The Long Wavelength Array Kickoff

September 20, 2007
1:30 p.m. – 6:00 p.m.
UNM's Science & Technology Park North
801 University Blvd. SE, Rotunda Room
Albuquerque, NM

Agenda

1330 Introduction by the LWA Executive Committee (Dr. John McIver, UNM)
The LWA Project is managed by an Executive Committee representing the partnering institutions. They will discuss the goals and ground rules for the meeting.

1400 LWA Project Context (Dr. Lee J Rickard, UNM)
Funding for the LWA began in April, so the programmatic activities are only now getting started. However, there has been a lot of prior work done by the individual institutions. The Executive Project Director will discuss this historical context, as well as the relationship of the LWA to other long-wavelength interferometry projects.

1430 ONR Project Context (Dr. Robert McCoy, ONR)
The Navy is particularly interested in the potential application of long-wavelength interferometric data to space physics problems that affect operational systems. The ONR Program Manager for the LWA will give an overview of these issues.

1500 LWA Scientific Capability (Dr. Christopher Watts, UNM; Dr. Namir Kassim, NRL)
Experience with such instruments as the VLA 74 MHz system has indicated the potential utility of the LWA for space physics and astrophysics problems. In particular, we will show how the VLA data have demonstrated the exquisite sensitivity of long-wavelength interferometers to ionospheric phenomenology. In order to encourage the engagement of the space physics and astrophysics communities at this early stage of the design, the Project Scientists will discuss the anticipated scientific capability of the LWA.

1600 Recent LANL Work (Dr. Patrick Colestock, LANL)

1620 Long Wavelength Demonstrator Array (Dr. David Munton, ARL)
A small test station has been developed by NRL and ARL, and has been operating at the VLA site for several months. We will report on the lessons learned from this experiment.

1640 Current Technical Concept of the LWA (Dr. Steven Ellingson, VT)
The System Engineer will give an overview of the current ideas for the technical execution of the LWA.

1710 LWA Program Plan (Rickard)
The Executive Project Director will give an overview of the program milestones and activities.

1730 LWA Site Acquisition (Dr. Gregory Taylor, UNM)
The potential difficulty of acquiring suitable sites for LWA stations, free from significant RFI yet linked to power and data communications, requires that we address this problem early in the project. The LWA Scientific Director will report on the status of this activity.

1750 Framework for Collaborative Ventures (Taylor)
The meeting will close with a discussion of how to generate greater engagement with the interested scientific communities.

Long Wavelength Array (LWA)
Funded Program Kickoff Meeting

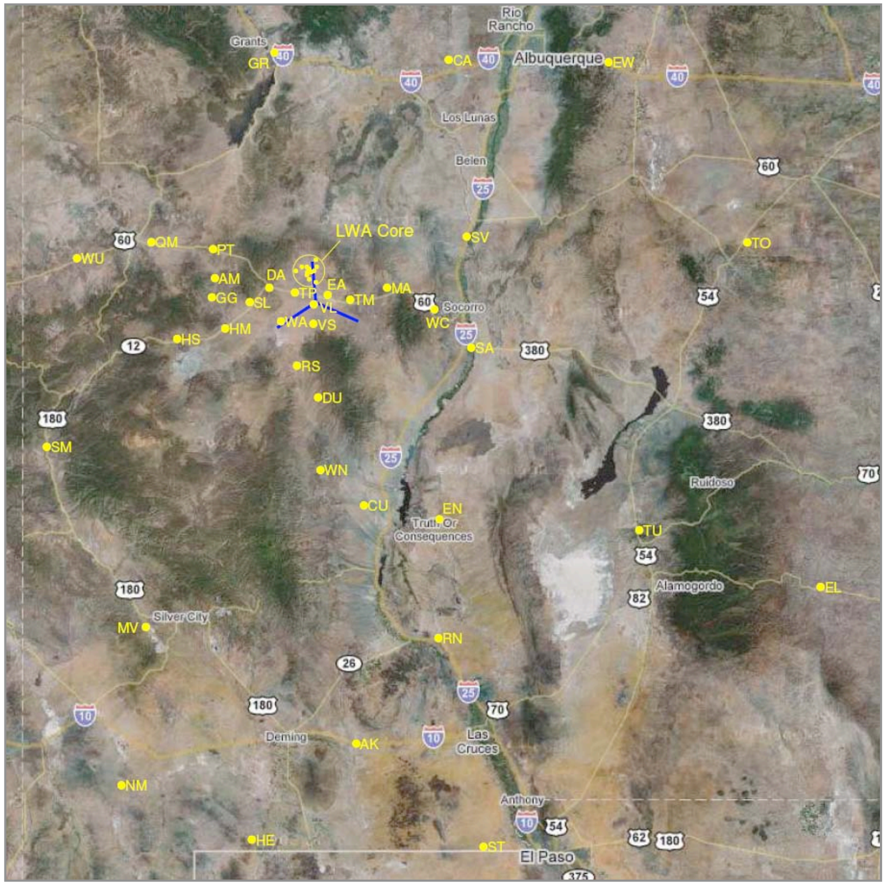
The University of New Mexico

Introduction
and Agenda

The University of New Mexico

LWA

- The LWA project will provide a world-class instrument for the study of space physics and astrophysics by means of radio interferometric measurements below the FM band (i.e., < 88 MHz).
- It is expected that the complete LWA will be composed of 52 stations, each consisting of > 250 broad-banded dipoles spread over a ~ 100 m diameter area. These stations will be spread across New Mexico, with maximum baselines of ~ 400 kilometers.



- Current project partners: UNM, Naval Research Lab, University of Texas Applied Research Lab, Los Alamos National Lab, Virginia Tech, University of Iowa

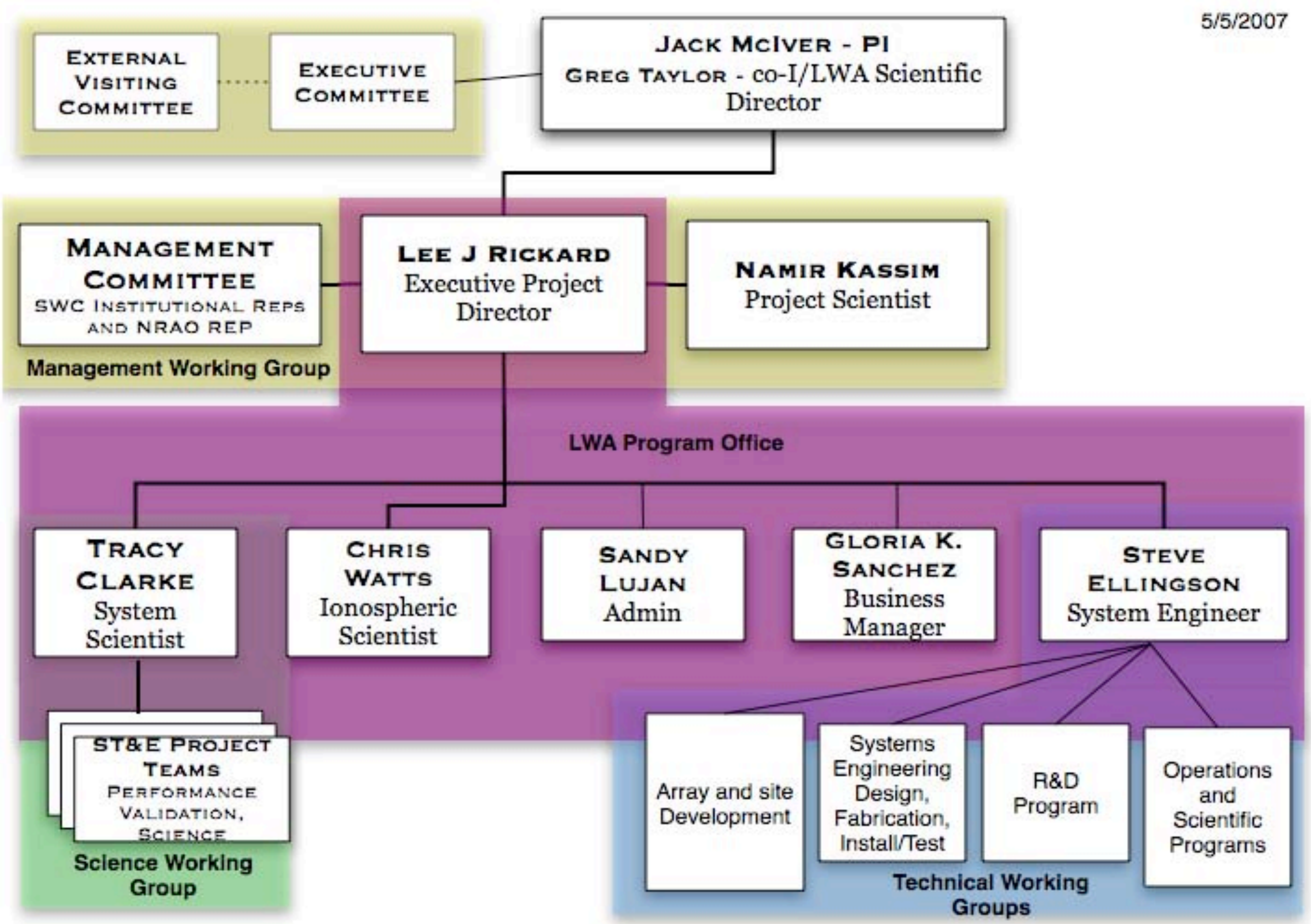
The University of New Mexico

Purpose of This Meeting

LWA

- LWA Project funding was received at UNM on April 6, 2007.
- Funds have been distributed to partners to begin design work. Program Office has been established; program plan development is under way.
- We want to acquaint the general community of potential users with our current and planned activities.
- As we approach System Requirements Review, it is important to ensure that all scientific requirements are captured.
- In particular, we want to get early input from the space physics community as we proceed towards the system specification.

LWA Project



5/5/2007
External Visiting Committee
Executive Committee
Jack McIver - PI
Greg Taylor - co-I/LWA Scientific Director
Management Committee
SWC Institutional Reps and NRAO Rep
Management Working Group
Lee J Rickard
Executive Project Director
Namir Kassim
Project Scientist
LWA Program Office
Tracy Clarke
System Scientist
Chris Watts
Ionospheric Scientist
Sandy Lujan
Admin
Gloria K. Sanchez
Business Manager
Steve Ellingson
System Engineer
ST&E Project Teams
Performance Validation, Science
Science Working Group
Array and site Development
Systems Engineering Design, Fabrication, Install/Test
R&D Program
Operations and Scientific Programs
Technical Working Groups

Phased Development Plan

Date	Phase	Milestone Description	Acronym
To 2006	0	Existing 74 MHz VLA	VLA74
2006 Q4	Ia	NRL/ARL Long Wavelength Demonstration Array	LWDA
2007 Q4	Ia	System Requirements Review	SRR
2008 Q1	Ia	Preliminary Design Review for First LWA Station	LWA1+ PDR
2008 Q4	Ia	Critical Design Review for First LWA Station	LWA1+ CDR
2009	Ib	Long Wavelength Array Station #1 + Options	LWA1+
2009-2011	IIa	9 Station Long Wavelength Intermediate Array	LWIA-9
2011-2013	IIb	16 Station LWIA with Partial Core	LWIA-16
2013-2015	III	High Resolution LWA	LWA
2010-	IV	LW Operations and Science Center	LWOSC

Agenda

- Introduction and agenda – Gilfeather
- LWA Project Context – Rickard
- ONR Project Context – McCoy
- LWA Scientific Capability
  - Space Physics Perspective – Watts
  - Astrophysics Perspective – Kassim
  - Recent LANL Work – Colestock
  - Lessons Learned from LWDA – Munton
- LWA Plan
  - Technical Concept – Ellingson
  - Program Plan – Rickard
  - Site Acquisition – Taylor
  - Opportunities for Collaborations – Taylor

The Long Wavelength Array (LWA) Project in Context

Lee J Rickard

LWA Executive Project Director

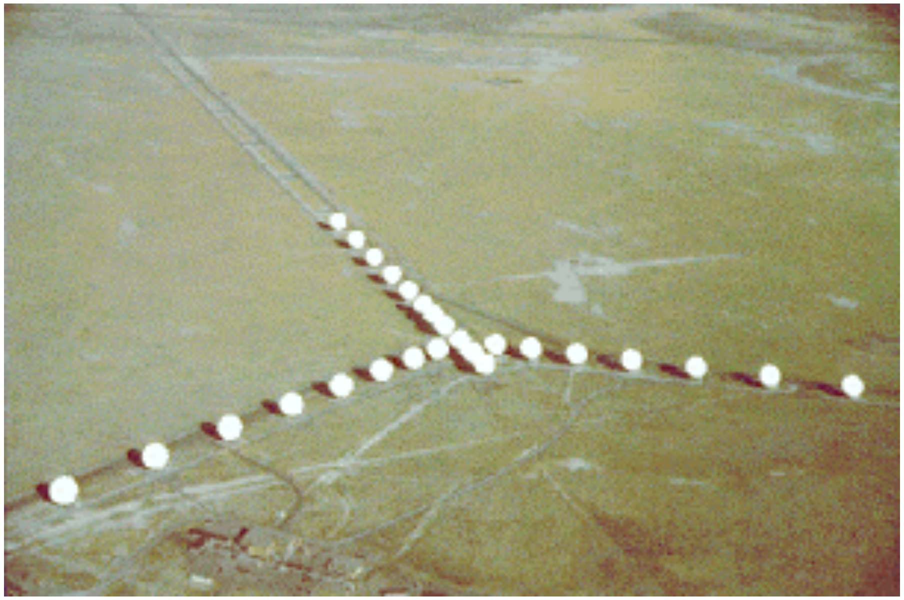
University of New Mexico

<http://lwa.unm.edu/>

Radio Interferometry

(AKA aperture synthesis – Fourier transform imaging)

