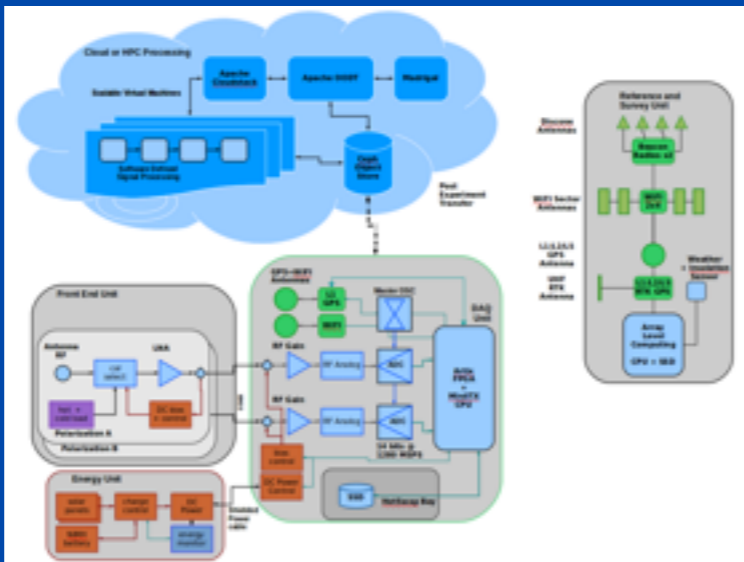
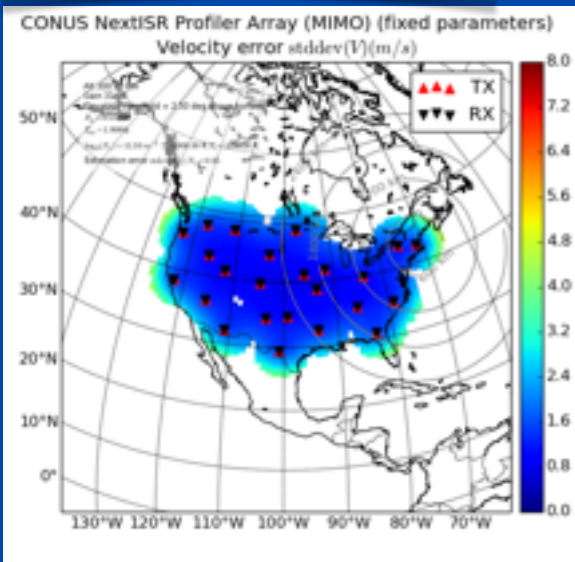
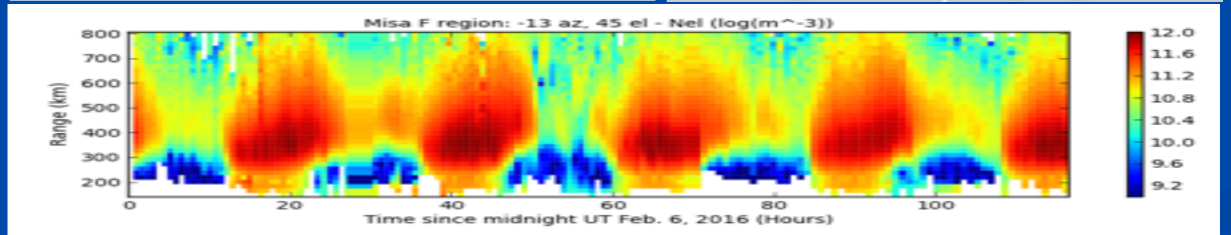
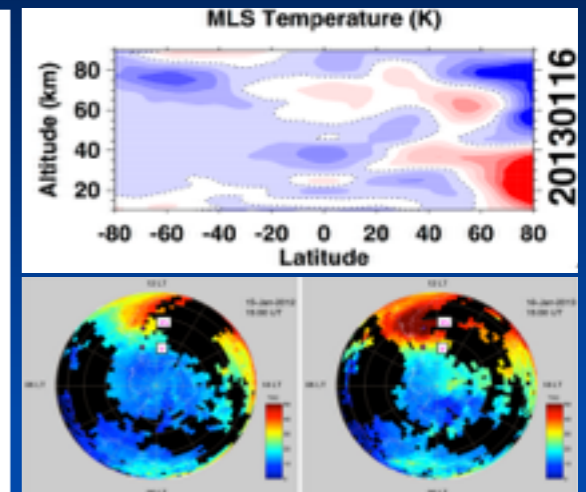
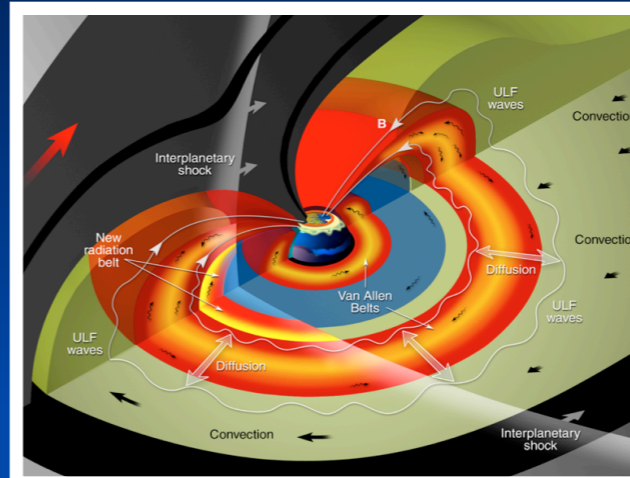
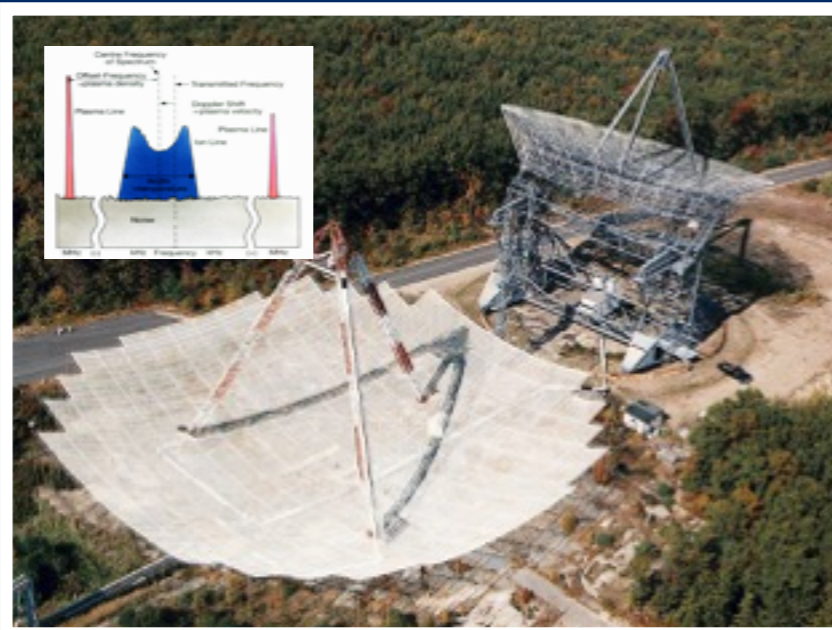
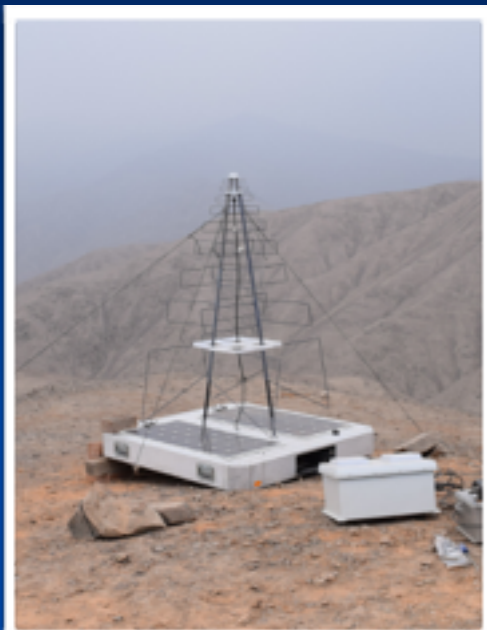


