# The Radio Frequency Spectrum

<table>
<thead>
<tr>
<th>Name</th>
<th>Frequency Range</th>
<th>Wavelength In Vacuum</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULF</td>
<td>&lt; 3 Hz</td>
<td>&gt;10⁵ km</td>
</tr>
<tr>
<td>ELF</td>
<td>3 Hz - 3 kHz</td>
<td>100 to 10⁵ km</td>
</tr>
<tr>
<td>VLF</td>
<td>3 – 30 kHz</td>
<td>10 to 100 km</td>
</tr>
<tr>
<td>LF</td>
<td>30 – 300 kHz</td>
<td>1 to 10 km</td>
</tr>
<tr>
<td>MF</td>
<td>0.3 – 3 MHz</td>
<td>0.1 to 1 km</td>
</tr>
<tr>
<td>HF</td>
<td>3 – 30 MHz</td>
<td>10 to 100 m</td>
</tr>
<tr>
<td>VHF</td>
<td>30 – 300 MHz</td>
<td>1 to 10 m</td>
</tr>
<tr>
<td>UHF</td>
<td>0.3 – 3 GHz</td>
<td>0.1 to 1 m</td>
</tr>
</tbody>
</table>
Ground-Based Radio Wave Techniques

• Ionosonde transmits a radio wave that reflects from the bottom of the ionosphere at the electron plasma frequency. Sounding can also be done from above.

• Transmission through the ionosphere
  – Riometer (Relative Ionospheric Opacity Meter)
  – Beacons detecting scintillations
  – Whistlers

• Scattering or partial reflectance
  – Coherent radars
  – Incoherent radars
Ionosonde

- **Principle**
  - Transmit radio pulse vertically and measure the time elapsed before the echo is received. The signal is reflected at the altitude at which the signal frequency equals the electron plasma frequency. The time delay is a measure of this height.

  \[ f_{pe}[kHz] = 8.97 \, n_e^{1/2} \, [cm^{-3}] \]

  - Maximum frequency to be reflected measures the maximum electron density of the ionosphere.

- **Application**
  - Complications include multiple echoes, multiple wave modes and complex vertical density profiles.
  - Sounding can be done from orbiting satellites as well as the ground.
  - HF Doppler measurements using a continuous wave and colocated receiver and transmitter can measure the velocity of the reflecting layer.
Transionospheric Propagation

• Phase delay measures column abundance of electrons along propagation path. There is a $360° \times n$ ambiguity in phase.

• Can be used to sound a planetary ionosphere. Doppler shifted frequency versus time is the observable.

• Modulation of the carrier at lower frequency can lower phase delay by factor $f_m/f_c$. The time delay of modulation is directly proportional to column abundance.

• Refraction by inhomogenities varies the ray path, causing scintillation.
Faraday Rotation

• The direction of linear polarization of a radio signal will rotate an angle proportional to the integrated product of the electron number density and the magnetic field strength.

• A linearly polarized signal is equivalent to the sum of a RH and LH wave. Since these two waves travel at different speeds, the direction of the linear polarization will rotate.
Riometers

- Riometers measure the amplitude of radio noise at about 30 MHz propagating from the galaxy through the ionosphere to a receiver.

- Precipitating energetic particles cause ionization in the D region which in turn absorbs energy from the radio waves.

- Thus passive riometers can monitor energetic particle precipitation.

- Modern riometers have multiple beams to image the precipitation region.
Probing the Ionosphere with Radars

- Large powerful radars can probe the ionosphere incoherently by scattering radar power from electrons by Thompson scattering.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Power (MW)</th>
<th>Freq. (MHz)</th>
<th>L-Value</th>
<th>Antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jicamarca, Peru</td>
<td>6</td>
<td>50</td>
<td>1.1</td>
<td>Array 290 x 290m</td>
</tr>
<tr>
<td>Arecibo, Puerto Rico</td>
<td>2</td>
<td>430</td>
<td>1.4</td>
<td>Spherical dish 300m</td>
</tr>
<tr>
<td>Millstone Hill, USA</td>
<td>5</td>
<td>440</td>
<td>3.2</td>
<td>68m parabola fixed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>46m parabola, steerable</td>
</tr>
<tr>
<td>Eiscat (Tromso), Norway</td>
<td>2</td>
<td>933</td>
<td>6.5</td>
<td>32m parabolas steerable</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>224</td>
<td>6.5</td>
<td>+2 distant receivers</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>120m x 40m cylinder</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N S steerable</td>
</tr>
<tr>
<td>Sondre Stromfjord, Greenland</td>
<td>5</td>
<td>1290</td>
<td>14</td>
<td>27m parabola steerable</td>
</tr>
</tbody>
</table>
Incoherent Scatter Radars

• Physical basis
  – Thomson scatter from free electrons
  – Cross section is small $10^{-28} \text{m}^2$ per electron
  – Requires a large powerful transmitter

• Frequency
  – 50 MHz to 1.3 GHz

• Spectrum
  – Line width controlled by Doppler shift from moving electrons
  – For $\lambda \geq \lambda_D$ ions control line width (narrow)
  – For $\lambda < \lambda_D$ electrons control line width (broad)

