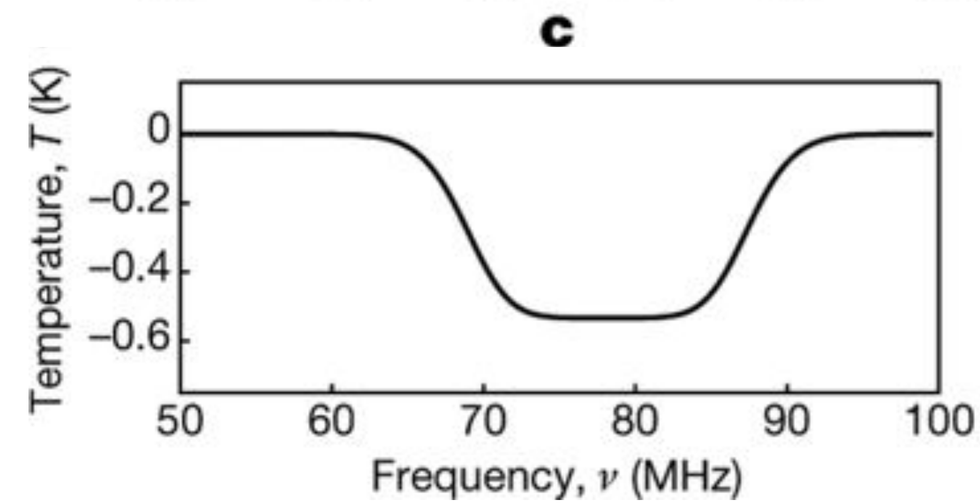
Q: How can we observe this time period?

A: Observe the hydrogen line (1.42 GHz)

First detection of the Epoch of Reionization signature.







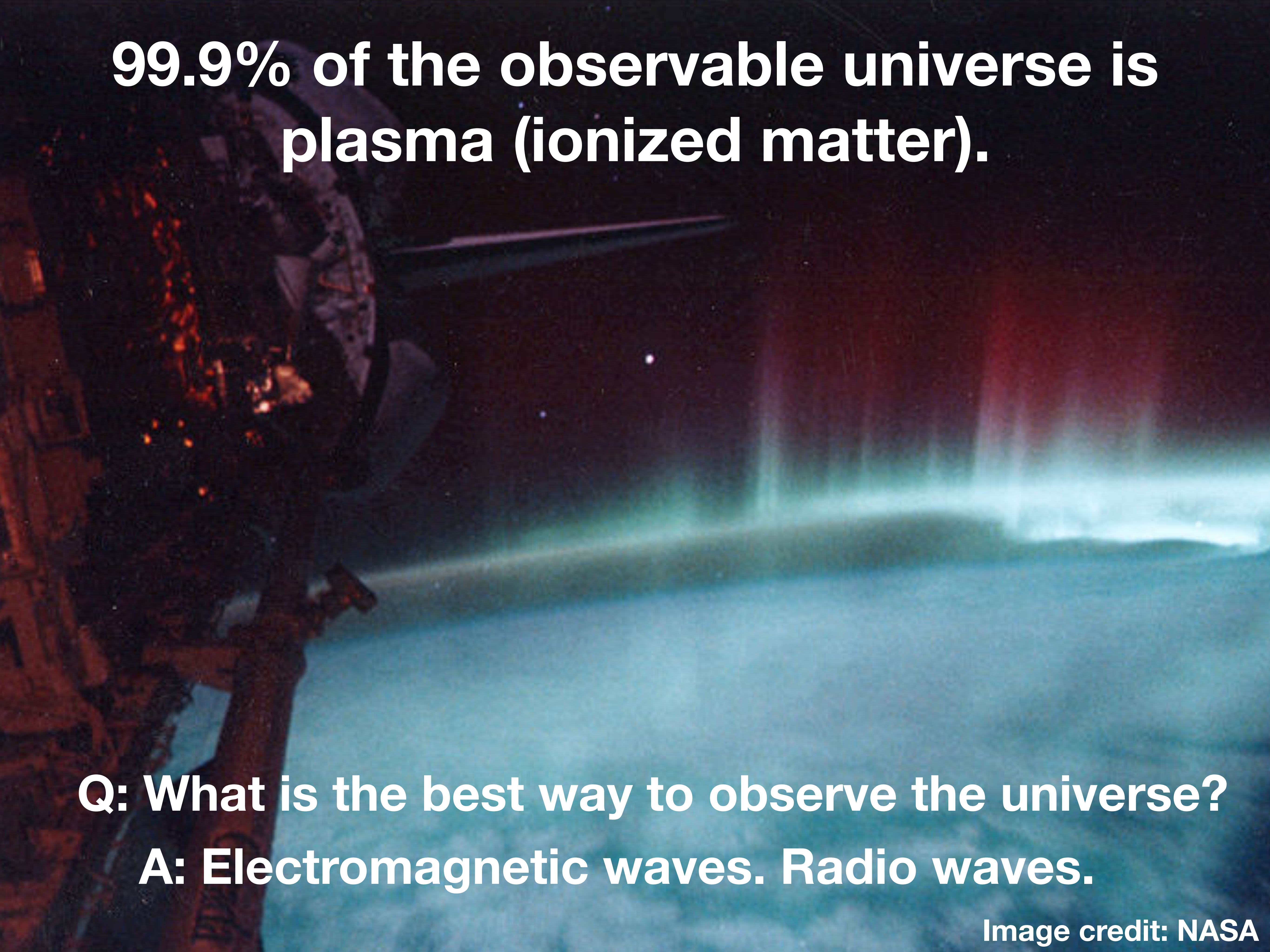
Bowman, Rogers, et.al., (2018)

A.E.E. Rogers, J. D. Bowman, J. Vierinen, R. Monsalve, and T. Mozdzen. “Radiometric measurements of electron temperature and opacity of ionospheric perturbations, 2015.

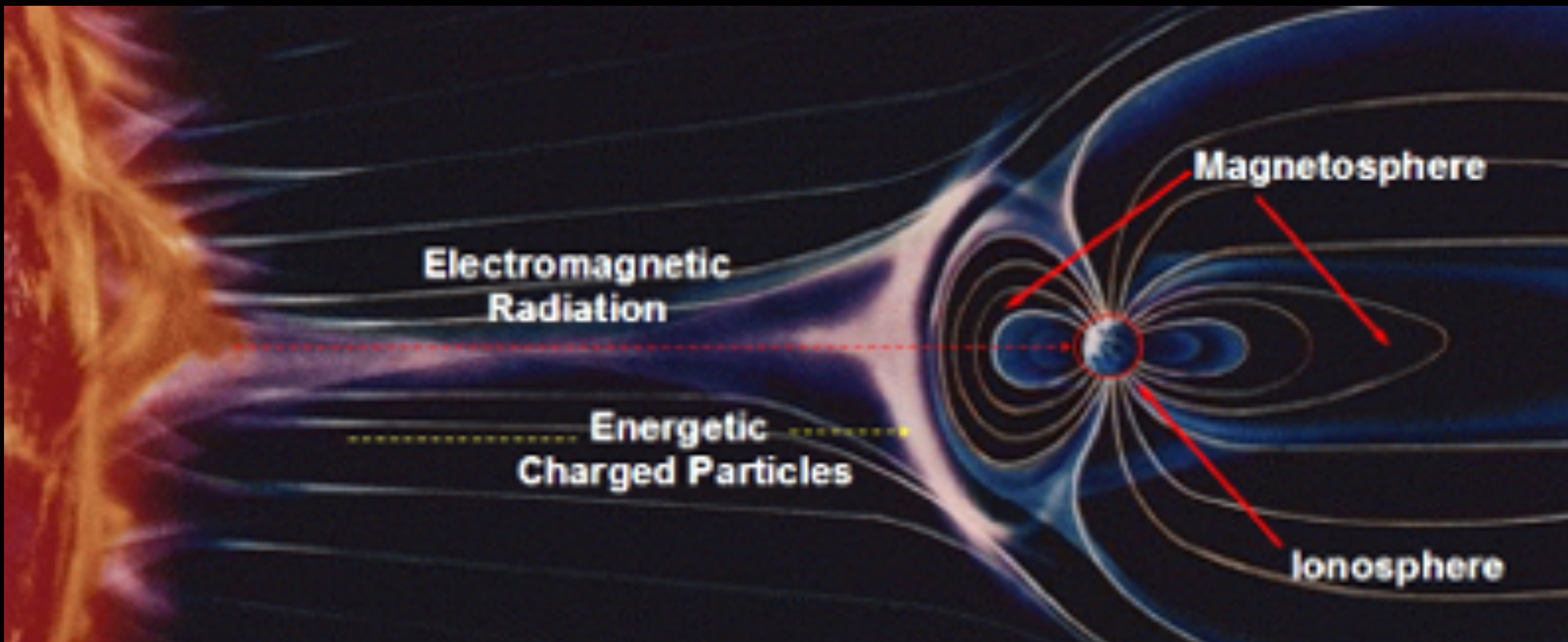
99.9% of the observable universe is plasma (ionized matter).

Q: What is the best way to observe the universe?

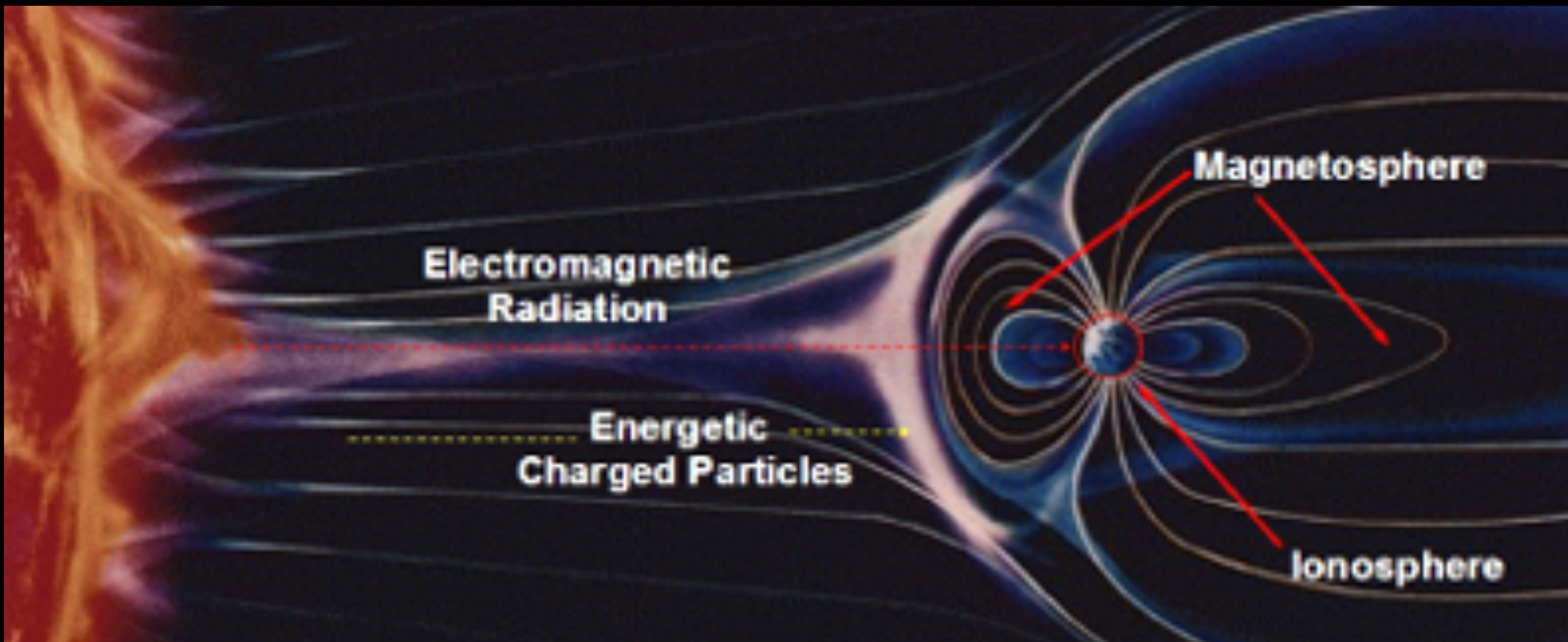
Image credit: NASA


99.9% of the observable universe is plasma (ionized matter).
Q: What is the best way to observe the universe?
A: Electromagnetic waves. Radio waves.
Image credit: NASA

Q: Where can we easily study space plasma?



Q: Where can we easily study space plasma?



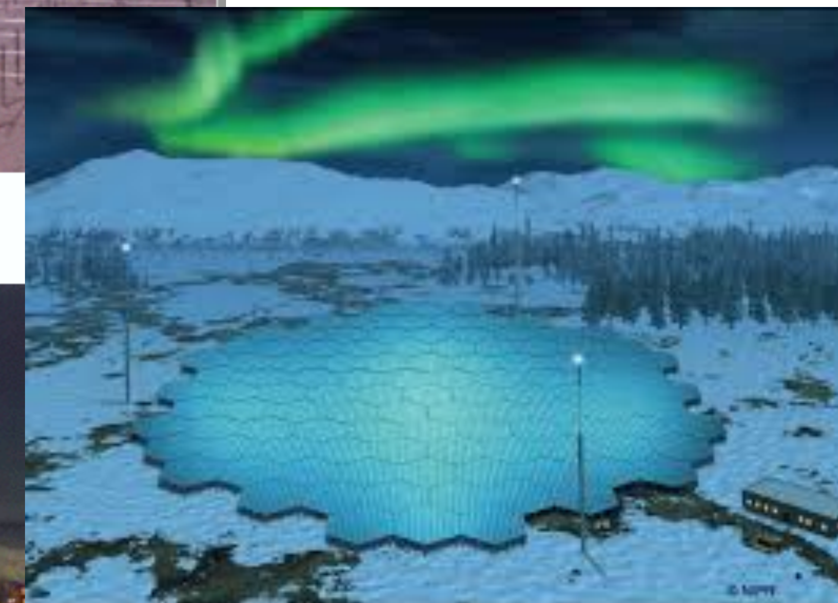
A: The easiest place to study plasma is our own backyard.

Megawatts and hectares of radar

Haystack

Arecibo

Jicamarca



EISCAT 3D

EISCAT Svalbard

EISCAT VHF and UHF

+ flexible hardware

+ open source signal processing

GNU Radio
THE FREE & OPEN SOFTWARE RADIO ECOSYSTEM

+ novel signal processing techniques =

better measurements

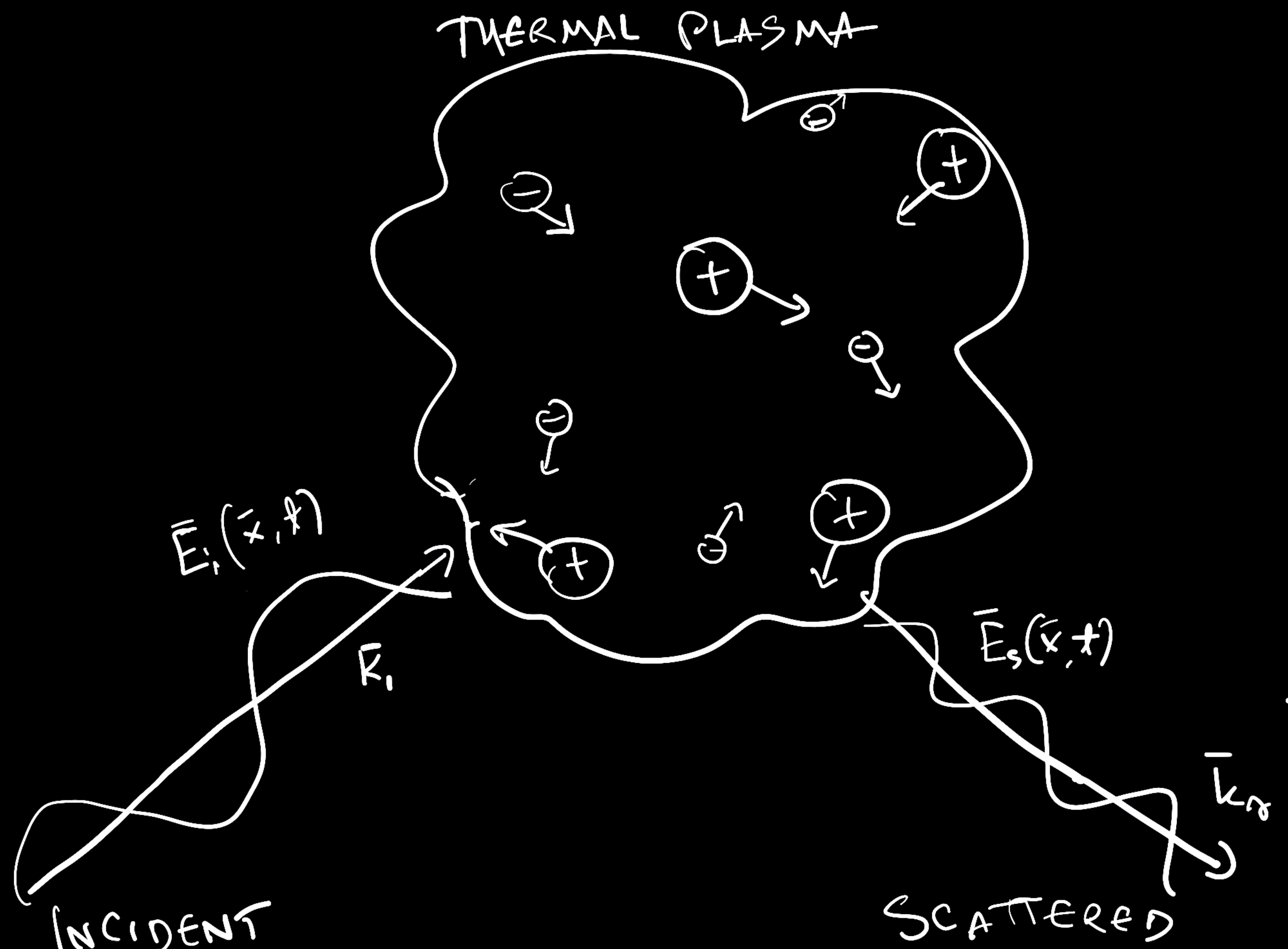
Q: What is the most sensitive radar in the world?

Arecibo

Image: Arecibo Observatory

Wide band ionospheric radar receiver at Arecibo

Q: Does theory of scattering of electromagnetic waves from thermal plasma agree with measurements?



Q: Does theory of scattering of electromagnetic waves from thermal plasma agree with measurements?

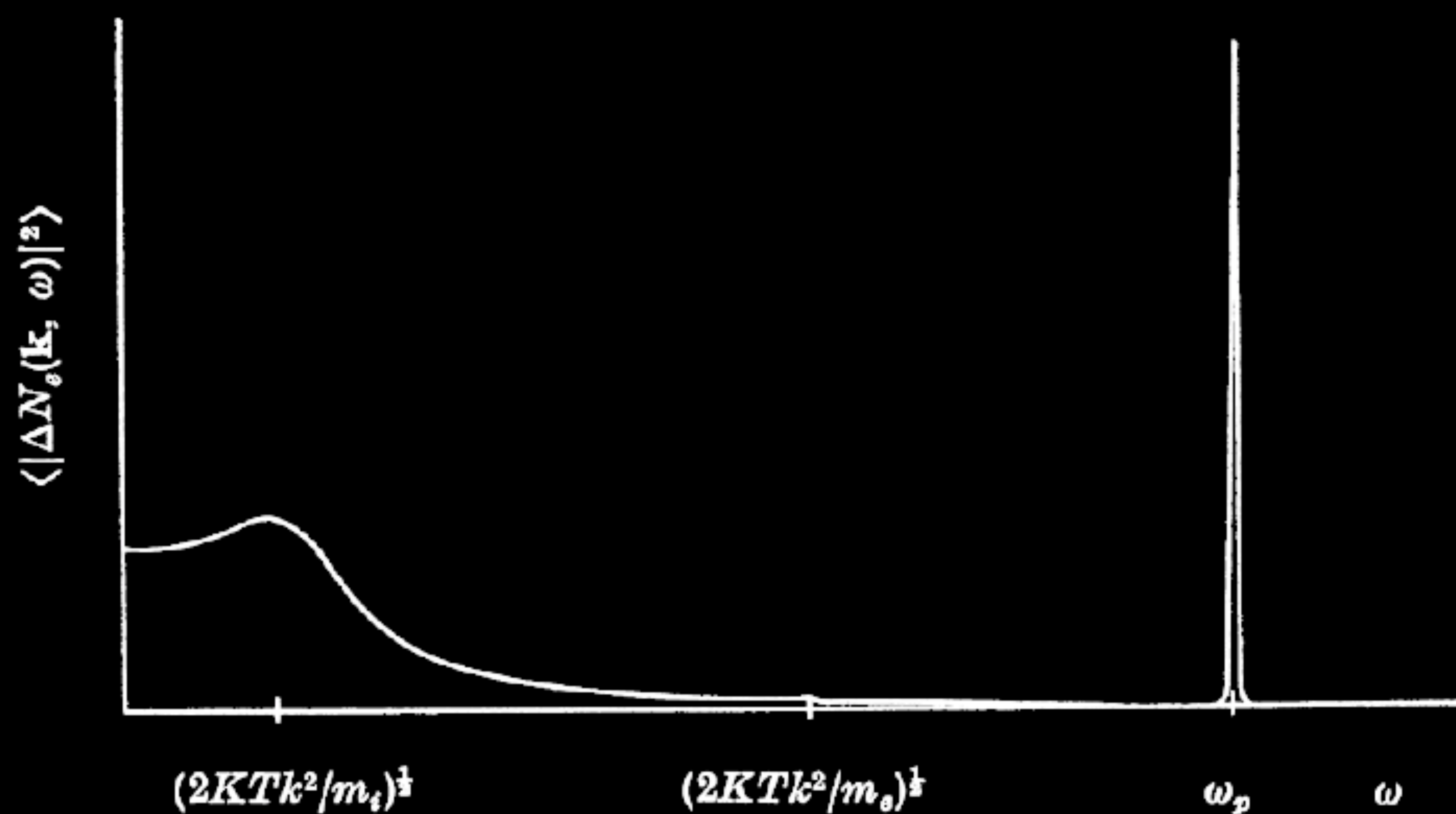
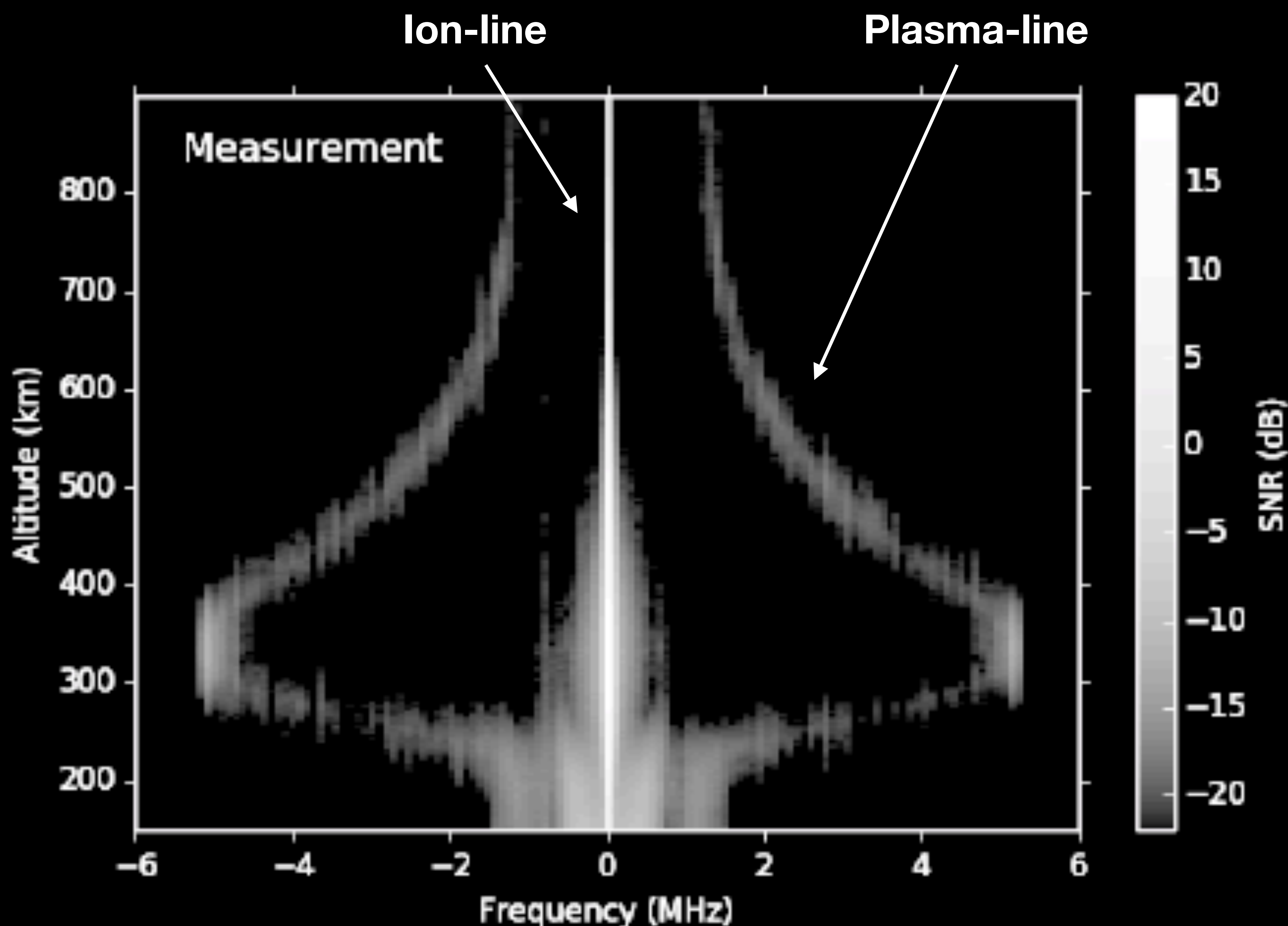


FIGURE 2. Diagrammatic sketch (not to scale) of the spectrum of the thermal density fluctuations of the electrons in a collision-less plasma over the whole range of frequencies.

