Software Defined Radio and Space Physics

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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)

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

Q: What is the best way to observe the universe?
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Q: What is the best way to observe the universe?  
Q: Where can we easily study space plasma?
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A: The easiest place to study plasma is our own backyard.
Me + novel signal processing techniques = better measurements

+ flexible hardware
+ open source signal processing

Megawatts and hectares of radar

Haystack Arecibo Jicamarca

EISCAT Svalbard EISCAT VHF and UHF

EISCAT 3D

GNU Radio

THE FREE & OPEN SOURCE SOFTWARE RADIO ECOSYSTEM
Q: What is the most sensitive radar in the world?
Wide band ionospheric radar receiver at Arecibo
Q: Does theory of scattering of electromagnetic waves from thermal plasma agree with measurements?
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\[ \langle |\Delta N_e(k, \omega)|^2 \rangle = \frac{|j \omega \epsilon_0 + \sum_i \sigma_i|^2 \langle |n_{t,e}(k, \omega)|^2 \rangle}{|j \omega \epsilon_0 + \sigma_e + \sum_i \sigma_i|^2} + \frac{|\sigma_e|^2 \sum_i \langle |n_{t,i}(k, \omega)|^2 \rangle}{|j \omega \epsilon_0 + \sigma_e + \sum_i \sigma_i|^2} \]

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.

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:

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

\[ W(\omega, r) \ast \langle |\Delta N_e(\omega, r)|^2 \rangle = m(\omega, r) \]
A: Measurements agree with theory

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

Under non-thermal conditions...

Doppler shift (MHz)

Range (km)

25 MHz

Radar echo from Langmuir waves

Radar echo from ion acoustic waves

Video: Phil Perillat, Arecibo
MIT Haystack
ISR spectrum, 13 min integration, Zenith antenna, Compressed dB scale
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

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

Attenuation of transmitted wave proportional to frequency.

\[ E(r) = E_0 e^{-\alpha r} e^{i\beta r} \]

\[ \alpha = \frac{\sigma}{2} \sqrt{\frac{M}{\varepsilon}} \]

\[ \omega = \omega_0 \varepsilon_r \tan \delta \]

\[ \Rightarrow \alpha = \omega \left( \frac{1}{2} \varepsilon_r \varepsilon_\ell \tan \delta \sqrt{\frac{M}{\varepsilon}} \right) \]
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

\[ f = 49.92 \text{ MHz} \]

North and South modules used for interferometry
Interferometric Range-Doppler

Apparent motion due to parallax and libration.

Campbell et al., (2007)

Rogers and Ingalls (1969)
Passive Radar

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.
Passive Radar Interferometry

\[ \langle z_1, z_2 \rangle = \rho(u, v) = \int B(n, m) e^{i (u \cos \angle - v \sin \angle)} \, dn \, dm \]
Ground clutter range time intensity relative phase difference
Q: What is the electric field in the ionosphere during geomagnetic storms?
Over the horizon radar

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

- ~2 to 50 MHz
- Chirp channel sounding mode

Image credits: Raytheon
Over the horizon radar

ROTHR Transmit Antenna (Image: Raytheon)
GNU Chirp Sounder

- Open source chirp sounding receiver
- Works for ROTH 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

RX ANT

\[ \text{DECHIRP (GPS TIMED)} \]

\[ \exp \{ -i (w_0 + w_1 t + w_2 t^2) \} \]

\[ \begin{array}{c}
\text{WHITENING FILTER} \\
(\text{Notches Out Broadcast})
\end{array} \]

\[ \text{LOW-PASS FILTER} \]

\[ \text{FFT} \]

\[ \text{DYNAMIC SPECTRUM} \]

\[ Z_{tx} = \text{A} \exp \{ \pi \text{i} (w_0 + w_1 t + w_2 t^2) \} \sim \text{TX SIGNAL} \]

\[ Z_{rx} = \sum_{r} \text{A} \exp \{ \pi \text{i} (w_0 + w_1 (t - r) + w_2 (t - r)^2) \} \sim \text{RX SIGNAL} \]

\[ Z_{rx} \exp \{ -i (w_0 + w_1 t + w_2 t^2) \} = \sum_{r} \exp \{ -i 2w_2 r t \} \sim \text{DECHIRPED SIGNAL} \]

\[ \sigma_r' = \sigma_r \text{A} e^{i w_2 t^2} e^{-i w_1 r} \sim \text{RADAR ECHO} \]
HF Radio Propagation

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

\[ m_t = \sum_{n=1}^{T} \sum_{r=0}^{R} \sigma_r^n \epsilon_n^{(t-r)} \mod N \]

\[ \hat{x} = \left( A^T A \right)^{-1} A^T m \]

\[ \hat{x} = \begin{bmatrix} \sigma_1 & \sigma_2 & \cdots & \sigma_R \end{bmatrix}^T \]

\[ m = \begin{bmatrix} m_0 & m_1 & \cdots & m_N \end{bmatrix}^T \]

\[ R < N \]

- 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
Up to 20 bounces between the ionosphere and the ground with 20 W
Thermospheric Gravity Waves

Doppler Shift (Hz)

Video: Patrick Lynett
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
MIMO Meteor Radar

Nico Pfeffer
MIMO Meteor Radar

60 meteor trail echoes per minute!

