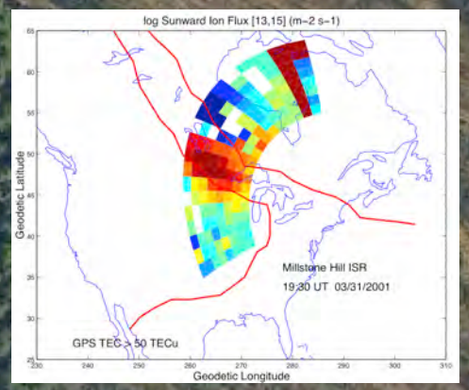
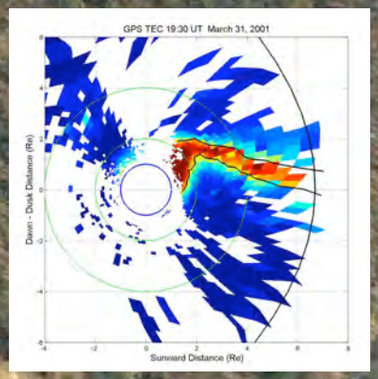
$$\sigma(\vec{k},\omega)d\omega = \pi^{-1}N_e r_e^2 \sin^2\delta \cdot \left(\left|\sum_j \mu_j y_j + ik^2\lambda_D^2\right|^2 \frac{Re[y_e]}{\omega - \vec{k}\cdot\vec{V}_{de}} + |y_e|^2 \sum_j \frac{\eta_j Re[y_j]}{\omega - \vec{k}\cdot\vec{V}_{dj}}\right) \cdot \left(\left|y_e + \sum_j \mu_j y_j + ik^2\lambda_D^2\right|^2\right)^{-1} d\omega$$

50 Years of Science, Technology and Innovations at Millstone Hill

P. J. Erickson
Atmospheric Sciences Group
MIT Haystack Observatory

CEDAR 2012
June 28, 2012





Westford, MA USA
42.61950 N
288.50827 E
0.146 km Alt
53.409 Inv Lat

MIT Haystack Observatory Complex
Westford, Massachusetts
Established 1956

Haystack Observatory

Radio Astronomy
Atmospheric Science
Space Surveillance
Radio Science
Education and Public Outreach