Millstone Hill Geospace Facility

Technical

Scientific



Community



Welcome to the Madrigal Database at Haystack Observatory



Phil Erickson
2018 ISR School
July 23, 2018

MIT Haystack Observatory Complex
Westford, Massachusetts
Established 1956

Haystack Programs:
Radio Astronomy
Atmospheric Science
Space Surveillance
Radio Science
Education and Public Outreach

Millstone Radar Complex
Westford, MA

**(MIT Haystack
Passive Optics Facility
not shown)**

Welcome to the 2018 ISR Summer School

MIT Haystack Observatory Complex
Westford, Massachusetts
Established 1956

Haystack Programs:
Radio Astronomy
Atmospheric Science
Space Surveillance
Radio Science
Education and Public Outreach

Millstone Radar Complex
Westford, MA

**(MIT Haystack
Passive Optics Facility
not shown)**

Haystack Mission

“To develop technology for radio science applications, and thereby to study the structure of our galaxy and the larger universe, to advance scientific knowledge of our planet and its space environment, and to contribute to the education of future scientists and engineers.”

- **Haystack maintains and serves a niche for midscale projects in an era of large facilities**
- **Stable mixture of radio science focus, research projects, and applied engineering**
- **Rich and dynamic field, and strong potential within the stated mission**

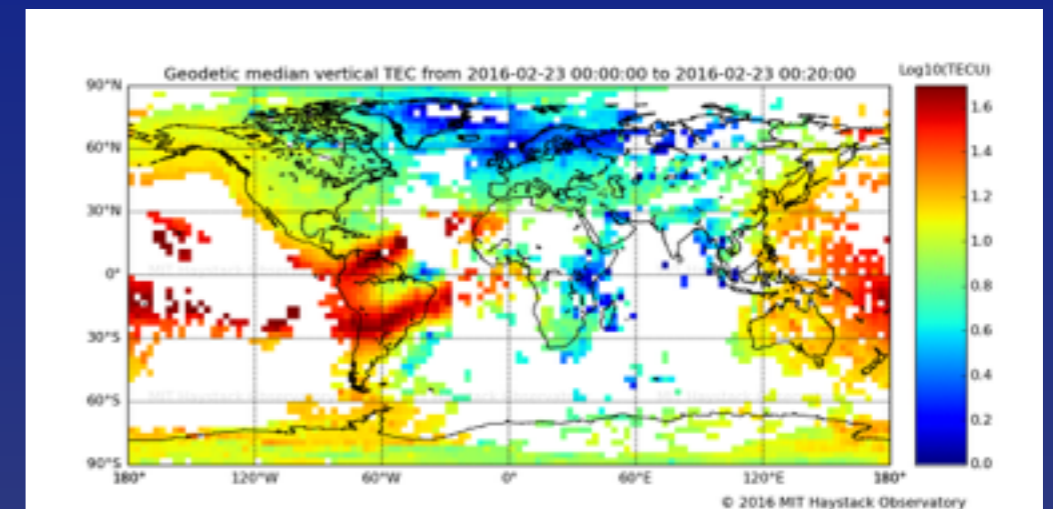
Millstone Hill Geospace Facility

Millstone Hill Incoherent Scatter Radar (1960 - present)



- 900-1000 hours/year
- Height-resolved plasma parameters
- Majority: community experiments
- Rapid response capability
- Wide field coverage of mid-latitude ionosphere, thermosphere, M-I coupling
- Coupled to frontier programs (e.g. Van Allen Probes, MMS)

GNSS TEC Processing (1998 - present)



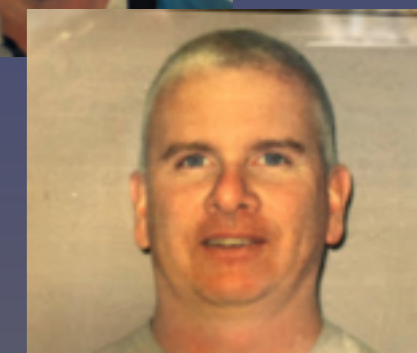
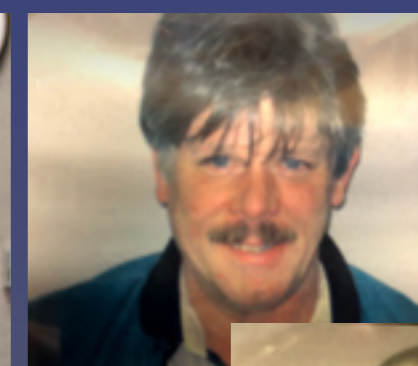
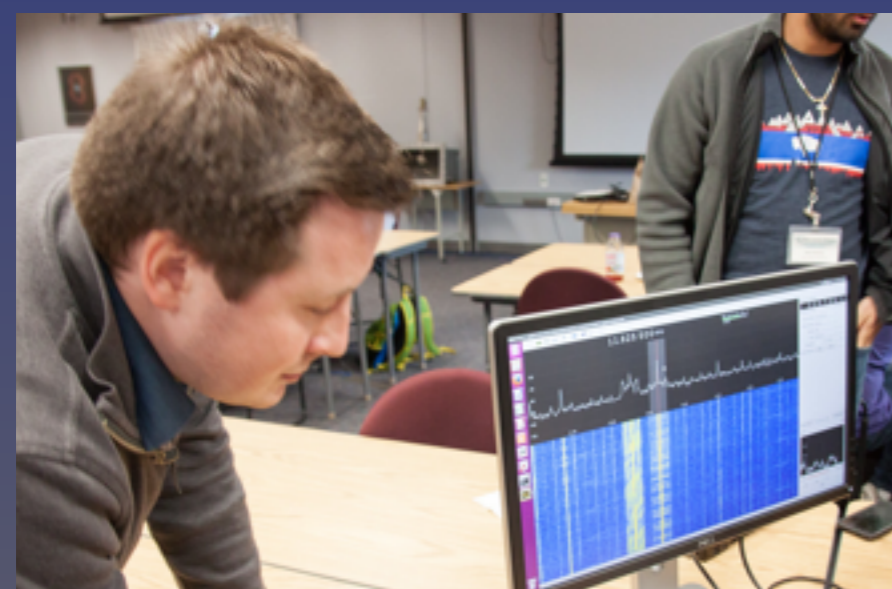
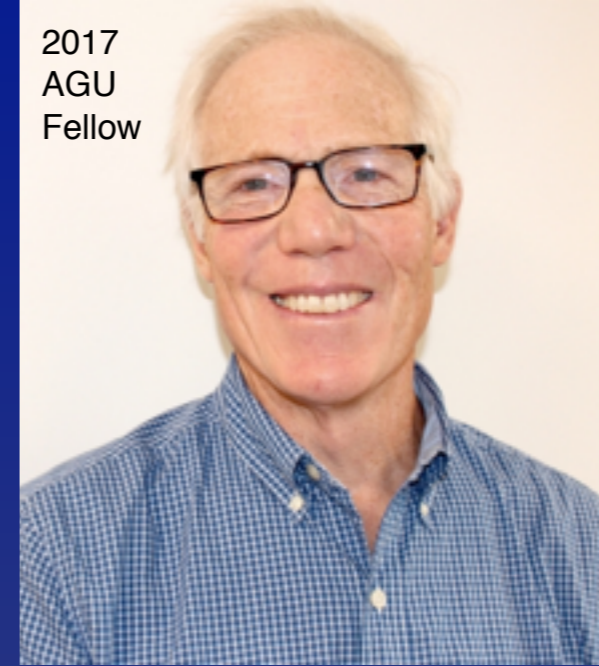
- World-wide, 1x1 deg x 5 min
- Vertical total electron content (TEC)
- New LOS TEC product