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

SCATTERING

NUMBER OF RECEIVE CHANNELS:

\( N_{tx} \times N_{rx} \)

RX SIGNAL:

\( z_{t,r} \)

TX INDEX

RX INDEX

EACH TX USES AN ORTHOGONAL TRANSMIT WAVEFORM

\( d_{cos \theta} \)

\( d_{\rho \cos \beta} \)

BEAMFORMING POINT TARGET:

\[
Z_{BF} = \sum_{t} \sum_{r} z_{t,r} e^{i \frac{2\pi}{\lambda} d_{\rho \cos \beta t} \cdot \rho_{r} + \frac{2\pi}{\lambda} d_{\rho \cos \beta t} \cdot \rho_{r}}
\]
MIMO Meteor Radar
The more TX-->RX links, the more meteors match the specular condition, and can be observed.
- 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

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

Space physics, Experiments, Inverse problems - Daily Reports (seiðr). Writings about various topics in plasma physics, radio science, space physics, rockets, radars, aurora, remote sensing, geophysics, radio astronomy, inverse problems, outdoors activities, electronics, and software defined radio.
Backup slides
PASSIVE RADAR SIGNAL PROCESSING

1) REMOVE STRONG GROUND PATH:

\[ m'_x = m_x - f_c(c_A) \]

\[ m_x \sim RX \text{ ANT} \]

\[ c_A \sim REF \text{ ANT (TX SIGNAL)} \]

2) ESTIMATE ACF OF ECHOES

\[ \rho(r,\tau) = f_{ACF}(m'_x, c_x) \]

WIENER - KHINCHIN:

\[ S(r,\omega) \leftrightarrow \rho(r,\tau) \]

SPECTRUM OF ECHOES IS F-TRANSFORM OF ACF.
PASSIVE RADAR SIGNAL PROCESSING

1) REMOVE STRONG GROUND PATH:

\[ m_A = \sum_{r=1}^{N_s} C_{r} \cdot \sigma + \frac{\epsilon}{\sigma} \iff m = A \cdot x_c + \frac{\epsilon}{\sigma} \]

\( C_r \sim \text{REFERENCE ANTENNA} \)

\( m_A \sim \text{ANTENNA MEASURING ECHOS} \)

\( \sigma \sim \text{GROUND CLUTTER} \)

\( N_g \sim \text{NUMBER OF GROUND CLUTTER RANGE GATES} \)

\( \frac{\epsilon}{\sigma} \sim \text{RECEIVER NOISE} \)

\( N_c \sim \text{COHERENCE LENGTH} \) (≈ 103)

ML ESTIMATE FOR GROUND CLUTTER:

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

CLUTTER REMOVED SIGNAL:

\[ m' = m - A \hat{x}_c \]
PASSIVE RADAR SIGNAL PROCESSING

2) LAG-PROFILE INVERSION

\[ m_{x} = \sum_{r=1}^{N_r} \sum_{d=1}^{N_d} c_{d,v} \sigma_{r,d} + \xi_d \]

\[ m_{x} m_{x}^* = \sum_{r=1}^{N_r} \sum_{d=1}^{N_d} c_{d,v} c_{d,v}^* \langle \sigma_{r,d} \sigma_{r,d}^* \rangle + \xi_d \xi_d^* \iff m_c = A_c x_c + \xi_c \]

\( \sigma_{r,d} \sim \text{RADAR ECHOES AT TIME } \tau \text{ AND RANGE } r \)

\( m_{x} \text{ is CLUTTER REMOVED SIGNAL} \)

\( c_d \sim \text{REF SIGNAL (RADIO STATION TX)} \)

\( \langle \sigma_{r,d} \sigma_{r,d}^* \rangle = \rho(r,v) \text{ ACF FOR TARGET SCATTER AT RANGE } r \text{ & LAG } v \)

\( \xi_d \sim \text{RX NOISE} \)

ML ESTIMATE:

\[ x_c = (A_c^H A_c)^{-1} A_c^H m \quad \text{THIS CAN BE IMPLEMENTED WITH FFT.} \]

ESTIMATE \( \rho(r,c) \) FOR ALL VALUES OF \( r \& c \).
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)


- 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.
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?
1. Helsinki University of Technology  
   2006-2012  
   PhD: Space physics, statistical inverse problems, and radar signal processing

2. MIT  
   2012-2016  
   Postdoc & research scientist

3. University of Tromsø  
   2016->now  
   Associate professor of space physics
HF Radio Propagation
What does the Moon look like with 6-meter wavelength?