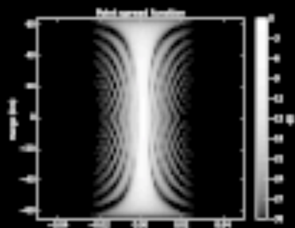
$$\left\langle|\Delta N_e(\boldsymbol{k},\omega)|^2\right\rangle = \frac{|j\omega\epsilon_0 + \sum_i \sigma_i|^2 \langle|n_{t,e}(\boldsymbol{k},\omega)|^2\rangle}{|j\omega\epsilon_0 + \sigma_e + \sum_i \sigma_i|^2} + \frac{|\sigma_e|^2 \sum_i \langle|n_{t,i}(\boldsymbol{k},\omega)|^2\rangle}{|j\omega\epsilon_0 + \sigma_e + \sum_i \sigma_i|^2}$$

The plasma-line will be "very difficult to observe using present techniques." (Dougherty and Farley 1960)

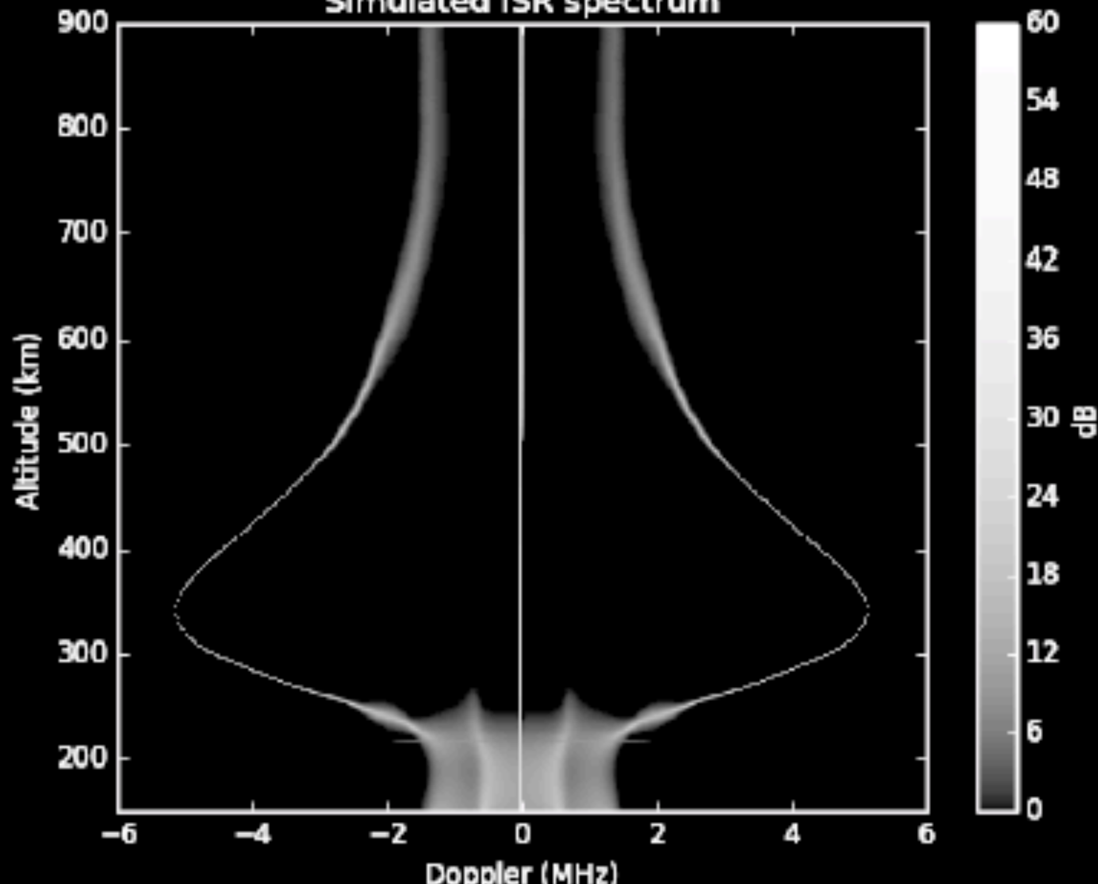
Step 1: Go to Arecibo and make a measurement:



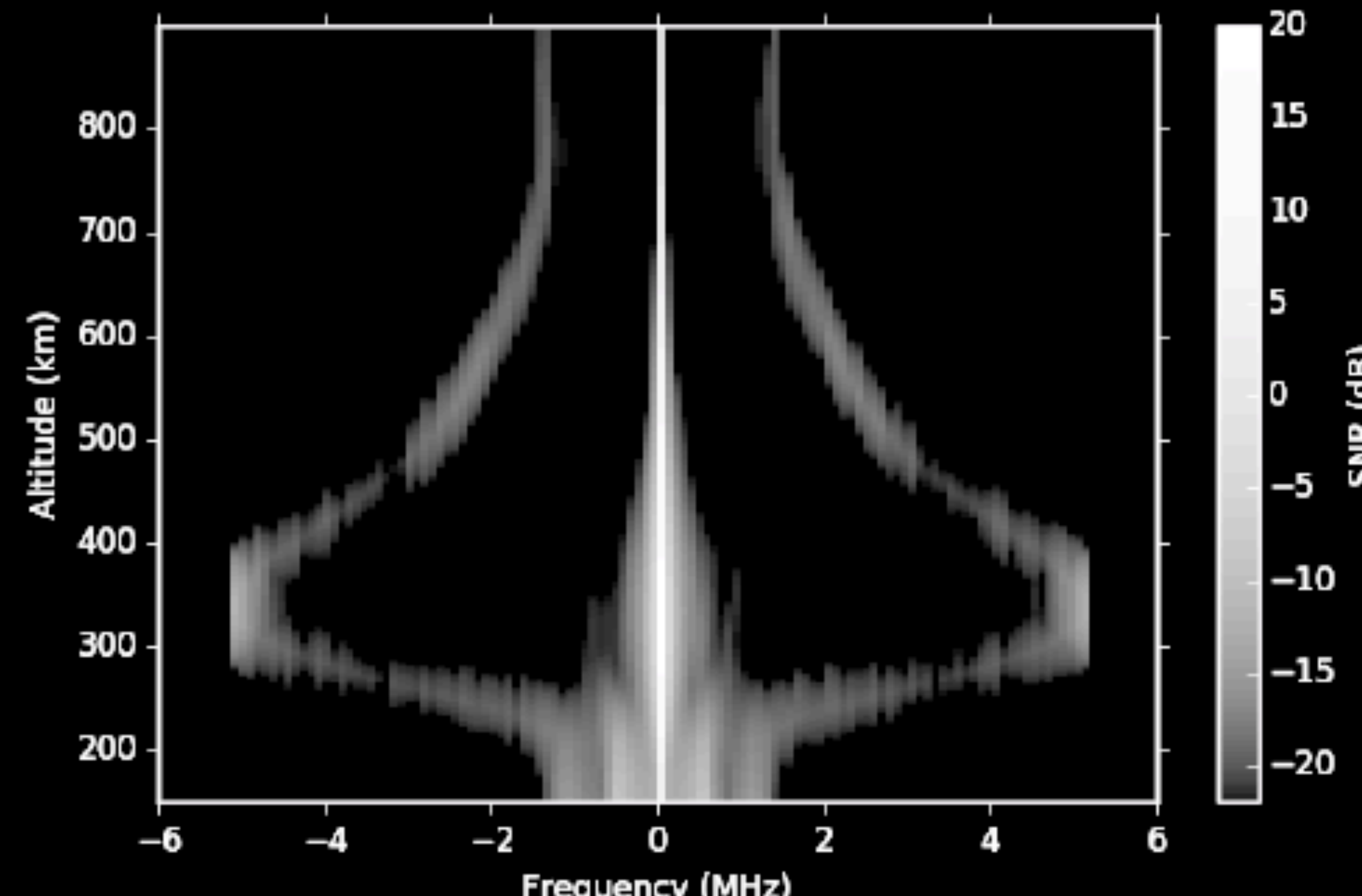
Step 2: Estimate plasma-parameters and forward model measurement.



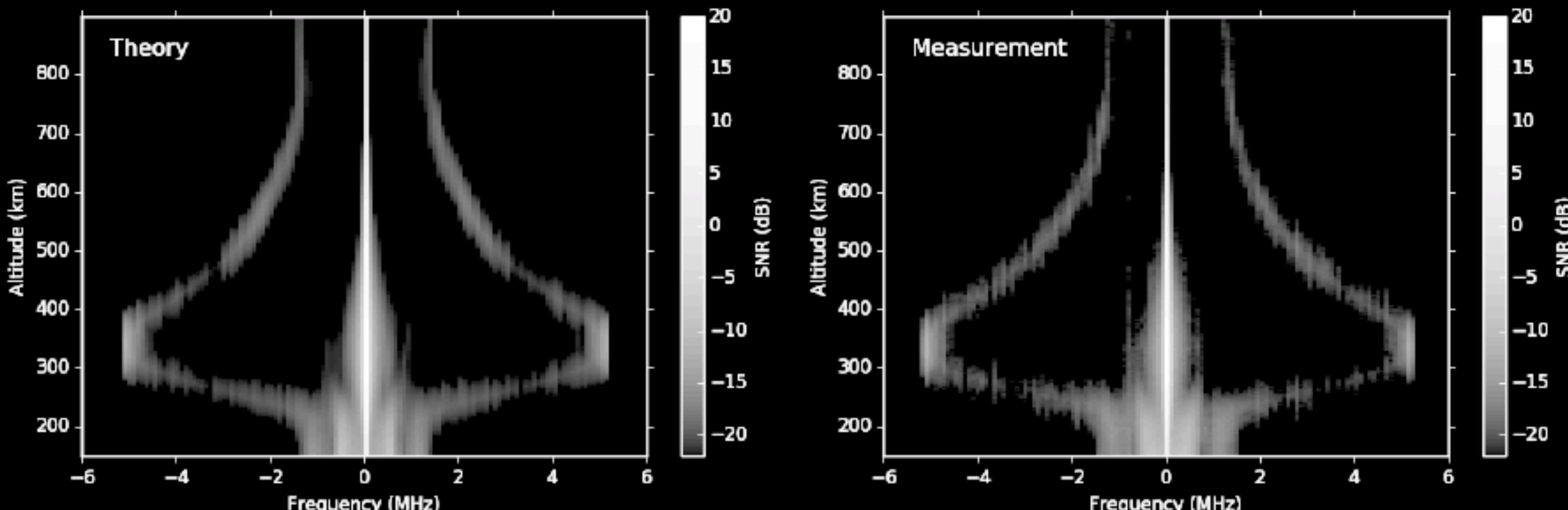
$$W(\omega, r) \ast \langle |\Delta N_e(\omega, r)|^2 \rangle \quad = \quad m(\omega, r)$$



Forward model of measurement



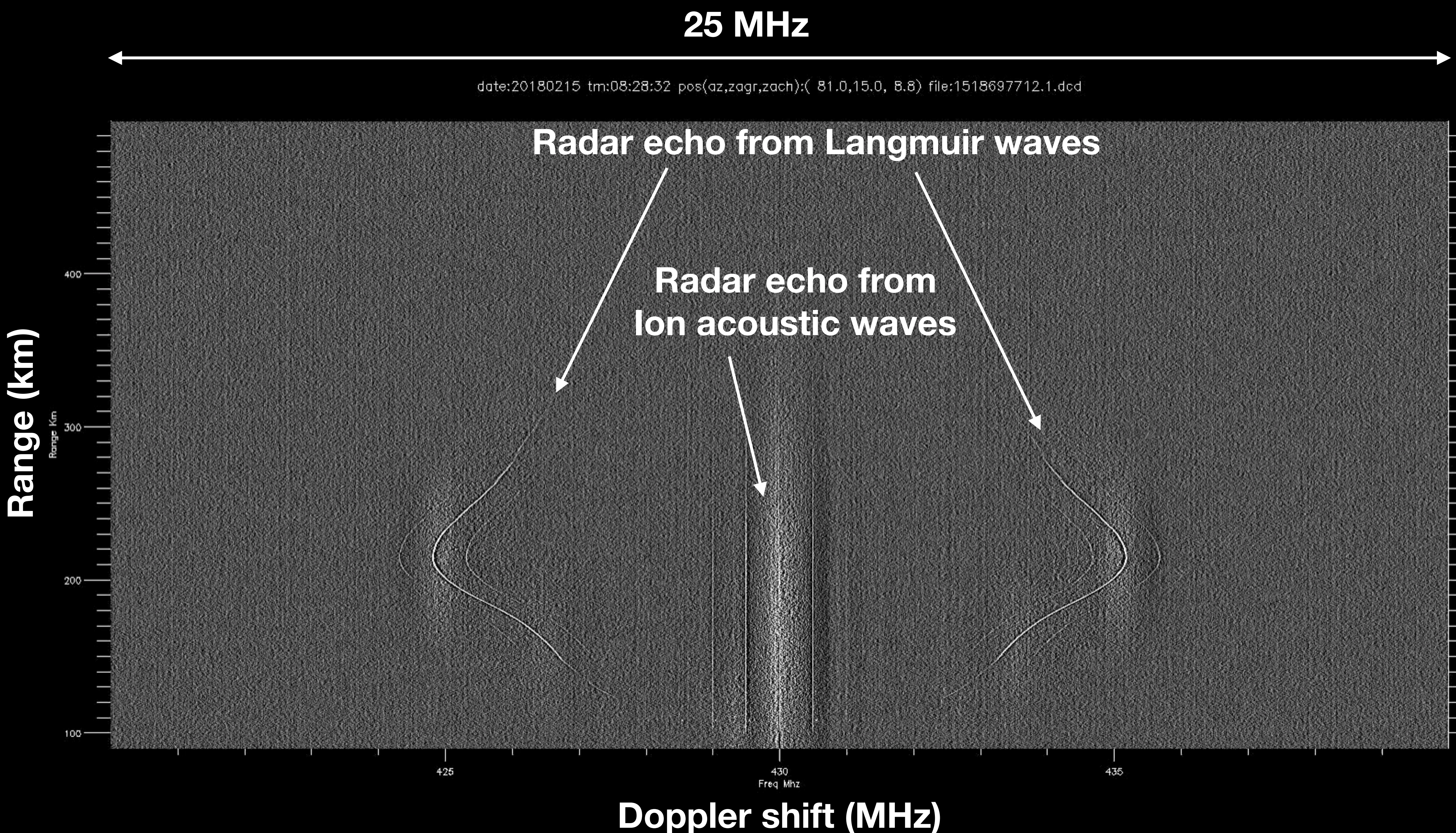
A: Measurements agree with theory



- Measurements agree with theory for thermal plasma.
- The gyro-line complex also agrees with theory.

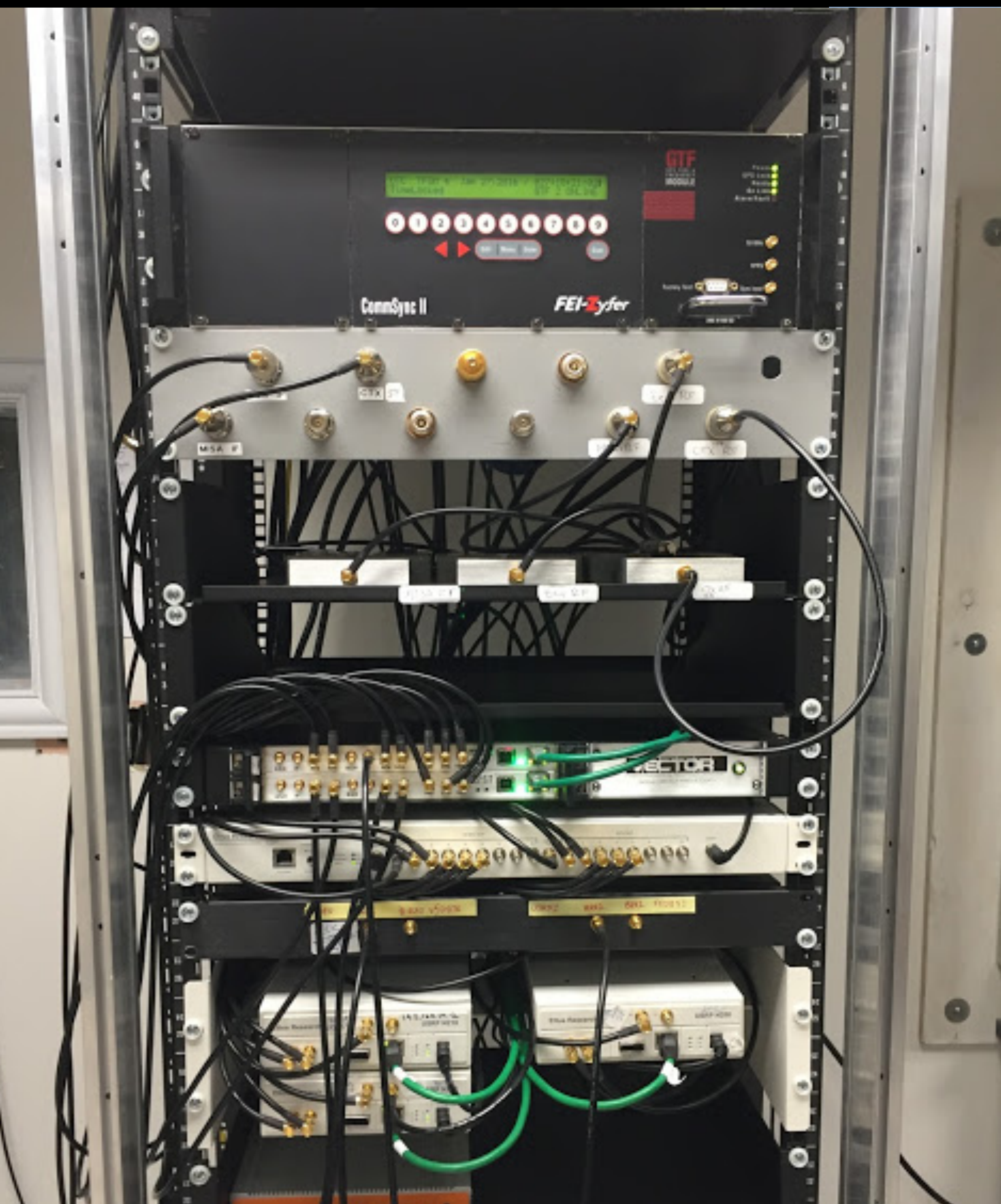
Vierinen et.al., “Radar Observations of Thermal Plasma Oscillations in The Ionosphere, GRL, 2017.

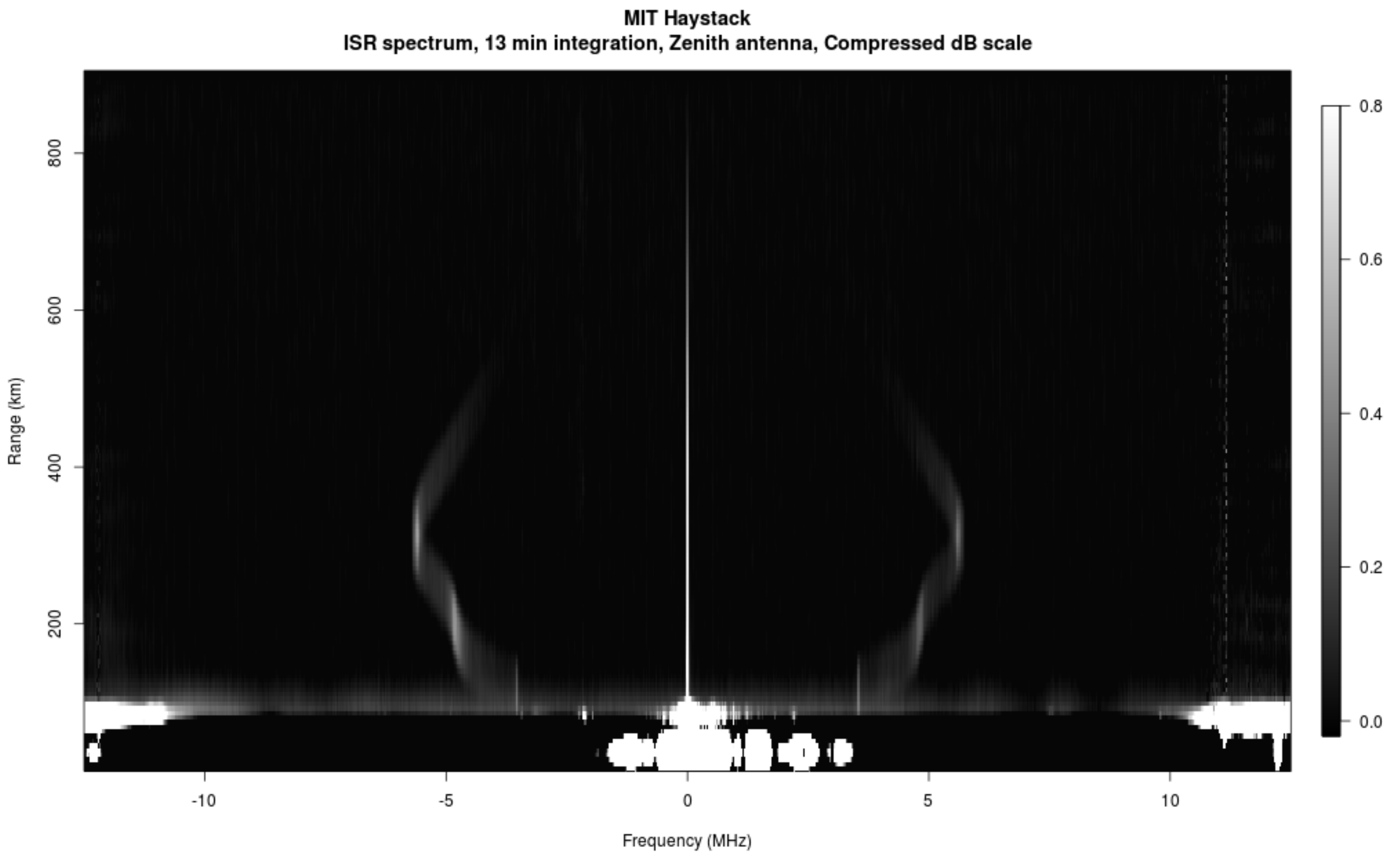
Under non-thermal conditions…



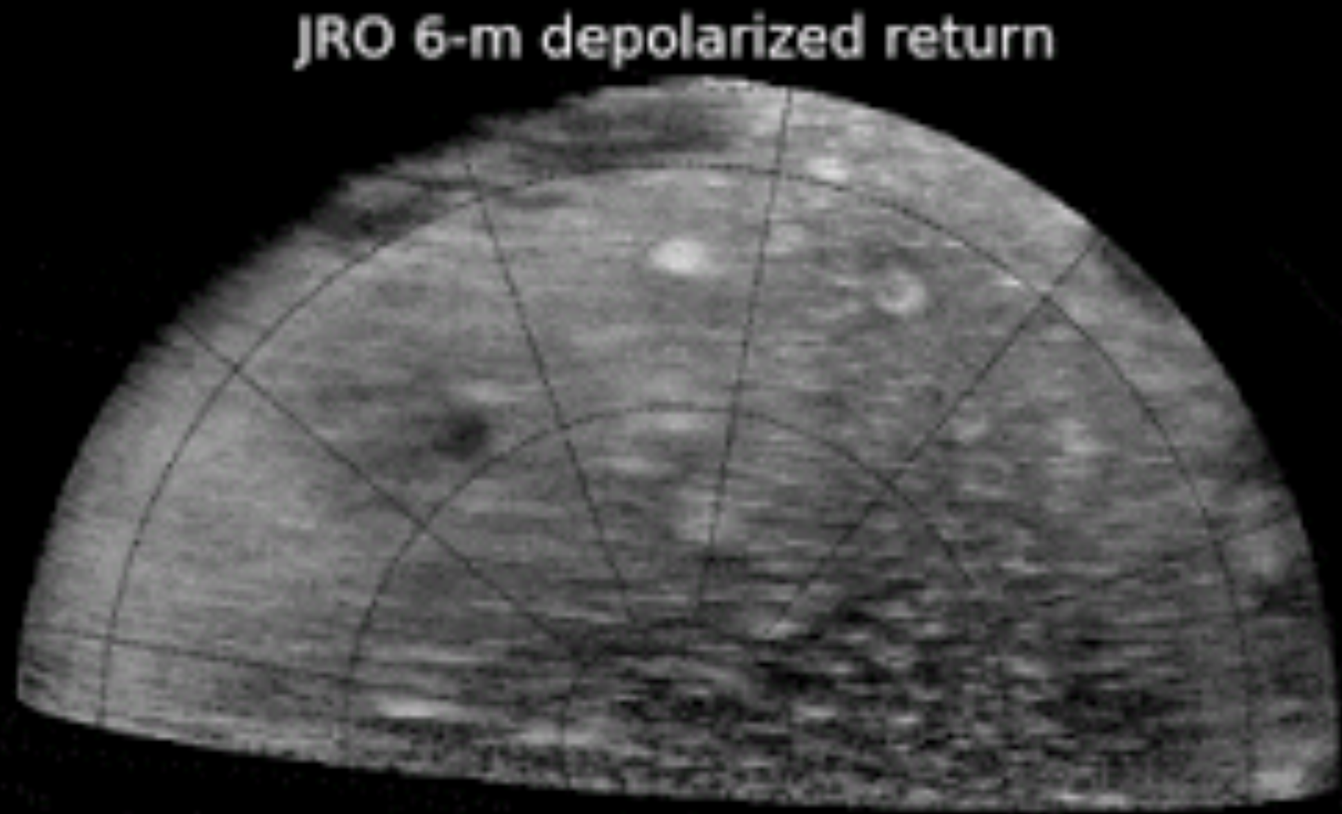
Video: Phil Perillat, Arecibo

MIT Haystack Observatory
Millstone Hill Radar




MIT Haystack
ISR spectrum, 13 min integration, Zenith antenna, Compressed dB scale
Range (km)
800
600
400
200
-10
-5
0
5
10
Frequency (MHz)
0.8
0.6
0.4
0.2
0.0

Radar studies of the Moon



Q: What is the origin of the Moon?

Q: How did it evolve?

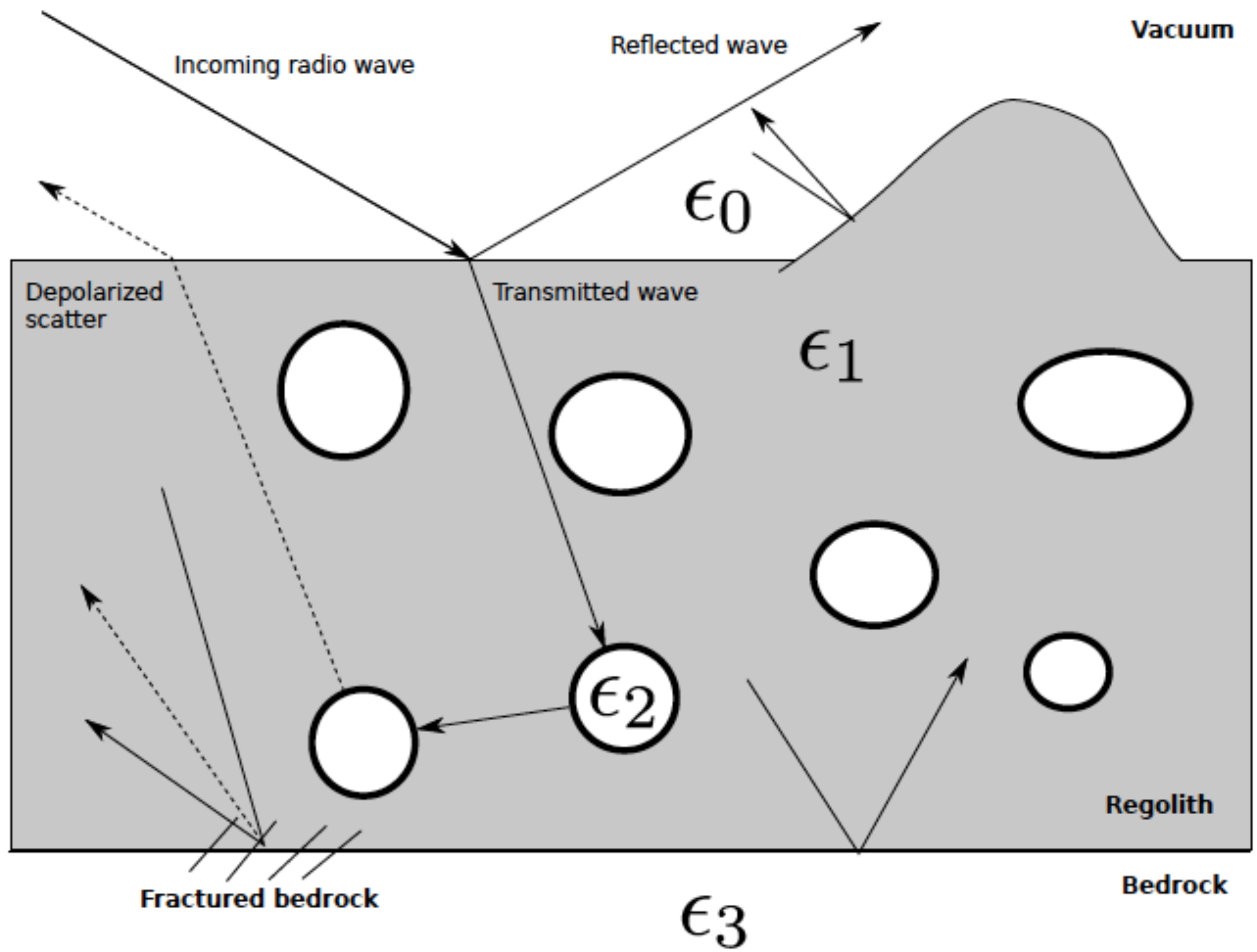
Q: What is the mineralogy?

Q: How can we obtain clues about these questions?