Madrigal Distributed Database



- Upper atmospheric community data archive and access

Millstone Hill Geospace Facility's Most Important Assets



Millstone Hill Geospace Facility Brief History

Millstone Radar Complex

MIT Lincoln Laboratory
Construction : 1956
Zenith Antenna : 1962

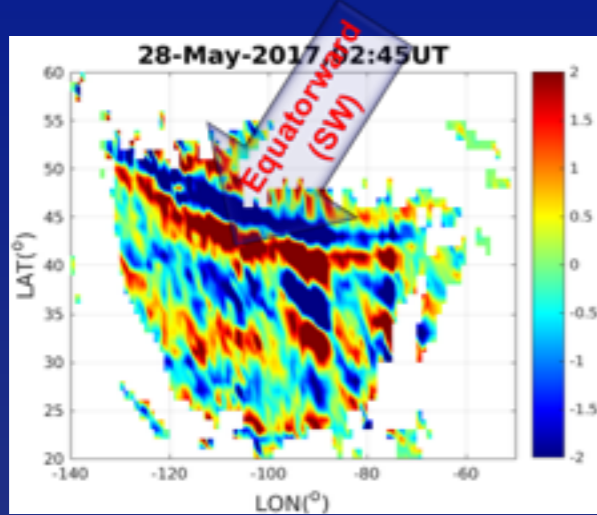
NSF support: 1974
MISA Antenna: 1978



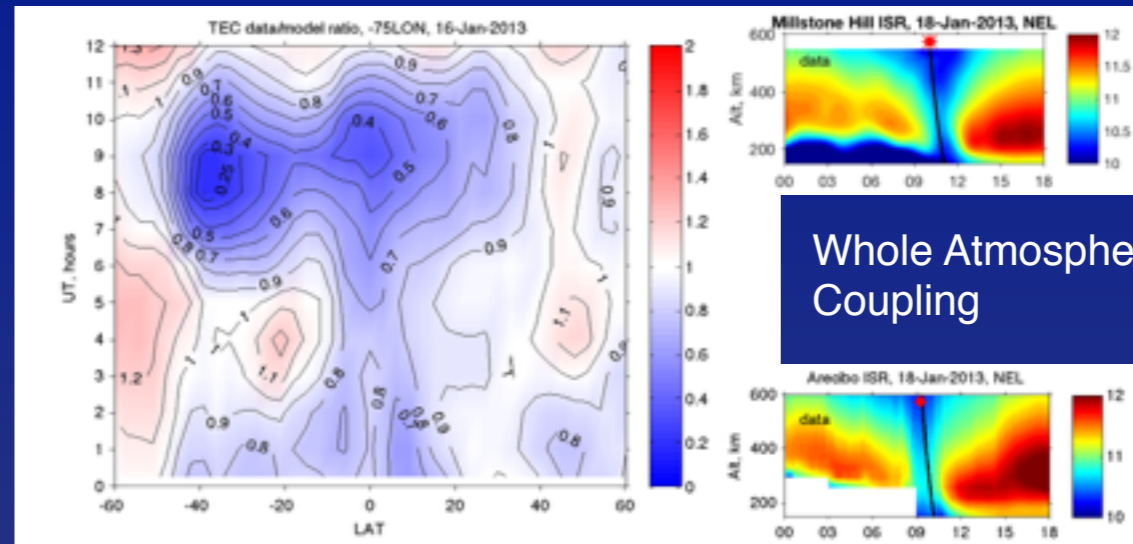
Selected milestones:

- 1956 - 1962:** UHF radar constructed by MIT Lincoln; first incoherent scatter (IS) obs.
- 1963:** UHF system transitioned to ionospheric research program using zenith antenna
- 1964 - 1974:** Pioneering IS observations (first computer analysis, vertical drifts, photoelectron effects, neutral exospheric temperature, meridional/zonal vector ion drifts and neutral winds)
- 1974:** Millstone Hill ISR activities transferred from ARPA to NSF Upper Atm. Section
- 1978:** MISA (46 meter fully steerable antenna) installed on site for wide field scanning
- 1979:** Millstone empirical high latitude electric field model, electron density trough studies, M-I coupling studies
- 1981:** Madrigal distributed database system begins as main data repository
- 1984-86:** Second UHF transmitter installed from USAF surplus
- 1989:** Radar/Optics ionosphere-thermosphere program begins using onsite FPI
- 1992:** Production software radar (MIDAS-1 in 1992; MIDAS-W in 2001)
- 1993:** Storm enhanced density / Subauroral polarization stream M-I coupling studies begin
- 2001:** SAR arc studies, GPS TEC maps begin
- 2002-2007:** ISRIM empirical models of all NSF ISRs; long term ionosphere climate studies begin
- 2008:** Whole atmosphere studies / SSW response studies begin
- 2011:** Madrigal becomes CEDAR community data repository system
- 2013:** Global system response studies using DMSP / GPS TEC / Millstone ISR / Van Allen Probes
- Current:** Plasma line, Eclipse, more SSW studies, M-I coupling, radiation belt, TIDs, ...