Millstone Hill
Observatory

Millstone Hill Radar

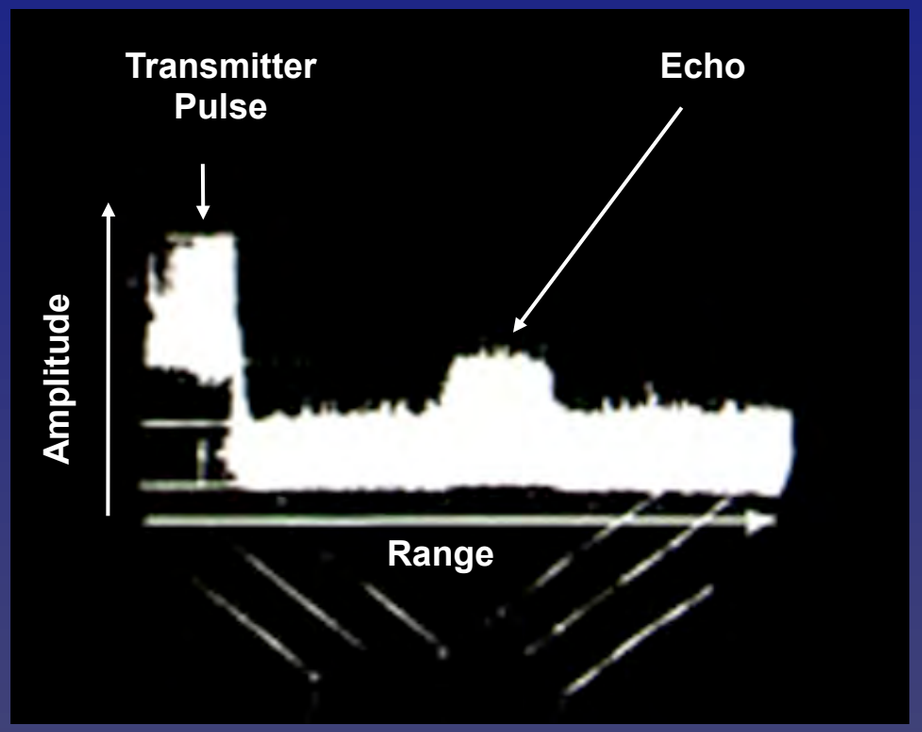
Firepond Optical
Facility

Millstone Hill: Pioneering Large Aperture Radar

The BMEWS Prototype

Millstone Radar
1957

First in Space Surveillance

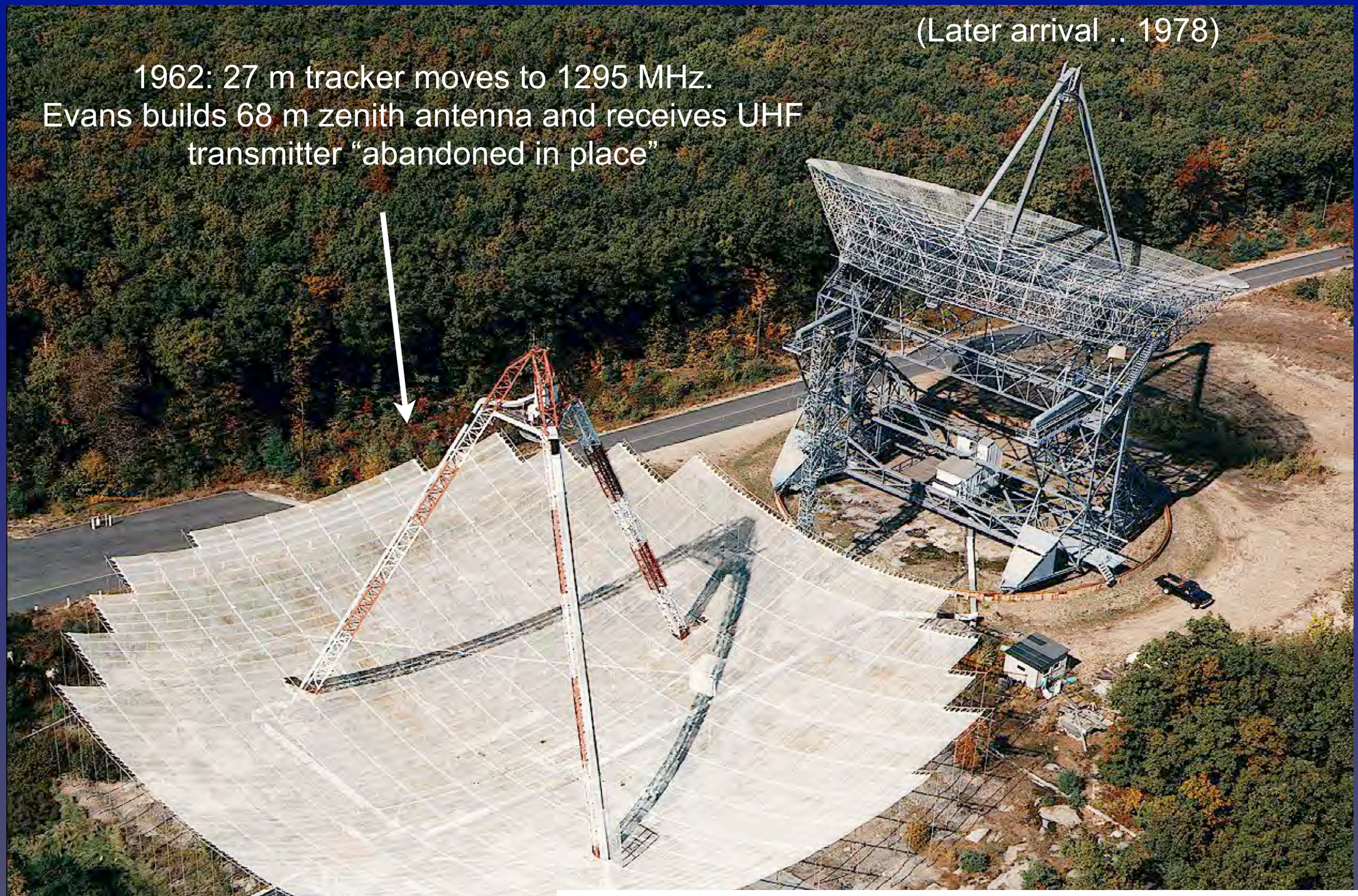


Sputnik
A-Scope Trace

High Power Large Aperture Radar Has Multiple Applications

(Later arrival .. 1978)

1962: 27 m tracker moves to 1295 MHz.
Evans builds 68 m zenith antenna and receives UHF transmitter “abandoned in place”



Dedicated ionospheric observation program starts.
1962 - 1974: ARPA funded
1974 onwards: NSF funded

NSF Geospace Facilities: IS Radar Chain

US National Science Foundation
Geospace Facilities
AGS Directorate

Millstone Hill Observatory:

Incoherent Scatter Radar (ISR):
440 MHz @ 2.5 MW Peak
68 m Zenith Antenna
46 m Steerable Antenna (MISA)

Wide Field of Coverage
Full Span of Mid-Latitude, Subauroral Processes

Radar Operations: 1000 – 2000 hours per year of ionospheric observations
Primary support via NSF Geospace Facilities program
Many community PIs - fully flexible for special dedicated experiments
Coordinated International Observations: ~750 hours per year
Separately funded research as possible : NASA, NRL, AFOSR, MIT Lincoln Lab

MIT Haystack Atmospheric Sciences Group

Geospace Science:
Collaborations, Campaigns,
Analysis

Geospace Radar Technology:
Software Radar, Madrigal d/b

Distributed Instruments:
ISIS, GPS TEC

Millstone Hill UHF
Incoherent Scatter Radar

Ancillary Community Site
Instruments:
Digisonde, Passive Optics

Community Training:
Teaching, Service, E/PO

International Collaborations
Europe, Asia, Canada, FSU

Kp = 6 event
F10.7 = 233
DsT -100 nT

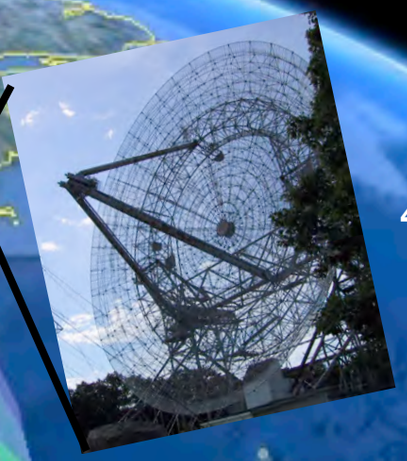
Millstone Hill UHF Radar
Azimuth Scan (4 deg El)
Log Electron Density m^-3 [10, 12.5]
1980-10-11 03:47:27 UTC