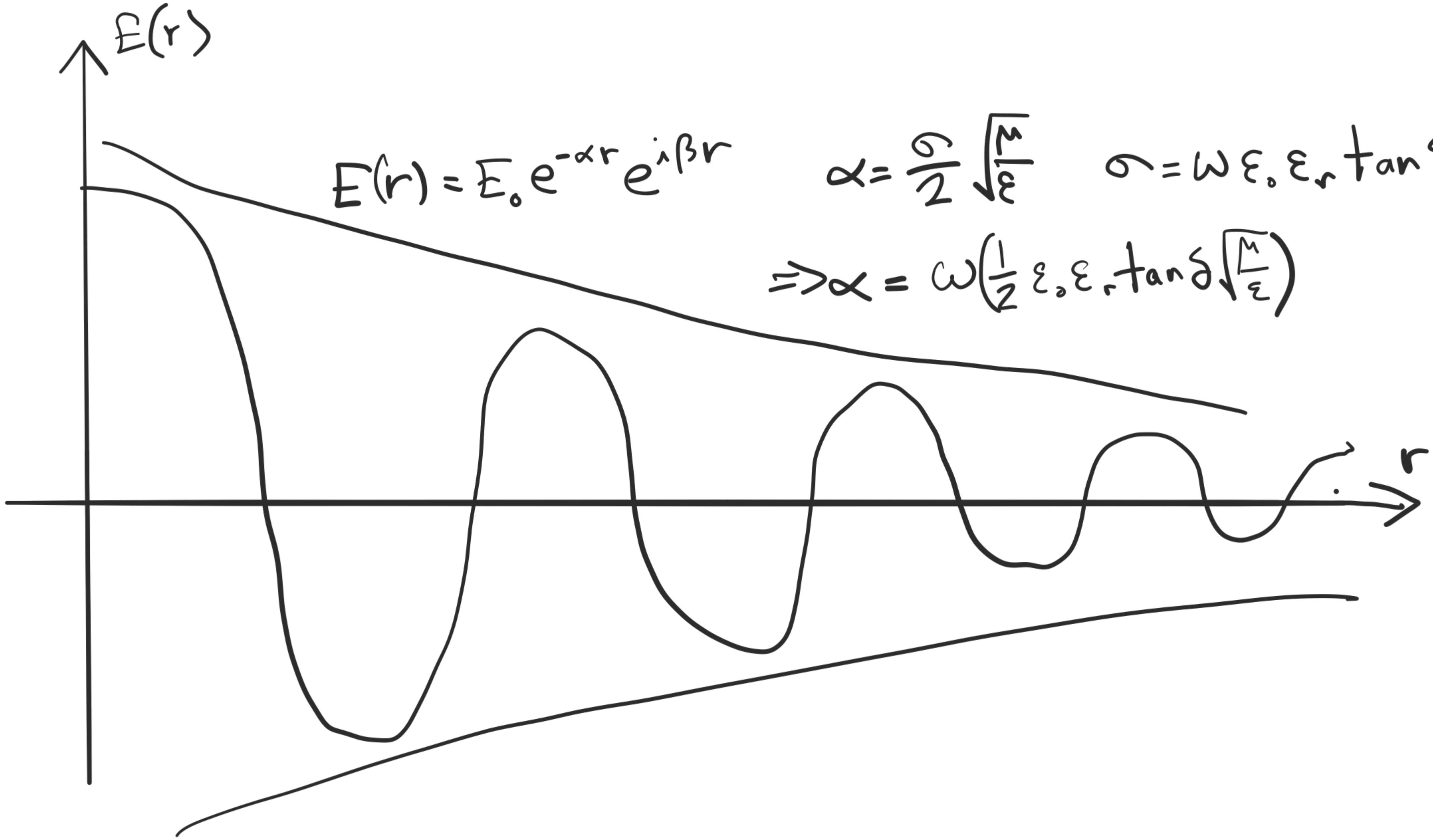
A: Study the subsurface of the Moon

[1] Vierinen et.al., Radar images of the Moon at 6-meter wavelength, Icarus, 2017.

Subsurface scattering



Q: How do we best observe the subsurface of the Moon?



Attenuation of transmitted wave proportional to frequency.

Q: What's the longest wavelength that can be used to make a map of the Moon from Earth?

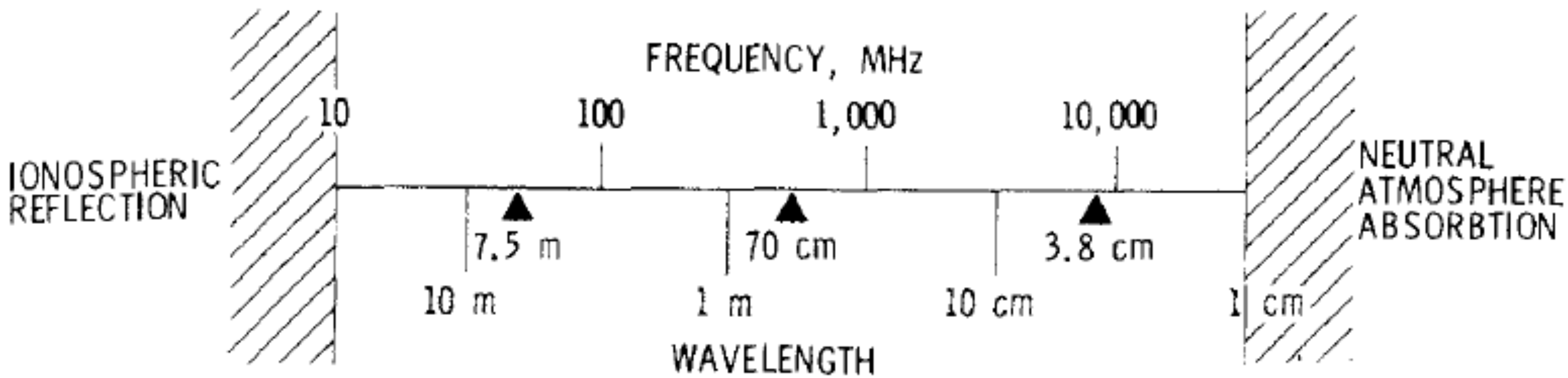
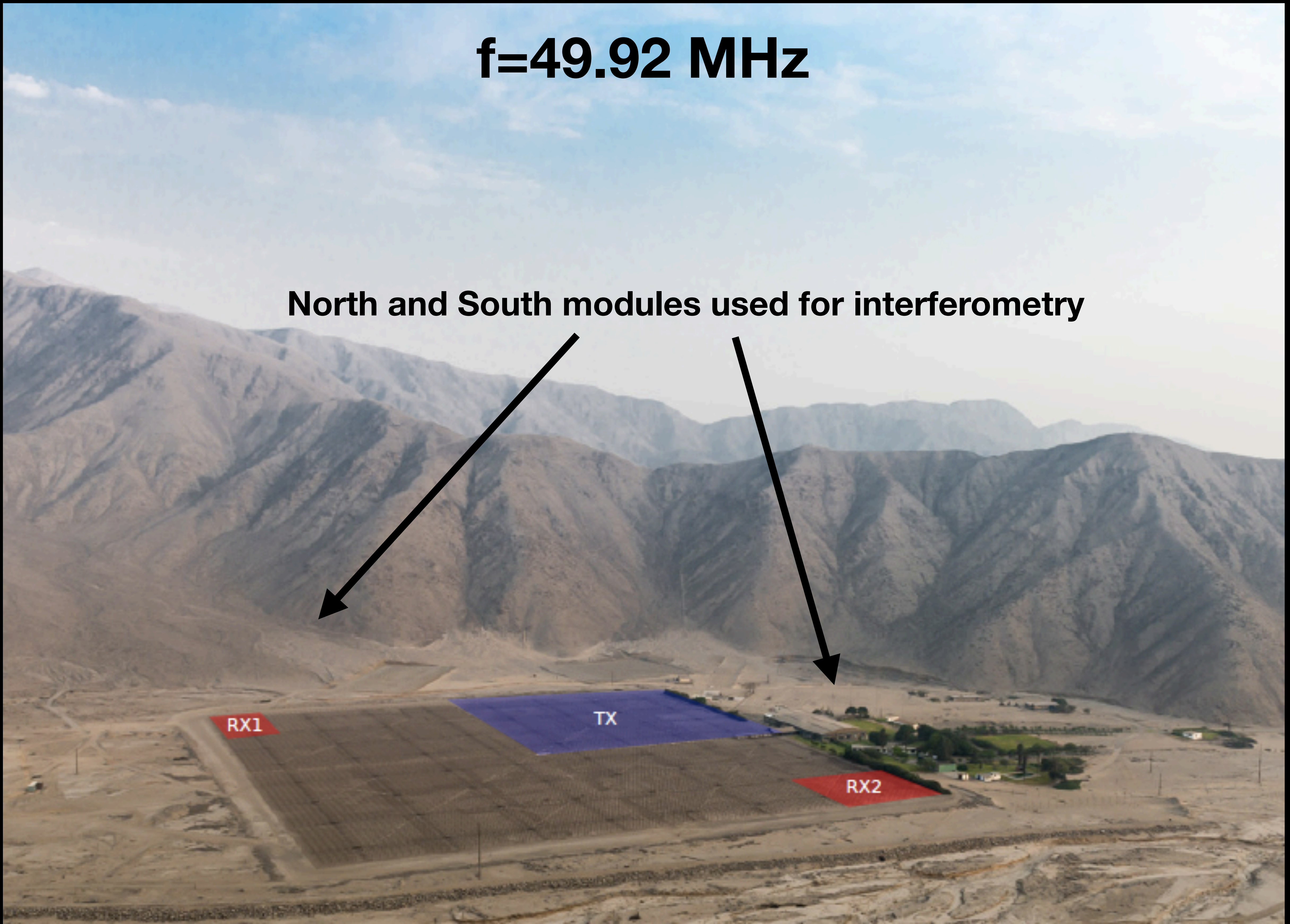


Fig. 2. The window for radio wave propagation through the Earth's atmosphere and ionosphere. Wavelengths longer than 30 m (frequencies less than 10 MHz) are reflected by charged particles in the Earth's ionosphere. Wavelengths shorter than about 1 cm (frequencies higher than 30 GHz) are absorbed by water and oxygen in the Earth's atmosphere. For more detail see Roger and Evans (1968). Triangles denote wavelengths used for the radar maps shown in Figures 3, 4, 5 and 9.

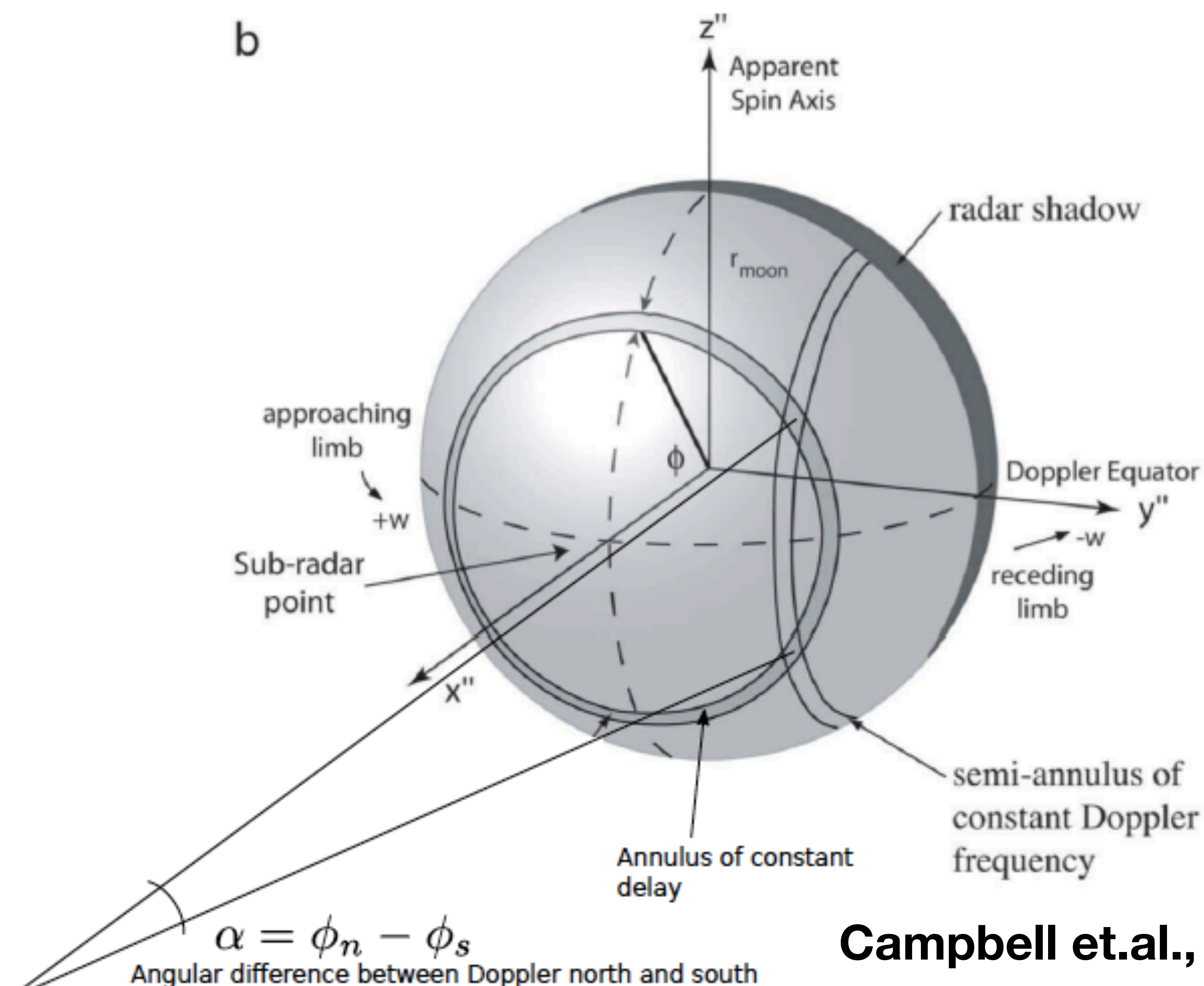
Figure: Thompson, 1979

Transmission up to 1 km below the surface at 6 meter wavelength

Jicamarca Lunar Experiment



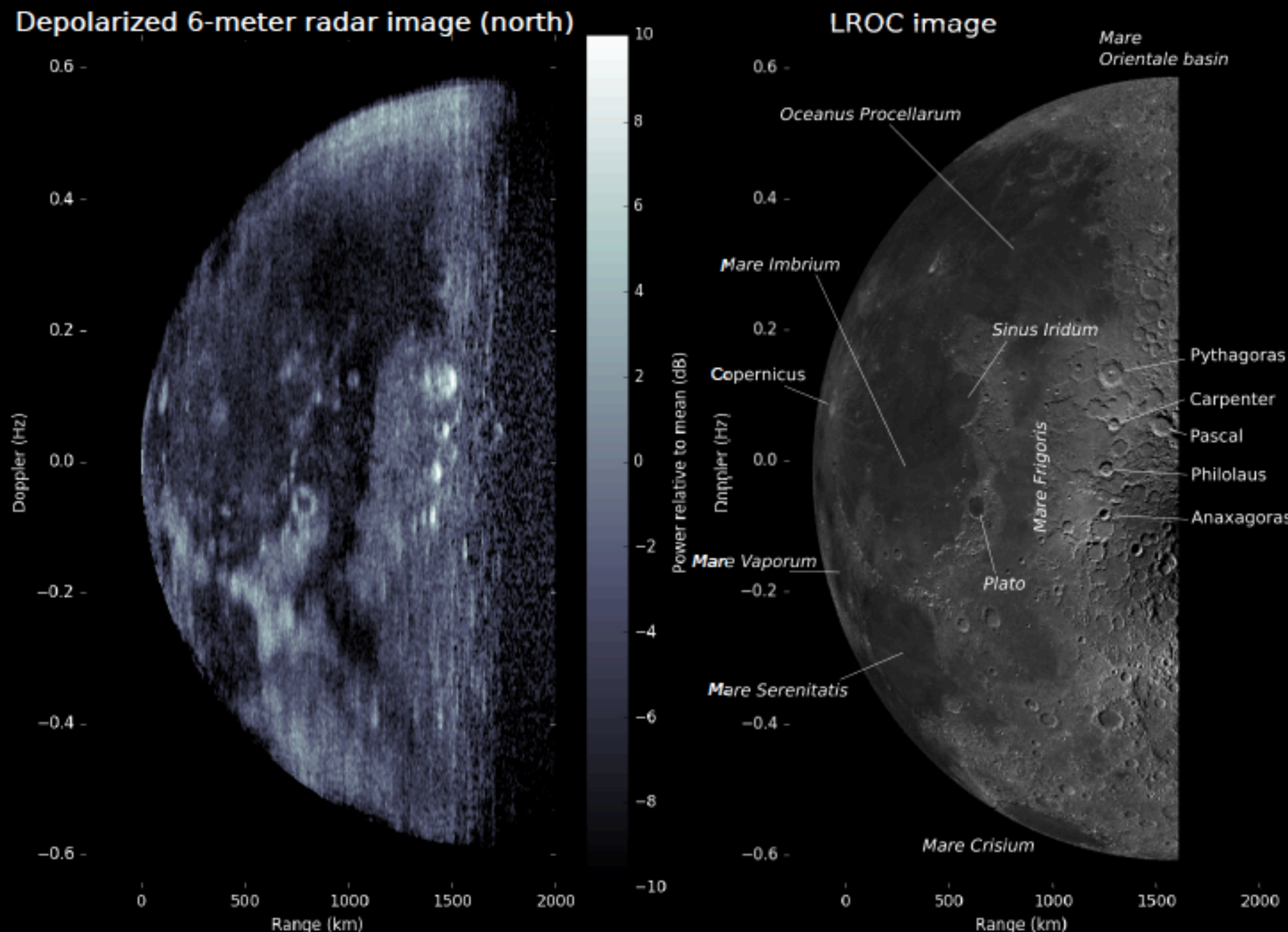
Interferometric Range-Doppler



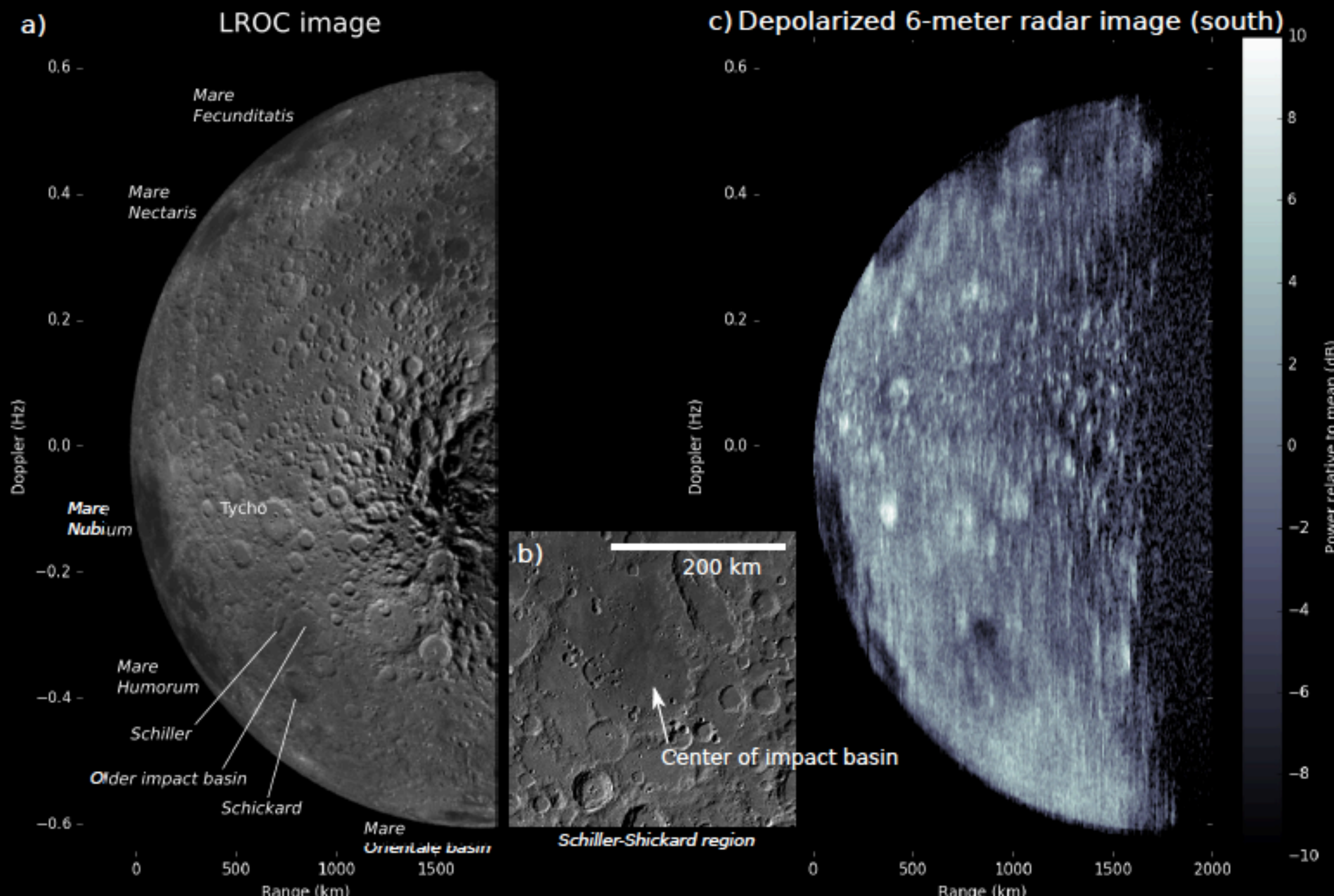
Campbell et.al., (2007)

Rogers and Ingalls (1969)

Apparent motion due to parallax and libration.

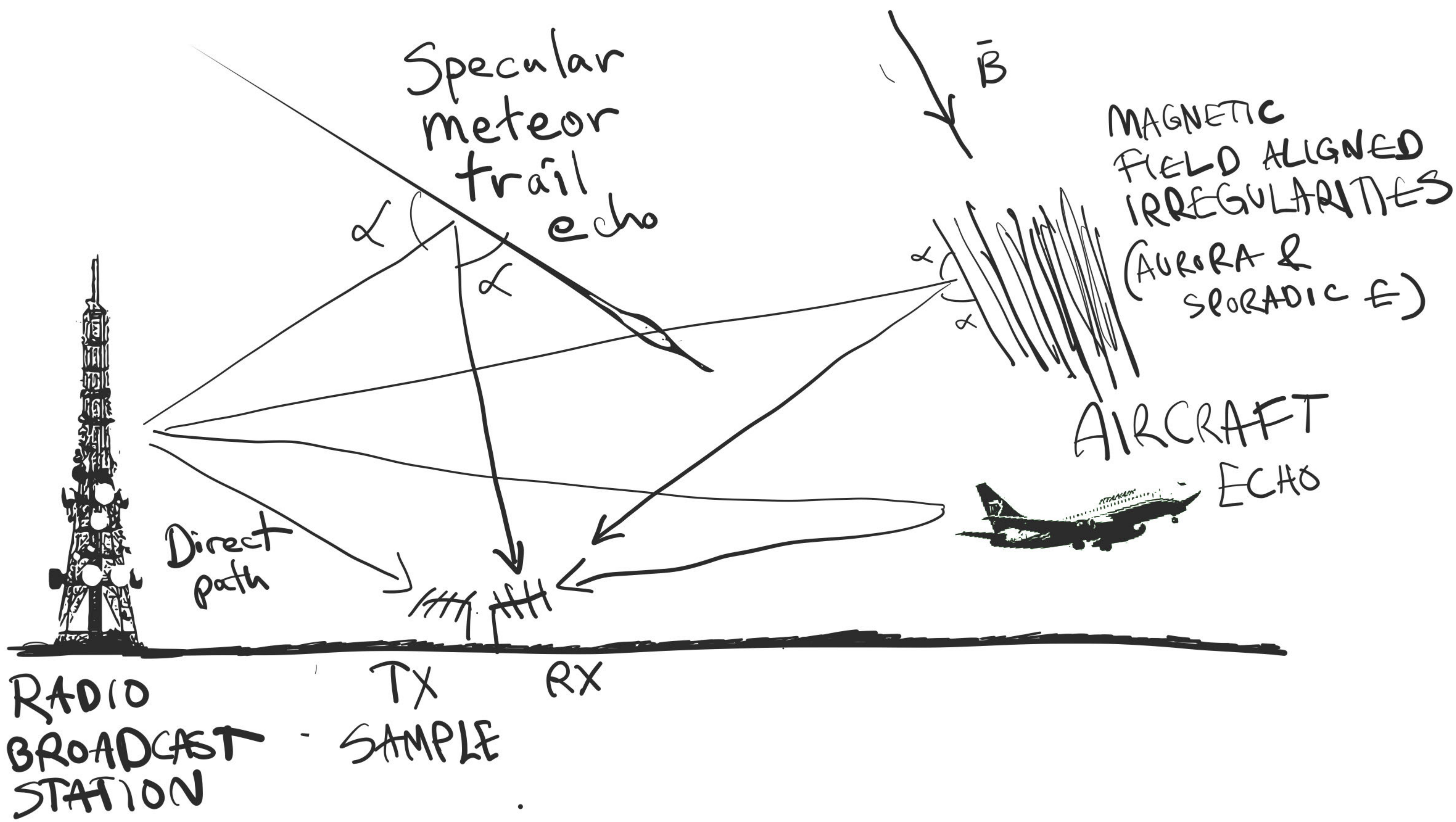


From: Vierinen et.al., 2017



From: Vierinen et.al., 2017

Passive Radar

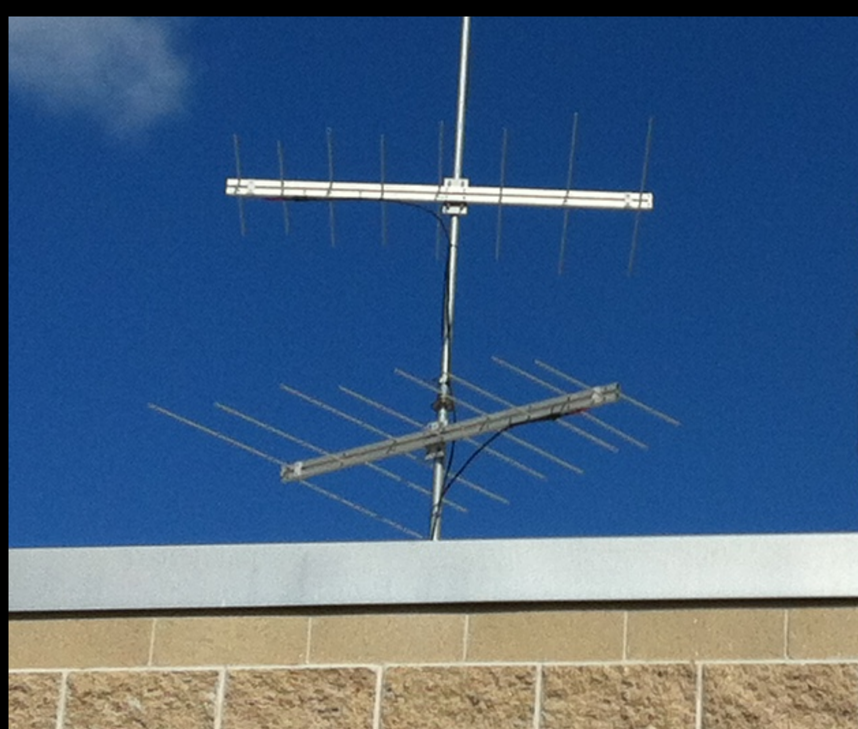


Use of Passive Radar for Space Physics pioneered by John Sahr and Frank Lind (1997, 1999)

Q: Can you build a passive radar receiver with $10?