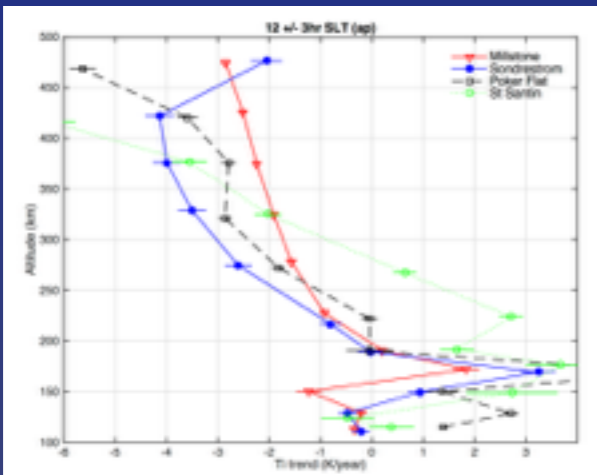
Haystack AGS Science (Wednesday)



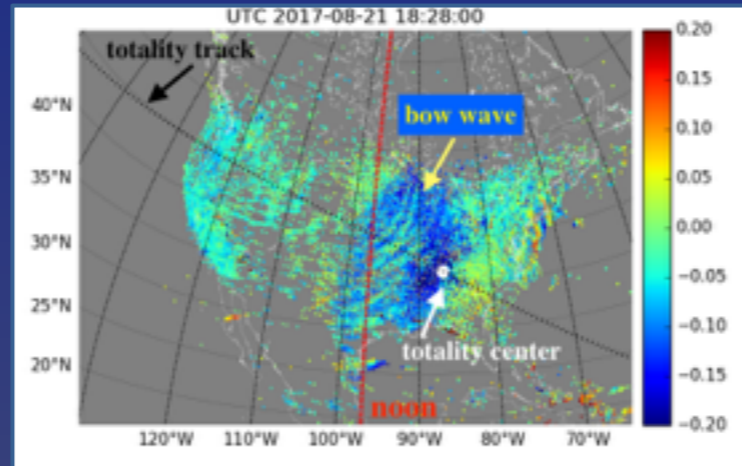
Traveling Ionospheric Disturbances



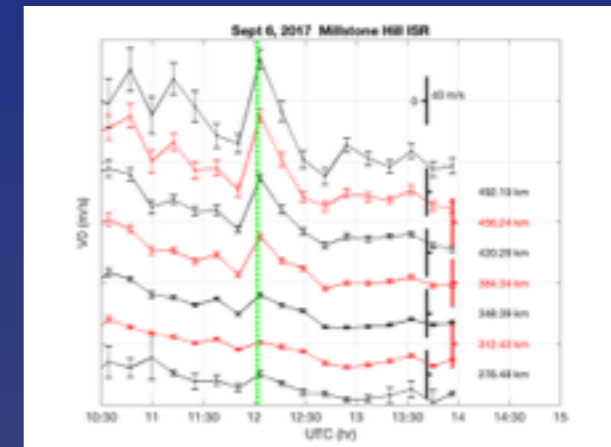
Whole Atmosphere Coupling



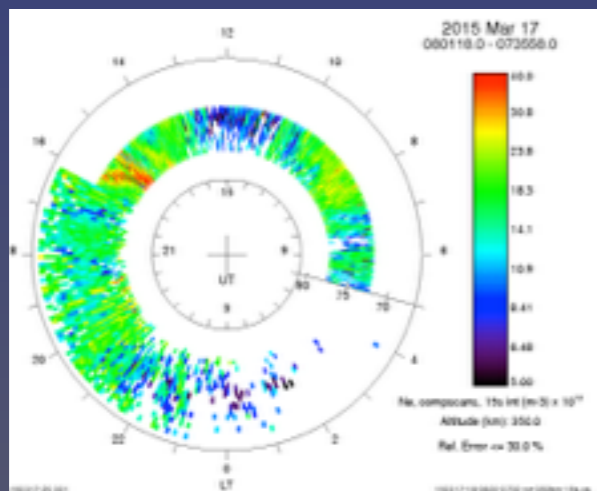
Long Term Climate Trends



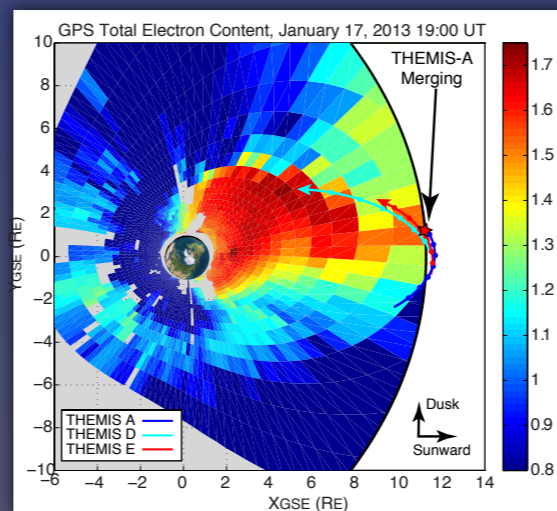
Eclipse Dynamics



Solar Flare Studies



Storm Effects: Patches, TOIs, SED, SAPS



Radiation Belt and Magnetosphere-Ionosphere Coupling

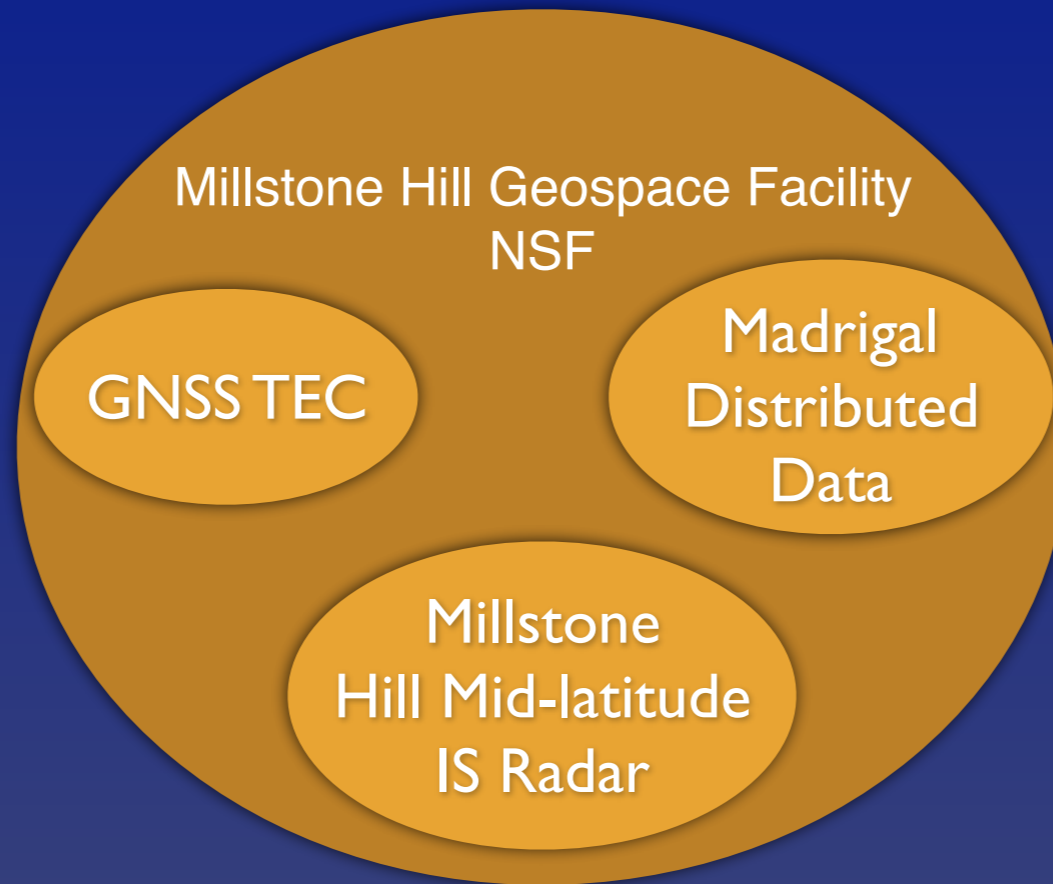
2017:
40+ publications
3 PhD committees
6 conference articles