High Latitude

SAPS

Plasmasphere Boundary Layer

Inner Plasmasphere



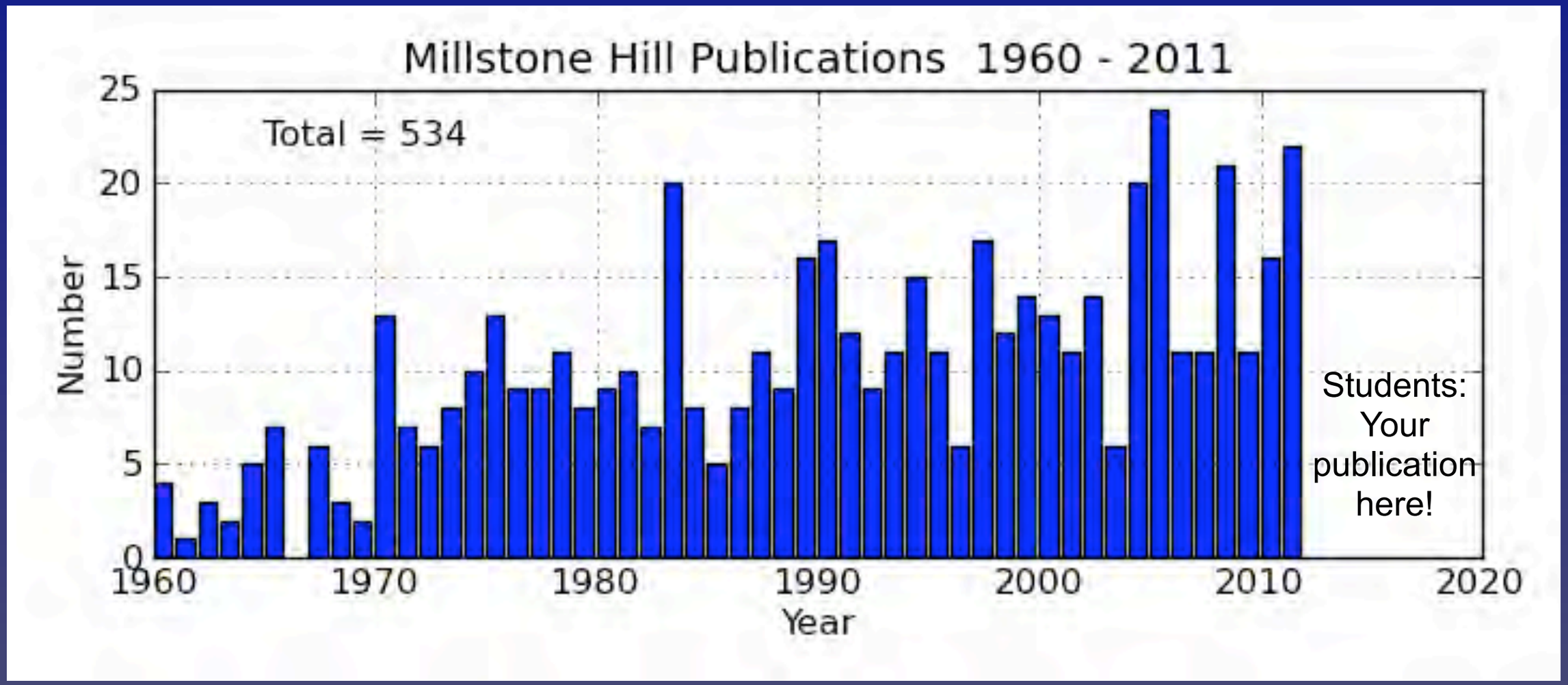
42.6 N, 288.5 E
54 MLAT
L ~ 2 to 4

Millstone Hill
Incoherent Scatter Radar:
Wide-Field Access To The
Full Plasma State

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

Eye alt 6087.89 km

Scientific and Observational Productivity at Millstone Hill In Partnership With the Geospace Science Community