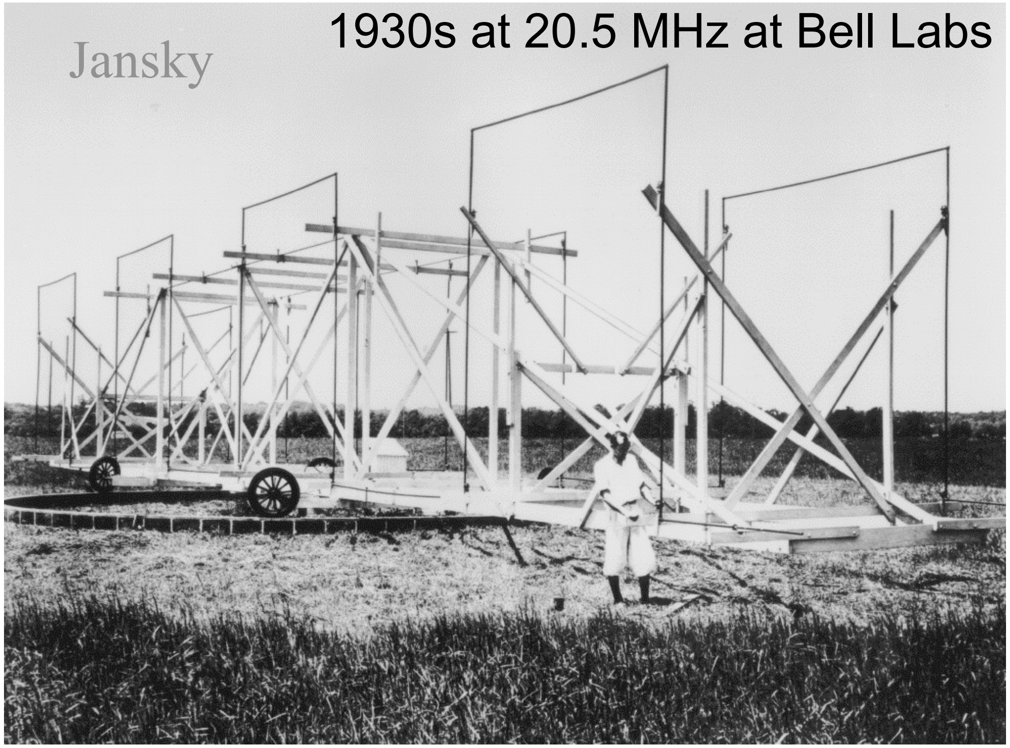
NRAO VLA, New Mexico

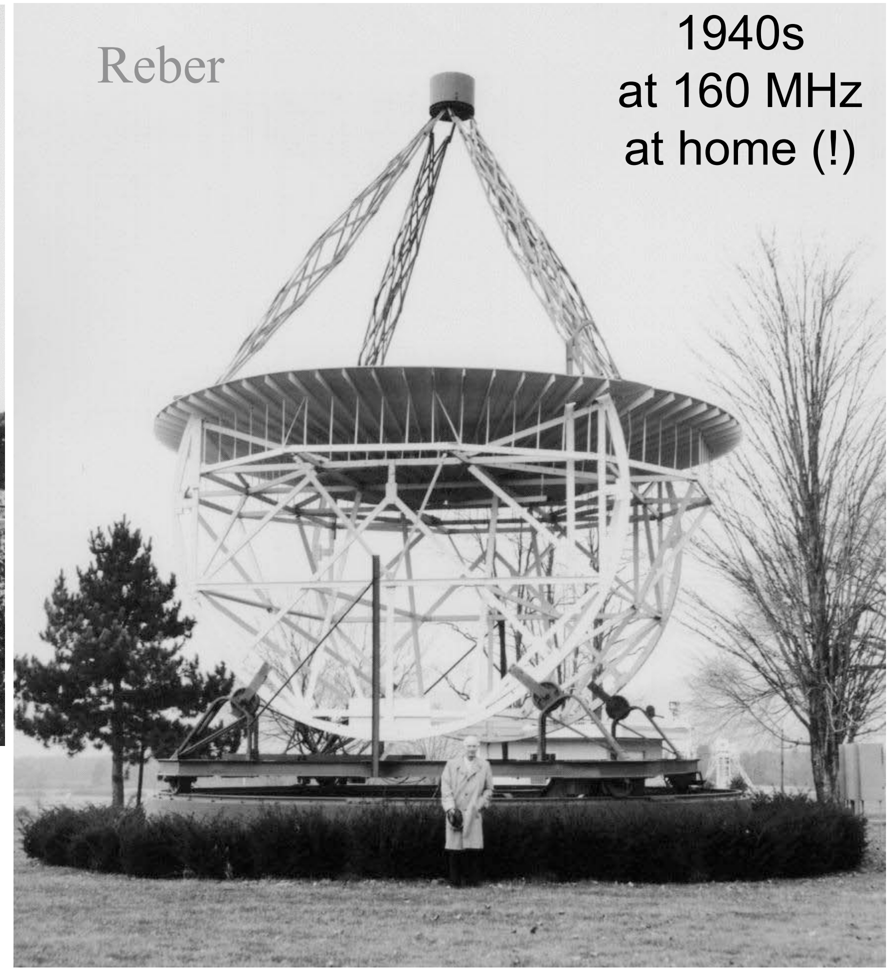


- Pairs of antennas measure the Fourier transform of the sky brightness.
- Earth rotation changes the orientation of the interferometer as seen from source, so we measure additional Fourier components.
- The maximum baseline (antenna separation) determines the highest angular resolution.
- The size and number of antennas determines the sensitivity.
- At cm wavelengths, typical angular resolutions are $\theta \sim 1''$ (i.e., 5 μrad), and sensitivities are mJy/beam.

(1 mJy is –290 dB W m^{-2} Hz^{-1})

Some History





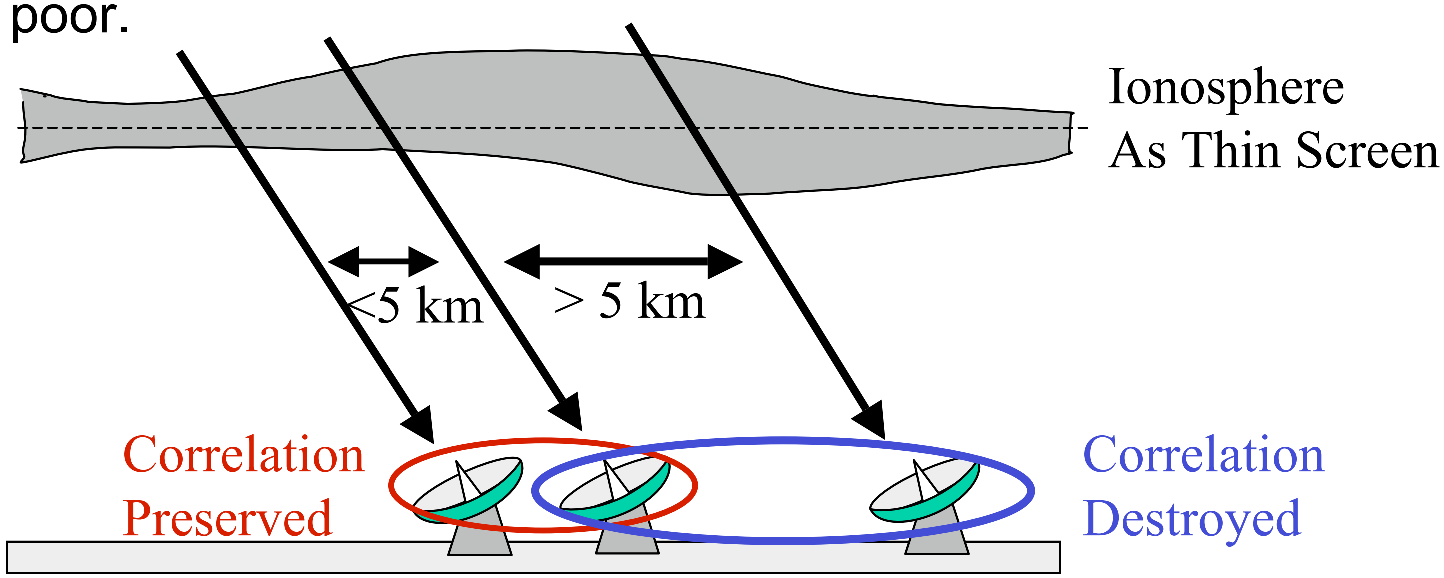
1940s: Most celestial emission is nonthermal.

1950s: Discrete background sources measured with aperture synthesis.

1970s: High-resolution cm-λ interferometers developed.

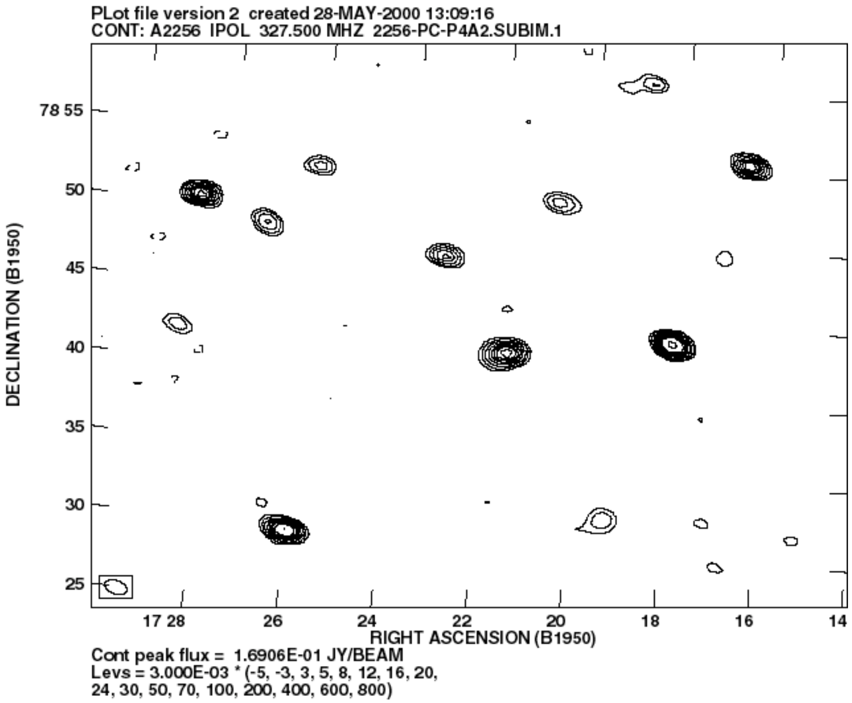
Low Frequency Radio Astronomy Was Left Behind

- "Low Frequency" here refers to HF & VHF (i.e., < 300 MHz)
- Need interferometric imaging to achieve useful angular resolution (and, because of confusion effects, sensitivity).
- But the scale of HF/VHF interferometry was severely limited by ionospheric decorrelation. (At 75 MHz, a column density fluctuation of 10^{14} m^{-2} produces a phase offset of 1 radian!)
- As a result, baselines were limited to a few km, and imaging was poor.