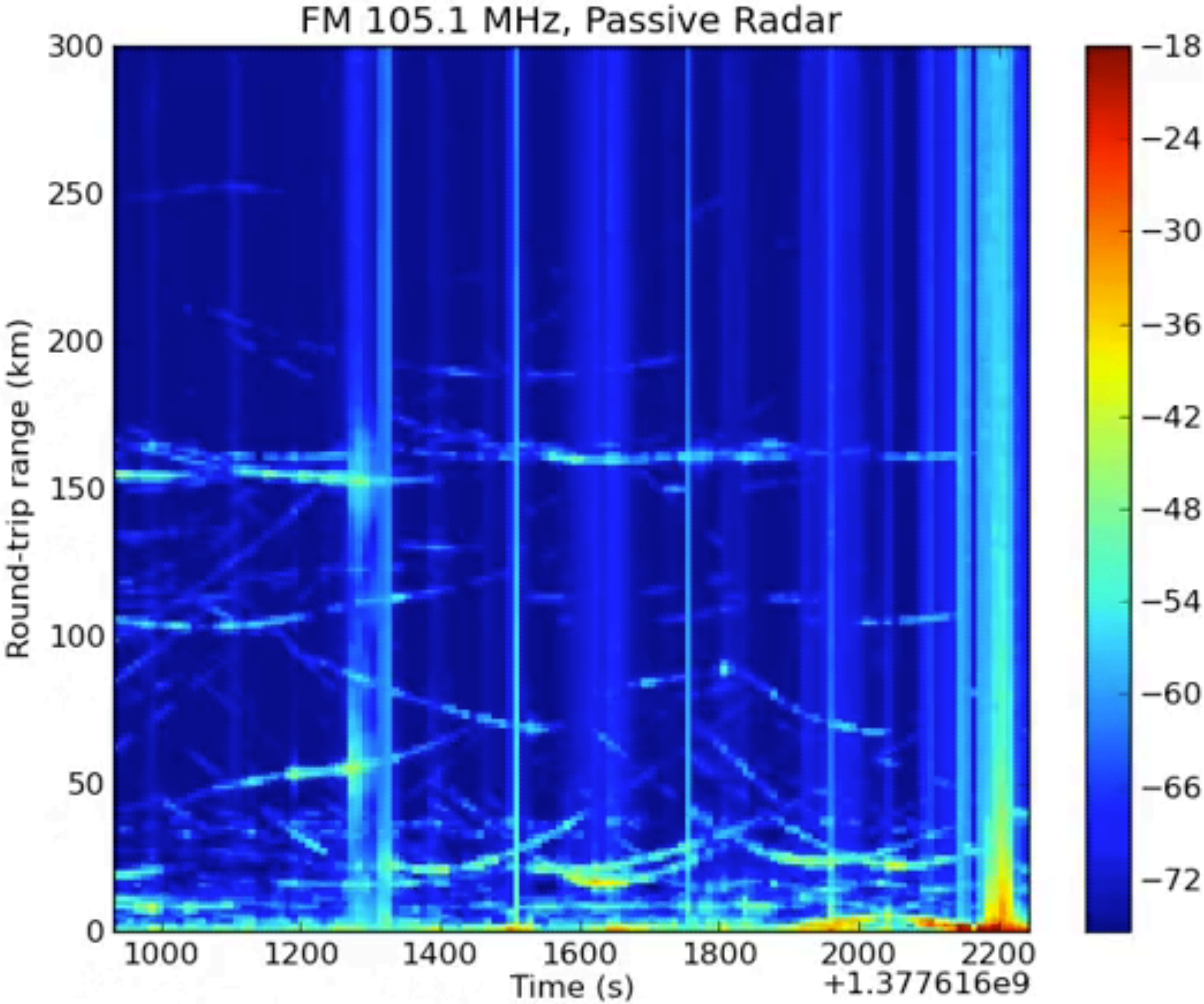
Passive Radar: Hardware


Hacked dual channel RTLSDR. Need to de-dither freq and align samples.
(much easier now with multi-rtl by Piotr Krysik. More info on superkuh.com)



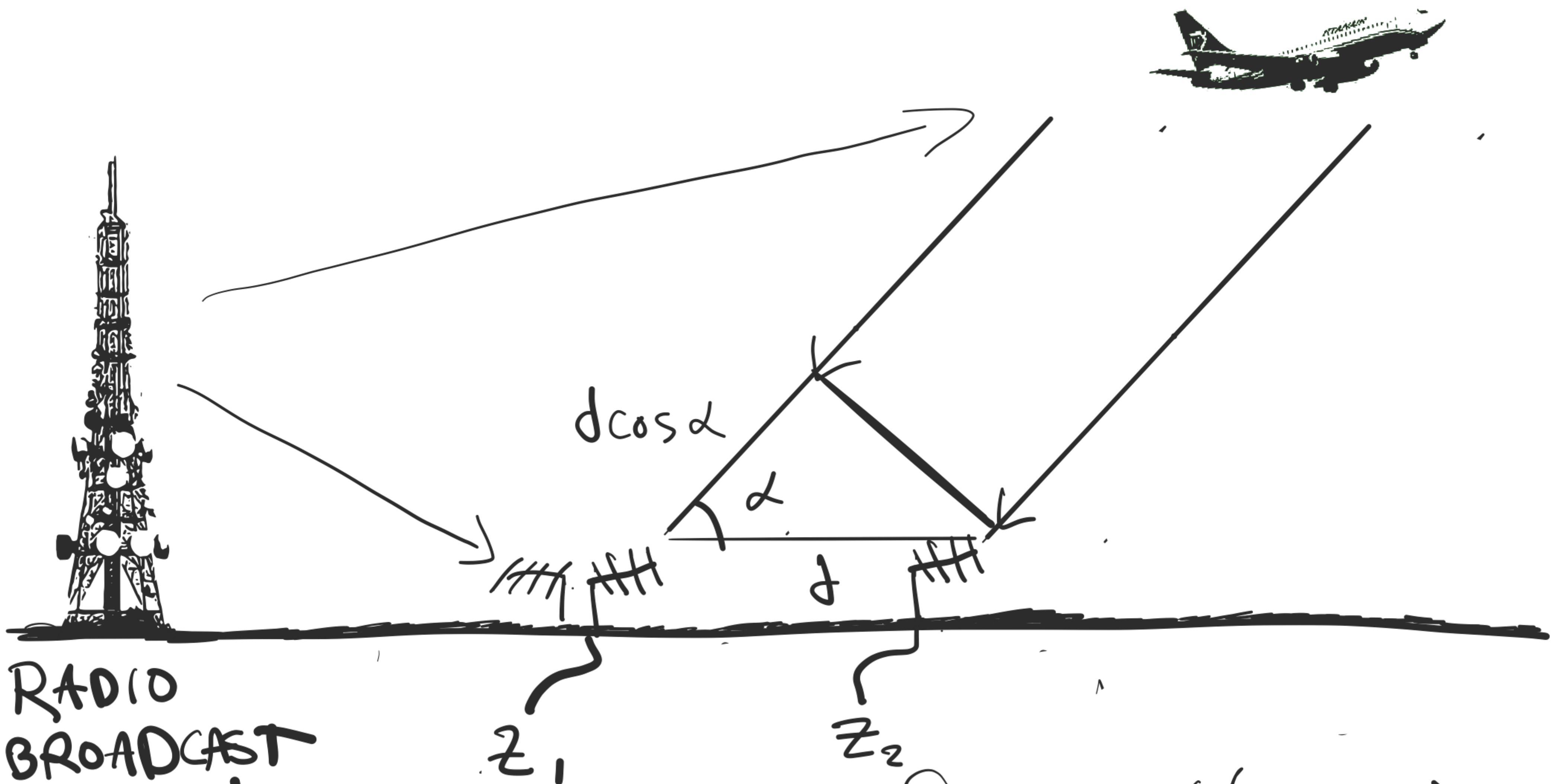
Two directional antennas

USRP N200, or any device with two more coherent channels.

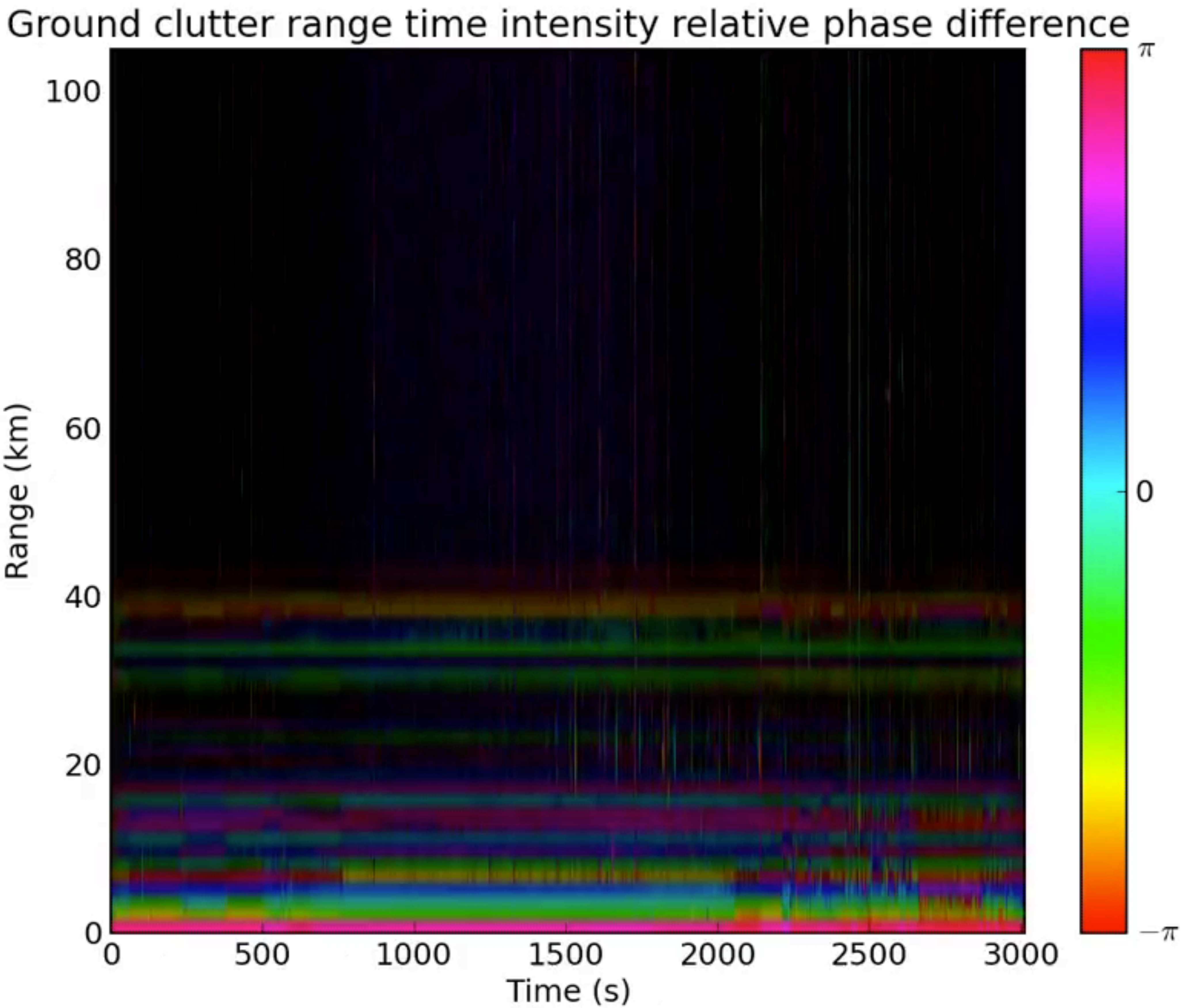


FM 105.1 MHz, Passive Radar
Round-trip range (km)
Time (s)
+1.377616e9
0
50
100
150
200
250
300
1000
1200
1400
1600
1800
2000
2200
−18
−24
−30
−36
−42
−48
−54
−60
−66
−72

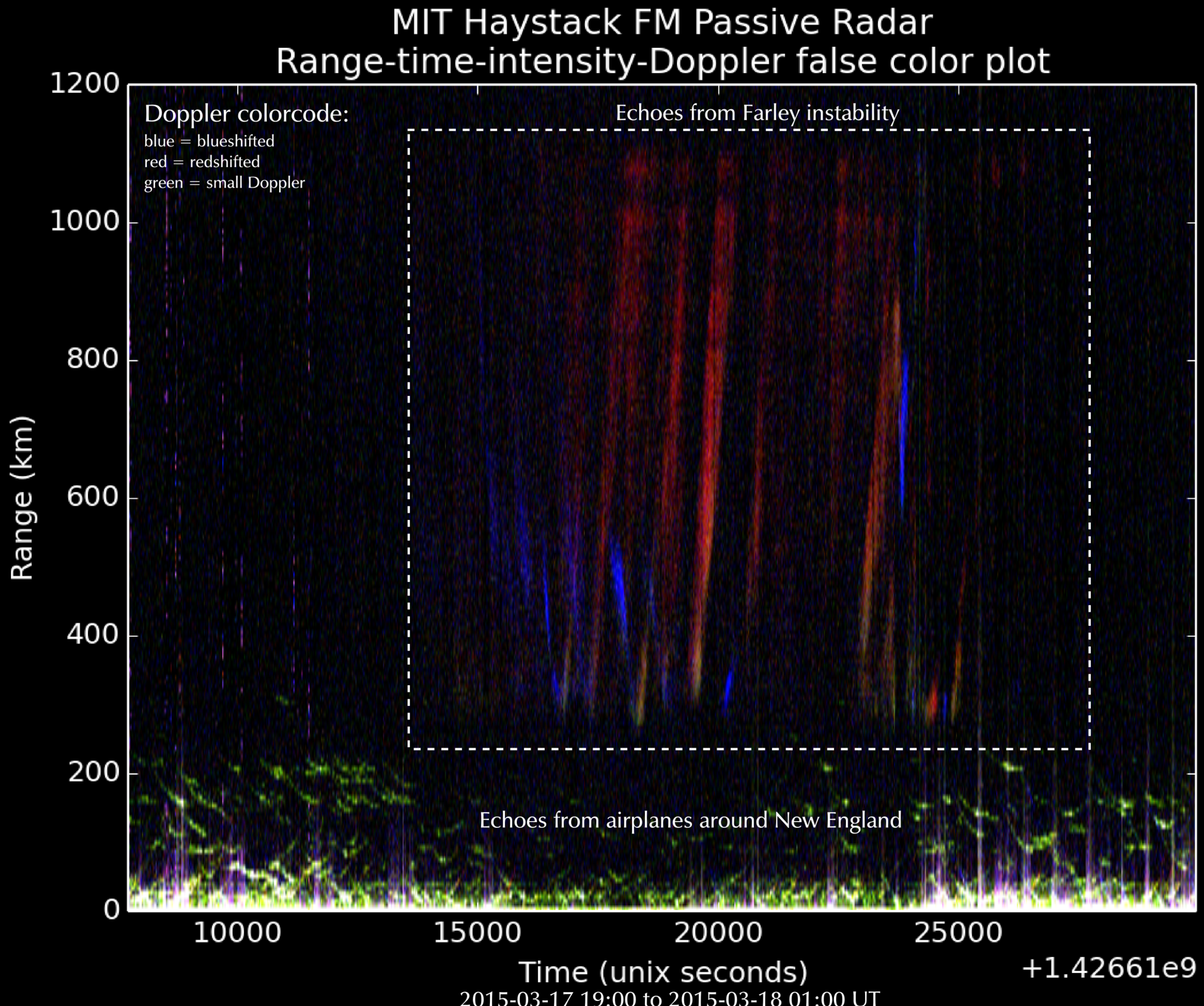
Passive Radar Interferometry



$$\langle z_1 z_2^* \rangle = \rho(u,v) = \int B(n,m)\, e^{-i(un+vm)}\, dn\, dm$$

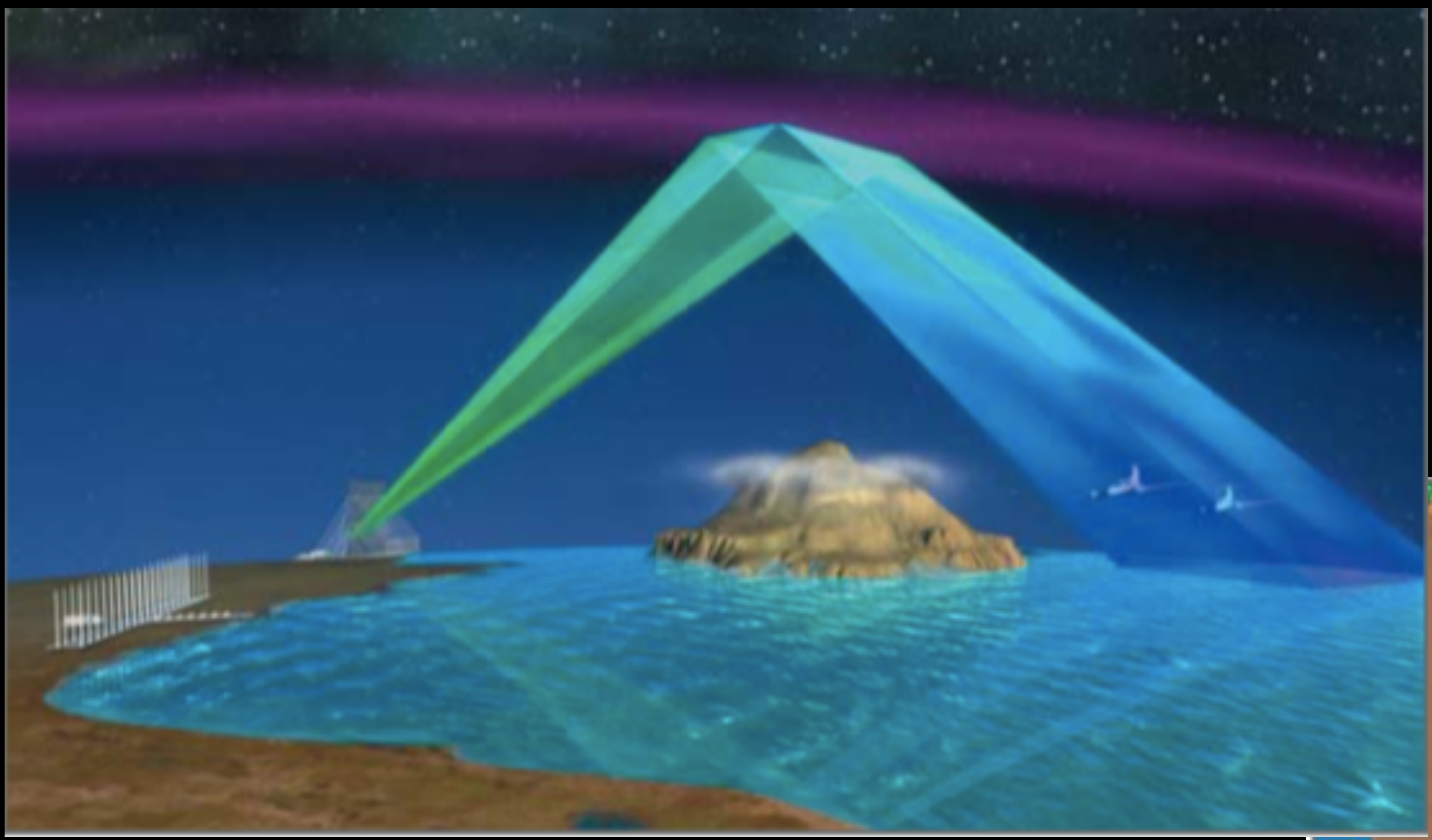


Ground clutter range time intensity relative phase difference
Range (km)
Time (s)
0
20
40
60
80
100
0
500
1000
1500
2000
2500
3000
π
0
−π

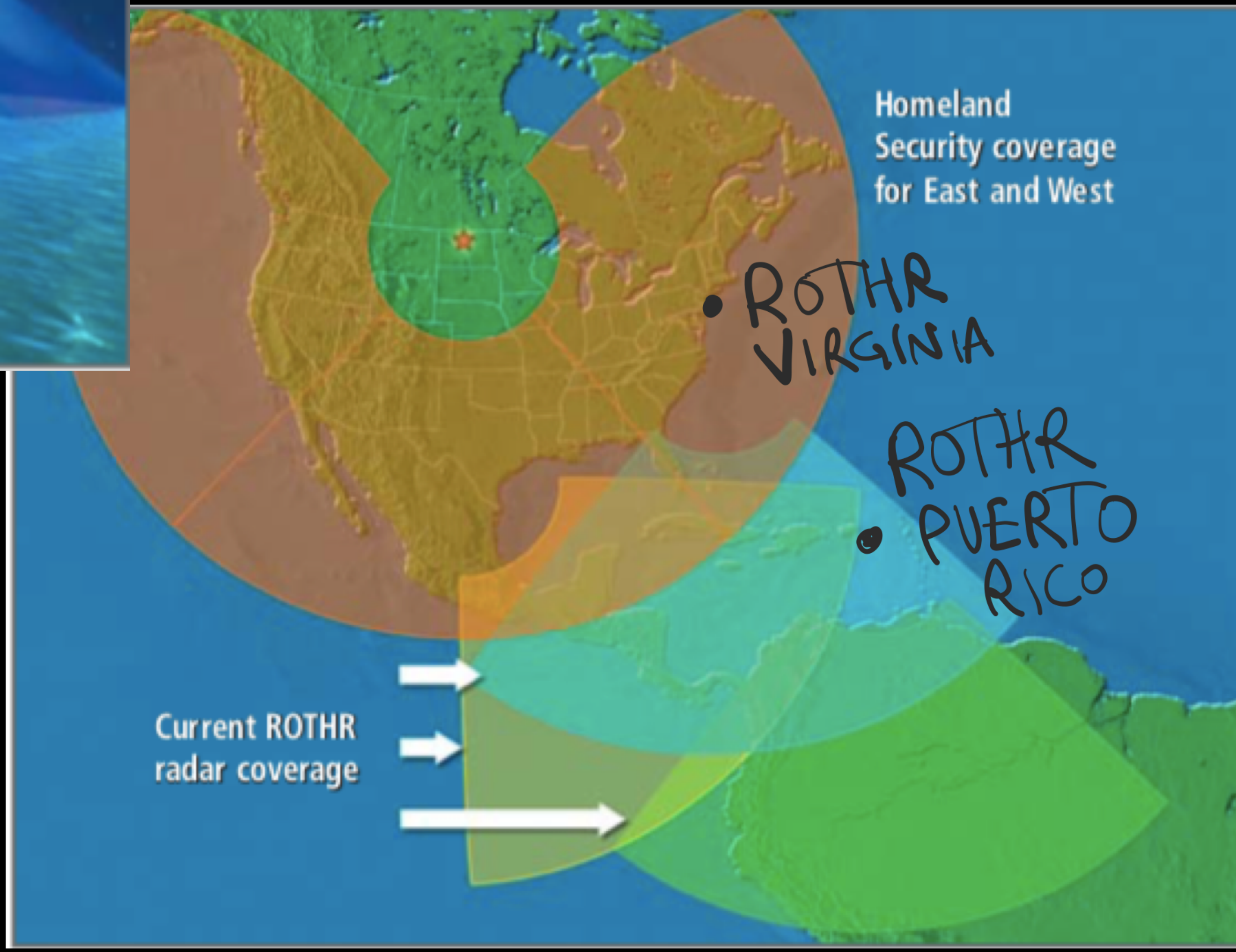


Q: What is the electric field in the ionosphere during geomagnetic storms?

Over the horizon radar



- ~2 to 50 MHz
- Chirp channel sounding mode



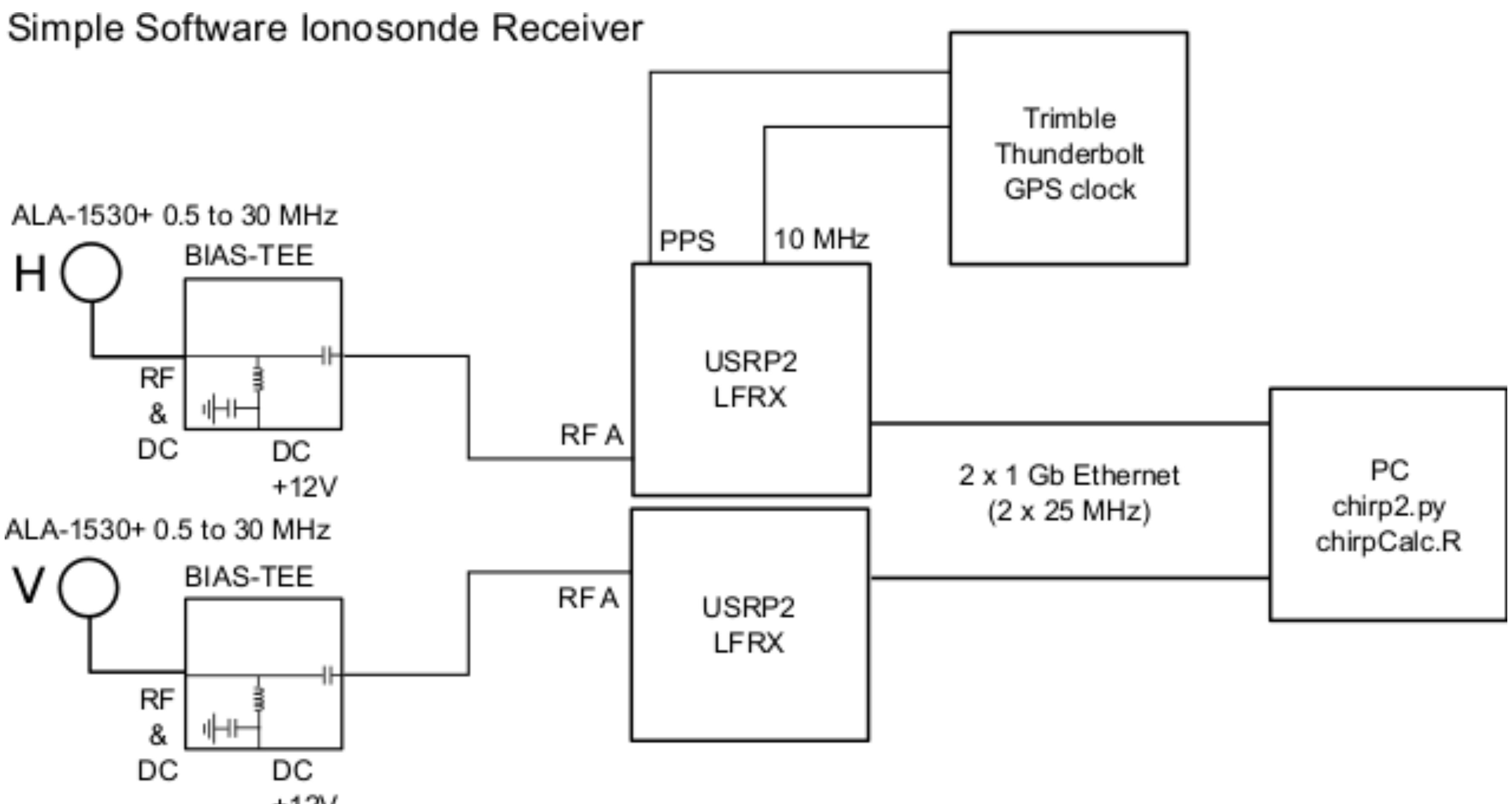
- Used to detect ships and airplanes
- Relies on ionospheric reflection
- Can be used to sound the ionosphere

Image credits: Raytheon

Over the horizon radar

ROTHR Transmit Antenna (Image: Raytheon)