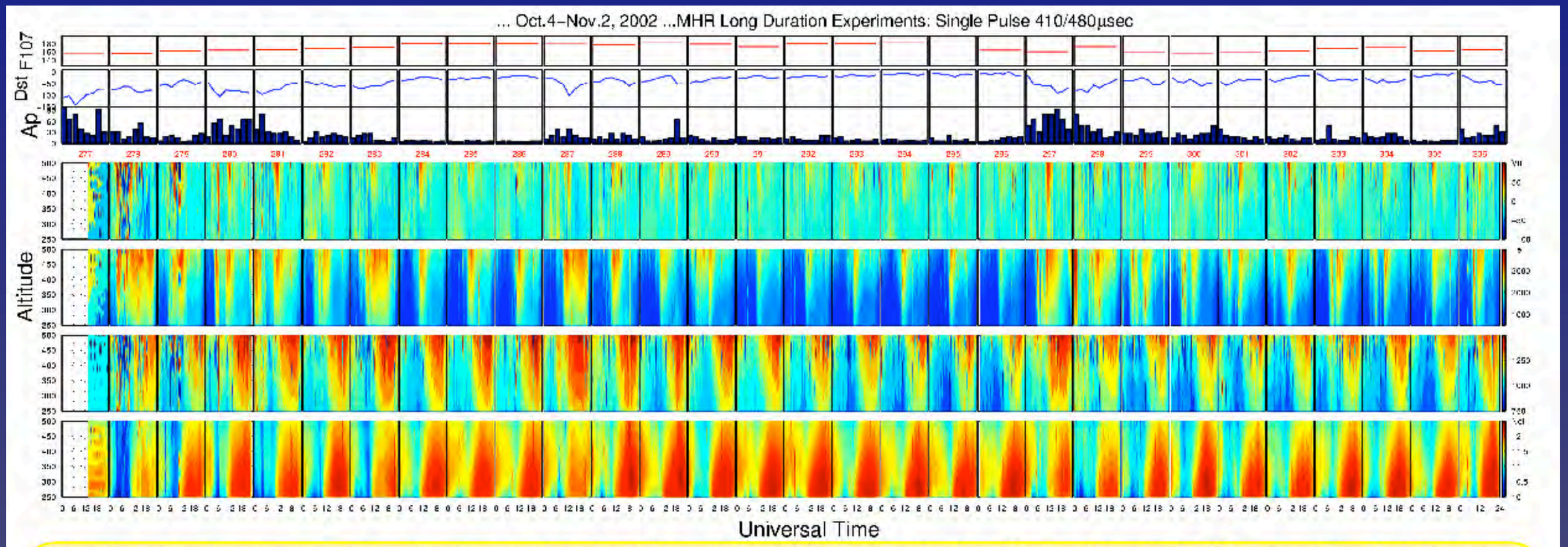


2007-2012: 90 publications (10 in press), 75% with external first authors
2010-2011: Madrigal @ MIT served 179 users at 116 institutions
2011: Millstone Hill experiments by 23 external principal investigators

Millstone Hill Geospace Science

Plasmasphere Boundary Layer
Storm Time Dynamics
Plasma Instabilities
Energy Coupling, Waves, Tides

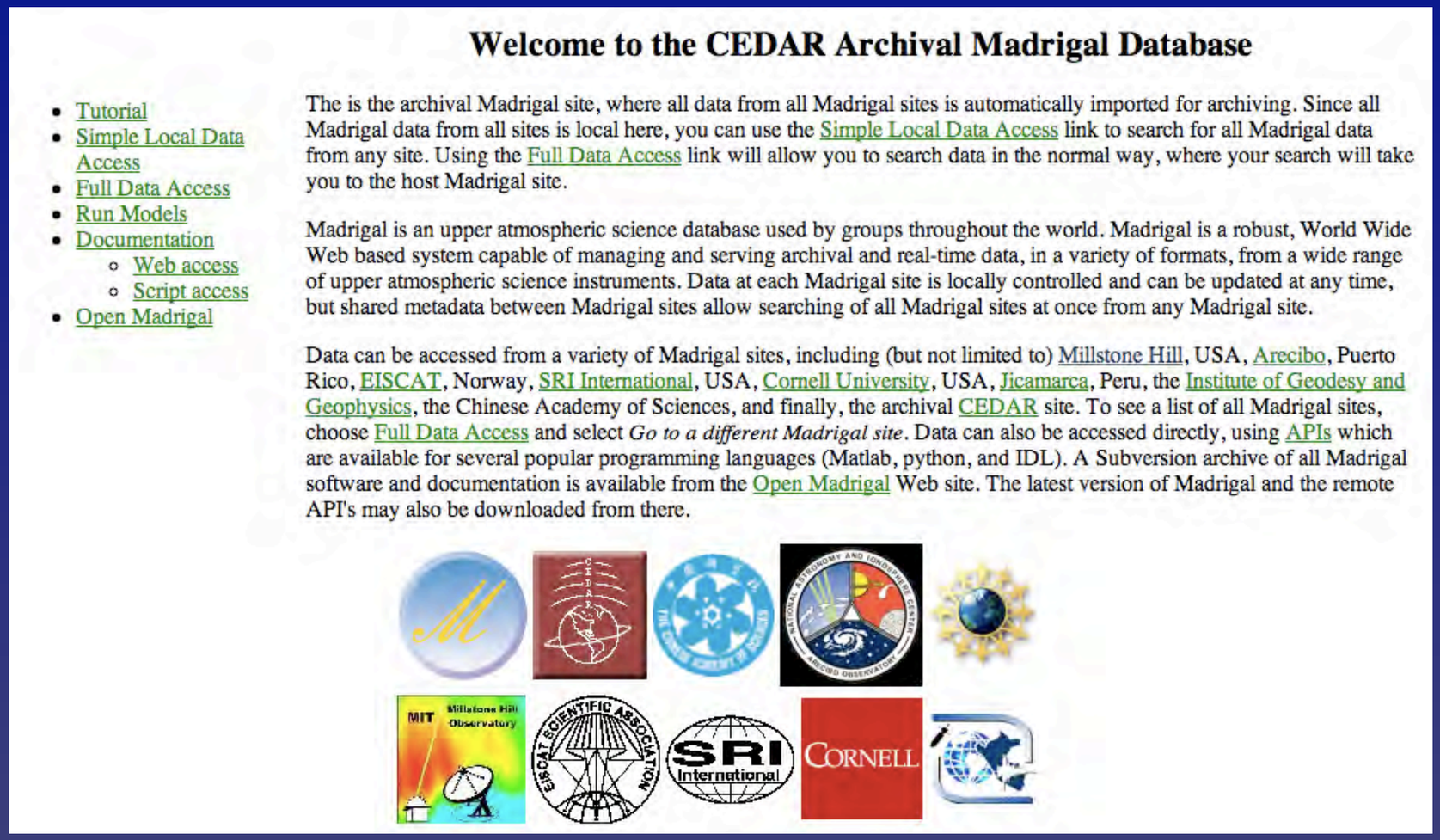
Physical Measurements
Ionospheric Radar
Incoherent Scatter
Coherent Scatter