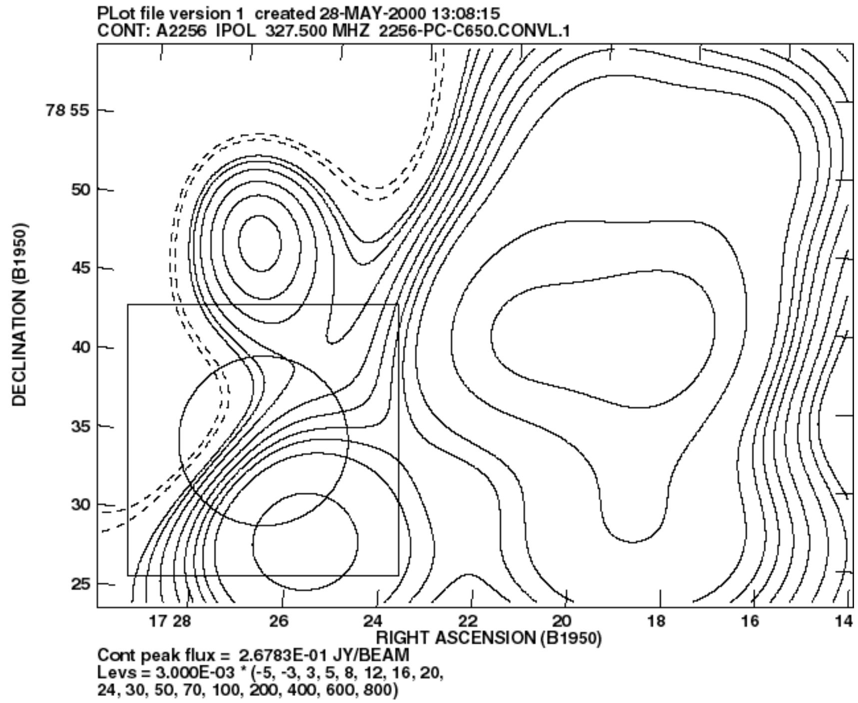


Low Angular Resolution Limits Sensitivity Because of Source Confusion

θ ~ 1’, rms ~ 3 mJy/beam

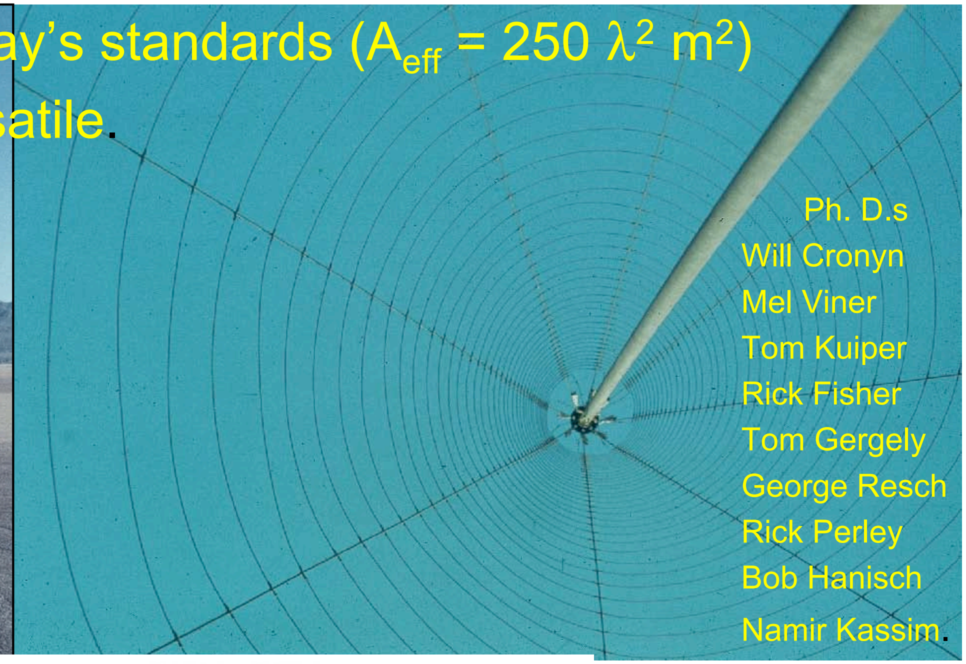


θ ~ 10’, rms ~ 30 mJy/beam

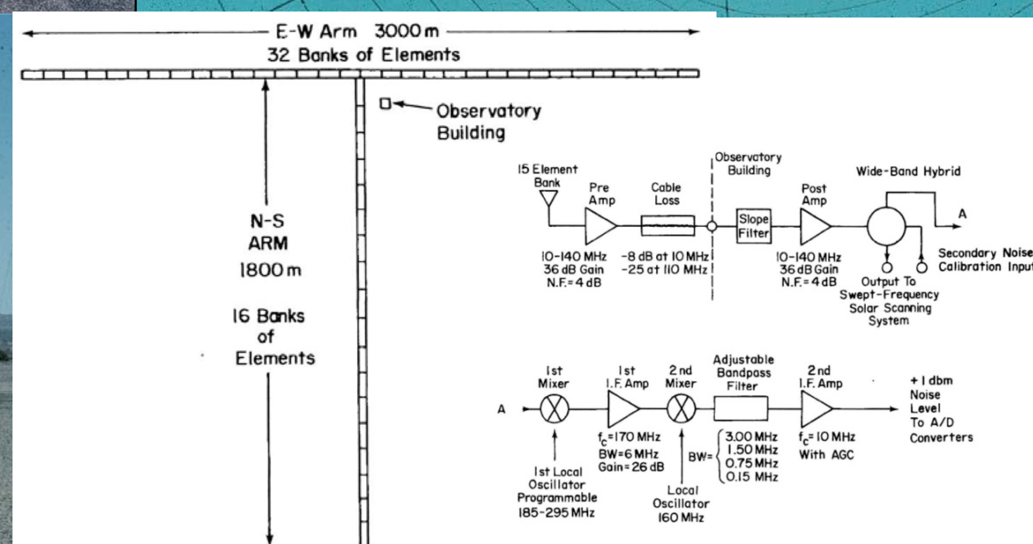


Pre-LWA: The Clark Lake TPT

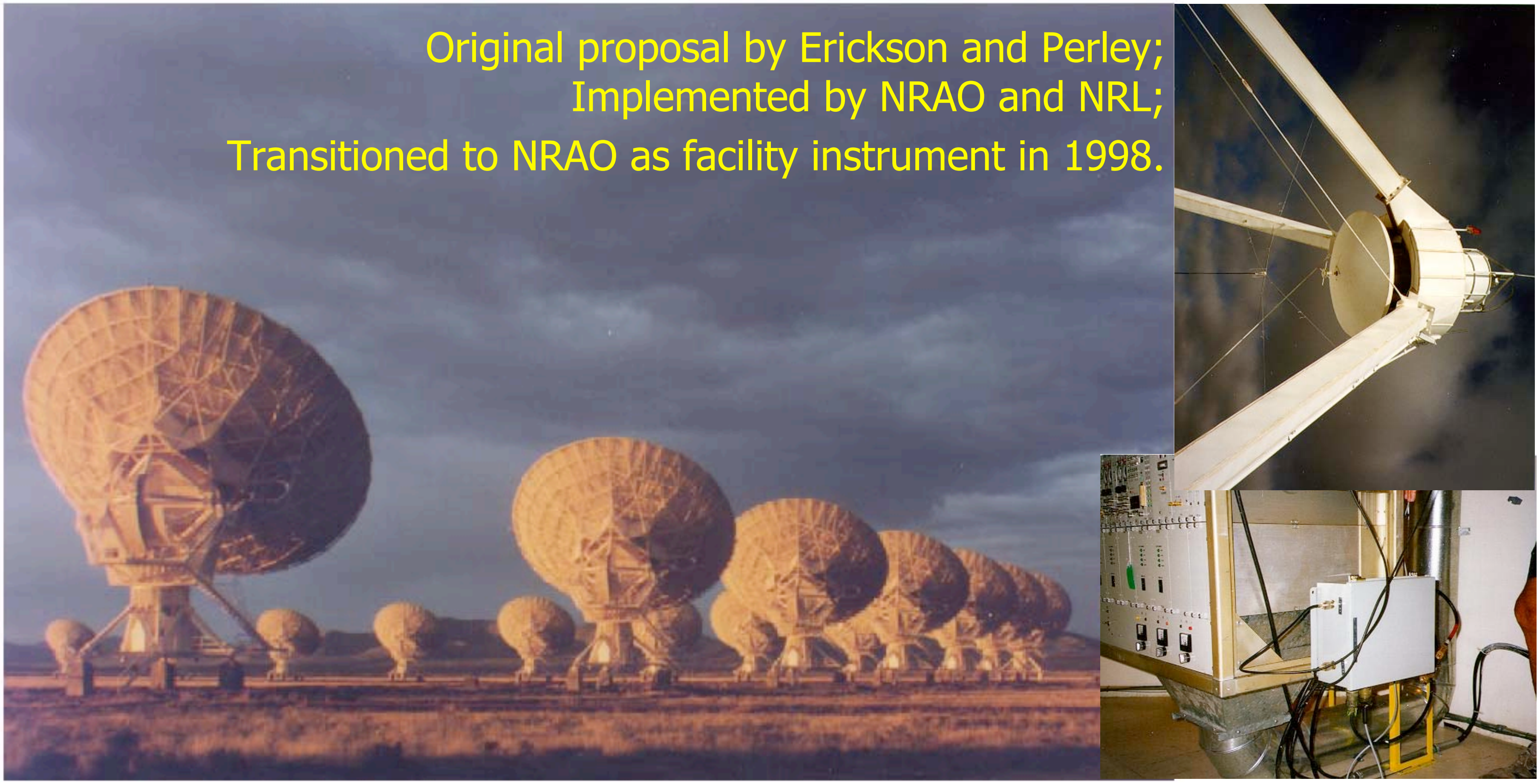
- Broad-band (15 – 123 MHz) instrument developed by Bill Erickson
- Moderate collecting area by today's standards ($A_{eff} = 250\ \lambda^2\ m^2$)
- Fully electronic, so fast and versatile.



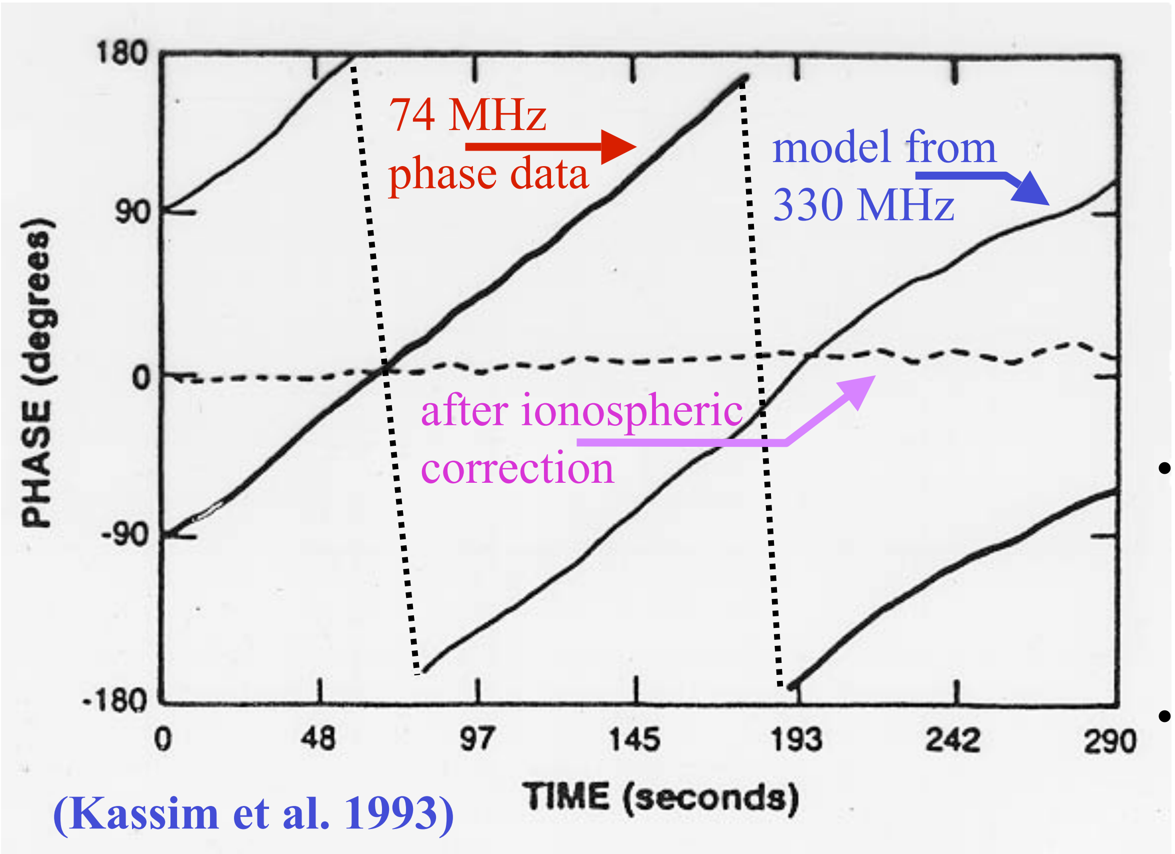
Ph. D.s
Will Cronyn
Mel Viner
Tom Kuiper
Rick Fisher
Tom Gergely
George Resch
Rick Perley
Bob Hanisch
Namir Kassim.