• Measurements
  – Electron density from total received power and frequency offset of plasma lines
  – $\text{Te}/\text{Ti}$ from spectral shape
  – $\text{Te}/\text{Mi}$ from peak separation
  – Bulk velocity from Doppler shift
  – Relative motion of electrons and ions from peak heights
  – Conductivities from electrons density and model collision frequencies
  – Gravity waves from height variations of horizontal velocities
Partial Reflection Radars

• Physical Basis
  – Partial reflection from variations in index of refraction
  – Requires large antenna with powerful transmitter

• Frequency
  – 2-6 MHz MF

• Measurements
  – D region 70 – 90 km
  – Electron density $10^2$-$10^4$ cm$^{-3}$
Coherent Scatter Radar

• Physical Basis
  – Partial reflection from field-aligned irregularities
  – Reflection at right angles to field returns signal to transmitter
  – Irregularities near radar wavelength add return signals coherently
  – Radar must be remote at high latitudes to get proper angle of incidence of beam

• Frequencies
  – HF (F region) and VHF (E region)
  – SABRE and STARE at 70 MHz
  – HF radars 8-20 MHz

• Measurements
  – E region winds (VHF)
  – F region winds (HF)
  – Twin radars can give both horizontal components

• Disadvantage
  – Irregularities are not always present
Measuring Convection with Coherent Scatter Radars

- Coherent scatter radars return the velocity along the line of sight.

- With overlapping radar measurements from two sites and a scanning beam, a two-dimensional velocity can be measured.

- These systems are only moderately expensive and easy to maintain.

- Many of the systems are in place around the world.

- Originally called DARN; with additional systems called Super DARN.

- Disadvantage is that echoes present only a fraction of the time.
Mesosphere-Stratosphere-Troposphere Radars

• Physical Basis
  – Scattering from index of refraction irregularities in air
  – Above 80 km scattering from irregularities in electron density
  – Spatial scale of irregularities about 3m
  – Requires large antenna (field of dipoles)
  – Requires a powerful transmitter

• Frequency
  – Usually about 50 MHz

• Height Range
  – Tropopause to about 12 km
  – Mesosphere, 60 to 75 km
  – Sometimes 80-90 km

• Measurements
  – Wind
  – Gravity waves
  – Scale and nature of turbulence
The Sun and the planets with strong magnetic fields emit radio signals into space.

These signals are diagnostic of processes occurring in the plasma such as shock waves and field-aligned currents.

When two directional spaced antennas are used, it is possible to trace the radio sources as they move through space.
**Terrestrial Plasma Waves: ISEE 1 and 2**

- ISEE 1 and 2 were co-orbiting spacecraft in highly elliptical Earth orbit.
- They were well instrumental for terrestrial plasma wave studies with search coils and dipole antennas.
- Here we show spectrum channel records of several phenomena whose magnetic counterparts we have discussed.
Terrestrial Plasma Waves: ISEE 1 and 2 continued

• Dipole antennas can be more than passive antennas.

• ISEE 1 propagated signals to ISEE 2 to obtain the integrated plasma density between them.

• ISEE 1 sounded the plasma to obtain its density and temperature.

• Antennas can be used as Langmuir probes to electron and ion measurements.

• Antennas can pick up distant radio signals from the Sun, the planets and the galaxy.
Pioneer Venus Plasma Wave Measurements

- Pioneer Venus carried a very simple plasma wave detector. The antenna was a pair of wire cages on the end of a short boom. The antenna did not deploy, but was held in tension against the shroud. Had it not been cheap and inexpensive, it would not have been flown.

- It had 4 very narrow band channels at 100 Hz, 730 Hz, 5.4 kHz, and 30 kHz.

- The impedance of the antenna depended on plasma parameters.

- The instrument detected spurious signals in daylight especially as one and then the other antenna entered the shadow and then emerged. It also detected wake effects.
Planetary Plasma Waves: Pioneer Venus

- Sunlit data were noisy, but instrument detected well signals at the bow shock and due to upstream ions and electrons.

- In eclipse, the spacecraft detected a) electrostatic signals associated with lightning, b) wake effects, c) electromagnetic burst associated with lightning.
Terrestrial Plasma Waves: CCE

- Almost identical to the instrument flown on PVO.
- Spin axis was pointed to the Sun avoiding much spin-associated interference.
- Included a channel that could detect AKR and a low-frequency waveform channel.
Planetary Plasma Waves: Galileo

- In contrast to PVO and CCE, Galileo was well instrumented with a dipole antenna and search coils.

- These sensors were well away from the main part of the spacecraft.

- Unlike the diagram, the high-gain antenna did not open, and the spacecraft had insufficient bandwidth to transmit to Earth all the data it was capable of obtaining.
Planetary Plasma Waves: Galileo

- The instrument depended mainly on obtaining data with its spectrum analyzer with only occasional use of its wideband waveform receiver.
Summary

• Radio waves and plasma waves provide diagnostics of processes occurring in space.

• The bandwidth needed to return waveforms is large, but techniques have been developed to process on board and return average power spectral densities as a function of frequency.

• Active techniques in which signals are broadcast through the plasma are also very useful.

• Ground-based and space-based wave measurements are an important component of our space plasma physics instrumentation.