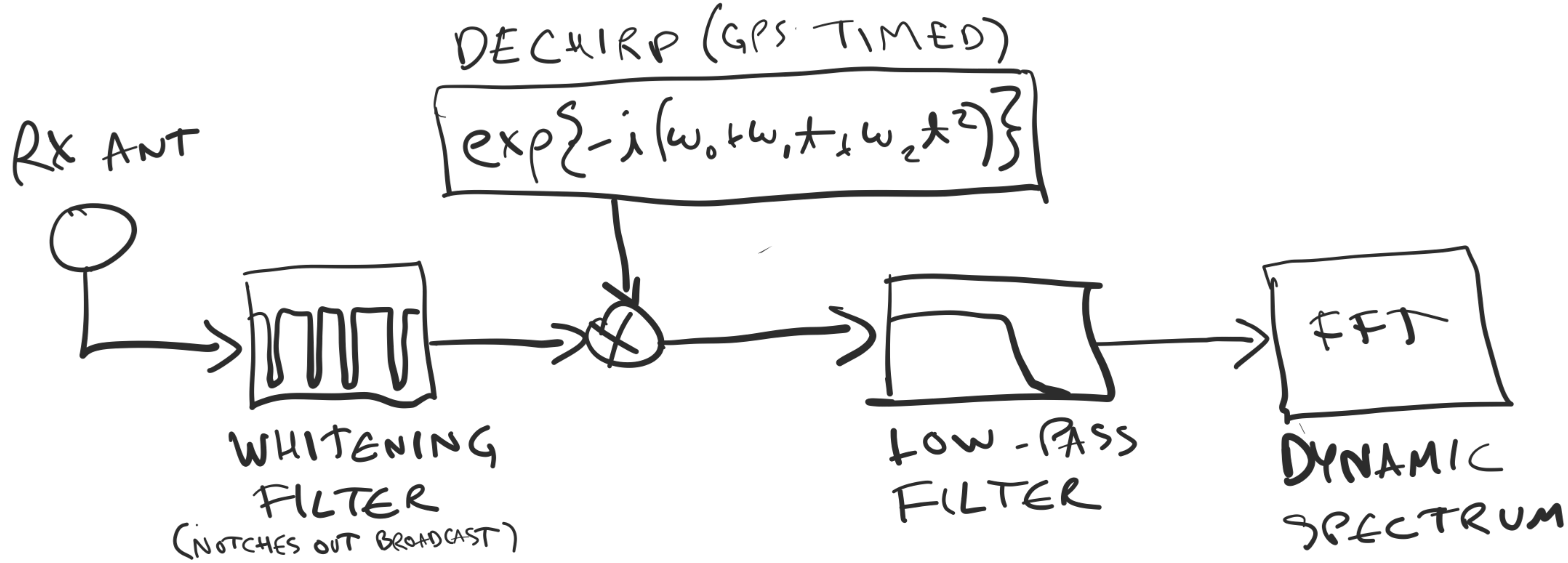
GNU Chirp Sounder



- Open source chirp sounding receiver
- Works for ROTHR and Cyprus OTHR channel sounding transmissions
- Can be used to listen to chirped ionosondes

http://www.sgo.fi/~j/gnu_chirp_sounder/

CHIRP SOUNDER SIGNAL PROCESSING



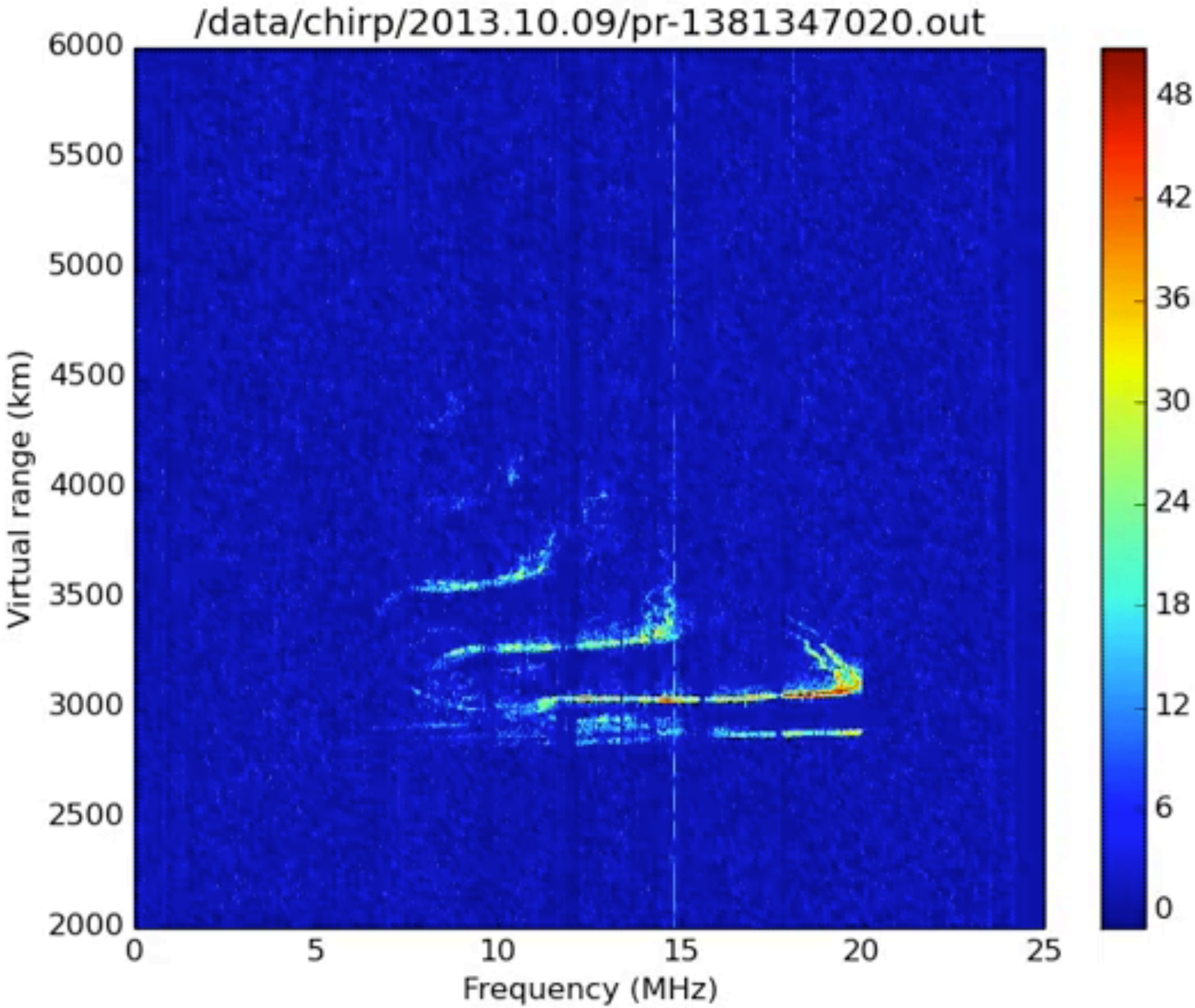
$z_t^{TX} = A\exp\{i(\omega_0+\omega_1 t+\omega_2 t^2)\}$ ~ TX SIGNAL

$z_t^{RX} = \sum_r \sigma_r A\exp\{i(\omega_0+\omega_1(t-r)+\omega_2(t-r)^2)\}$ ~ RX SIGNAL

$$z_t^{RX}\exp\{-i(\omega_0+\omega_1 t+\omega_2 t^2)\} =$$

$\sum_r \sigma_r' \exp\{-i2\omega_2 r t\}$ ~ DECHIRPED SIGNAL.

$\sigma_r' = \sigma_r A e^{i\omega_2 r^2} e^{-i\omega_1 r}$ ~ RADAR ECHO.



http://www.sgo.fi/~j/gnu_chirp_sounder/

HF Radio Propagation

$$n^2 = 1 - \frac{X}{1 - iZ - \frac{\frac{1}{2}Y^2 \sin^2\theta}{1-X-iZ} \pm \frac{1}{1-X-iZ}\left(\frac{1}{4}Y^4 \sin^4\theta + Y^2\cos^2\theta(1-X-iZ)^2\right)^{1/2}}$$

Ionospheric Physics with HF

- Q: What is the volumetric structure of the electron density within the ionosphere?
- Q: What are the propagation characteristics of atmospheric gravity waves?
- Q: How is the energy transported by gravity waves within the thermosphere?
- Q: What does the universe look like at HF?

Q: What is technically the best way to implement an HF radar that sounds the ionosphere?

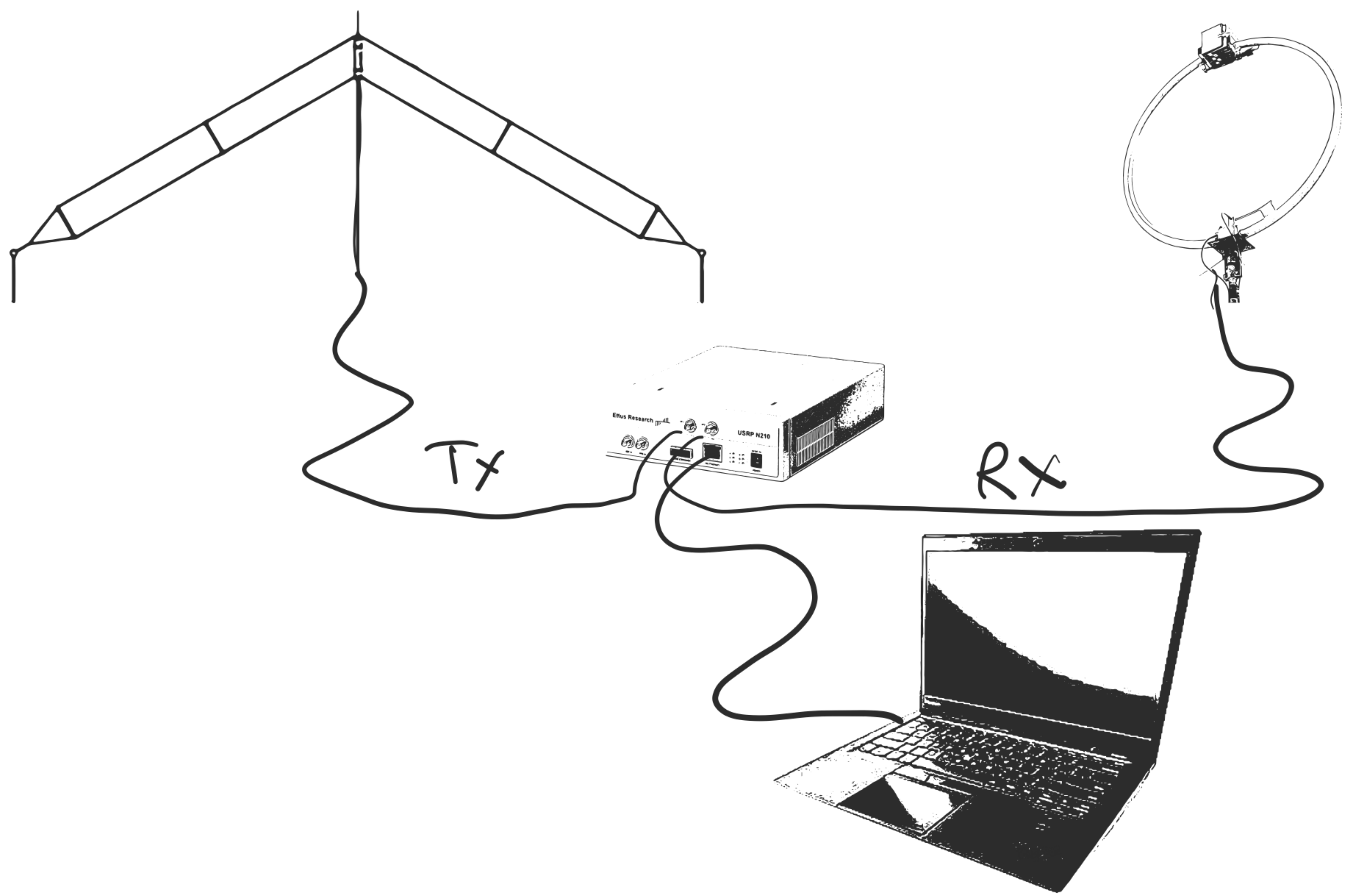
- A: Spread spectrum. Using continuous pseudorandom noise as transmit waveform

- Noise is orthogonal with other signals, allows MIMO, tolerant to RFI

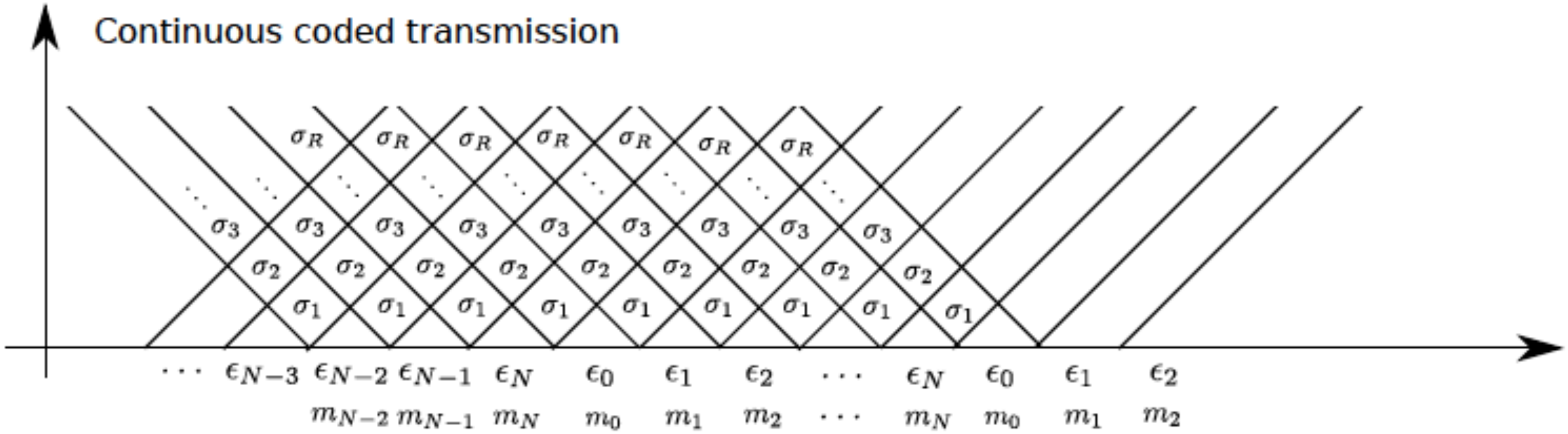
- Noise is a nearly perfect radar code in terms of statistical estimation errors

- Least amount of peak power spectral density, least amount of interference to other users of the band

Spread Spectrum HF Radar



Multi-static HF radar equation



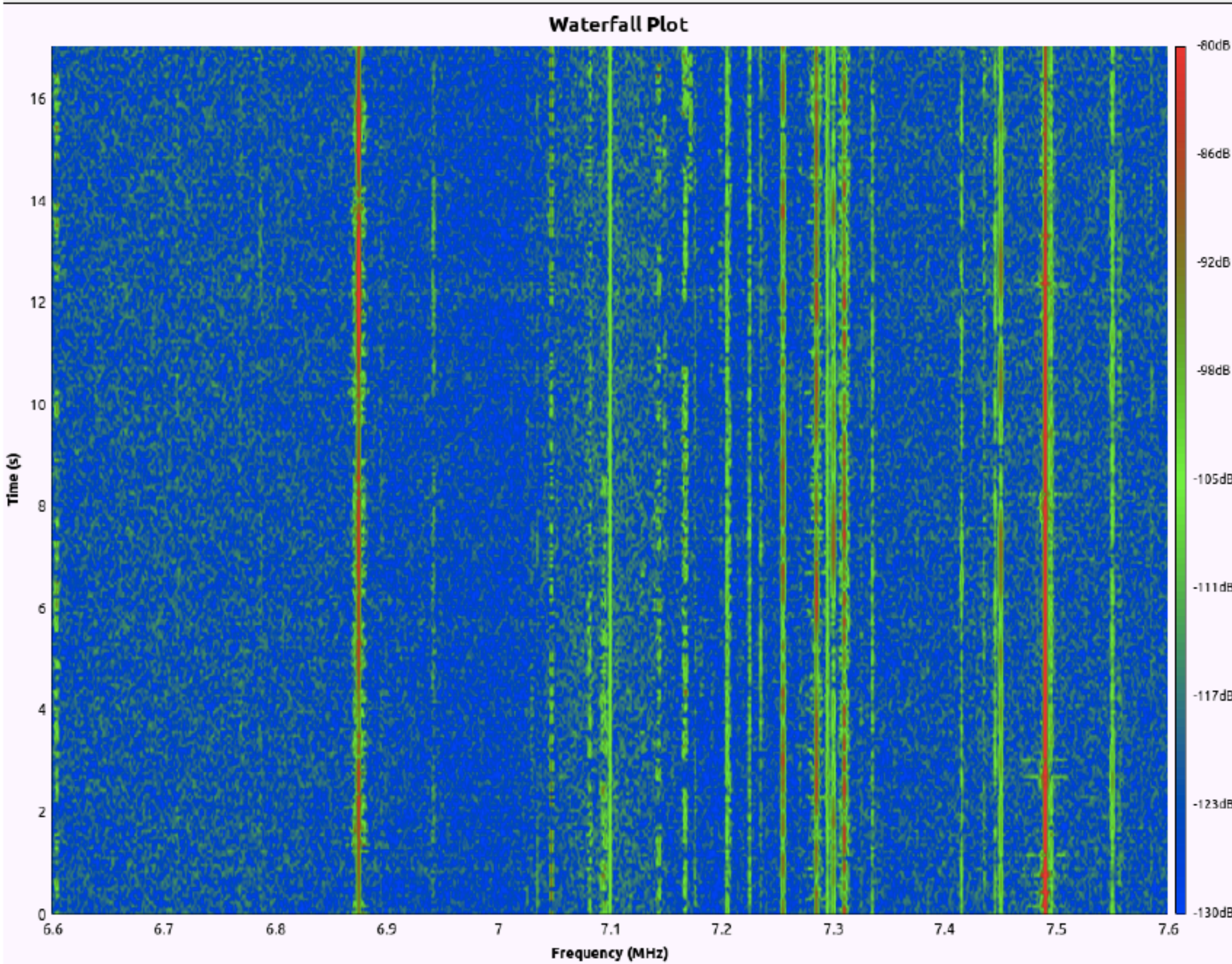
$$m_t = \sum_{n=1}^{T} \sum_{r=0}^{R} \sigma_r^n \epsilon_{(t-r) \mod N}^n \qquad \hat{x} = [\sigma_1, \sigma_2, \cdots, \sigma_R]^T$$

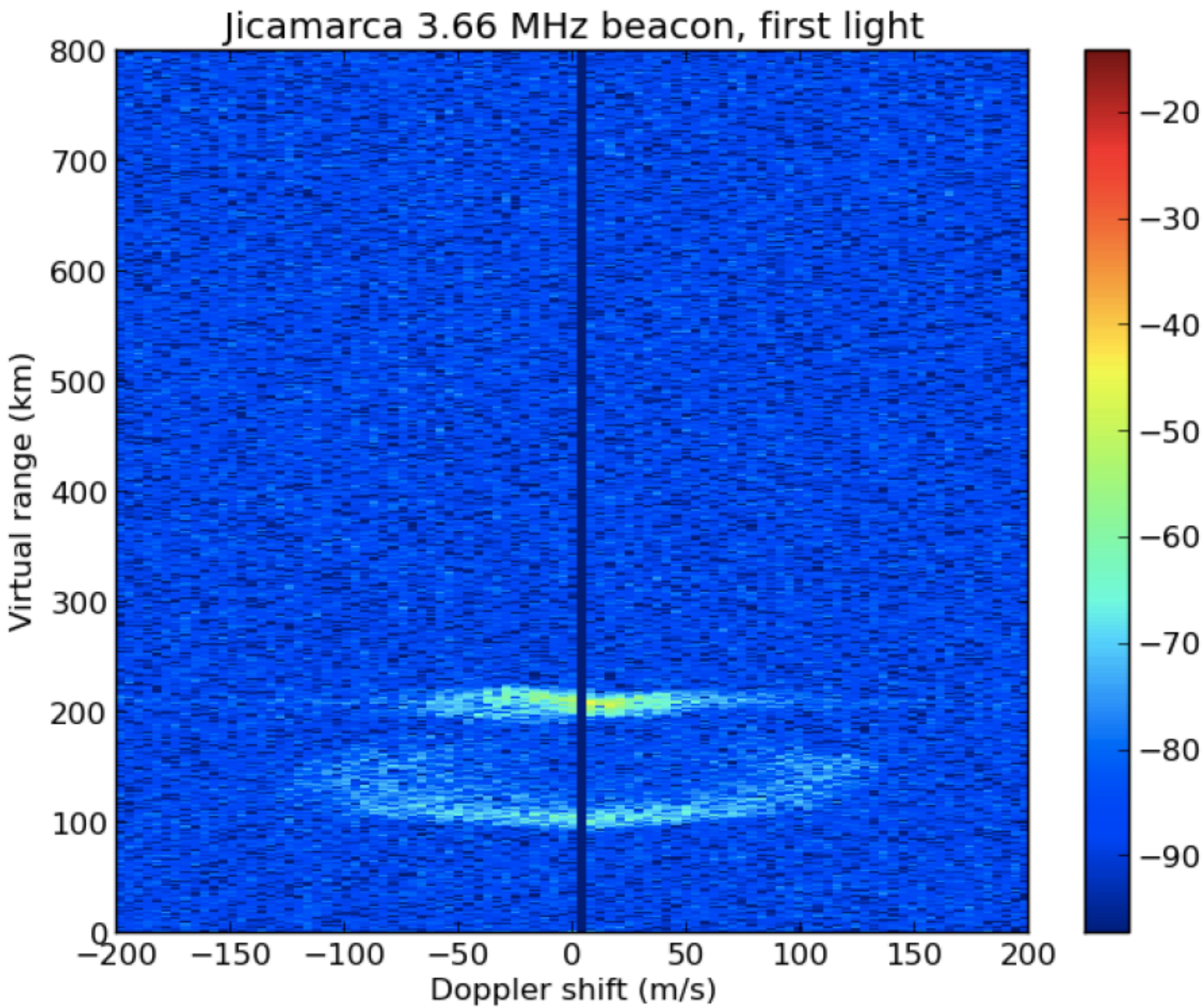
$$\hat{x} = \underbrace{(\overline{A}^T A)^{-1} \overline{A}^T}_{B} m \qquad m = [m_0, m_1, \cdots, m_N]^T$$

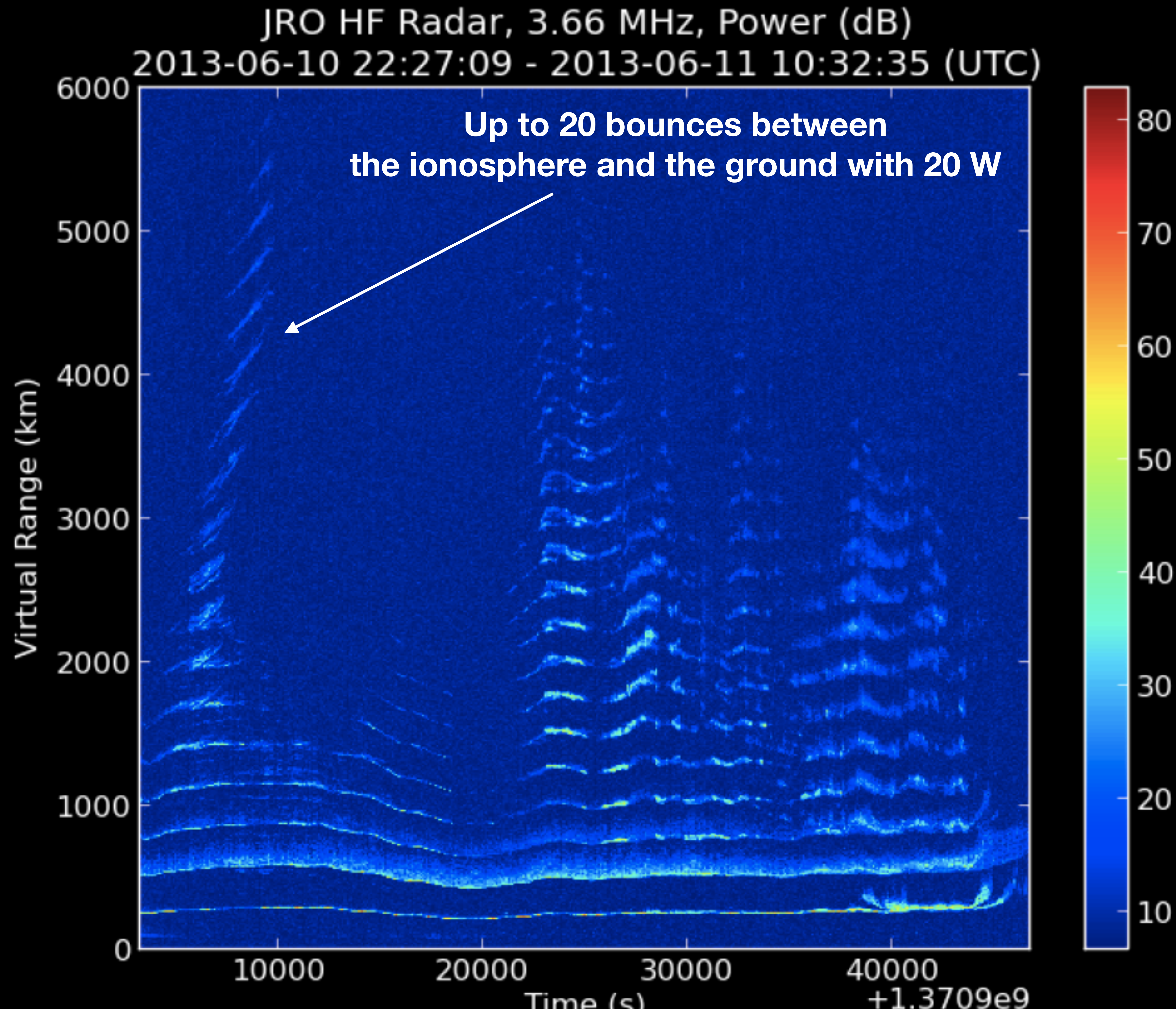
$$R < N$$

- Continuous transmit and receive, cyclic convolution assumption valid due to long coherence, *high coding gain*.
- Multiple simultaneous transmitters using the same channel.
- Perfect codes exist for $T = 1$ (Frank and Chu codes)
- Pseudorandom sequences are very close to optimal for $R \ll N$ (Evans and Hagfors 1968; Woodman 1979; Sulzer 1986)