The 74 MHz NRL-NRAO VLA System



Phase Transfer



(Kassim et al. 1993)

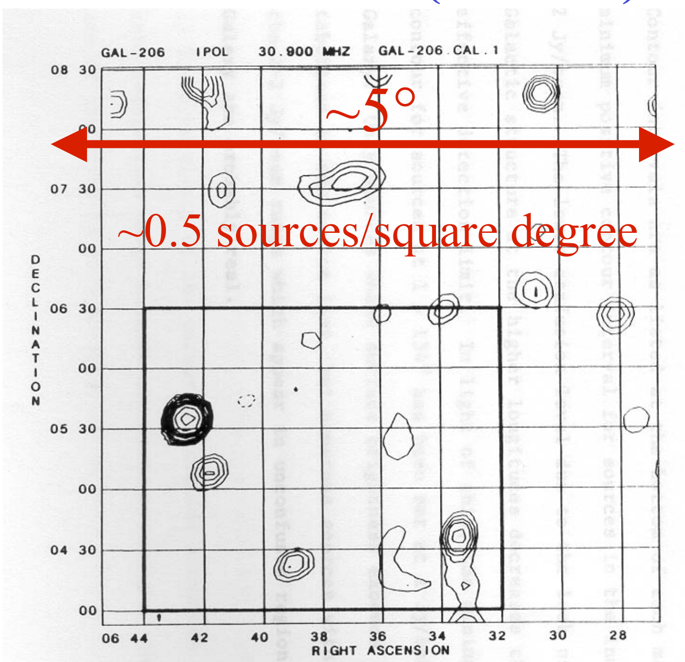
- At 74 MHz, a perturbation of 1% in TEC (such as a TID with a wavelength of 30 km moving at a speed of 100 km/hr) causes a phase offset of 10 radians between antennas 30 km apart, and changes the phase at a rate of 1 rad/min.
- This can be modeled and removed by observing the same source at a higher frequency.
- Self-calibration (using the target as the phase reference) can remove residual effects.

74 MHz VLA System

- Prototype system, 1993–1997; demonstrated phase transfer.
- Full (N = 27) system, 1998; demonstrated that self-calibration alone can correct much of the ionospheric effect.
  - Over-determined problem manageable with high N array and initial model.
  - Works well at VLA (N=27).
  - Generates archive of high-precision ionospheric measurements.
- VLA 74 MHz system is now the most powerful long wavelength interferometer in the world.
- Working with the VLA at 330 MHz and the Indian GMRT, it is also demonstrating solutions to other problems:
  - Radio frequency interference (RFI) detection and excision
  - "3D imaging" (correcting for the fact that, because of the large field of view of the array, the Fourier inversion is no longer a two-dimensional problem)

Comparison of Low Frequency Performance

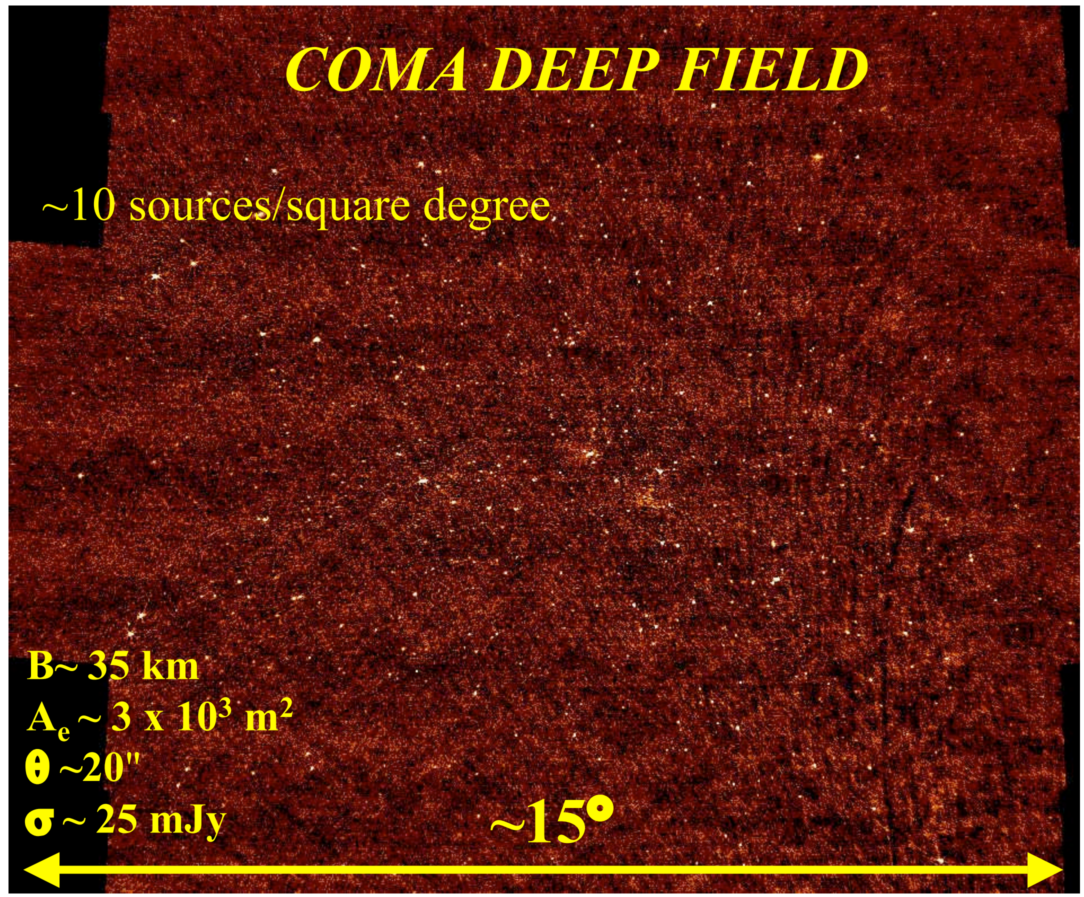
Clark Lake (30 MHz)



Kassim 1989

- B ~ 3 km
- A_e ~ 3 x 10^3 m^2
- θ ~ 15' (900")
- σ ~ 1 Jy

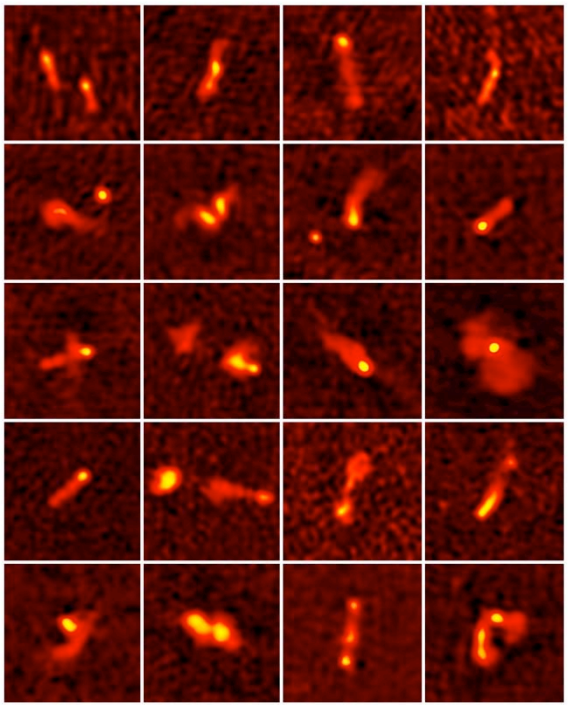
VLA (74 MHz)

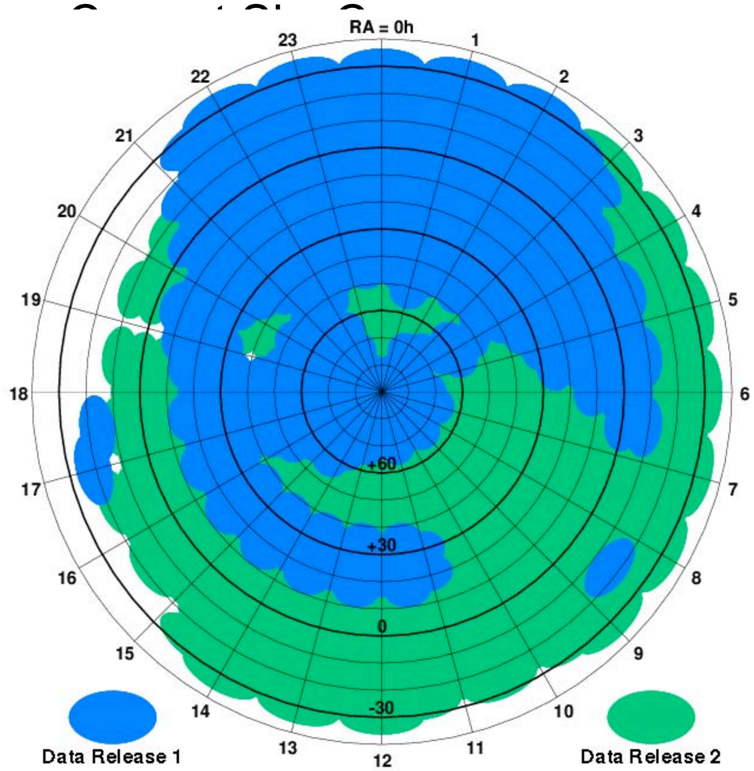


Enßlin *et al*. 1999

VLSS: The VLA Low-Frequency Sky Survey

Source Samples





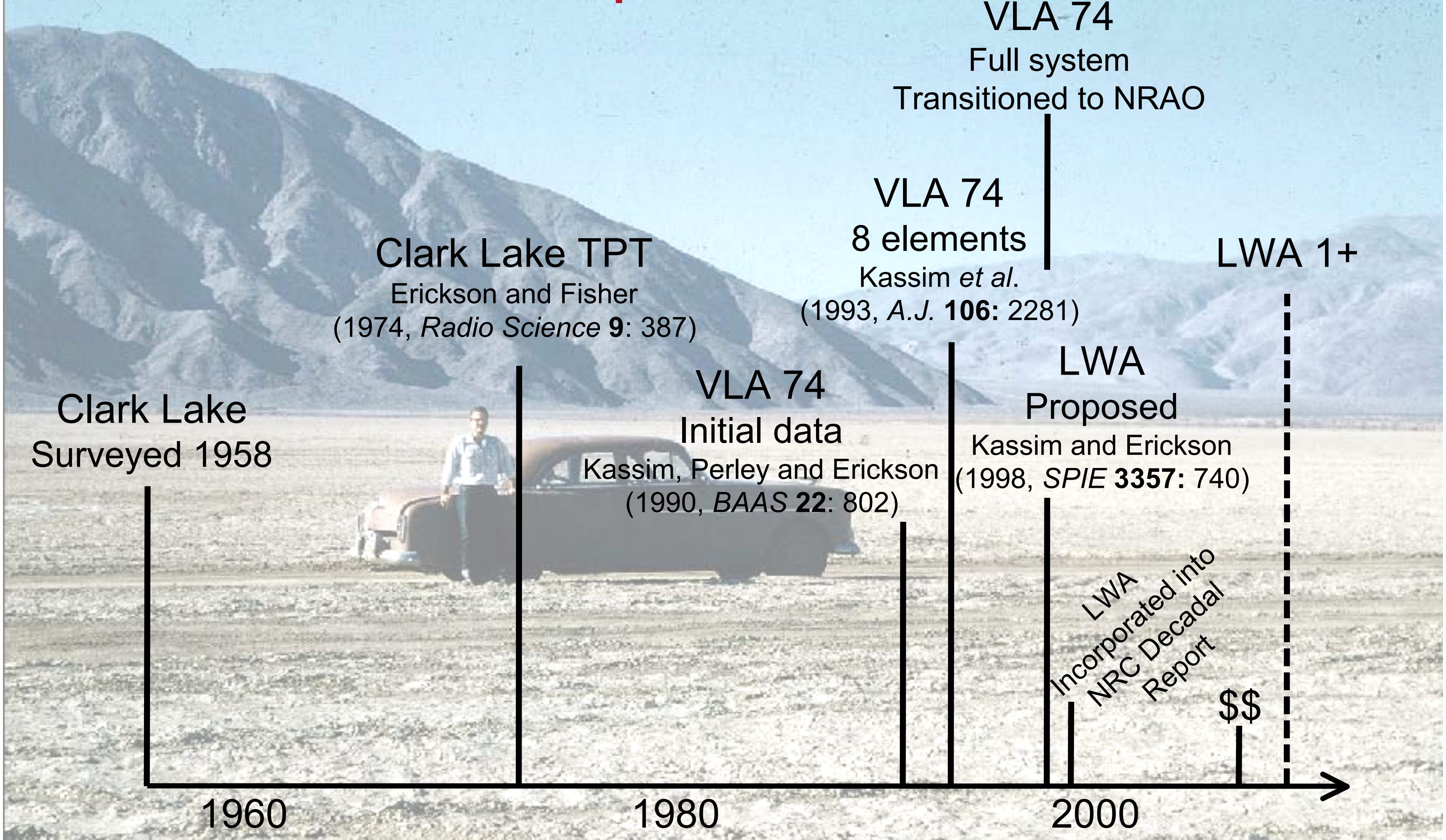
- Over 95% successfully completed.
- Over 67,000 sources detected.
- Demonstrates success of HF/VHF Adaptive Optics within limited regime of VLA 74 MHz system.