Technical Activity Focal Points

Established

Developing

Emergent
Future



Community-Oriented Radar
Technical Development

Advanced, Flexible
Radio Arrays

Software for
Geospace Discovery

Innovative
Distributed Instruments

Millstone Hill Incoherent Scatter Radar System



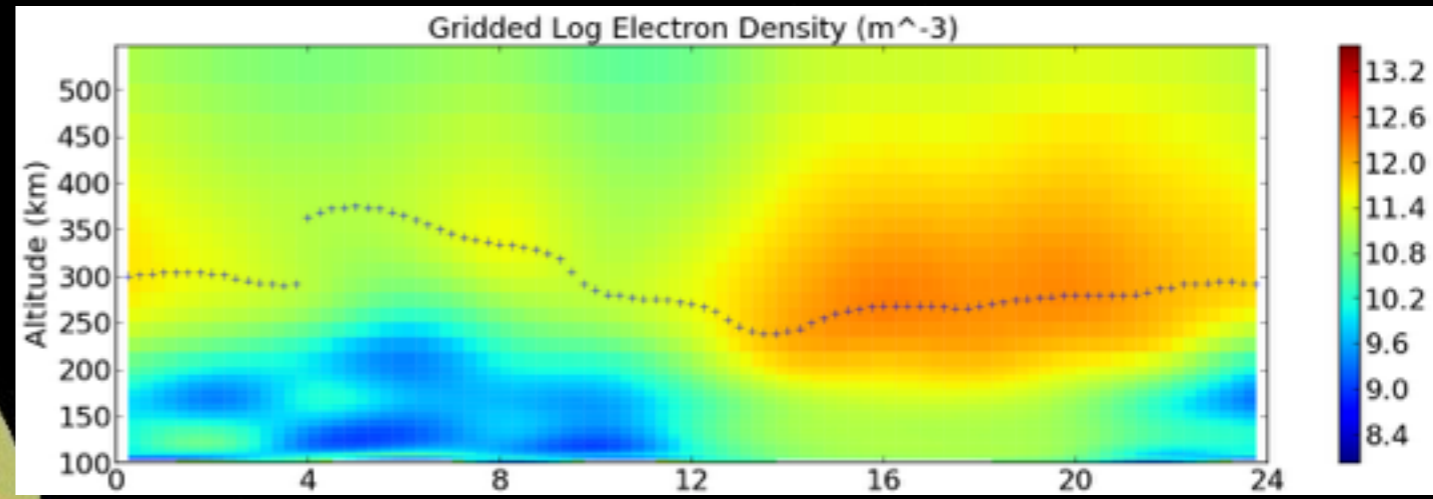
Location	Westford, MA
Transmitter Power	2.5 MW Transmitter
Antennas	46m Steerable Antenna 68m Zenith Antenna
Frequency	440 MHz
Operations	1000 to 2000 hours per year
Support	National Science Foundation Geospace Facilities Program



Now over 50 Years of Operations:
Millstone, Jicamarca, Arcibo!

Unique Long Term Geospace Climate Record
New Observations: Large Fidelity Improvements
New, Fundamental Geospace Process Discoveries

Millstone Hill
Incoherent Scatter Radar
Spatial Coverage
Azimuth Scan (4 deg EI)
Log Electron Density, m^{-3}
[10, 12.5]



Above:
Vertical Full Altitude, High Sensitivity
Ionospheric Plasma Profiles
At L = 3.3

High Latitude
Ionosphere

Plasmasphere
Boundary Layer

Inner
Magnetosphere/
Plasmasphere



42.6 N, 288.5 E
54 MLAT
L ~ 2 to 4

**Millstone Hill:
Unique, Wide-Field Access
To The Full Ionospheric
Plasma State**

© 2010 Europa Technologies
US Dept of State Geographer
© 2010 INEGI
© 2010 Google