A long-duration incoherent scatter radar experiment was carried out at Millstone Hill from 1340 UT on October 4 to 1300 UT on November 4, 2002. The experiment included single-pulse and alternating-code measurements. During the periods between 2300 UT October 4 and 1100 UT October 7 and between 2300 UT October 7 and 1100 UT October 8, the pulse length was 410 µsec. At other times, a 480 µsec pulse was utilized. The alternating-code scheme was used from 1100 UT October 8 onwards.

Sustain Highly Reliable and Efficient Operations
A Key Element in a Mesoscale Geospace System Science Picture
Long Term Trends and Climate Change
Technical Staff Capabilities Available for NSF Community Efforts

Madrigal Geospace Data System



- Tutorial
- Simple Local Data Access
- Full Data Access
- Run Models
- Documentation
  - Web access
  - Script access
- Open Madrigal

Welcome to the CEDAR Archival Madrigal Database

The is the archival Madrigal site, where all data from all Madrigal sites is automatically imported for archiving. Since all Madrigal data from all sites is local here, you can use the Simple Local Data Access link to search for all Madrigal data from any site. Using the Full Data Access link will allow you to search data in the normal way, where your search will take you to the host Madrigal site.

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. 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 from any Madrigal site.

Data can be accessed from a variety of Madrigal sites, including (but not limited to) Millstone Hill, USA, Arecibo, Puerto Rico, EISCAT, Norway, SRI International, USA, Cornell University, USA, Jicamarca, Peru, the Institute of Geodesy and Geophysics, the Chinese Academy of Sciences, and finally, the archival CEDAR site. To see a list of all Madrigal sites, choose Full Data Access and select *Go to a different Madrigal site*. Data can also be accessed directly, using APIs which are available for several popular programming languages (Matlab, python, and IDL). A Subversion archive of all Madrigal software and documentation is available from the Open Madrigal Web site. The latest version of Madrigal and the remote API's may also be downloaded from there.

Established 1980
J. M. Holt

Full community development and technology sharing model

Upper atmospheric science database
Distributed, web-based
Multiple data types [radar, optical, etc.]
CEDAR database format
Data locally controlled
Shared inter-site metadata
Derived parameters [e.g. Mag field]
Global search
Full programming interface
Open source [www.openmadrigal.org]

Reliable data sharing and scientific productivity optimization for the CEDAR, GEM, and Geospace scientific community

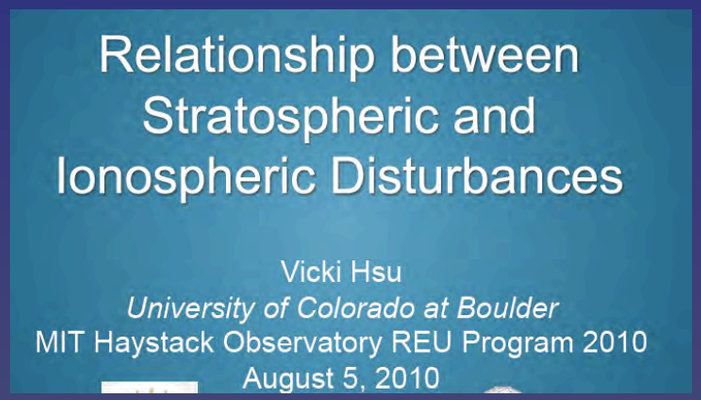
OpenRadar Workshops:
Collaborative Open Source Community Development

The Open Radar Initiative
Reliable Technology for Radio Science

Grass roots initiative to jointly implement next generation Software Radar for GF community
Focused workshop on software radar for geospace applications
Review experiences to date with software radar
Discuss common use cases and potential common infrastructure, architectures

Initial 1 week workshop with Millstone Hill, Jicamarca staff
Follow-ons planned under OpenRadar initiative [www.openradar.org]