Most powerful low frequency sky survey to date

http://lwa.nrl.navy.mil/VLSS

Cohen *et al.* 2007 *Astron. J.* **134** *1245*

Steps to LWA



VLA 74
Full system
Transitioned to NRAO
VLA 74
8 elements
Kassim *et al*.
(1993, *A.J.* **106:** 2281)
Clark Lake TPT
Erickson and Fisher
(1974, *Radio Science* **9**: 387)
LWA 1+
LWA
Proposed
Kassim and Erickson
(1998, *SPIE* **3357:** 740)
VLA 74
Initial data
Kassim, Perley and Erickson
(1990, *BAAS* **22**: 802)
Clark Lake
Surveyed 1958
LWA
Incorporated into
NRC Decadal
Report
$$
1960
1980
2000

HF/VHF Astrophysics

- This frequency range favors studies of nonthermal (synchrotron) sources.
  - Intrinsic link to shock physics, high energy phenomena (> MeV electrons)

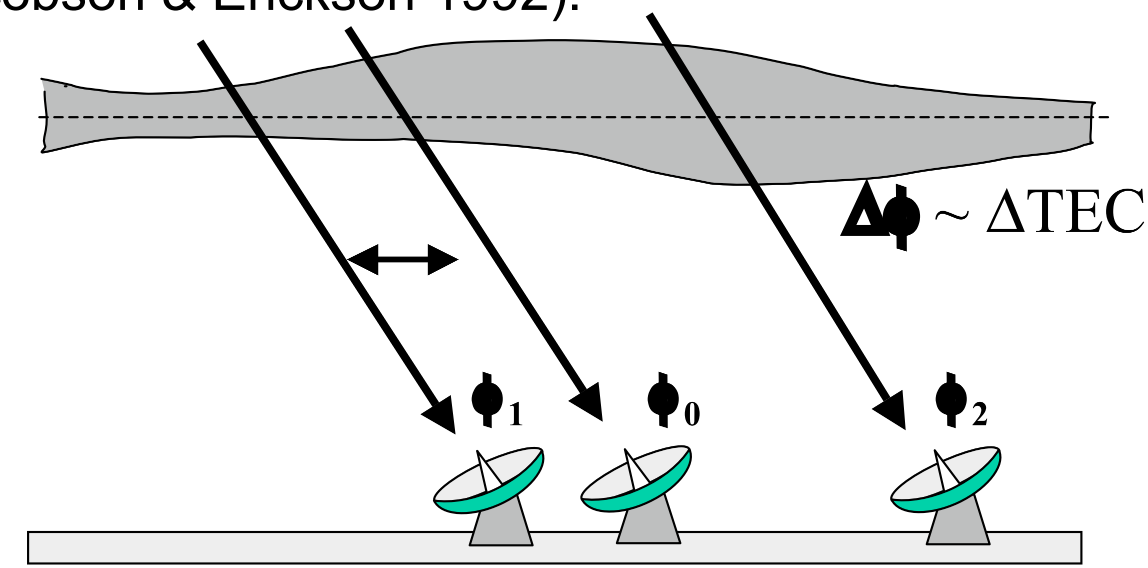
- It also provides unique insights into the interaction of thermal & nonthermal phenomena, e.g., through studies of self-absorption processes.

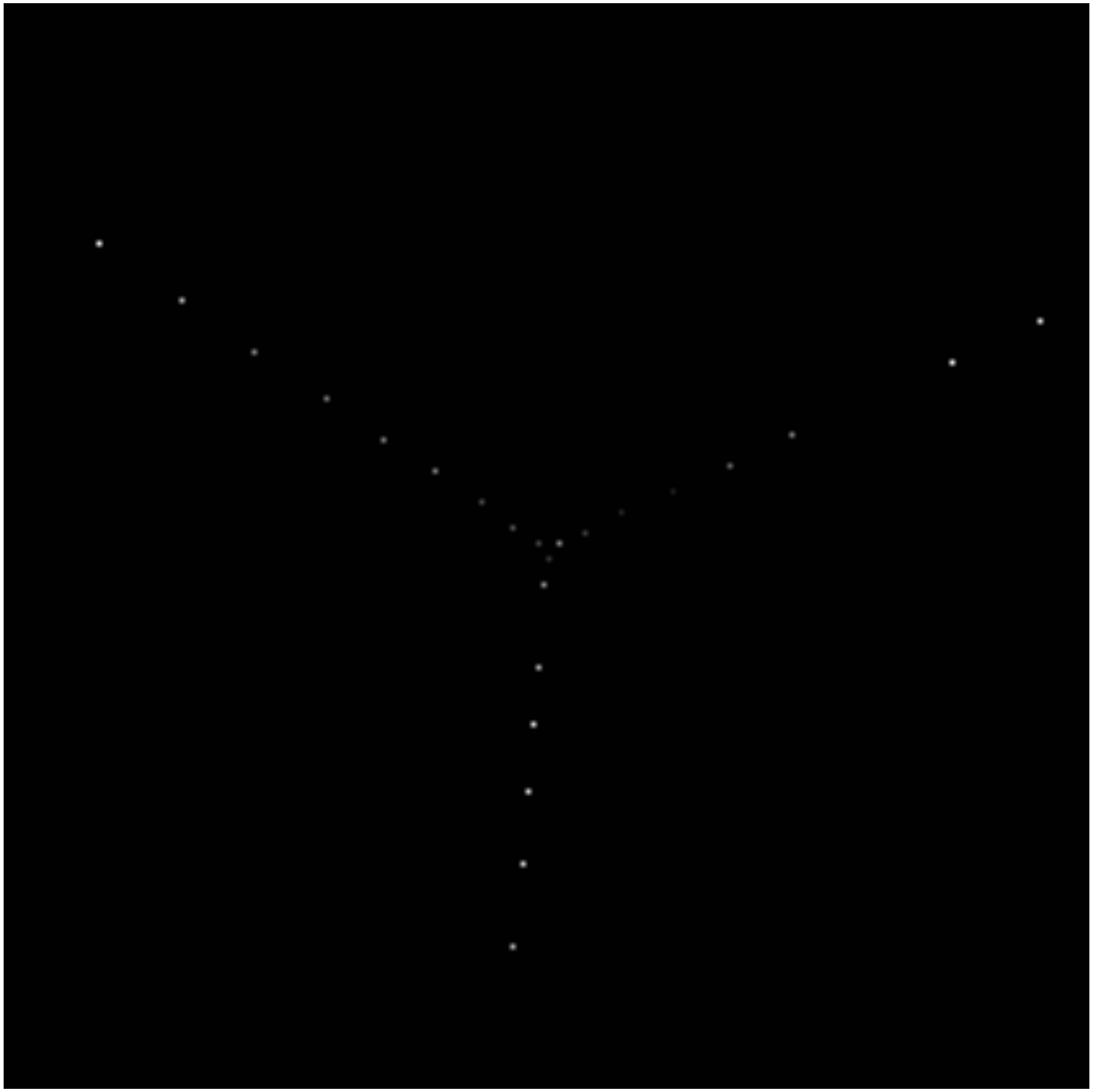
- The large field of view and high surface brightness sensitivity are often advantages in providing synoptic views of astrophysical phenomena.

- The objects studied range from local (solar) to Galactic (star forming regions, supernova remnants, pulsars) to extragalactic (energetic galaxies, galaxy clusters, cosmological effects).

VLA 74 MHz System as an Ionospheric Probe

- Self-calibration (with enough antennas) enables deriving offset phases for each antenna. The phase differences are sensitive measures of ΔTEC.
  - $\Delta\phi$[radians] ~ 0.85 [ΔTEC/mTECU] / [ν/100 MHz]
  - Variable gradients of the magnitude of ~0.1% of the TEC per km are very common except under unusually quiet ionospheric conditions.
  - The VLA measures $\Delta\phi \sim (1/30)$ rad, or ~ 3×10^{-5} TECU.
- Ionospheric waves have a wide spectrum of spatial and temporal scales which include the baseline lengths and time periods over which we observe (Jacobson & Erickson 1992).
- With a self-cal solution, each source direction produces a set of (N-1) ΔTEC measurements (N = # of antennas).

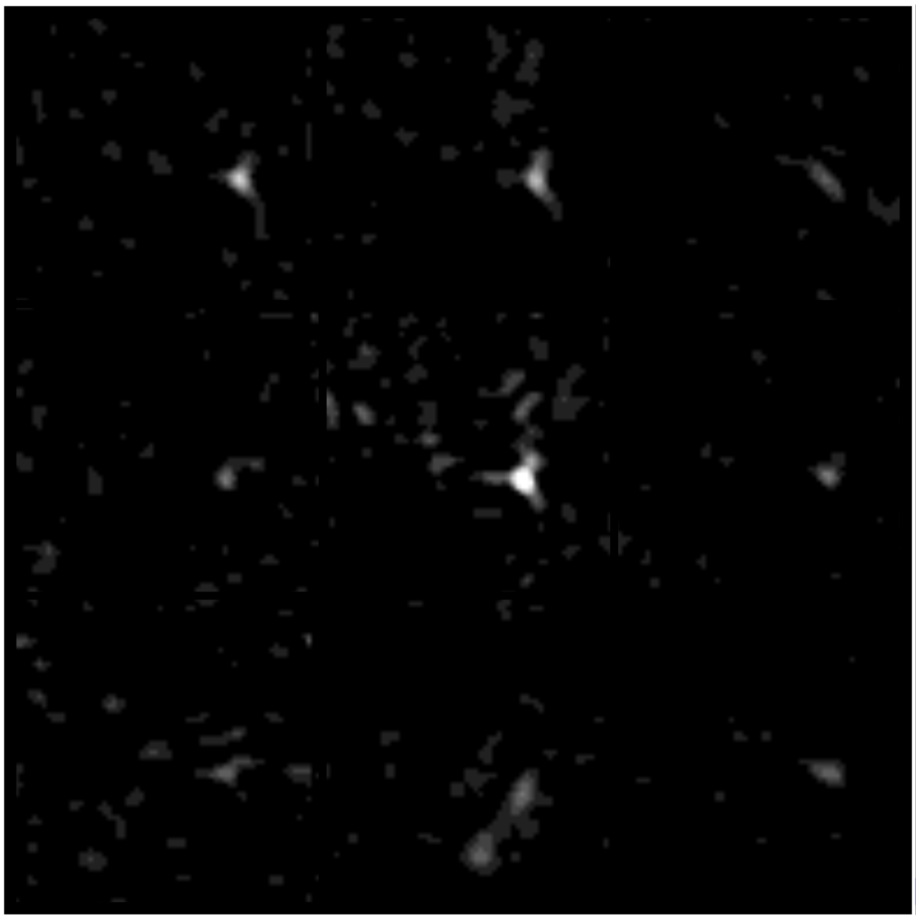




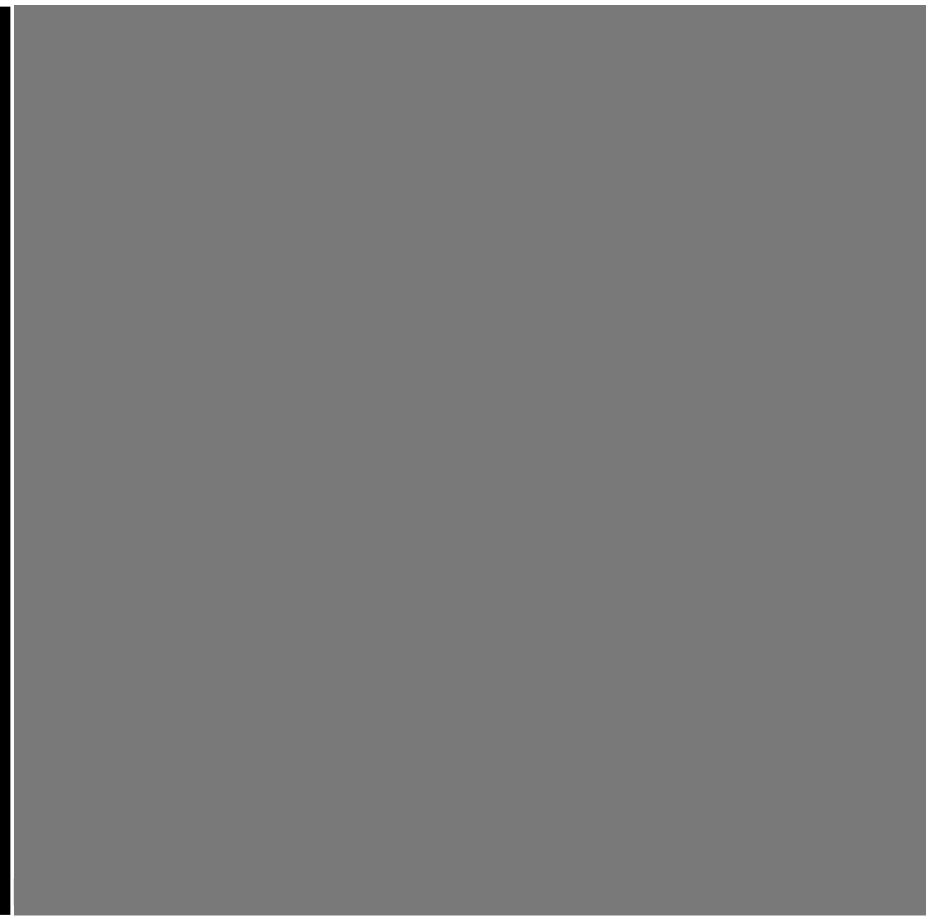
Field-based Calibration

Zernike polynomial fitting procedure developed by Bill Cotton (NRAO) demonstrated range of ionospheric effects extractable from VLA 74 MHz data.