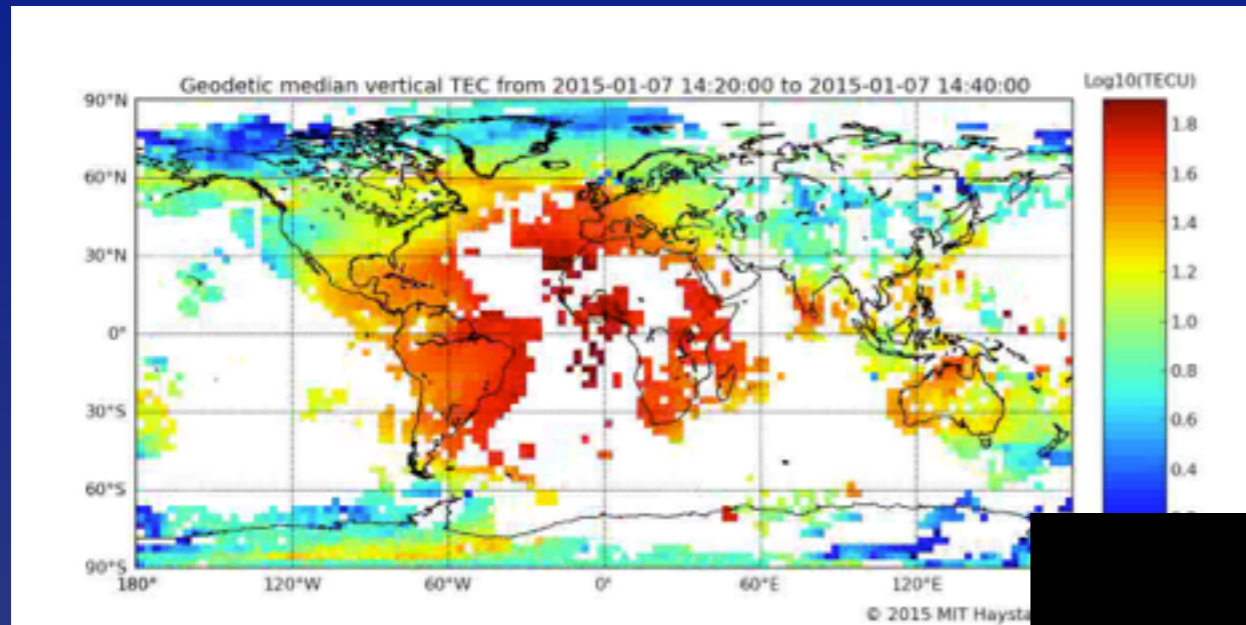
©2009 Google

39°52'41.15" N 81°05'52.87" W elev 278 m

Eye alt 6087.89 km

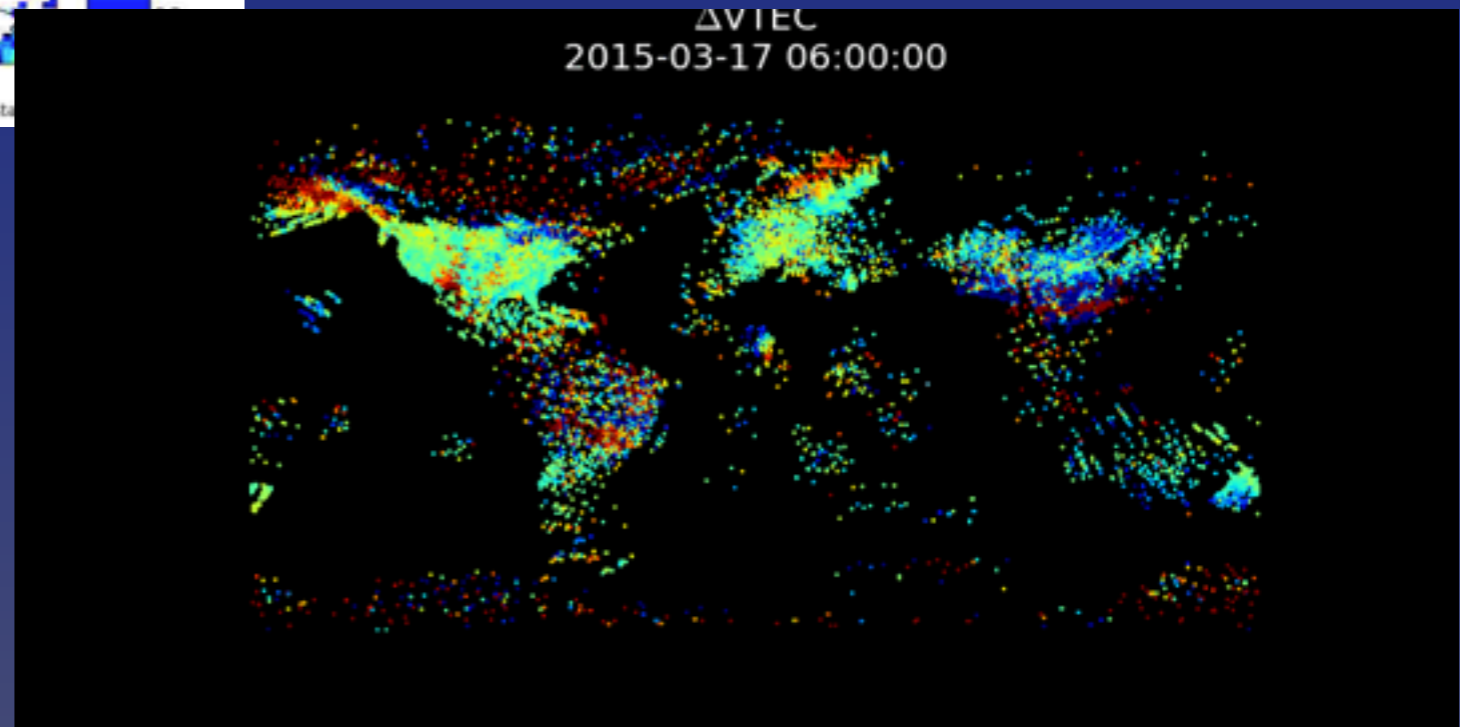
GNSS TEC Global Products

A Community Science Product Providing Multiscale System Science



Line of Sight
Very high density

Vertically binned
1 x 1 deg
5 minute resolution
Summary plots at 20 minute resolution



- MIT Haystack MAPGPS software suite: global GNSS TEC maps, deposited in Madrigal for community use
- Data from > 21 worldwide receiver networks, thousands of receivers
- Available 3-4 days behind realtime
- Supported as part of Millstone Hill Geospace Facility activities
- **2017: 234 unique community users from 107 unique institutions**

Madrigal

A Community Distributed Database System

- Upper atmospheric science database
- **Distributed, web-based**
- Multiple data types [radar, optical, etc.]
- Multiple database formats available
- Data locally controlled
- Shared inter-site metadata
- Full service, 'white glove' support for **quick, efficient ingestion** of historical and new community instrument data
- Derived parameters [e.g. Mag field]
- Global search
- **Full programming interface**
- Open source development
[www.openmadrigal.org]
- Site support for Madrigal nodes
- Active interactions with EarthCube, VIRBO, other community data sites

Developed at MIT Haystack
1981 - present

Welcome to the Madrigal Database at Haystack Observatory

Madrigal is an upper atmospheric science database used by groups throughout the world. Madrigal is a robust, World Wide Web based system capable of managing and serving archival and real-time data, in a variety of formats, from a wide range of upper atmospheric science instruments. The basic data format is the same as that used by the [National Science Foundation](#) supported Coupling, Energetics and Dynamics of Atmospheric Regions (CEDAR) program, which maintains a [CEDAR Database](#) at the National Center for Atmospheric Research (NCAR). Data files are easily exchanged between the two sites, but Madrigal has a significantly different emphasis. Data at each Madrigal site is locally controlled and can be updated at any time, but shared metadata between Madrigal sites allow searching of all Madrigal sites at once.

Data can be accessed from the Madrigal sites at [Millstone Hill, USA](#), [Arecibo, Puerto Rico](#), [EISCAT, Norway](#), [SRI International, USA](#), [Cornell University, USA](#), [Jicamarca, Peru](#), [The Institute of Solar-Terrestrial Physics, Russia](#), and Wuhan Ionospheric Observatory, the Chinese Academy of Sciences. and directly, using [APIs](#) which are available for several popular programming languages. A CVS archive of all Madrigal software and documentation is available from the [Open Madrigal](#) Web site. The latest version of Madrigal may also be downloaded from there.