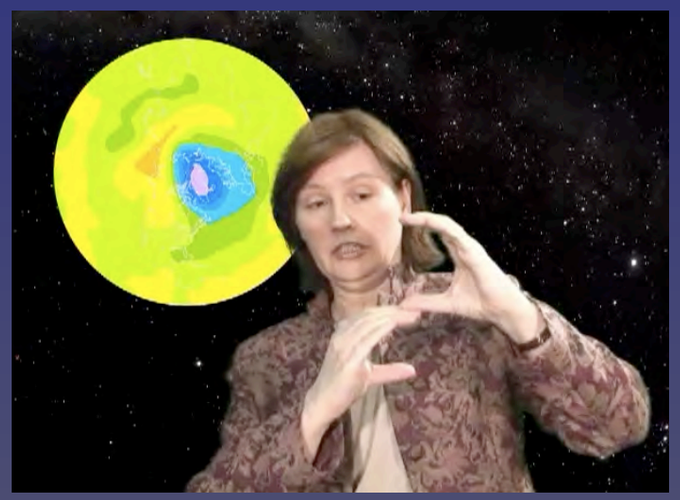
MIT Haystack Education and Public Outreach



NSF Research Experiences for Undergraduates [27th year]
NSF Research Experiences for Teachers [11th year]

8 undergraduate projects per year [4 in atm. sci.]
4 high school teachers per year
4 Puerto Rico precollege students per year
Presentation at end of 10 week program
Some students coauthor papers, attend AGU
Teachers develop classroom units covering GF science

Public lectures, tours
Exposing GF science to wide audiences



Space Weather FX
Video podcast 8 episode series
On iTunes, YouTube, MIT site
1000s of views covering GF science

GF Geospace Science Center at Millstone Hill

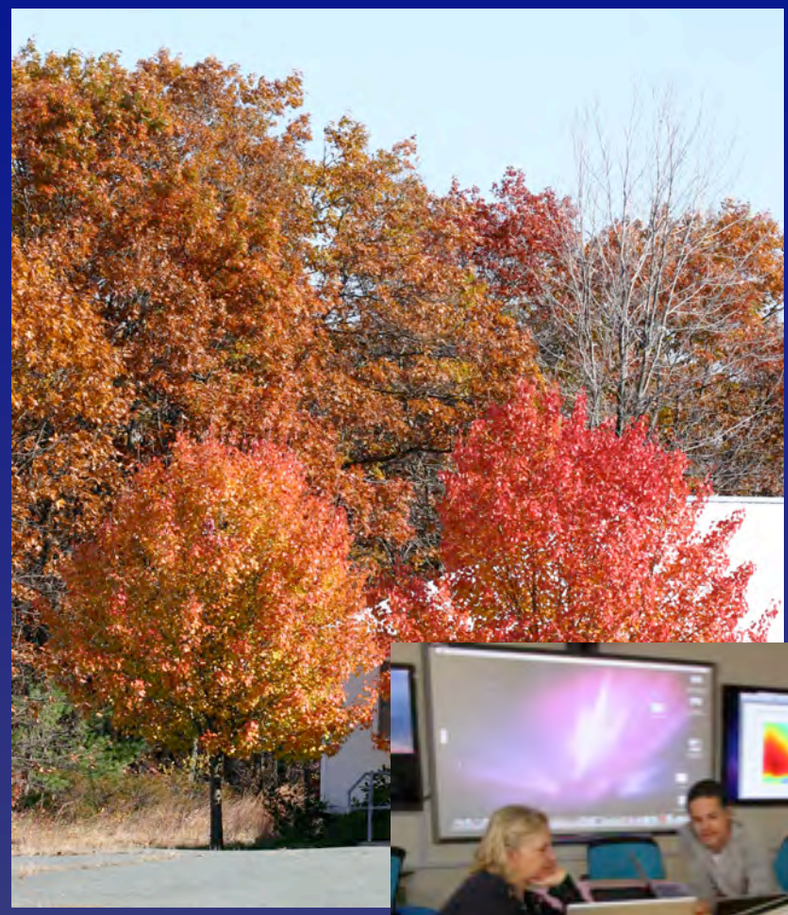
NSF ARRA Award from GF Program

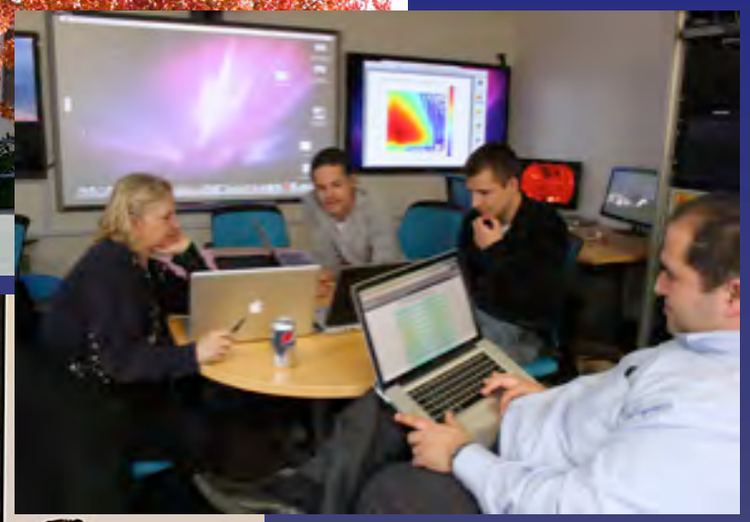
Center for Workshops
Science Campaign Coordination

Distributed Instrument Operations
- Incoherent Scatter Radar Systems
- Distributed Instruments (DASI)
- Community Geospace Operations
- NSF Small Satellites