Sources selected from field



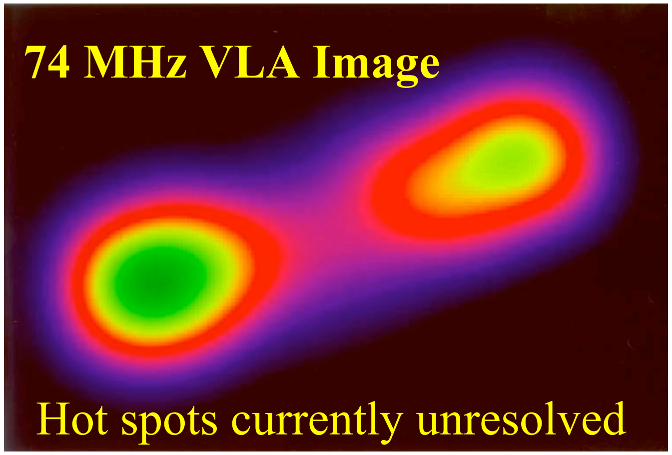
Zernike Model



Biggest Problem: We Need Something *Much Larger*

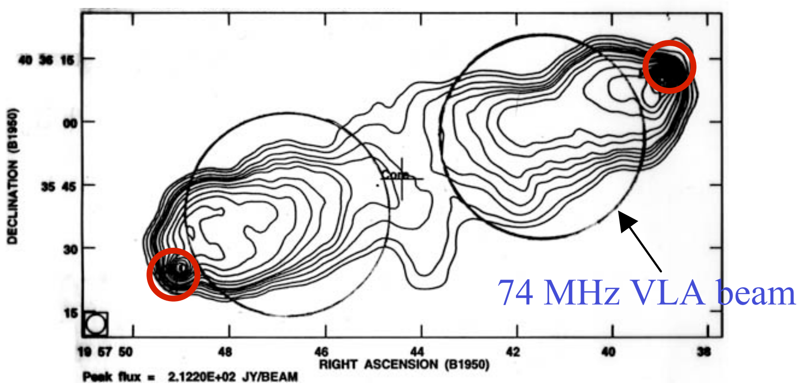
- The VLA was not designed to provide good sensitivity below 1000 MHz: ε ~15%, sidelobes ~ 20dB, T_{sys}/A_e too high, single frequency
- Below 150 MHz: need much more **collecting area** ($A_e \sim 10^{5\text{-}6}$ m^2) spread over much **wider area** (≤ 500 km) - also **need broad-band response** and ability to observe **multiple narrow frequency channels**
- Technically:
  - Front-end dominated system temperature scales as $\lambda^{2.6}$, driving A_e
  - λ /D dependence of angular resolution affects sensitivity via confusion (number of background sources in beam)
- Scientifically Crucial
  - Many (most?) astrophysical applications demand it
    - Steep-spectrum sources, compete against higher frequency systems
    - Cosmic rays, high redshift universe, epoch of reionization
  - Radar applications: solar radar & CMEs, magnetospheric physics
  - Ionospheric physics applications: spatial and temporal TEC spectra

Why We Need Higher Angular Resolution

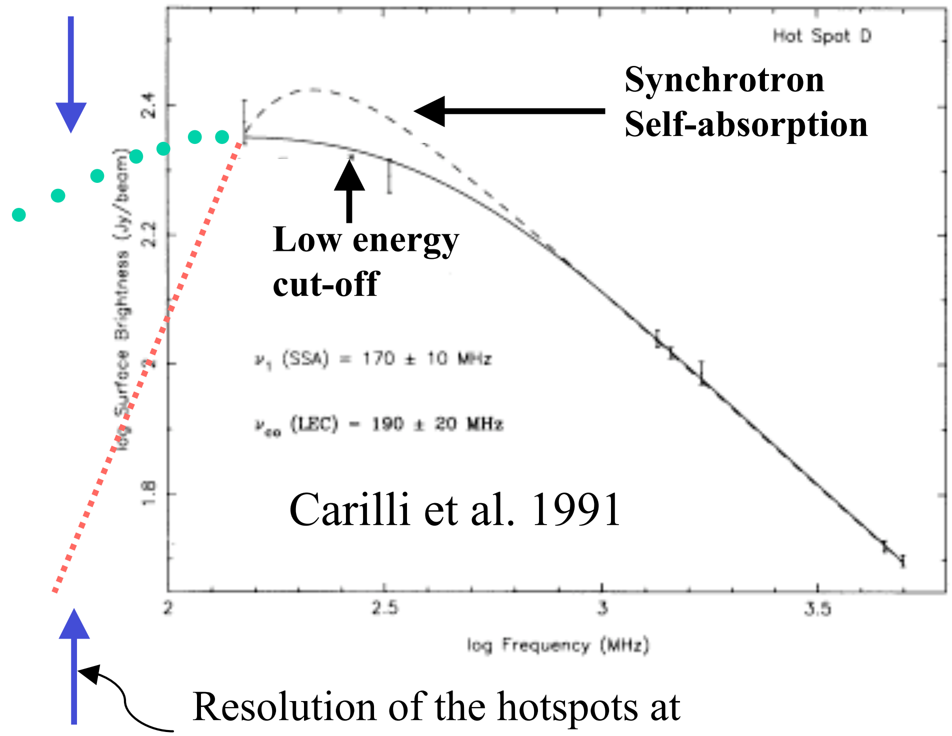


Kassim et al. 1996

330 MHz VLA Image



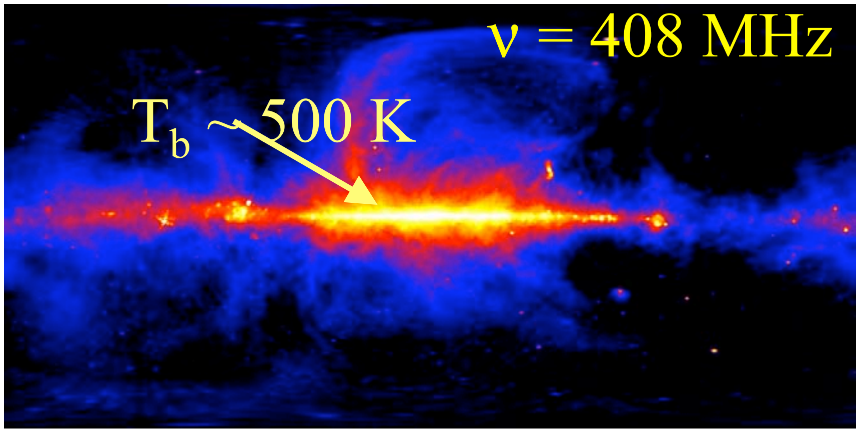
○ ➔ "Hotspots"

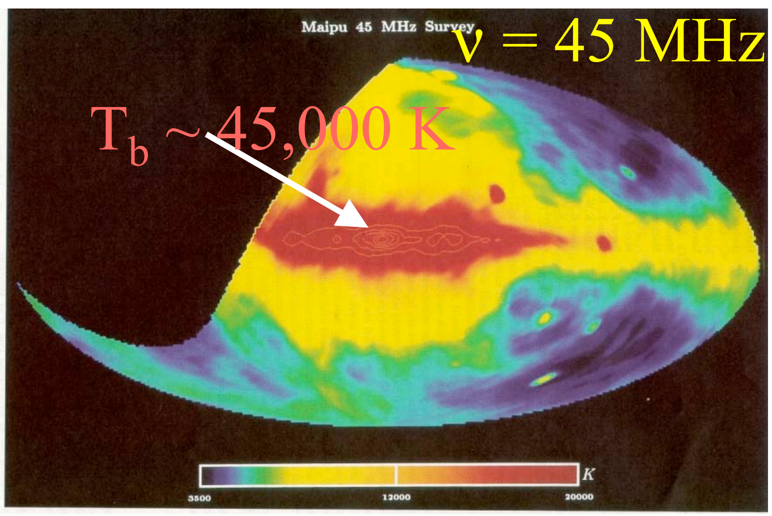


Resolution of the hotspots at 74 MHz will differentiate easily between competing models for spectral turnover

Note also desire for broad-band

Why We Need More Collecting Area





The sensitivity of our observations is gauged by the rms noise, which is

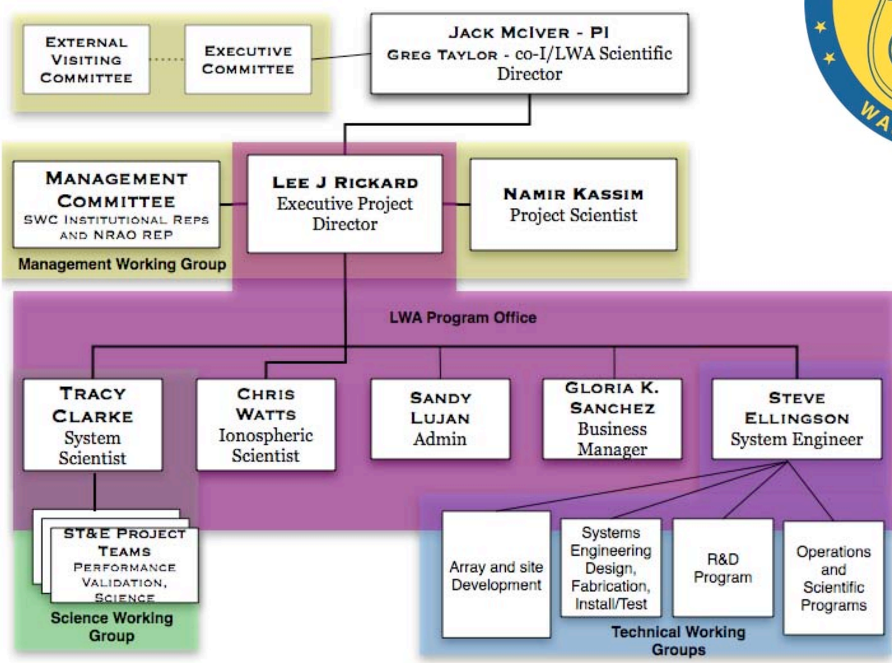
$\sim T_{sys}/A_{e}.$

At higher frequencies, the noise includes effects of both receiver and sky. Better receivers mean better sensitivity.

At low frequencies, the sky noise dominates the system. Only collecting area can improve the sensitivity.

LWA Project

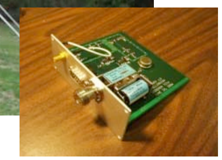
Southwest Consortium formed 2003, after LOFAR site decision.



LWA Project funded in FY 06 budget; funds received April 6, 2007.

LWA Team Brings Wide Range of Capability to the Project

High Dynamic Range Direct Sampling
RFI Mitigation

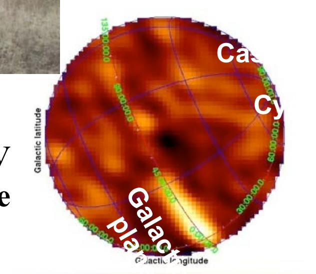


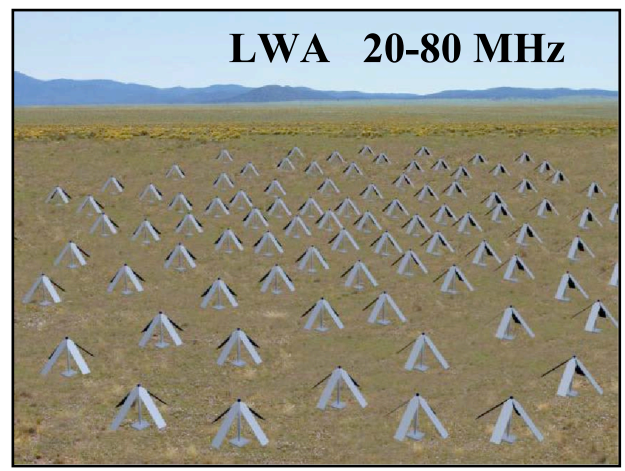
20-80 MHz
Receiver

High-Resolution Imaging,
Ionospheric Calibration

Low Self-RFI Design (to EVLA stds)