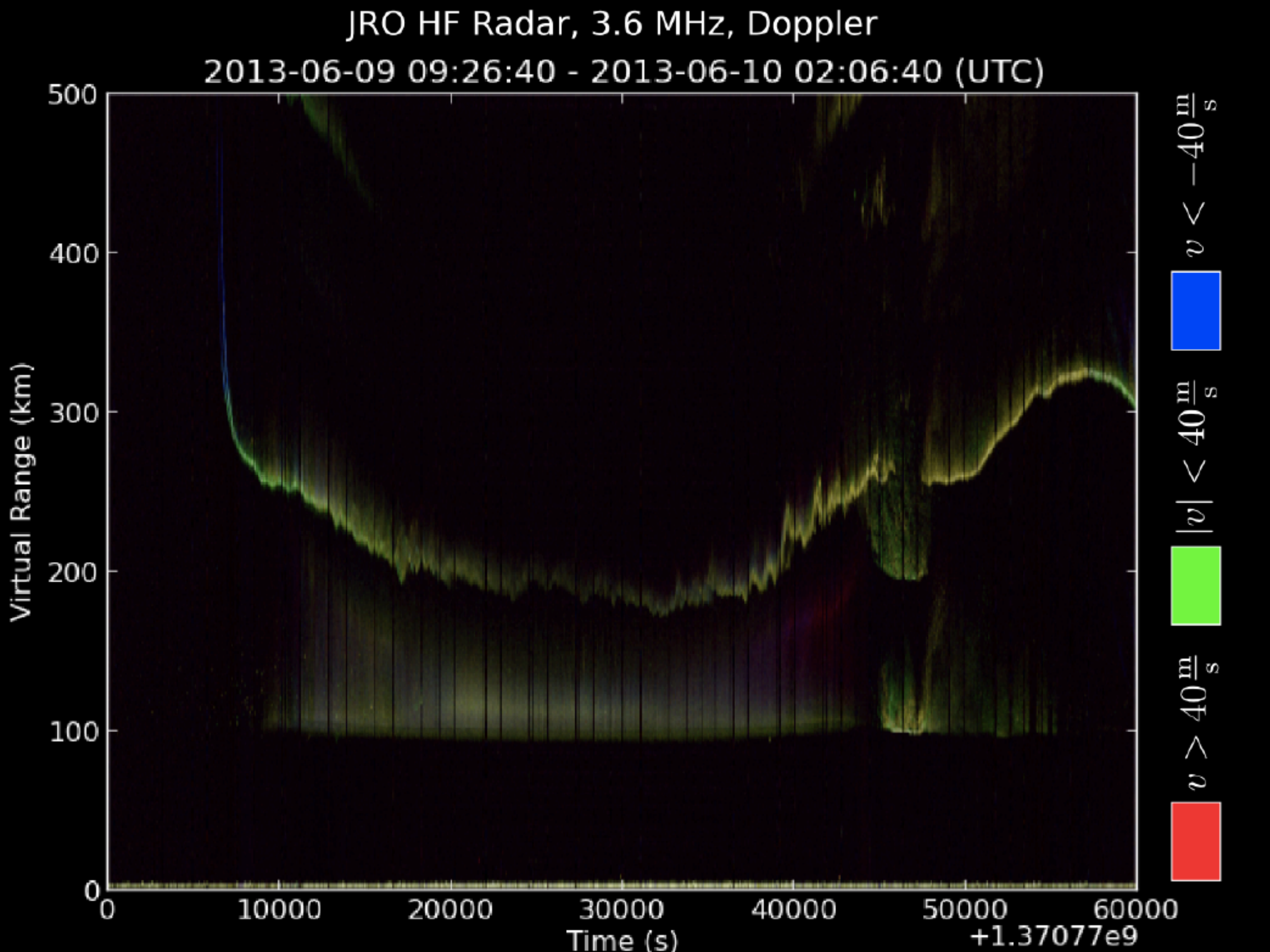
Very little interference

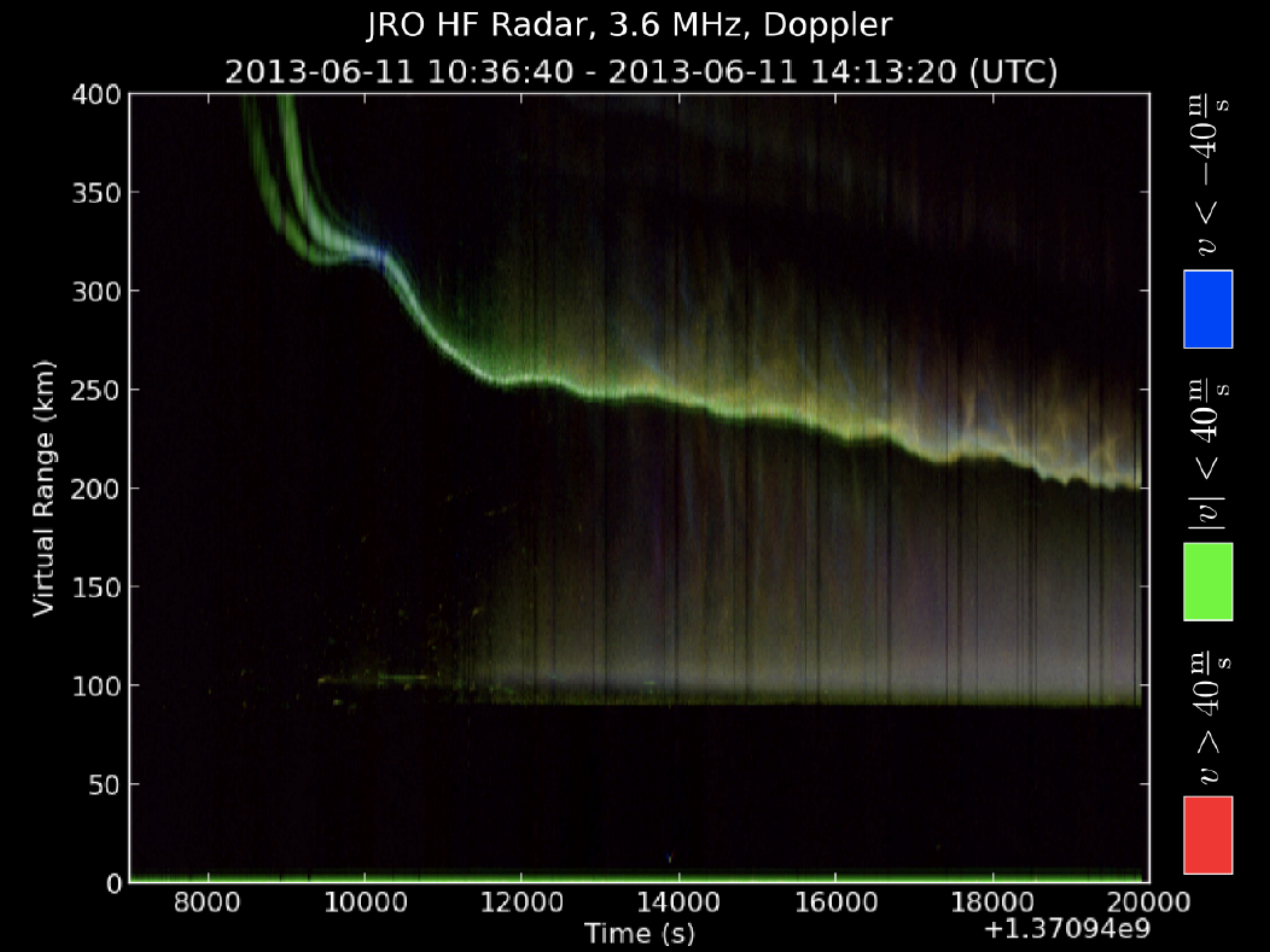



Jicamarca 3.66 MHz beacon, first light
Virtual range (km)
800
700
600
500
400
300
200
100
0
−200
−150
−100
−50
0
50
100
150
200
Doppler shift (m/s)
−20
−30
−40
−50
−60
−70
−80
−90



JRO HF Radar, 3.66 MHz, Power (dB)
2013-06-10 22:27:09 - 2013-06-11 10:32:35 (UTC)
Up to 20 bounces between
the ionosphere and the ground with 20 W
Virtual Range (km)
0
1000
2000
3000
4000
5000
6000
10000
20000
30000
40000
Time (s)
+1.3709e9
10
20
30
40
50
60
70
80


JRO HF Radar, 3.6 MHz, Doppler
2013-06-09 09:26:40 - 2013-06-10 02:06:40 (UTC)
Virtual Range (km)
Time (s)
+1.37077e9
0
100
200
300
400
500
10000
20000
30000
40000
50000
60000
$v < -40\frac{m}{s}$
$|v| < 40\frac{m}{s}$
$v > 40\frac{m}{s}$

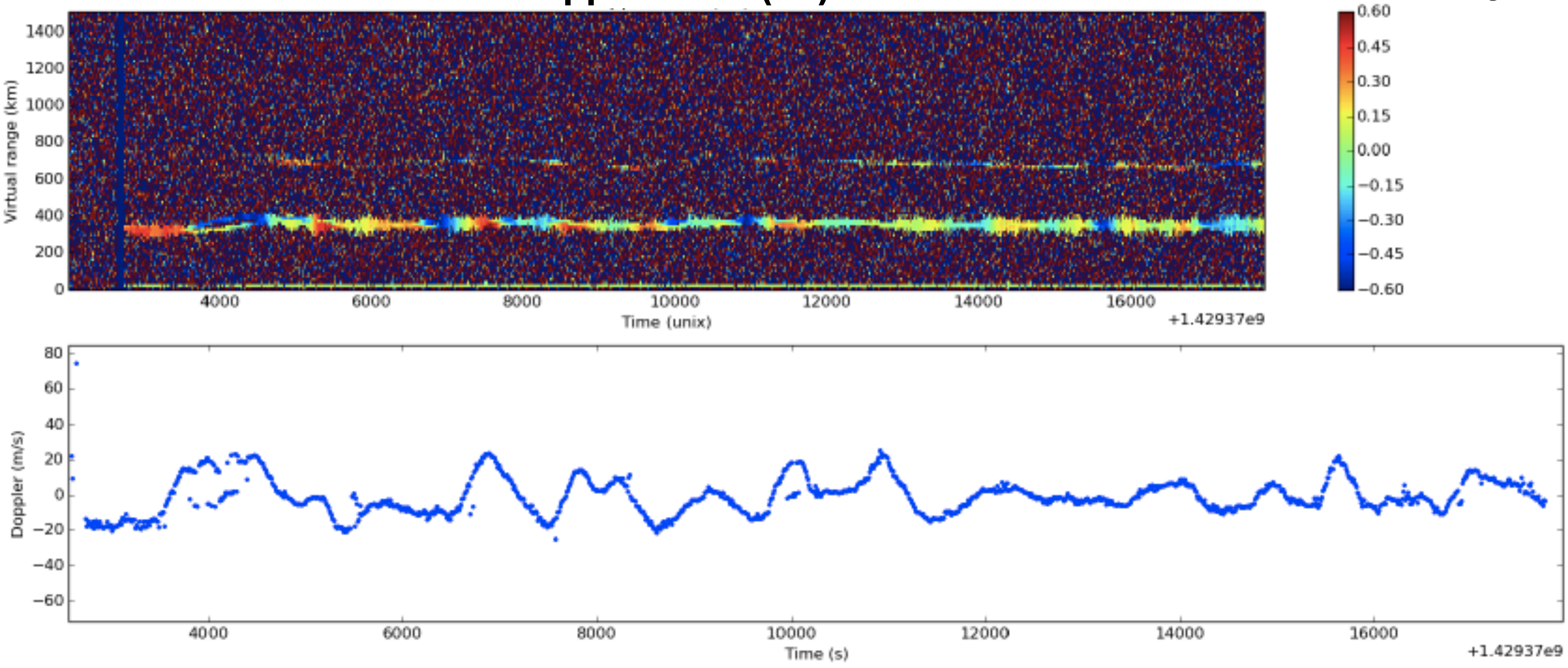


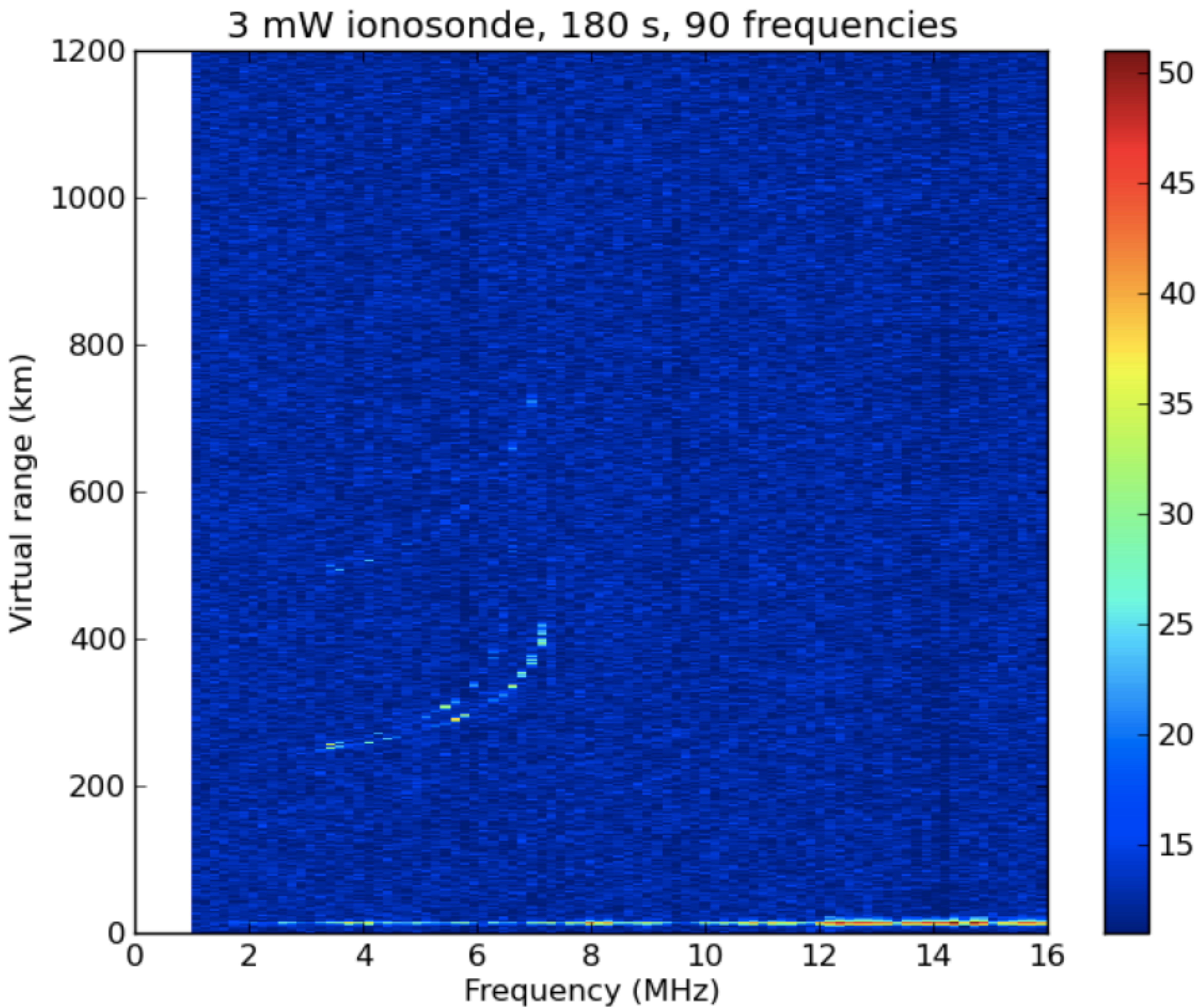
JRO HF Radar, 3.6 MHz, Doppler
2013-06-11 10:36:40 - 2013-06-11 14:13:20 (UTC)
Virtual Range (km)
400
350
300
250
200
150
100
50
0
8000
10000
12000
14000
16000
18000
20000
Time (s)
+1.37094e9
$v < -40\frac{m}{s}$
$|v| < 40\frac{m}{s}$
$v > 40\frac{m}{s}$

Thermospheric Gravity Waves

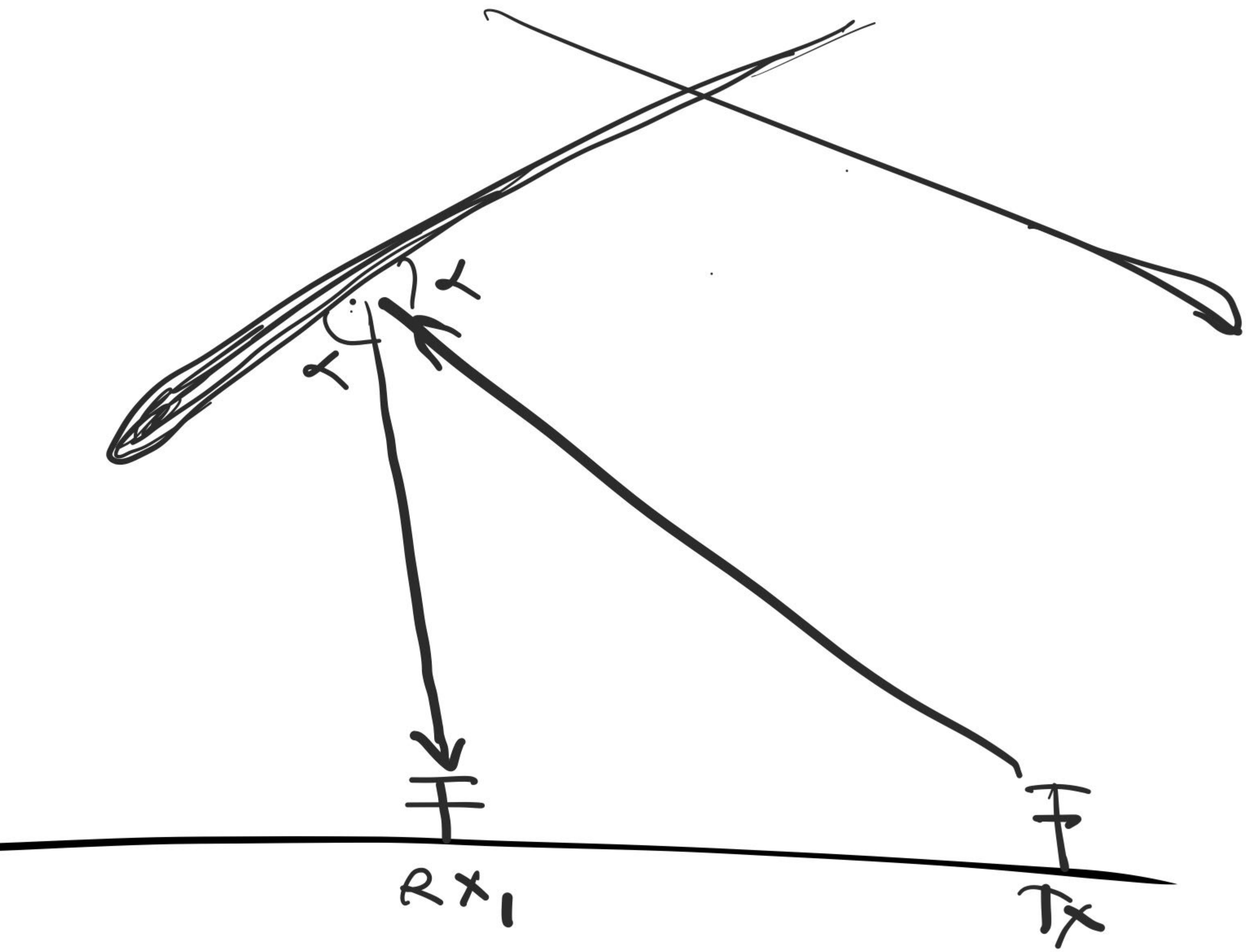
Video: Patrick Lynett

Doppler Shift (Hz)



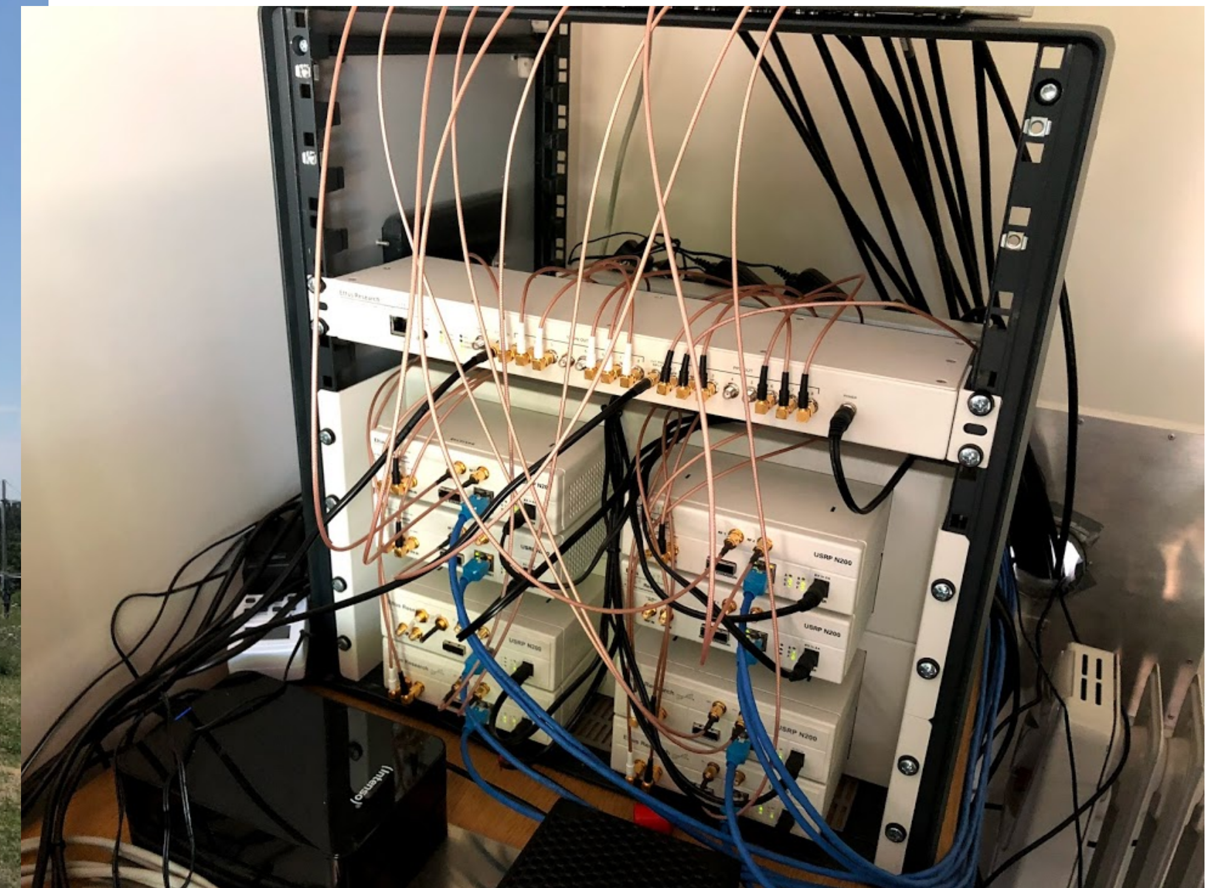

3 mW ionosonde, 180 s, 90 frequencies
Virtual range (km)
Frequency (MHz)
0
200
400
600
800
1000
1200
2
4
6
8
10
12
14
16
15
20
25
30
35
40
45
50

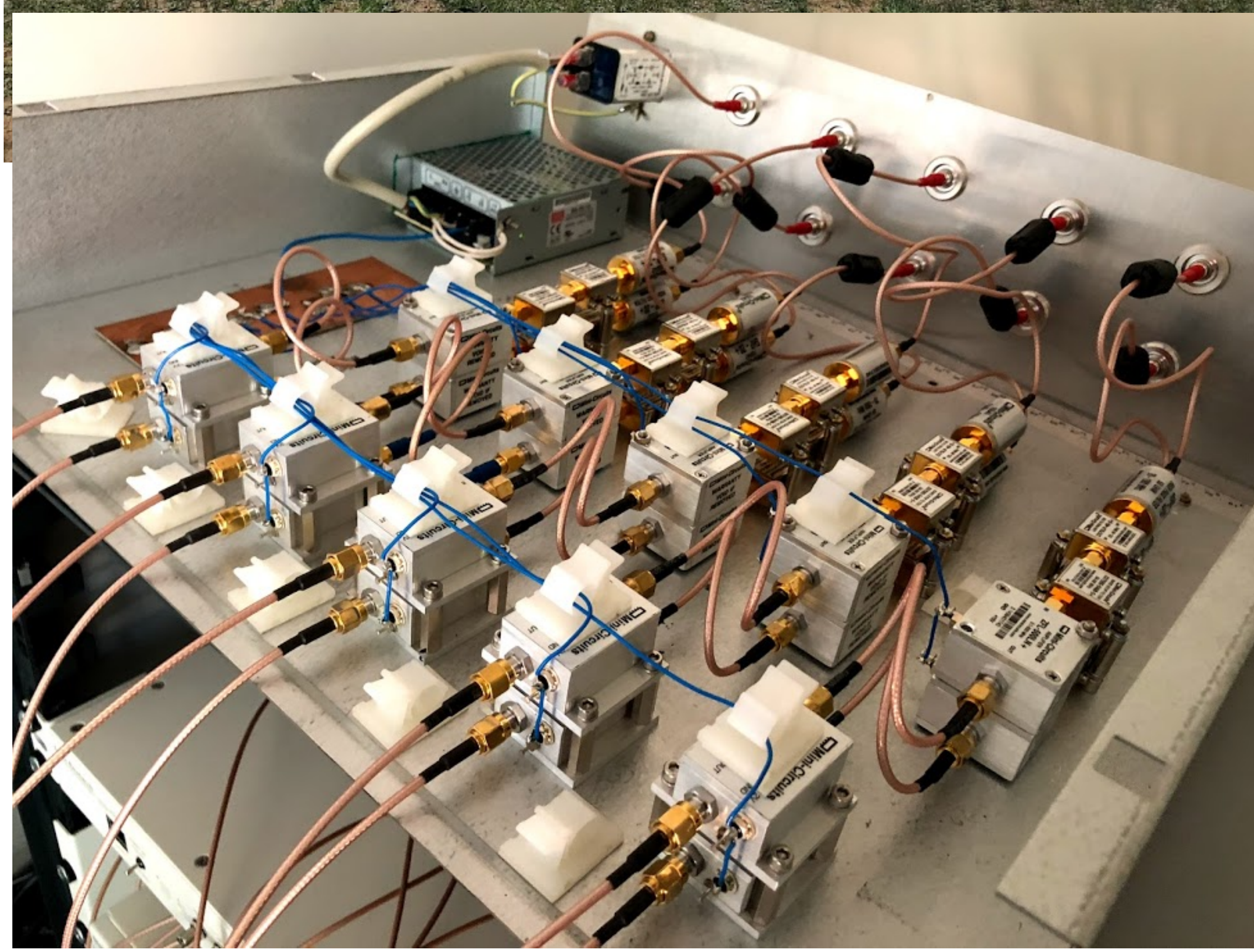
MIMO Spread spectrum meteor radar

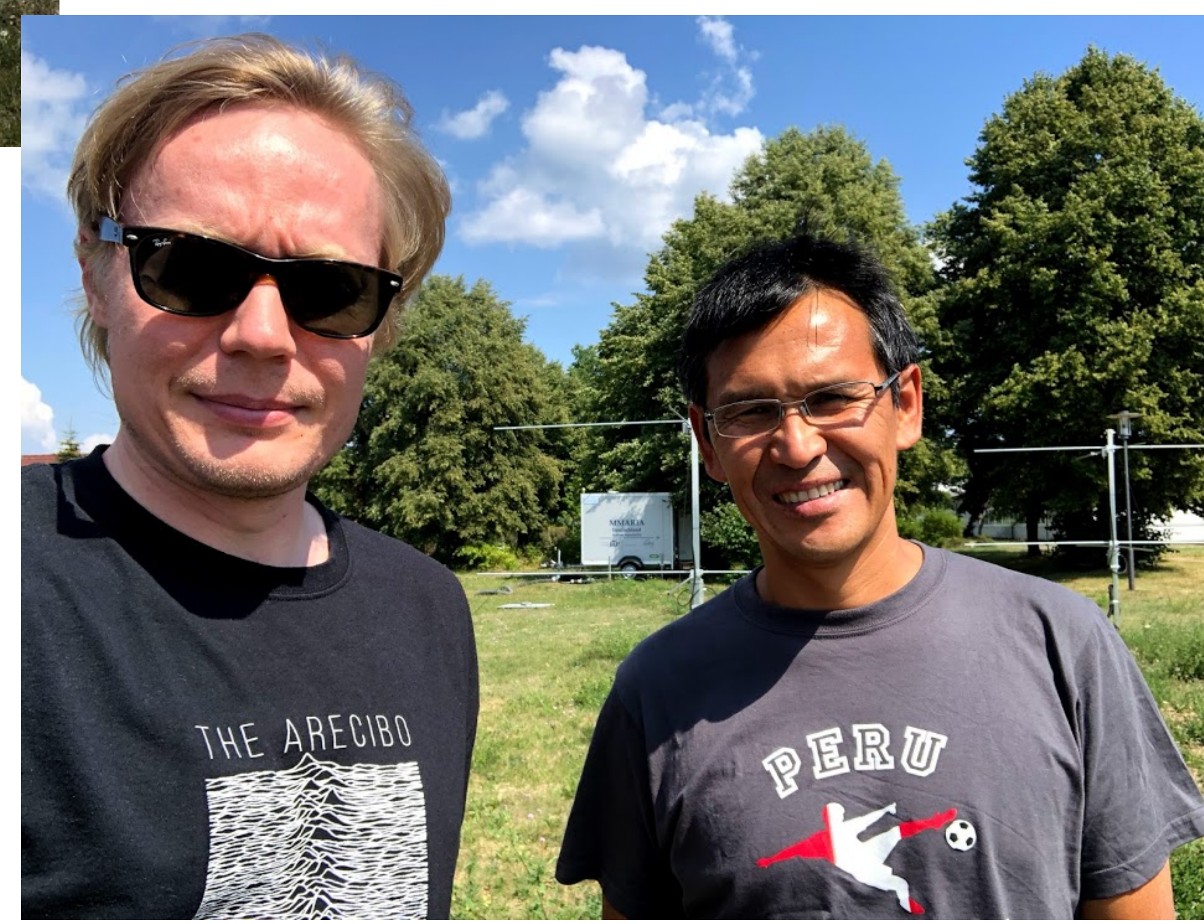


- Q: How much meteoric matter enters the Earth's atmosphere?
- Q: What is the dynamic structure of the mesosphere?
- Q: Why have we never measured an interstellar micrometeoroid?