Enhanced Computing Facility

UHF Radar Control Upgrade
- Distributed Antenna Control System
- Distributed Safety Control System



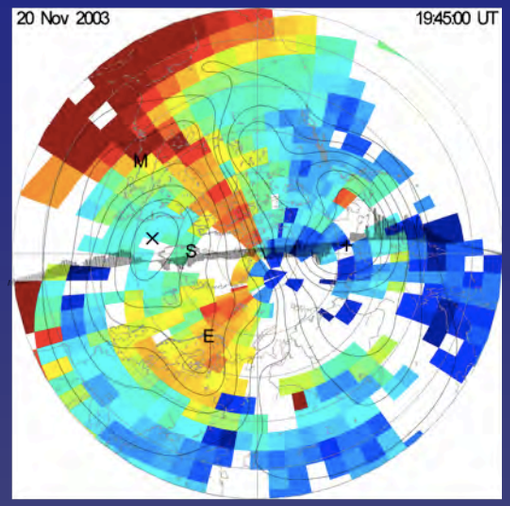


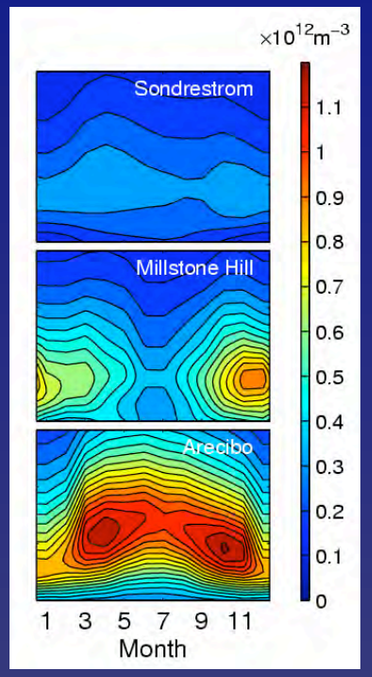
A User Facility For The Space Science Community

The Future at Millstone Hill: Science

Community coordinated, CEDAR/GEM aligned, multi-diagnostic studies

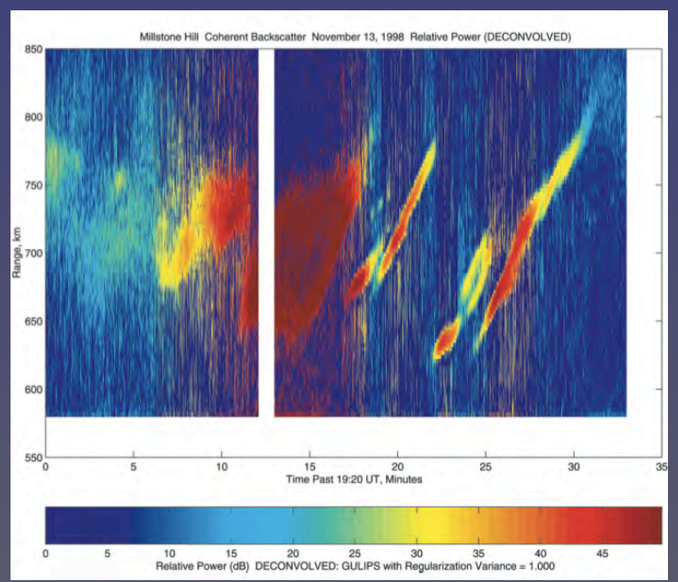
- Ionosphere-atmosphere coupling
- Plasmasphere boundary layer Geospace coupling
- Mid-latitude ion-neutral coupling

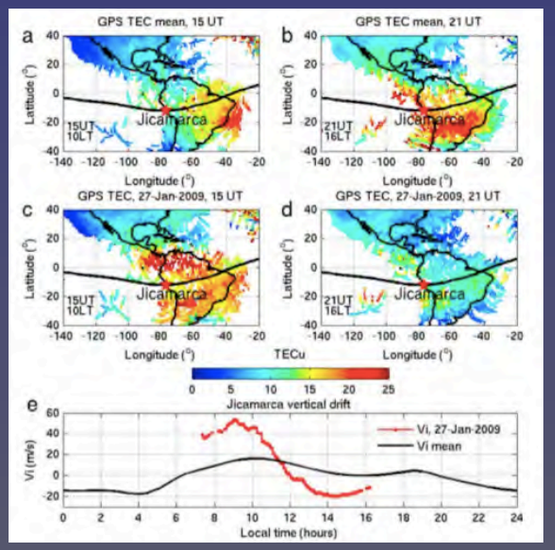




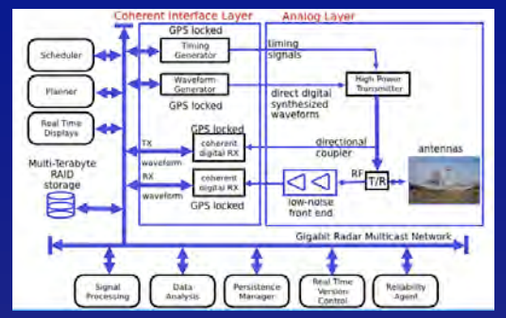
Unique radio science based plasma physics studies

- UHF coherent backscatter
- Mid-latitude sporadic E layers
- Meteoroid head and trail echoes