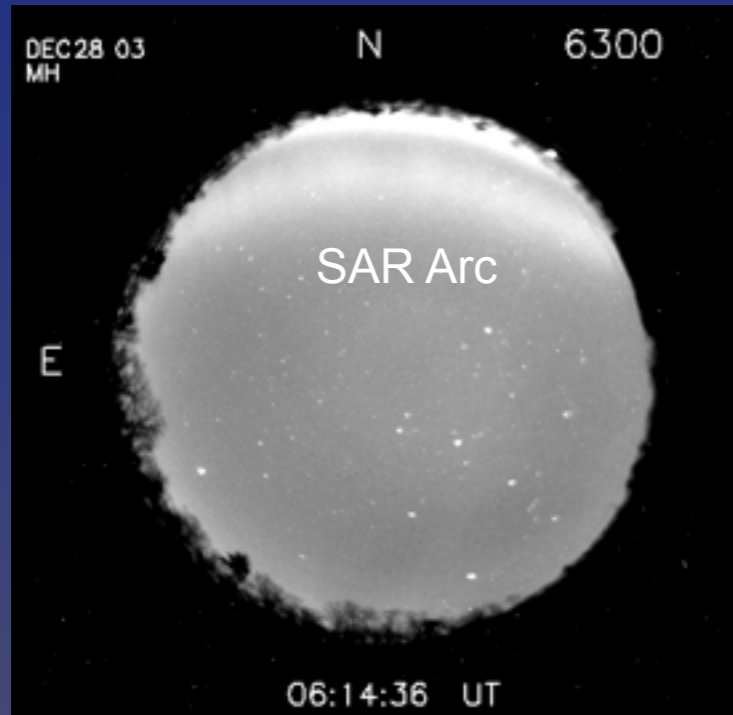


**CEDAR / upper atmospheric
community data repository:
now centered, maintained at
MIT Haystack by
Millstone Hill GF activities**

Millstone Hill Geospace Facility

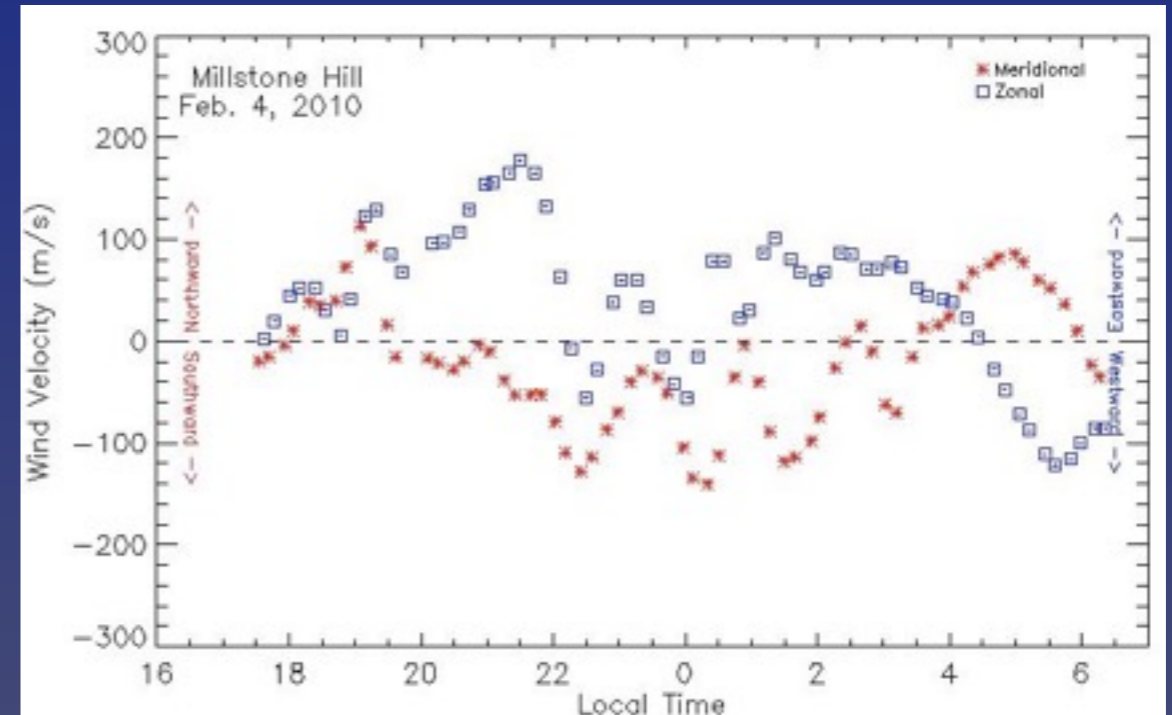
Passive Optics

MIT provides site infrastructure
Power, building, ethernet
Separately funded instruments



Boston University All-Sky Imager

6300 A; other wavelengths
Clear nights
buimaging.com



Separate NSF grant [J. Noto, SSI; Q. Wu, NCAR]
Fabry-Perot Interferometer

6300 A red line winds/temperatures since late 2009
Continues 1989-2001 data record [D. Sipler]
Green line also operational
Patrol mode - operates every clear night

Modern Software Radios

Largely FPGA Based + Return of the Tuner

GPS radios are now showing up!