Vierinen et.al., Coded continuous wave meteor radar, 2016





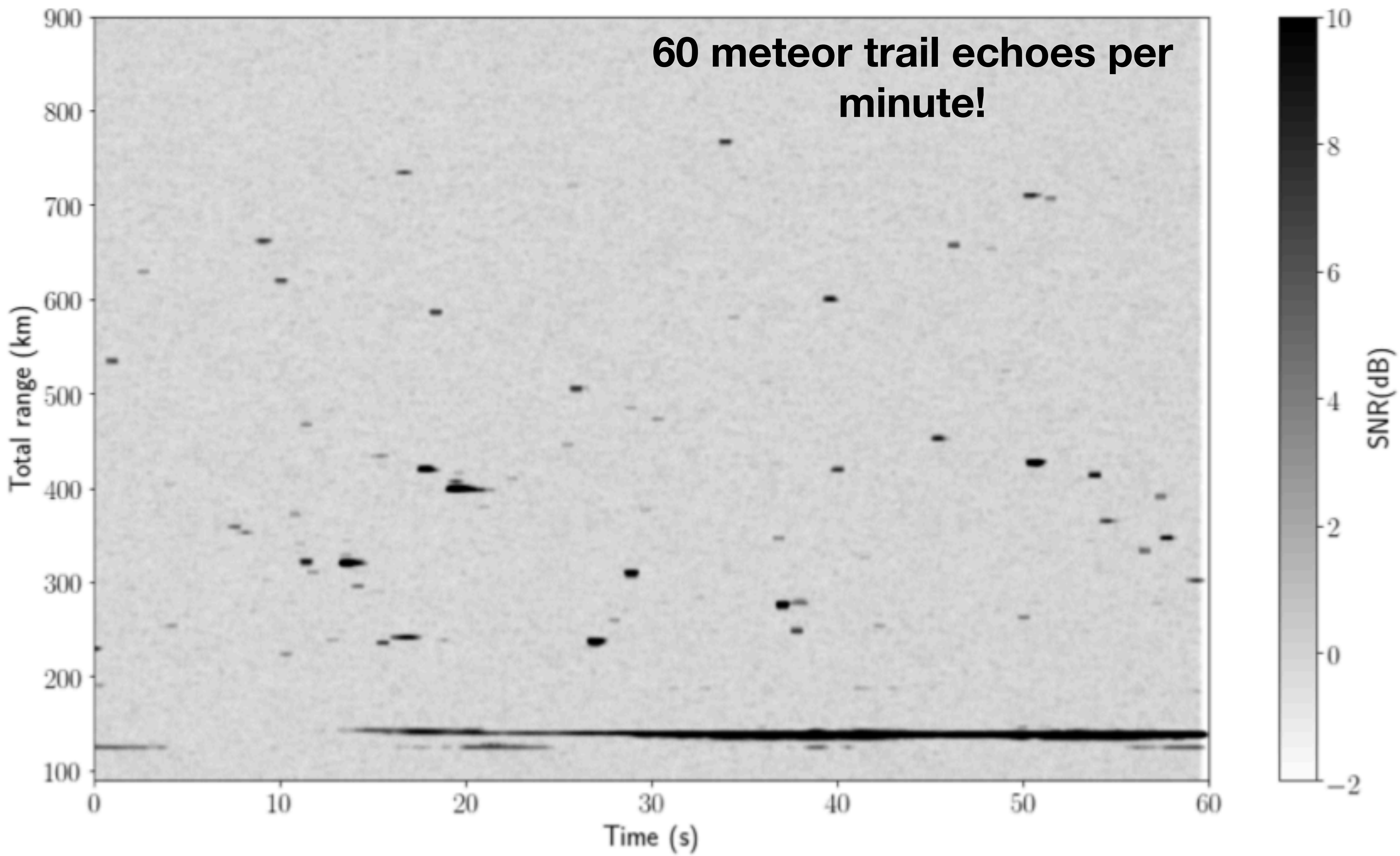


Jorge L. Chau

MIMO Meteor Radar

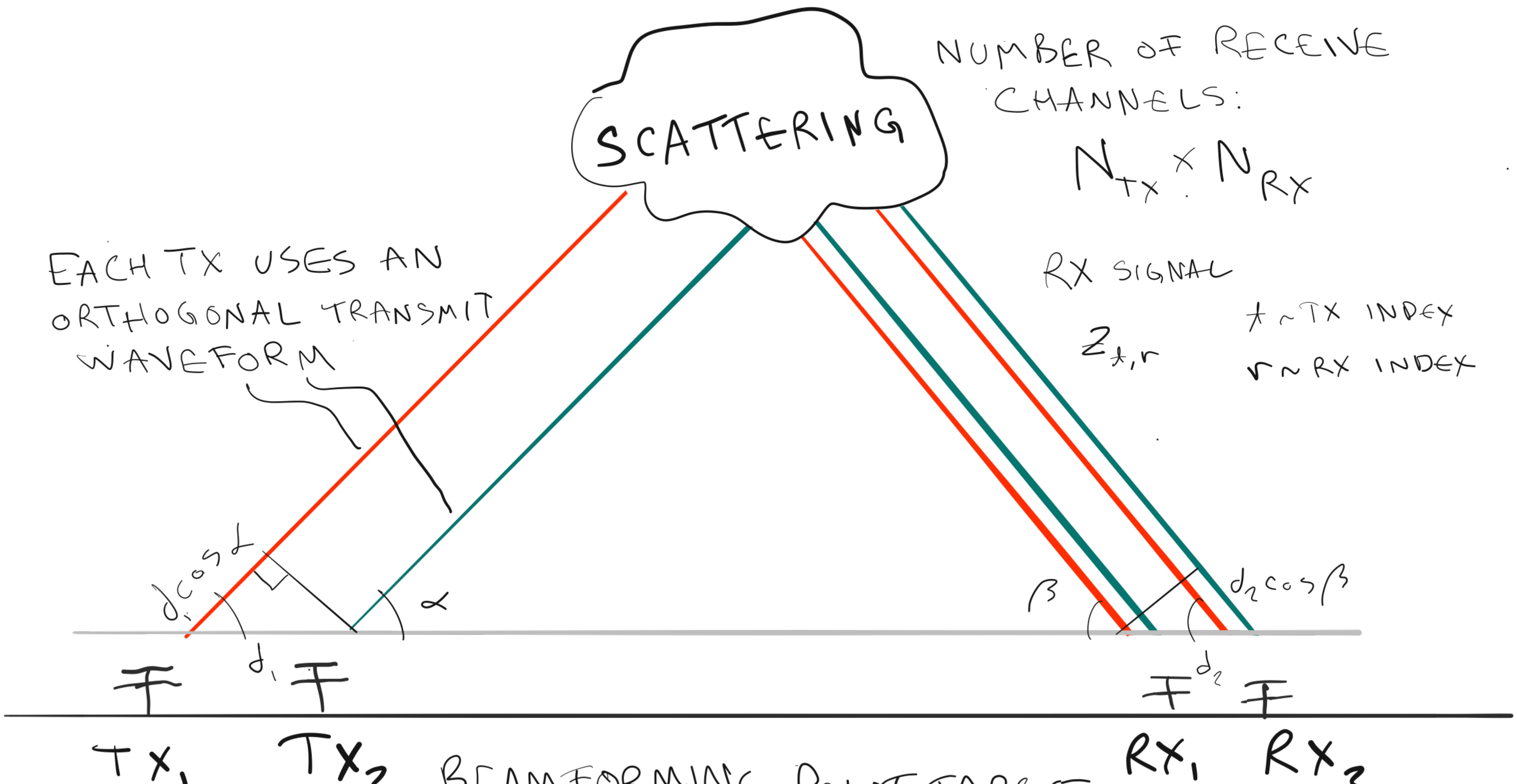
Nico Pfeffer

MIMO Meteor Radar



Chau et.al., Novel specular meteor radar systems using coherent MIMO techniques to study the mesosphere and lower thermosphere, 2018.

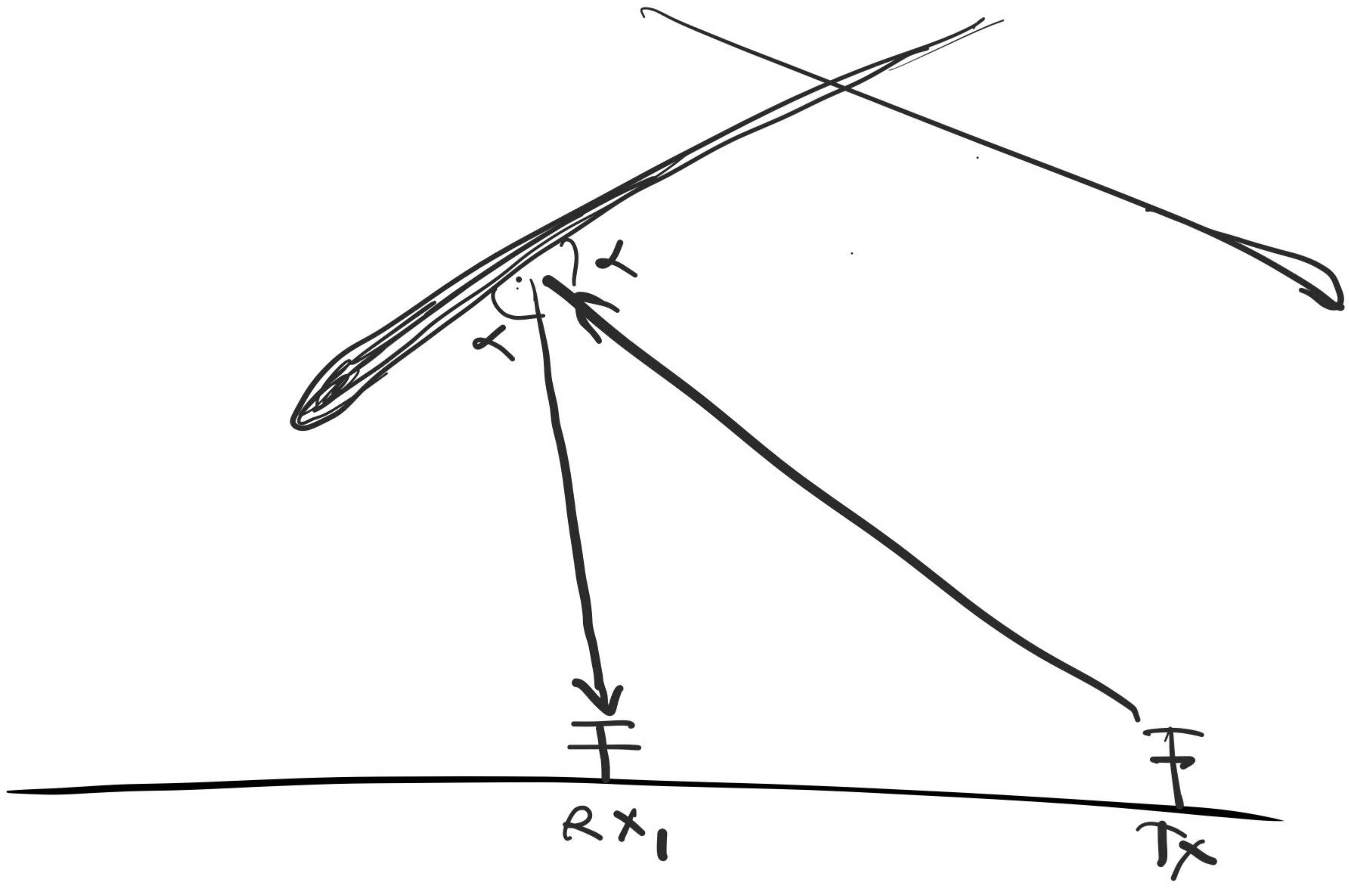
MIMO Meteor Radar



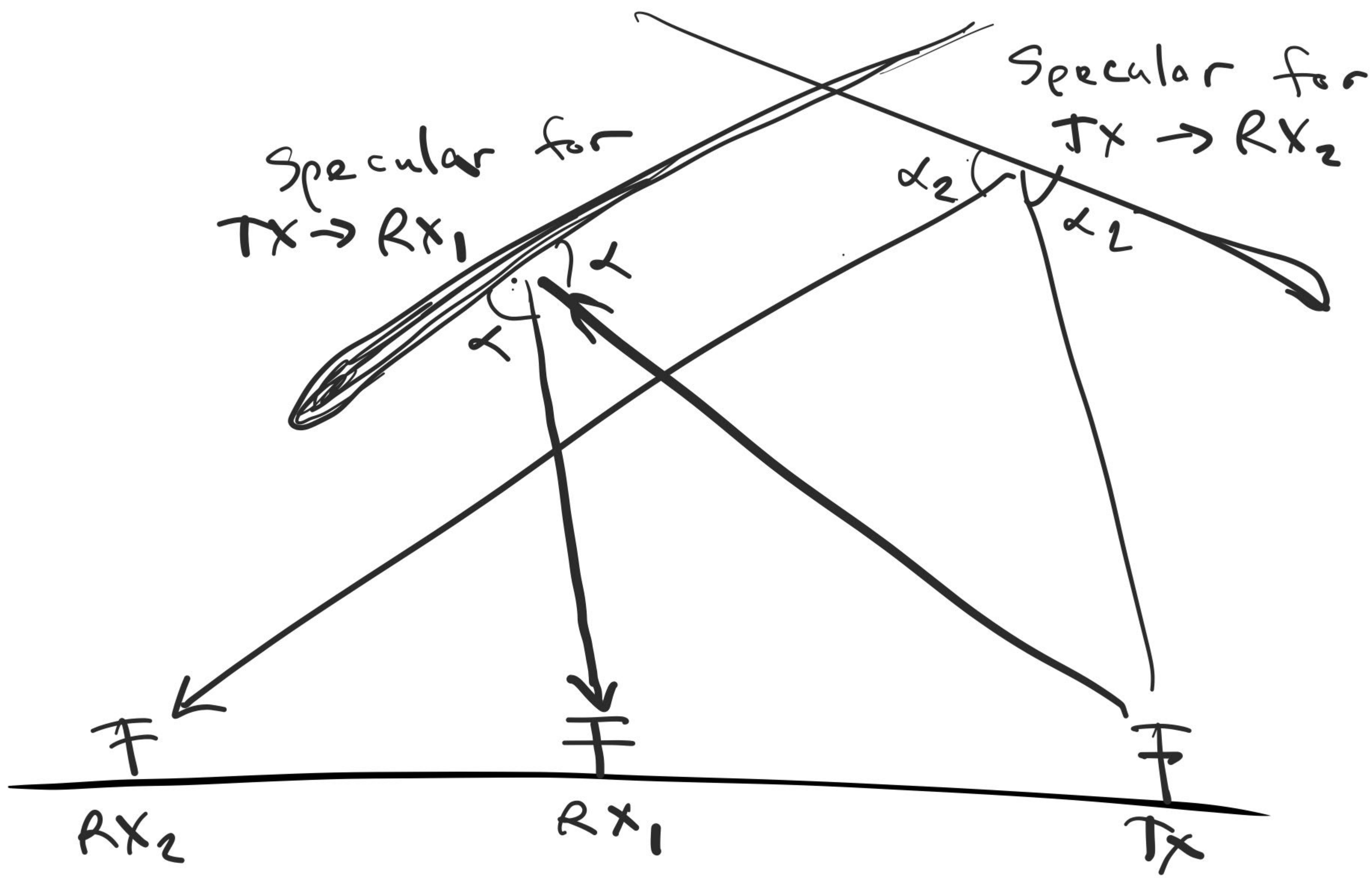
BEAMFORMING POINT TARGET:

$$z_{BF} = \sum_t \sum_r z_{t,r} \exp\left\{-i \frac{2\pi}{\lambda} d_t \cos\alpha\right\} \exp\left\{-i \frac{2\pi}{\lambda} d_r \cos\beta\right\}$$

MIMO Meteor Radar



MIMO Meteor Radar



The more TX->RX links, the more meteors match the specular condition, and can be observed.

DIGITAL RF

- Developed at MIT Haystack Observatory

- Standardized HDF5 based data format for complex baseband radio signals

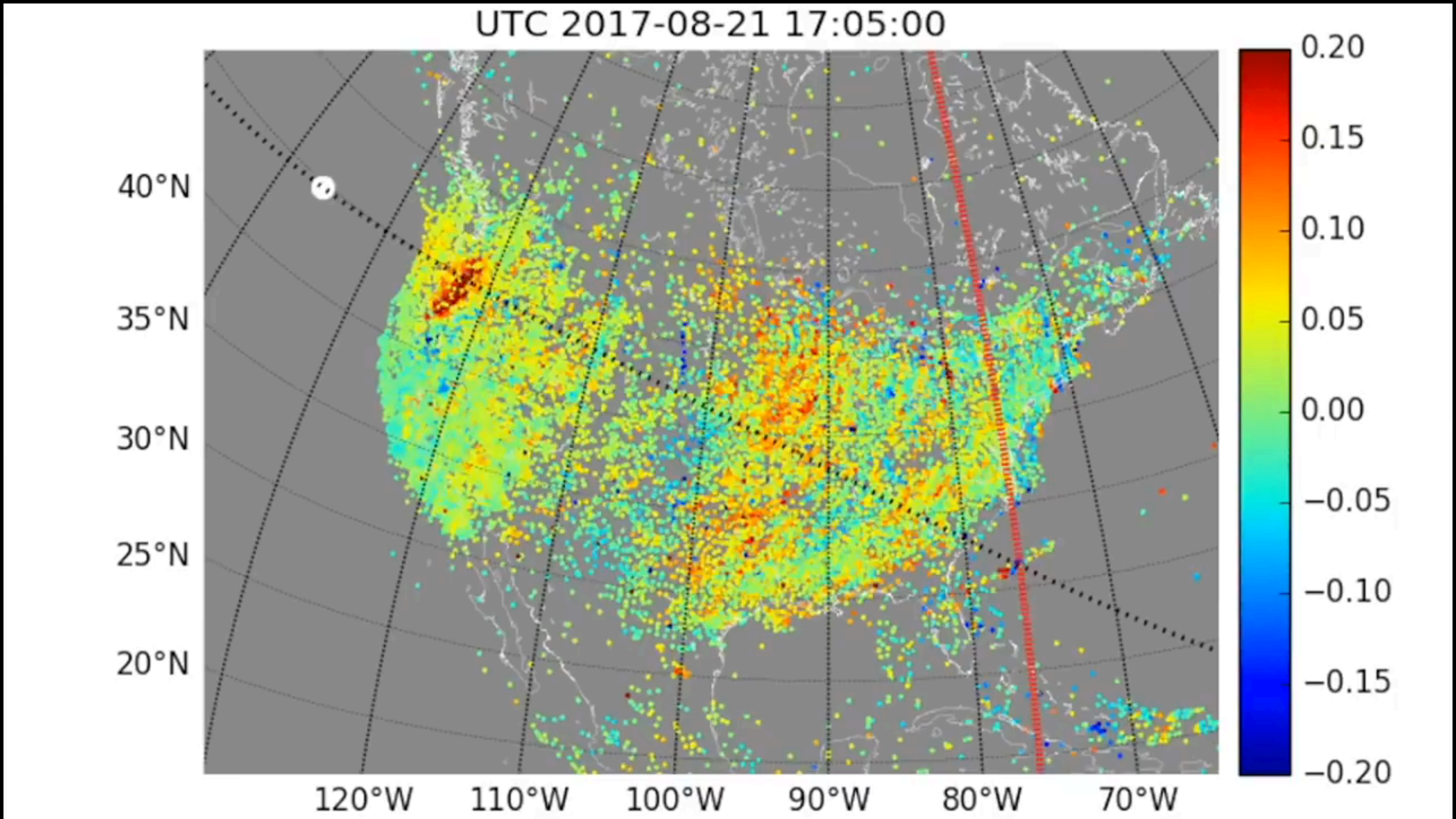
- THOR - The Haystack Observatory Recorder. Swiss army knife for recording RF

- Spread spectrum HF radar signal processing implementation

- Other application examples

https://github.com/MITHaystack/digital_rf

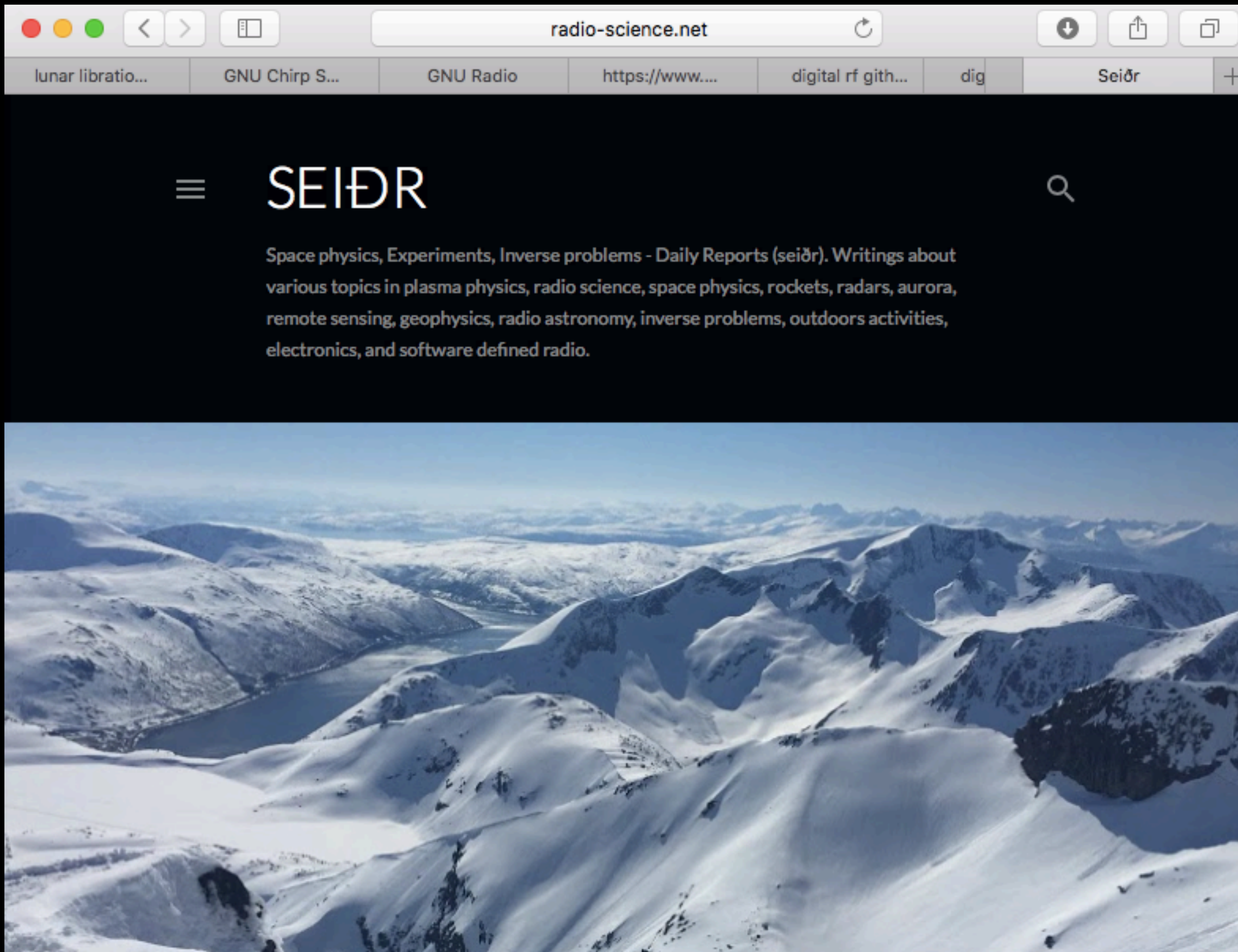
Conclusions



Zhang et.al., (2017)

- Let’s develop meteor radars, ionospheric sounders, passive radars. Operate a global network of them, and distribute the data publicly for science.

www.radio-science.net



Backup slides

PASSIVE RADAR SIGNAL PROCESSING

1) REMOVE STRONG GROUND PATH:

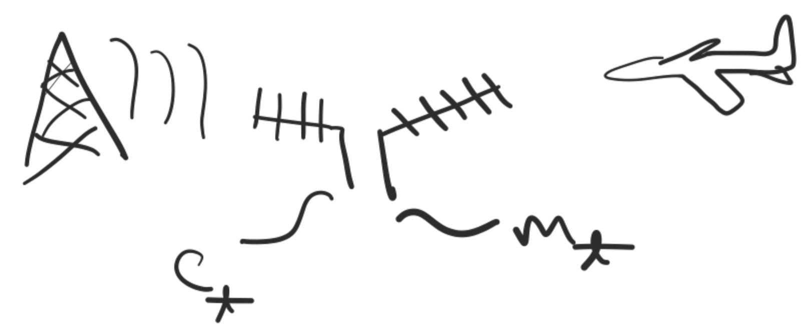
$$m'_t = m_t - f_c(c_t)$$

$m_t \sim$ RX ANT

$c_t \sim$ REF ANT (TX SIGNAL)

2) ESTIMATE ACF OF ECHOES

$$\rho(r,\tau) = f_{ACF}(m'_t, c_t)$$



WIENER-KHINCHIN:

$$S(r,\omega) \overset{\mathcal{F}}{\Longleftrightarrow} \rho(r,\tau)$$

SPECTRUM OF ECHOES IS F-TRANSFORM OF ACF.

PASSIVE RADAR SIGNAL PROCESSING

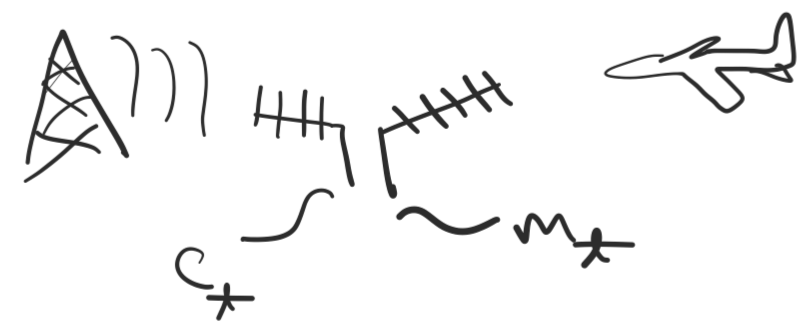
1) REMOVE STRONG GROUND PATH:

$$m_t = \sum_{r=1}^{N_g} c_{t-r}\,\sigma_r + \xi_t \iff m = A x_c + \xi$$

$m \in \mathbb{C}^{N_c \times 1}$
$A \in \mathbb{C}^{N_c \times N_g}$
$x_c \in \mathbb{C}^{N_g \times 1}$
$\xi \sim \mathcal{N}_c(0, \Sigma)$

c_t ~ REFERENCE ANTENNA

m_t ~ ANTTENNA MEASURING ECHOES.