The Future at Millstone Hill: Technology, Education

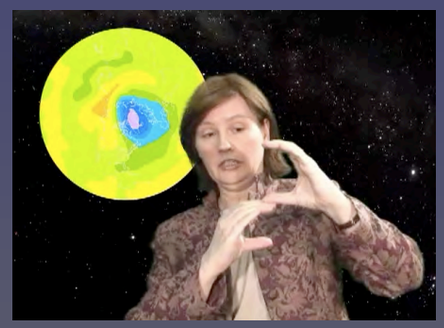


Technology and Support for Science:

- Double Millstone Hill radar community observation time
- New high time/space resolution radar, radio remote sensing techniques
- Advanced Software Radar technology: improve operational efficiency, capability
- Enhance community data access
- Train and support the space science community in Madrigal use and development
- Advanced analysis products: Greater community use of all Geospace Facility chain data

Educate and Inform the Community:

- User and technical training [ISR school, community tech and Madrigal workshops]
- Extensive graduate student involvement [MIT Campus, Boston University, Dartmouth, Virginia Tech, Stanford, University of Washington, UNH, U Mass Lowell, ...]
- Millstone Hill resident visitor programs
- Research experiences for undergraduates, high school students, K-12 teachers [REU, RET, Puerto Rico pre-college programs]
- General public outreach for GF and Geospace science & technology

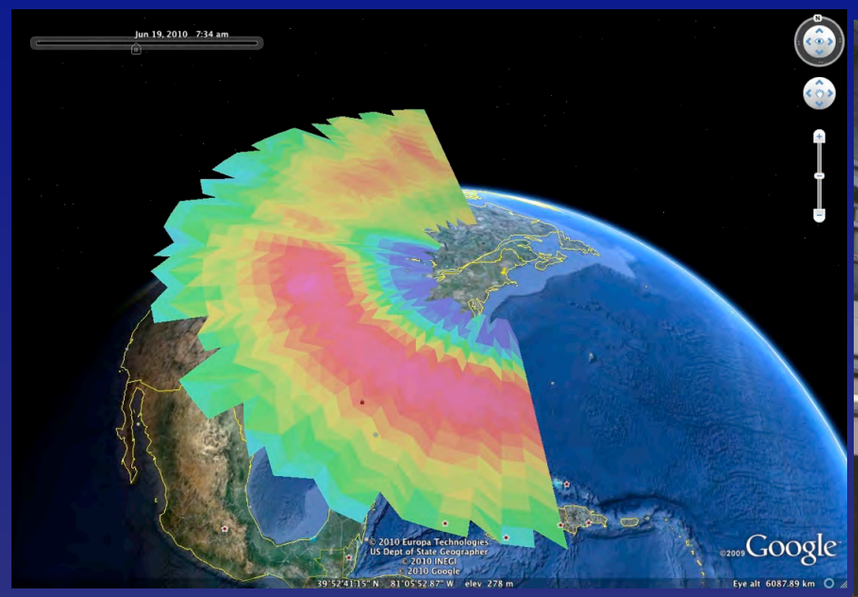


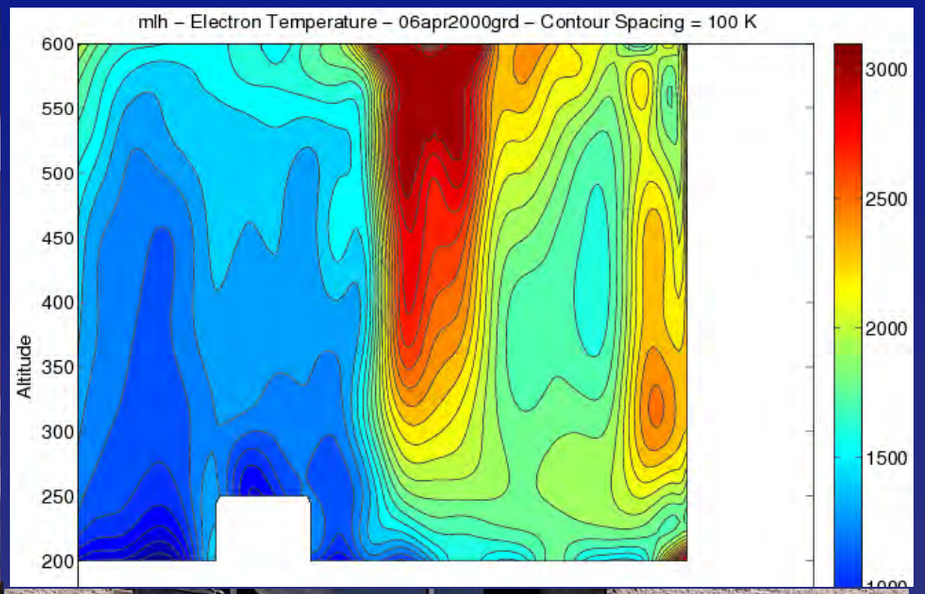
Ways to get involved with Millstone Hill:

- Request an experiment
- Come for a visit (and conduct an experiment)
- Analyze data

We are a full service NSF Geospace Facility and we love faculty and student collaborations

Summary





Millstone Hill:
Exploring the Coupled Geospace System
as an Integral Part of the Space Science Community