Low Cost Software Defined Radios

GNU Radio Framework

Result of high performance computing

Radio cost varies from ~ \$10 to \$10,000+

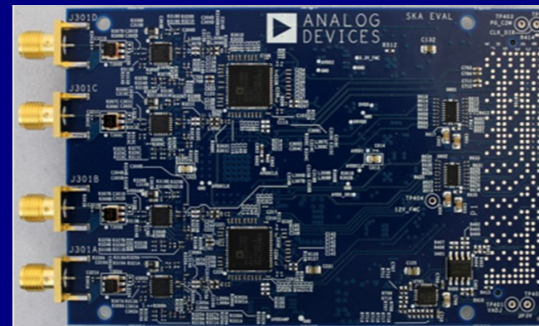
Highly Capable / Integrated Radios

Tuning ranges and bandwidths increasing

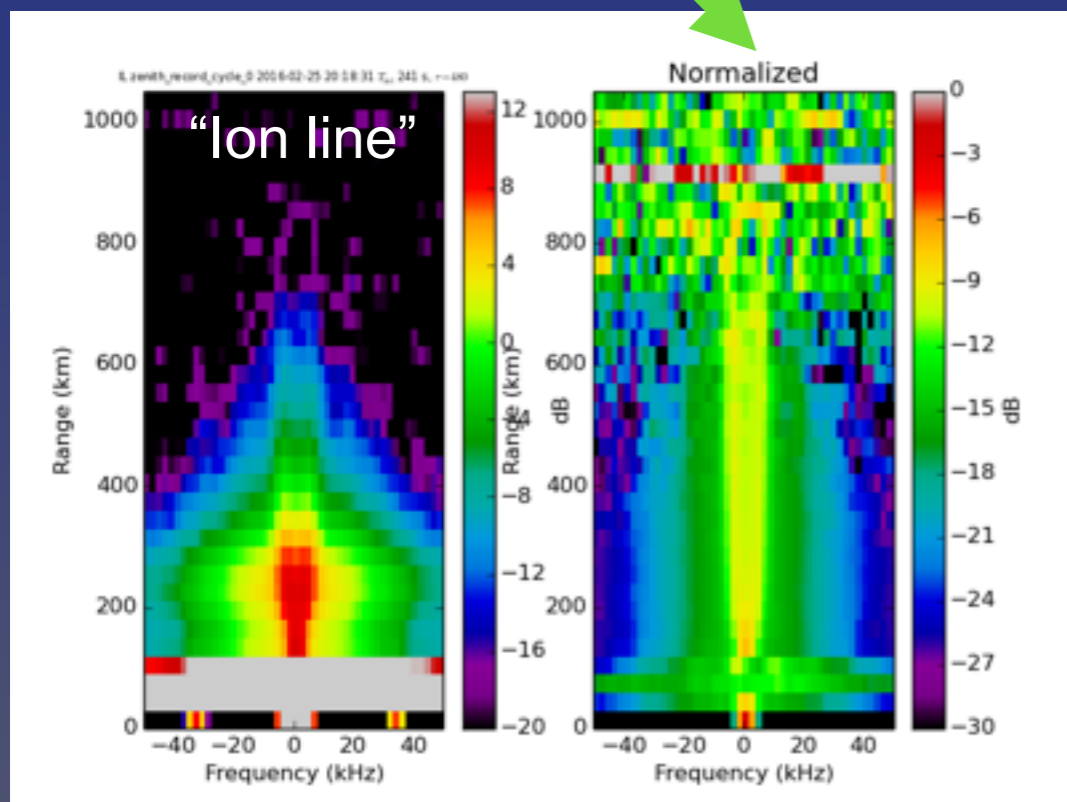
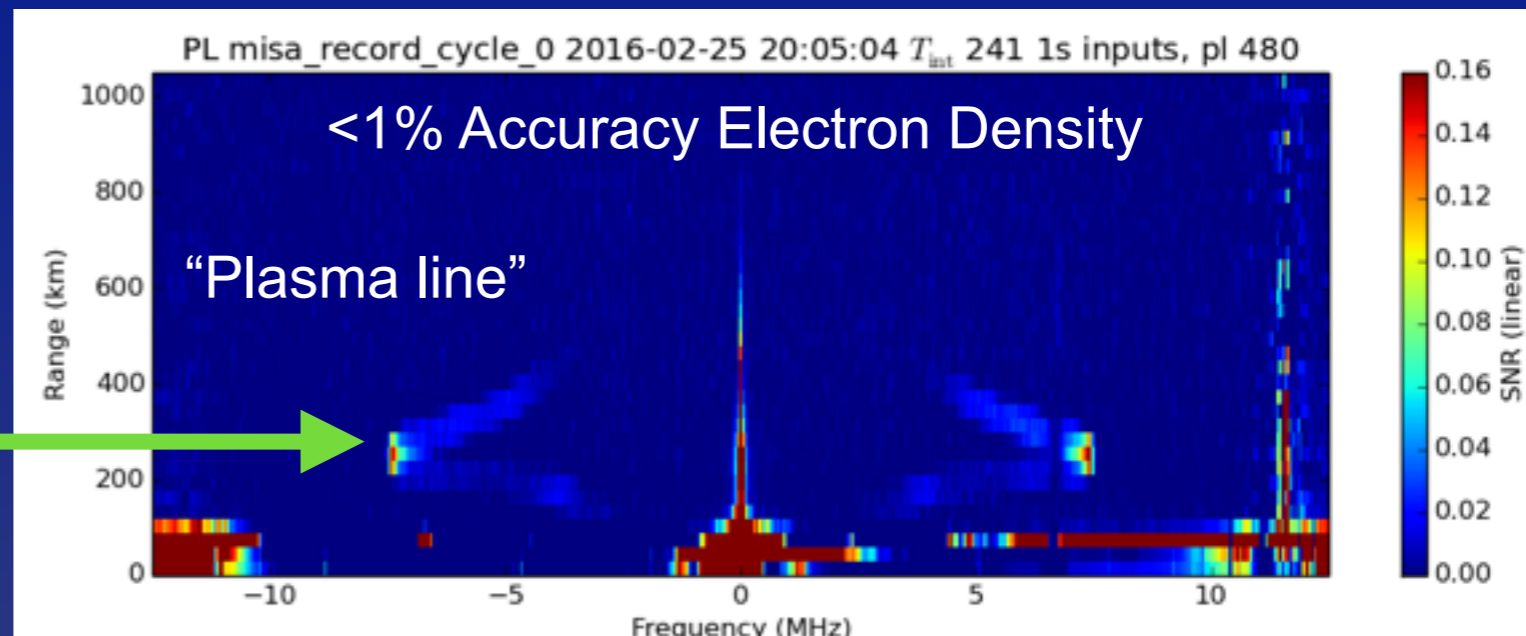
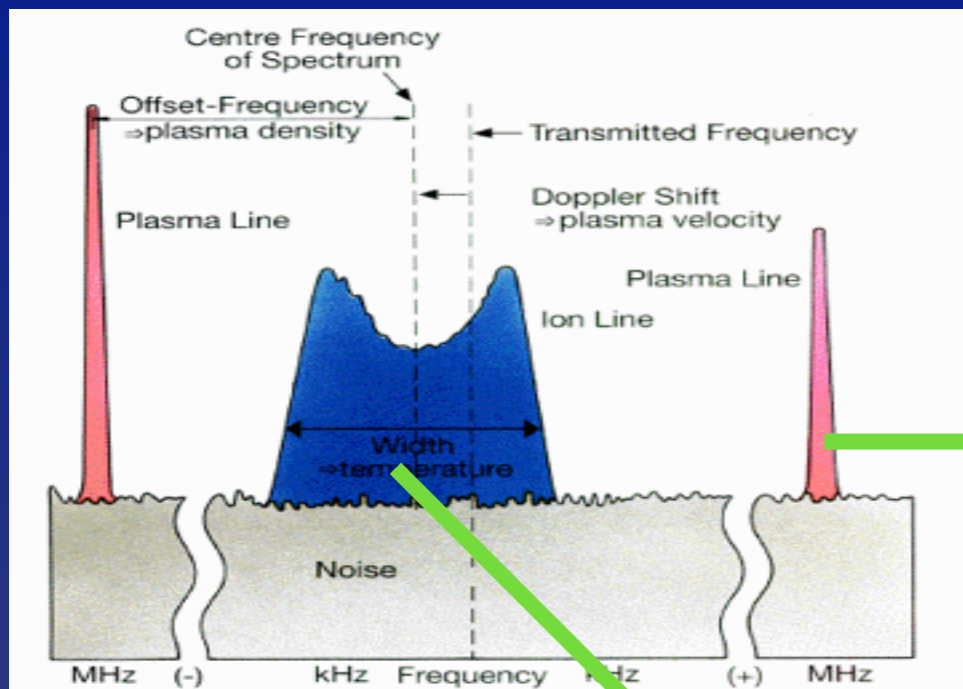
Channel counts slowly increasing

The specific radios change almost daily...

The radios are not the important part!



IS Radar Technical Development



Above: Plasma Line profiles
 Absolute electron density
 F2 peak value in ~few sec
 Full profile in 1-4 minutes: mostly daytime

Left: Ion Line profiles
 Traditional ISR data product
 Density, temperature, velocity, composition
 ~minute time scales

**Software Radar Platform Now Captures
 All Geophysical Information Available from Scattering Process**