σ_r ~ GROUND CLUTTER

N_g ~ NUMBER OF GROUND CLUTTER RANGE GATES

ξ_t ~ RECEIVER NOISE

N_c ~ COHERENCE LENGTH ($\approx 10^9$)

ML ESTIMATE FOR GROUND CLUTTER:

$$\hat{x}_c = (A^H A)^{-1} A^H m$$

CLUTTER REMOVED SIGNAL:

$$\underline{m' = m - A\hat{x}_c}$$

PASSIVE RADAR SIGNAL PROCESSING

2) LAG-PROFILE INVERSION

$$m_t = \sum_{r=1}^{N_r} c_{t-r}\, \sigma_{r,t} + \xi_t$$

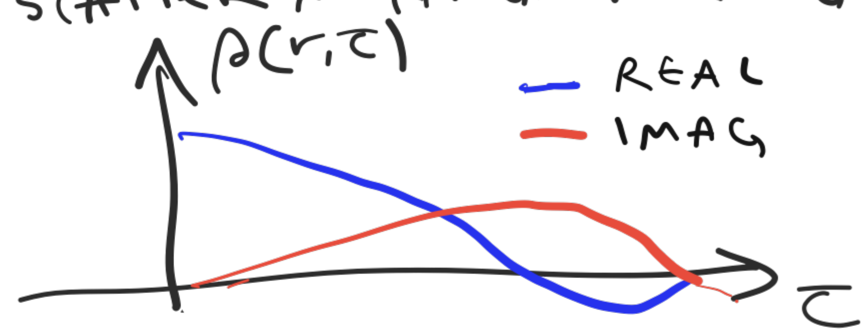
$$m_t m^*_{t+\tau} = \sum_{r=1}^{N_r} c_{t-r}\, c^*_{t-r} \langle \sigma_{r,t}\, \sigma^*_{r,t+\tau} \rangle + \xi'_t \iff m_\tau = A_\tau x_\tau + \xi$$

$\sigma_{r,t}$ ~ RADAR ECHOES AT TIME t AND RANGE r

m_t ~ CLUTTER REMOVED SIGNAL.

c_t ~ REF. SIGNAL (RADIO STATION TX)

$\langle \sigma_{r,t}\, \sigma^*_{r,t+\tau} \rangle = \rho(r,\tau)$ ~ ACF FOR TARGET SCATTER AT RANGE r & LAG τ



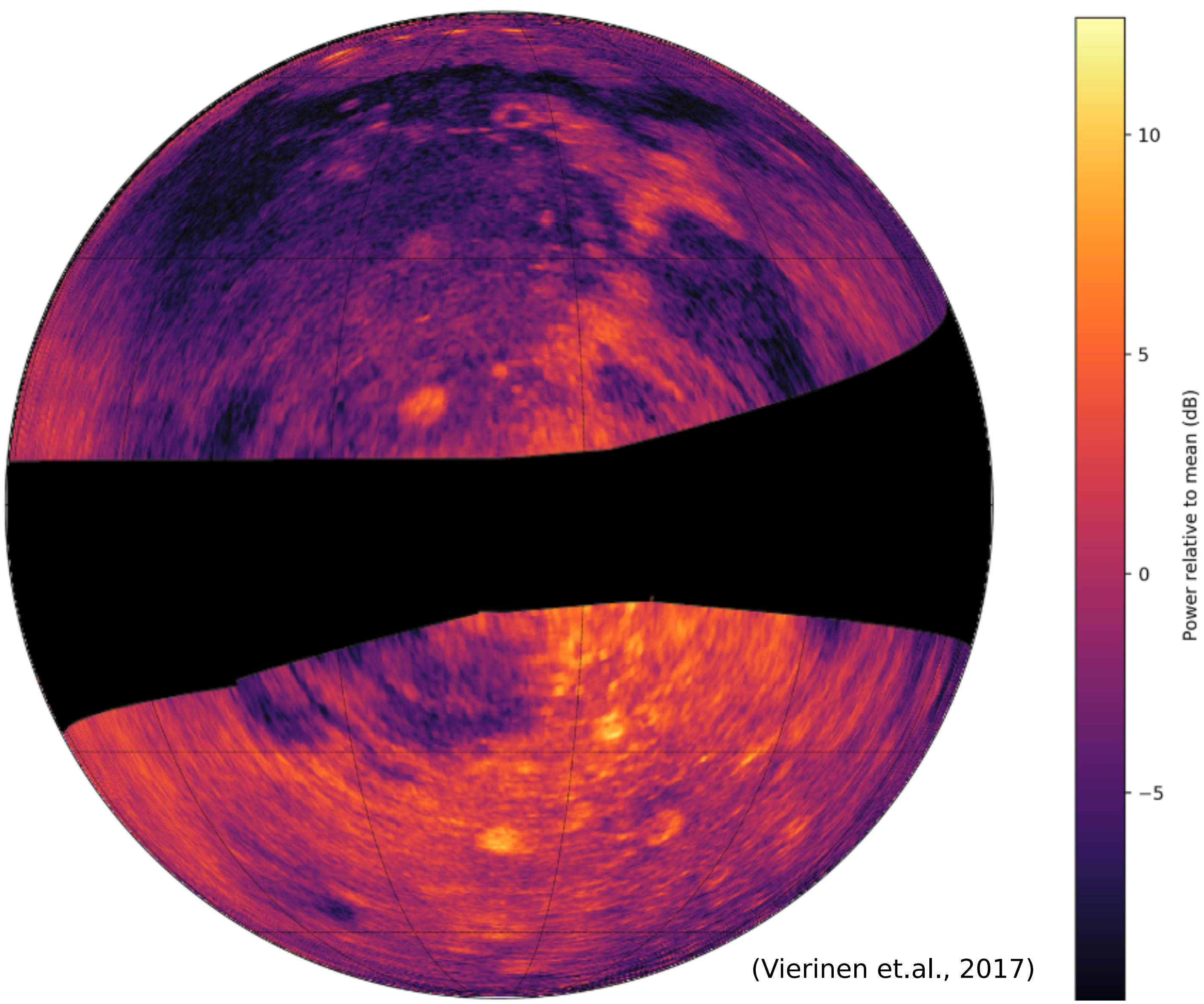
ξ'_t ~ RX NOISE.

ML ESTIMATE:

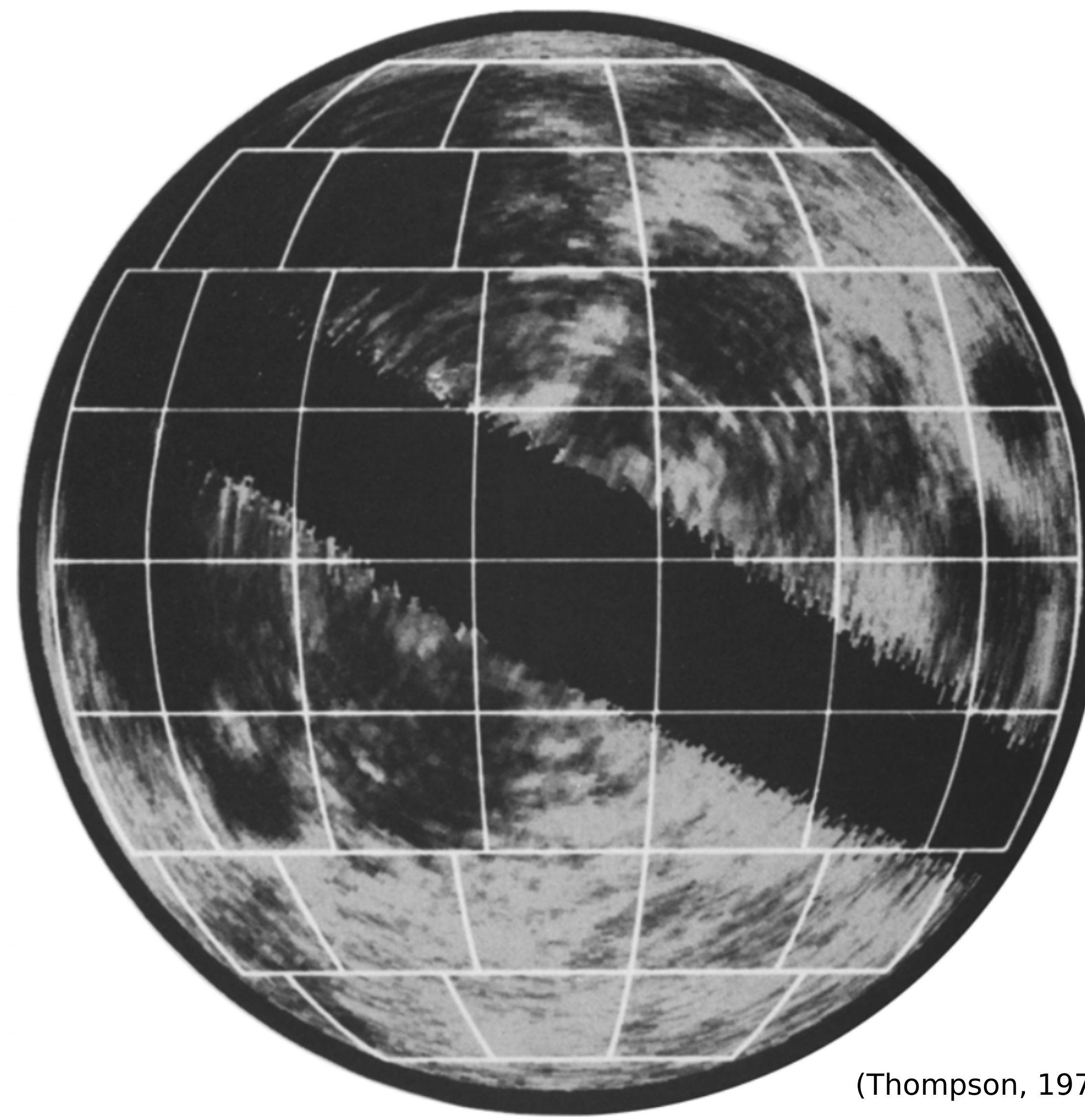
$\hat{x}_\tau = (A^H_\tau A_\tau)^{-1} A^H_\tau m$. THIS CAN BE IMPLEMENTED WITH FFT.

ESTIMATE $\rho(r,\tau)$ FOR ALL VALUES OF τ & r.

Comparison

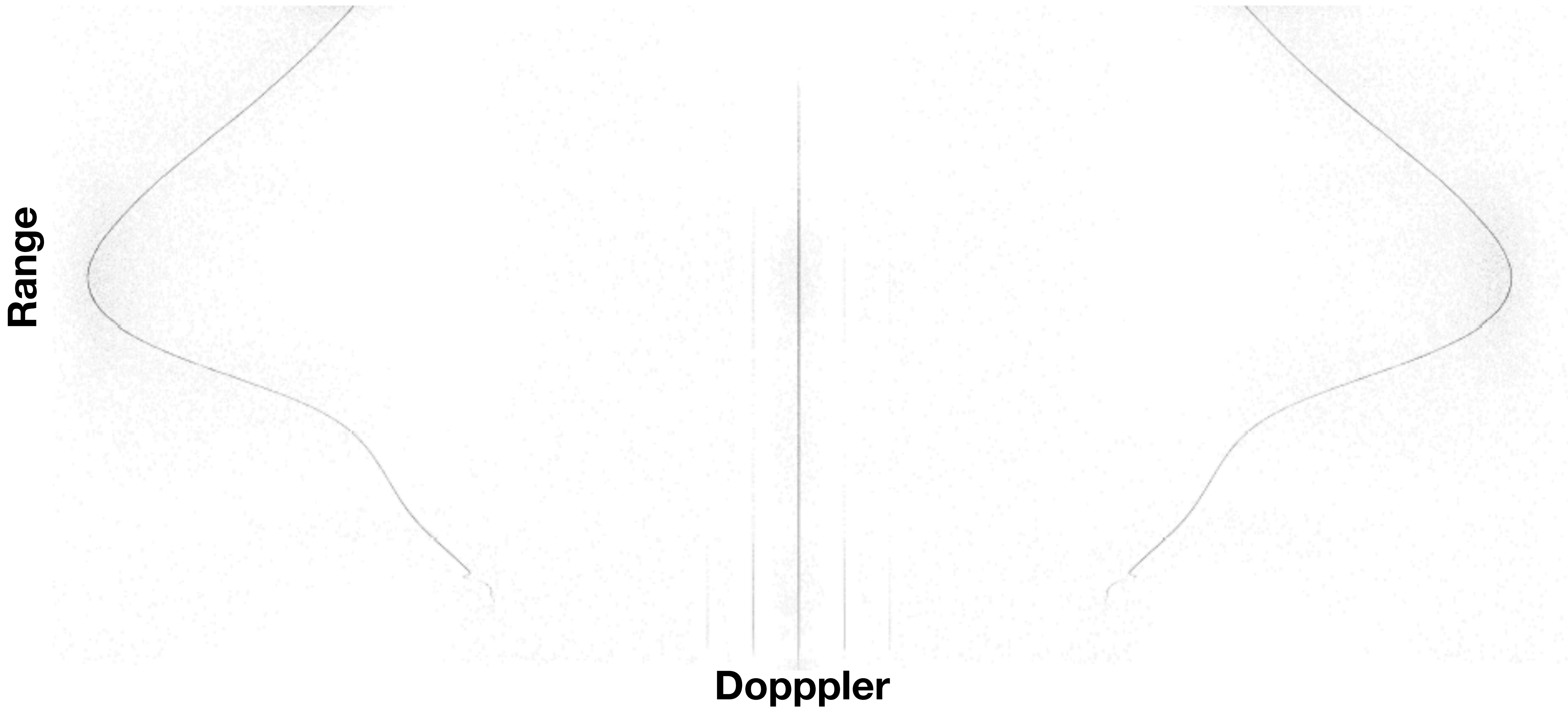


(Vierinen et.al., 2017)



(Thompson, 1970)

Full incoherent scatter radar spectrum



- Day time photoelectron enhancement
- Inverse filter deconvolution, coded long pulse
- 8000 150 m gates
- 11000 frequency bins (2.2 kHz)

Q: Can we make it affordable?

- Cheaper: Red Pitaya ($200)

- Even cheaper: Raspberry Pi PLL Mod (rpitx, works for WSPR) + rtlsdr dongle. ($100)

- Even cheaper? TX: FL2000 & RX: RTLSDR HF direct sampling mod. ($30)

- Michael Hirsch and a group of students at BU worked on Red Pitaya: https://www.scivision.co/pi-radar/

Q: Is the upper atmosphere of the Earth ionized?

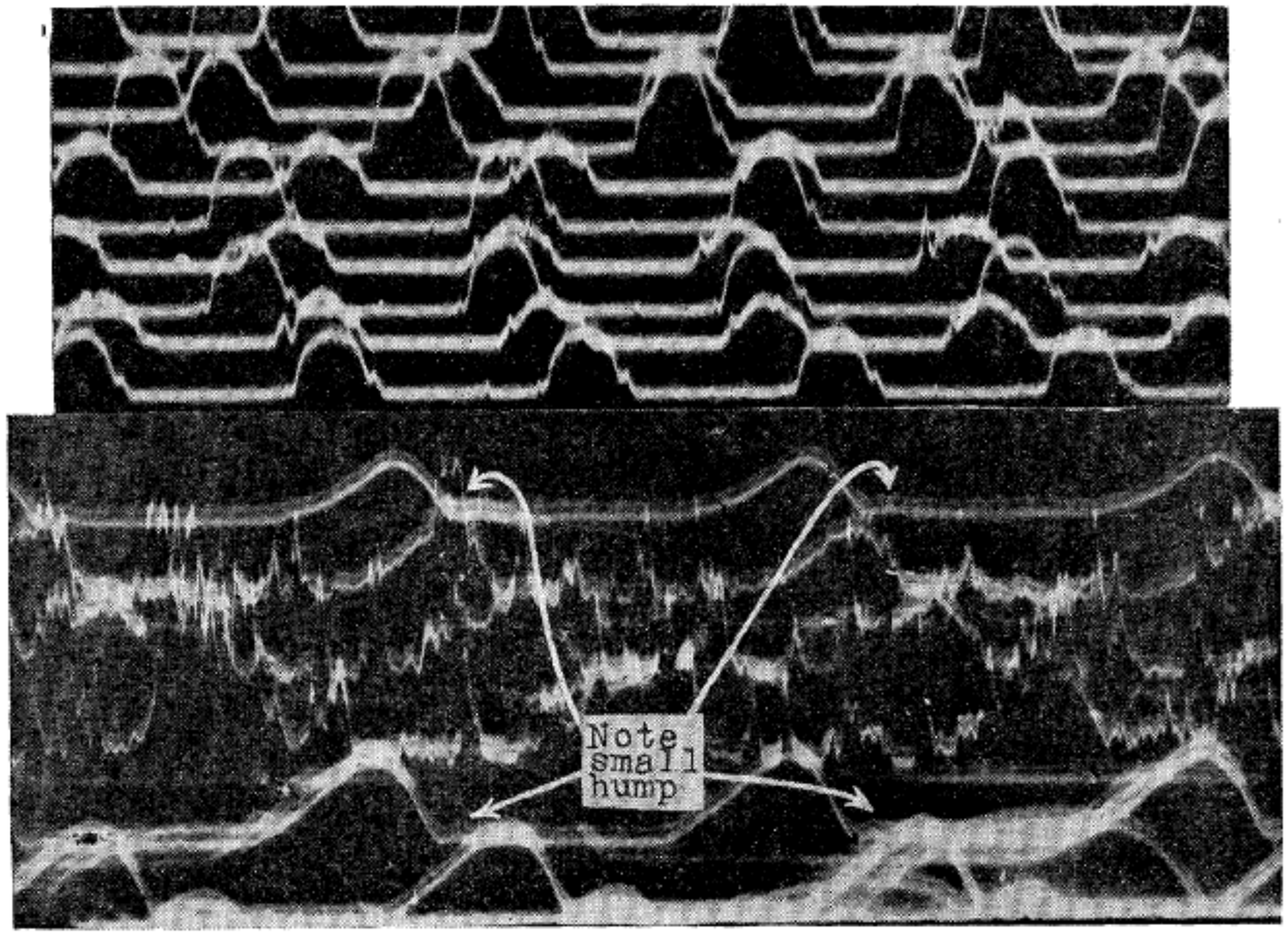


Fig. 6. Wave forms of KDKA, Pittsburgh, Pa.; $\lambda = 309$ meters; modulation frequency, 60; type of modulation, A.C. on plate.

A Test of the Existence of the Conducting Layer

G. Breit and M. A. Tuve

Phys. Rev. **28**, 554 – Published 1 September 1926

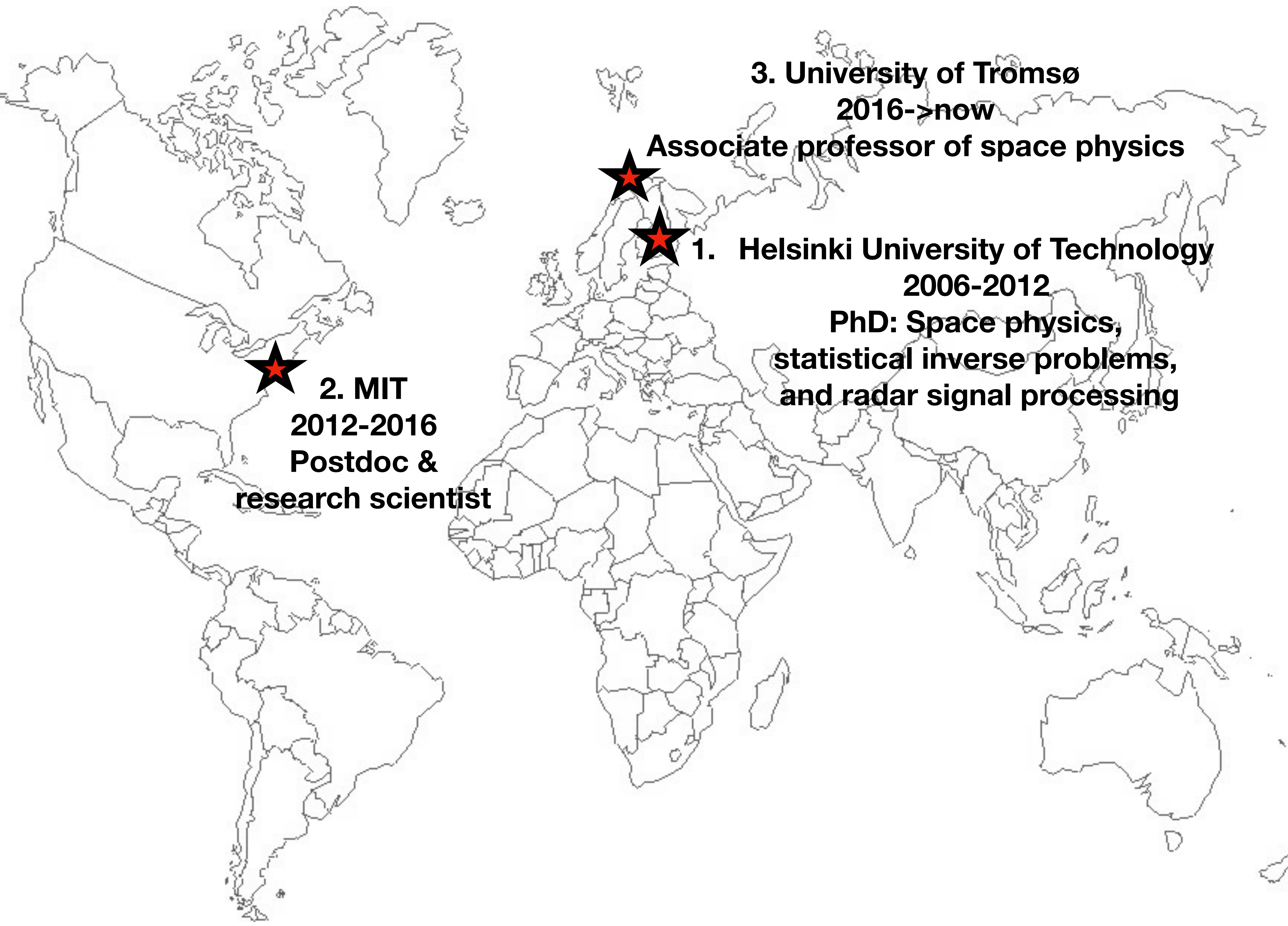
Passive Radar: Ideas

- High power VHF Digital TV would make a very sensitive meteor radar
- Commercial HF broadcast for sounding the ionosphere
- AM radio, for ionospheric sounding
- Synthetic aperture radar imaging.

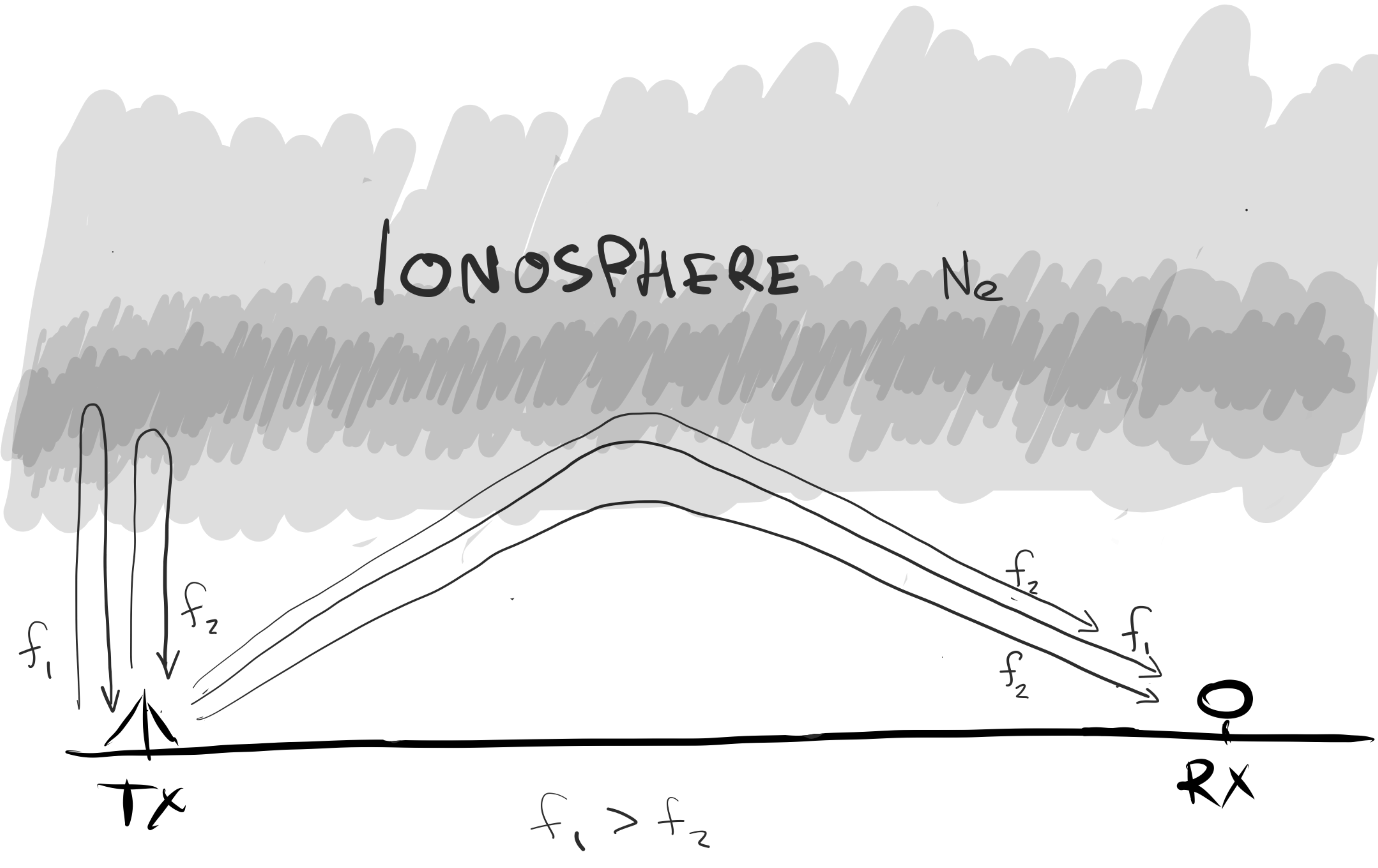
- Q: What is the small scale structure of the mesospheric wind?
- Q: What is the propagation direction of gravity waves?
- Q: What is the small scale structure of the electric field in the E-region within aurora?

Ionosondes around the world.

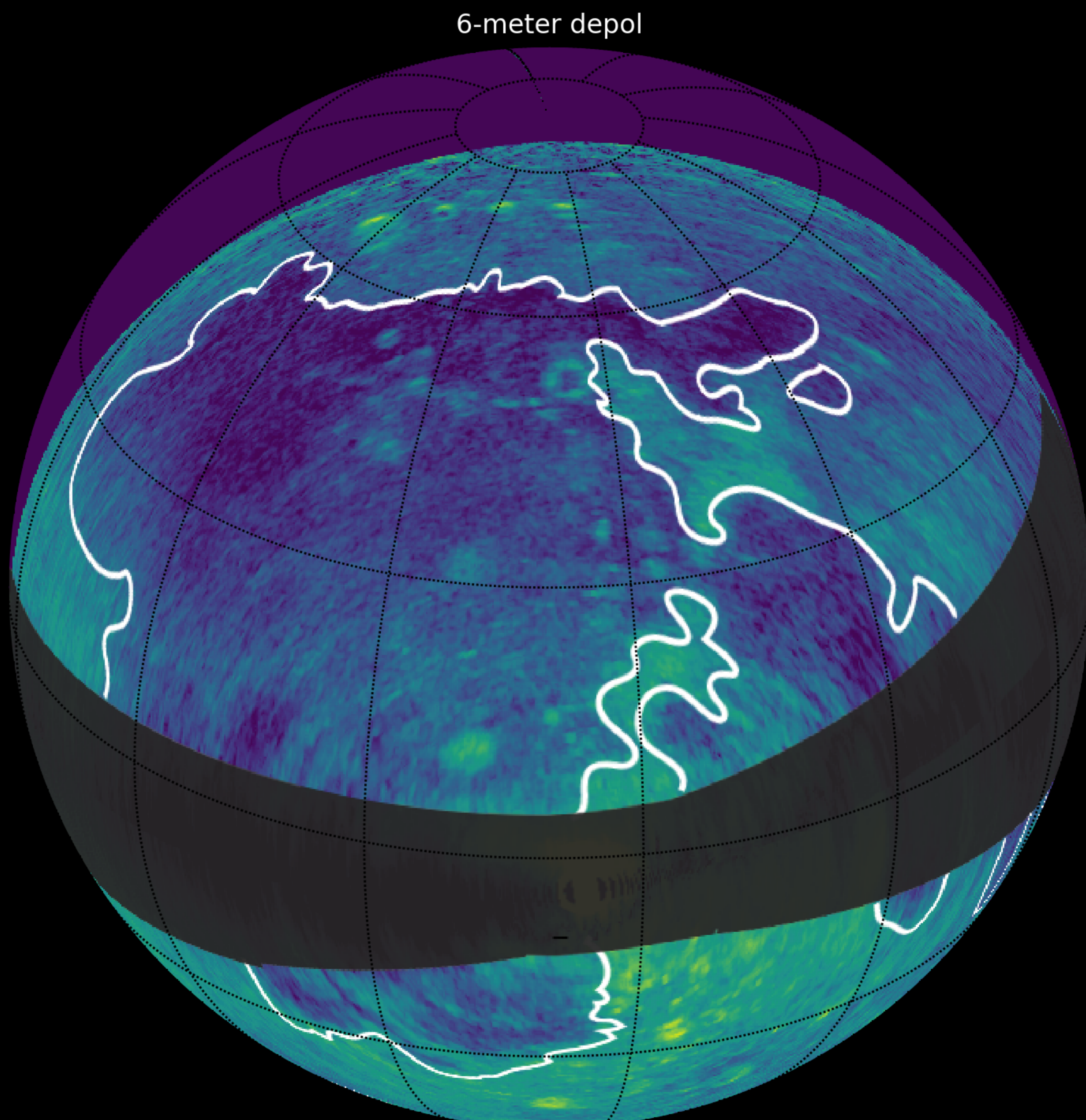
Q: Who am I?


3. University of Tromsø
2016->now
Associate professor of space physics
1. Helsinki University of Technology
2006-2012
PhD: Space physics,
statistical inverse problems,
and radar signal processing
2. MIT
2012-2016
Postdoc &
research scientist

HF Radio Propagation



What does the Moon look like with 6-meter wavelength?



Northern Hemisphere

Southern Hemisphere