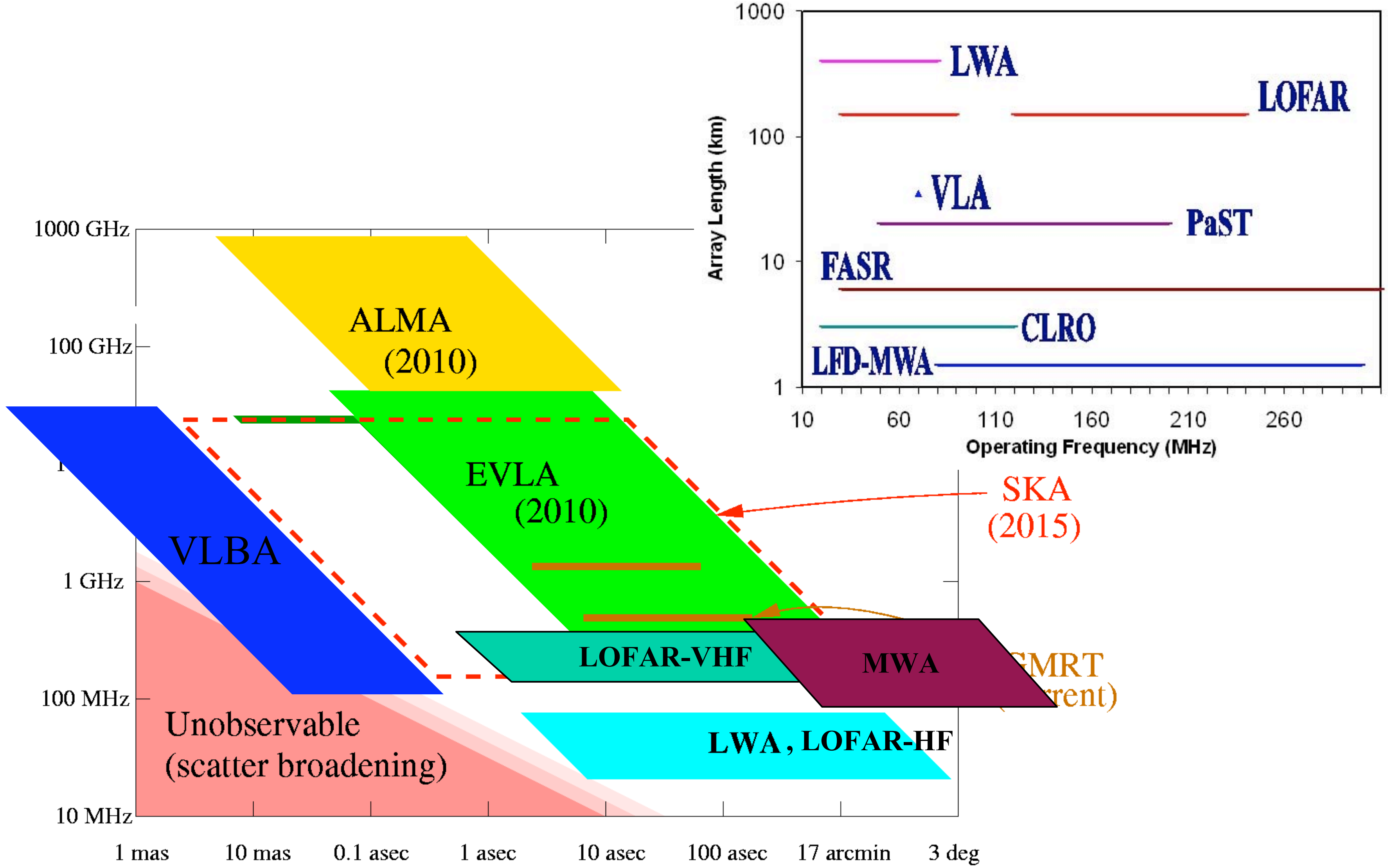
Large FOV
Experience

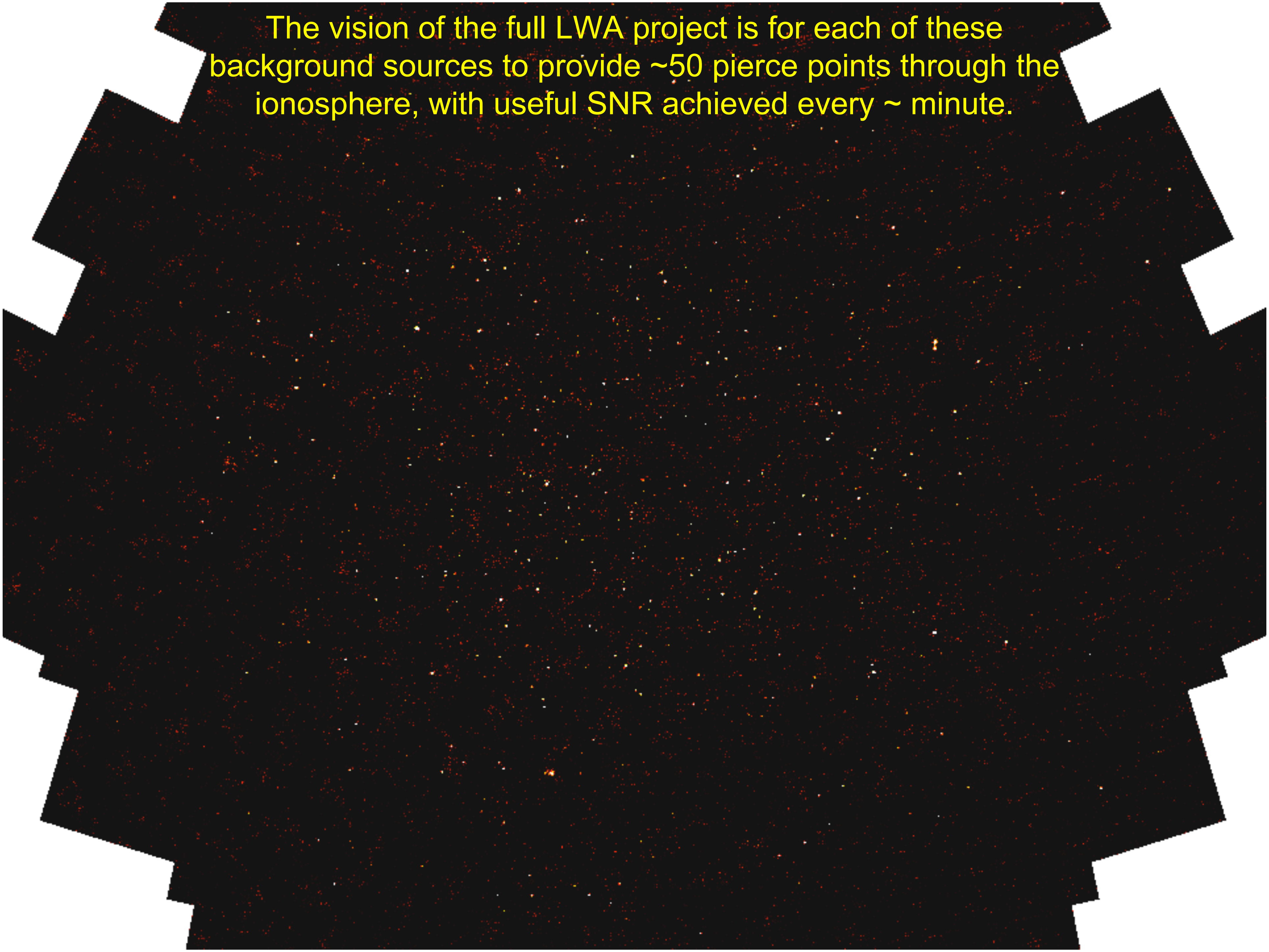




LWA Discovery Space

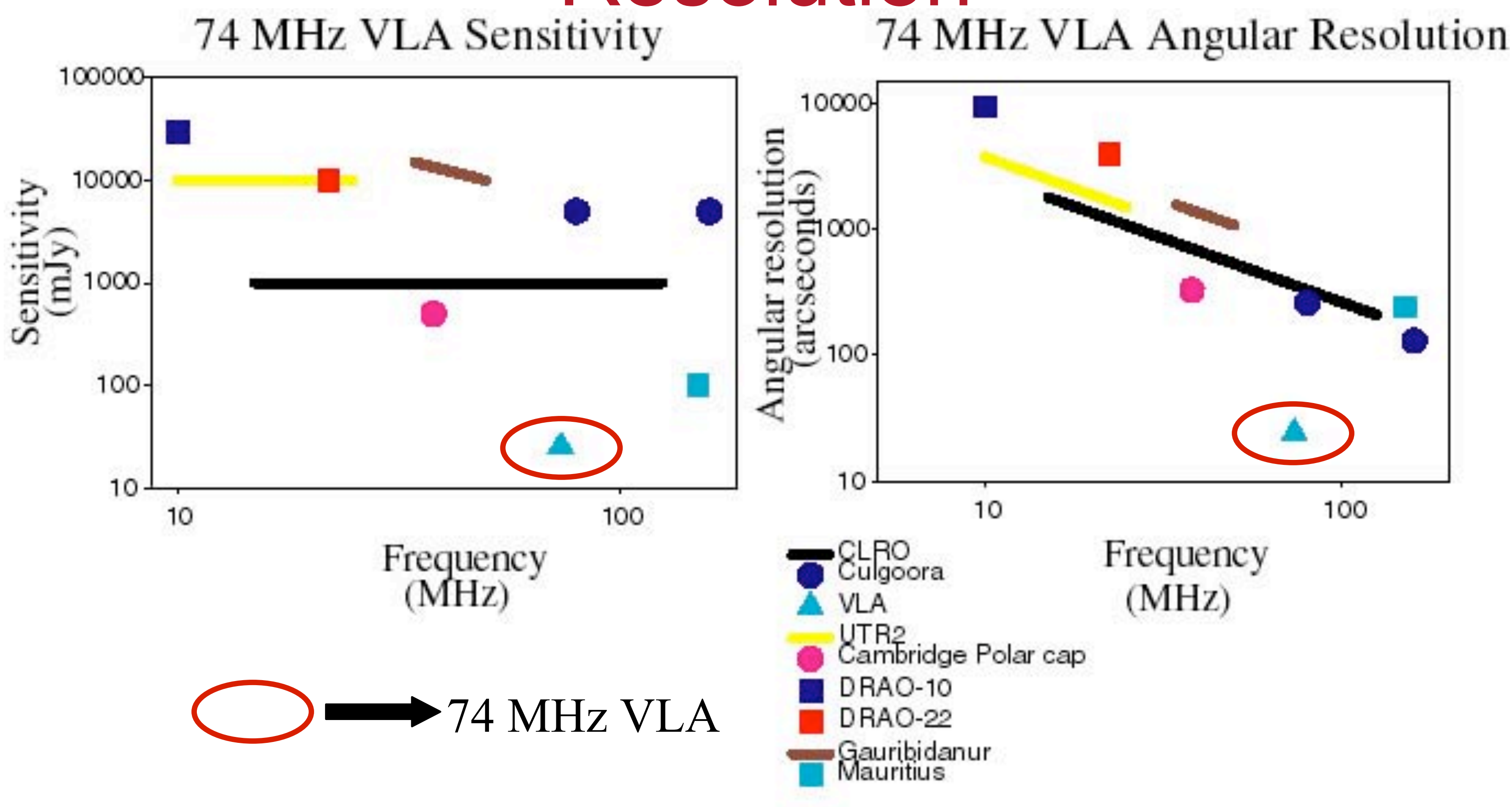
(in frequency and resolution)




The vision of the full LWA project is for each of these
background sources to provide ~50 pierce points through the
ionosphere, with useful SNR achieved every ~ minute.

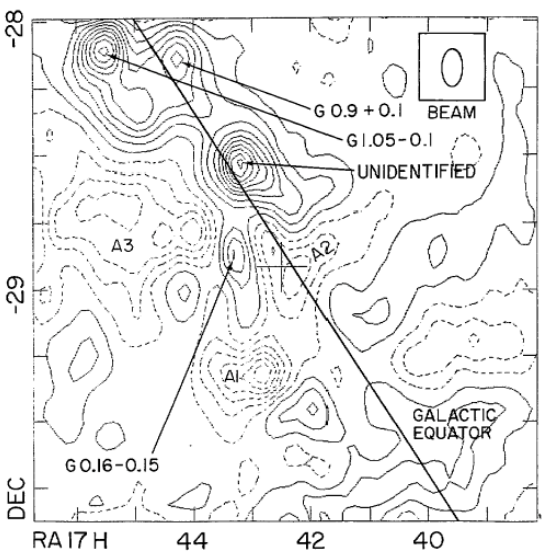
Backup Slides

74 MHz VLA: Significant Improvement in Sensitivity and Resolution



Steps to LWA

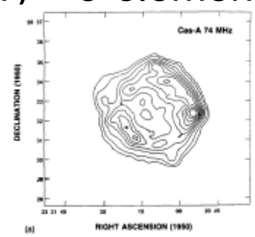
Clark Lake Heritage

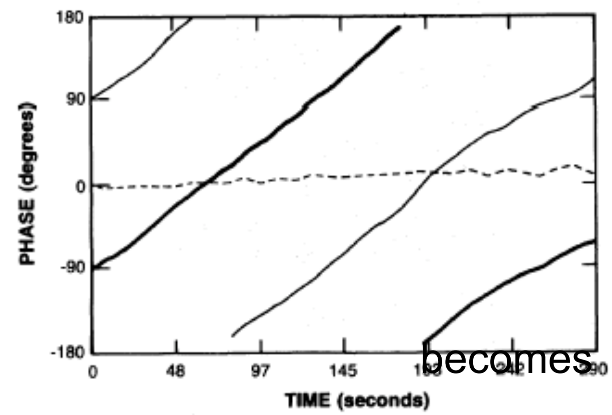


LaRosa and Kassim (1985, *Ap. J. (Lett.)* **299**: L13) – Galactic Center at 80 MHz

74 MHz VLA System and Beyond

- 1990 Kassim, Perley and Erickson (1990, *BAAS* **22**: 802) – Report of first observations with initial 74 MHz system
- Kassim et al. (1993, *A.J.* **106:** 2281) – 8-element VLA data





- 1998 – full 74 MHz system becomes VLA facility instrument
- Kassim and Erickson (1998, *SPIE* **3357:** 740) – proposal to build large low-frequency array
- 1999 – concept incorporated in NAS Decadal Plan
- 2000 – establishment of International LOFAR Consortium
- 2003 – establishment of SouthWest Consortium

Space Weather – Learn from the Meteorologists

Dr. Robert McCoy
321 SP
Office of Naval Research
(703) 696-8699
bob.mccoy@navy.mil

Outline

- Motivation for Improved Ionospheric Specification & Forecast
- Data Assimilation – Comparisons with Meteorology - GAIM
- New Ionospheric Satellite Data Sources
  - UV (SSULI & SSUSI) on DMSP; GPS Occultation (COSMIC)
  - Remote Atmospheric & Ionospheric Detection System (RAIDS) on the ISS
- Ionospheric Irregularities & Scintillation Storms – Geostationary Imagery
- New Themospheric & Ionospheric Modeling Initiatives
  - DTRA Seamless Model Ocean to Space
  - 2007 AFOSR MURI for Neutral Atmosphere
  - 2008 ONR Departmental Research Initiative (DRI) Forecast
- ONR Innovative Naval Prototypes (INP) & TacSat Program

Naval Needs In Space:

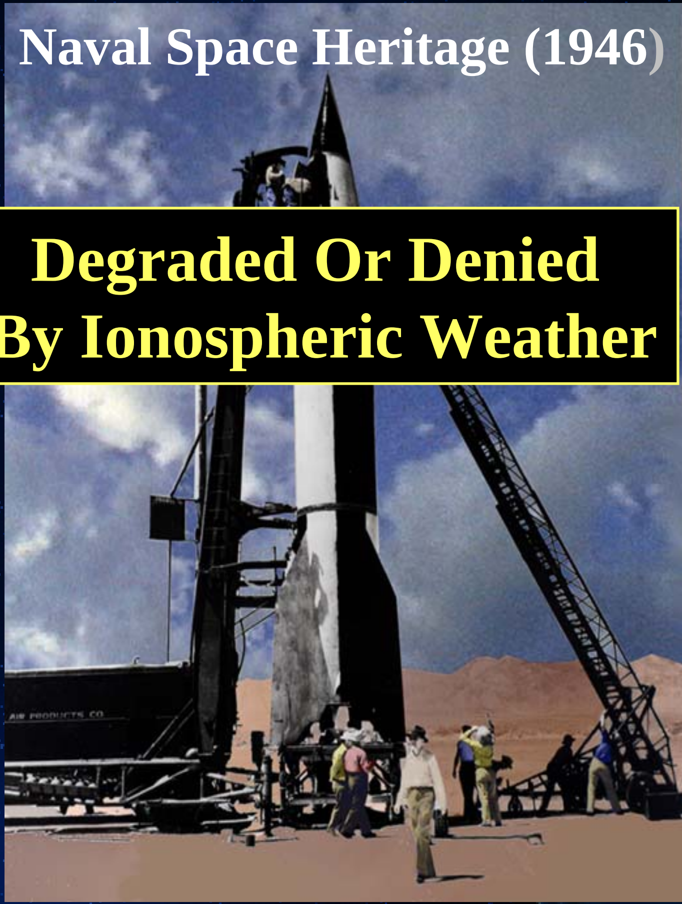
Navy Is Permanently Forward Deployed and *Critically Dependent* on Space for:

- **Communication - (ELF - HF - UHF)**
- **Navigation - (GPS & Autonomous Celestial)**
- **Surveillance, Precision Geolocation, Space Radar**
- **Space Tracking, National Missile Defense**
- **Satellite Meteorology & Oceanography**
- **Satellite Ocean Altimetry**

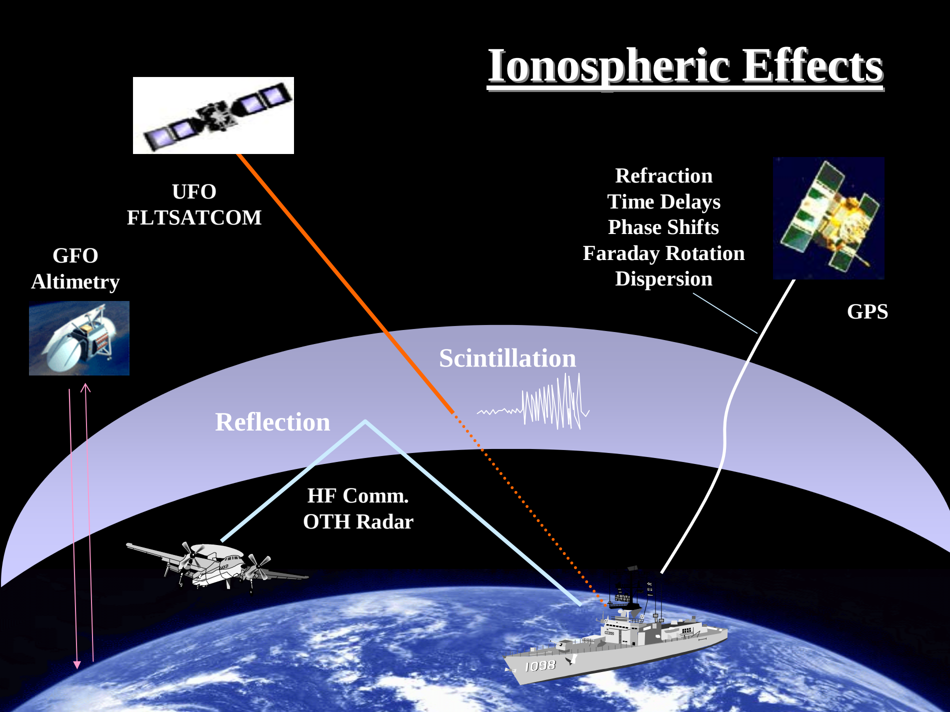
Degraded Or Denied By Ionospheric Weather

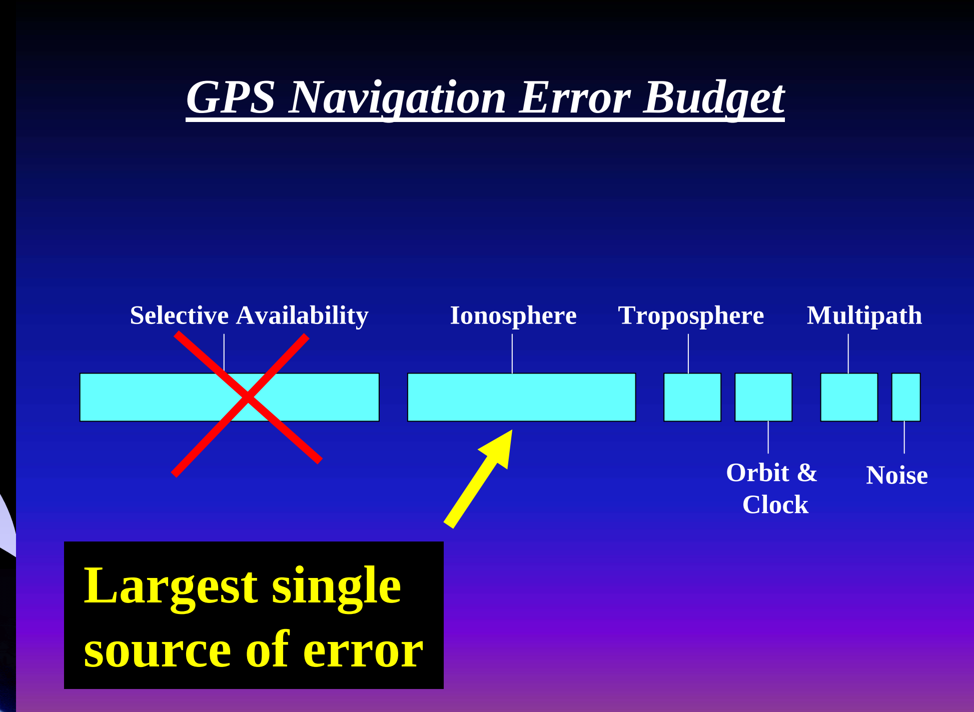
Strategy: Leadership in Targeted Basic Research

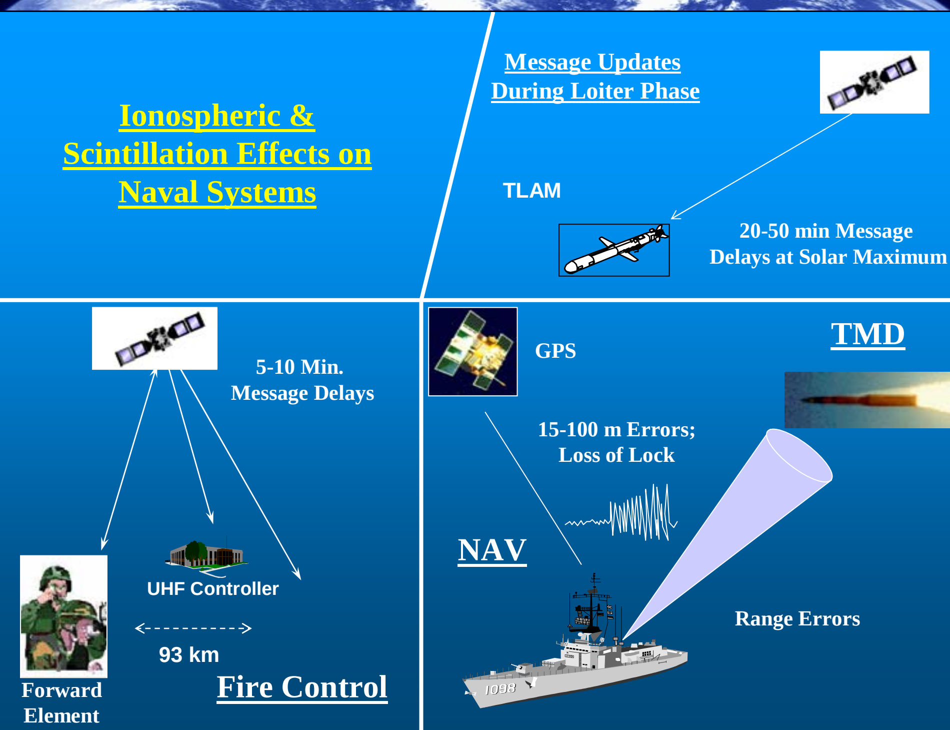
- **Influence Space Acquisition/Operations**
- **Transitions (Often 6.1) To AFWA, DMSP or NOAA SEC**

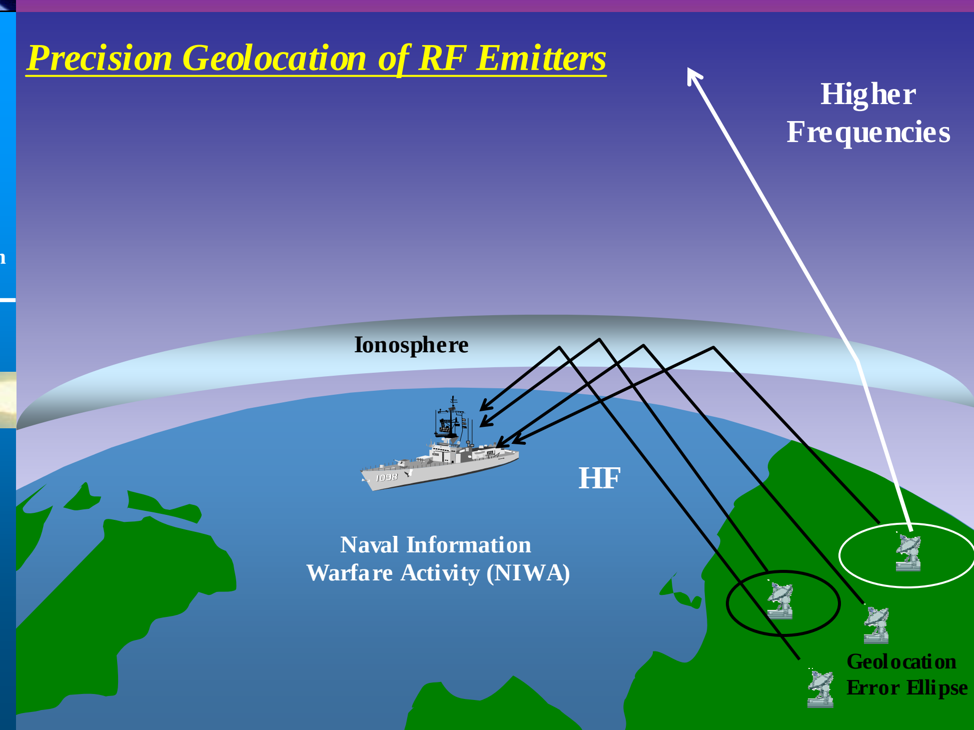


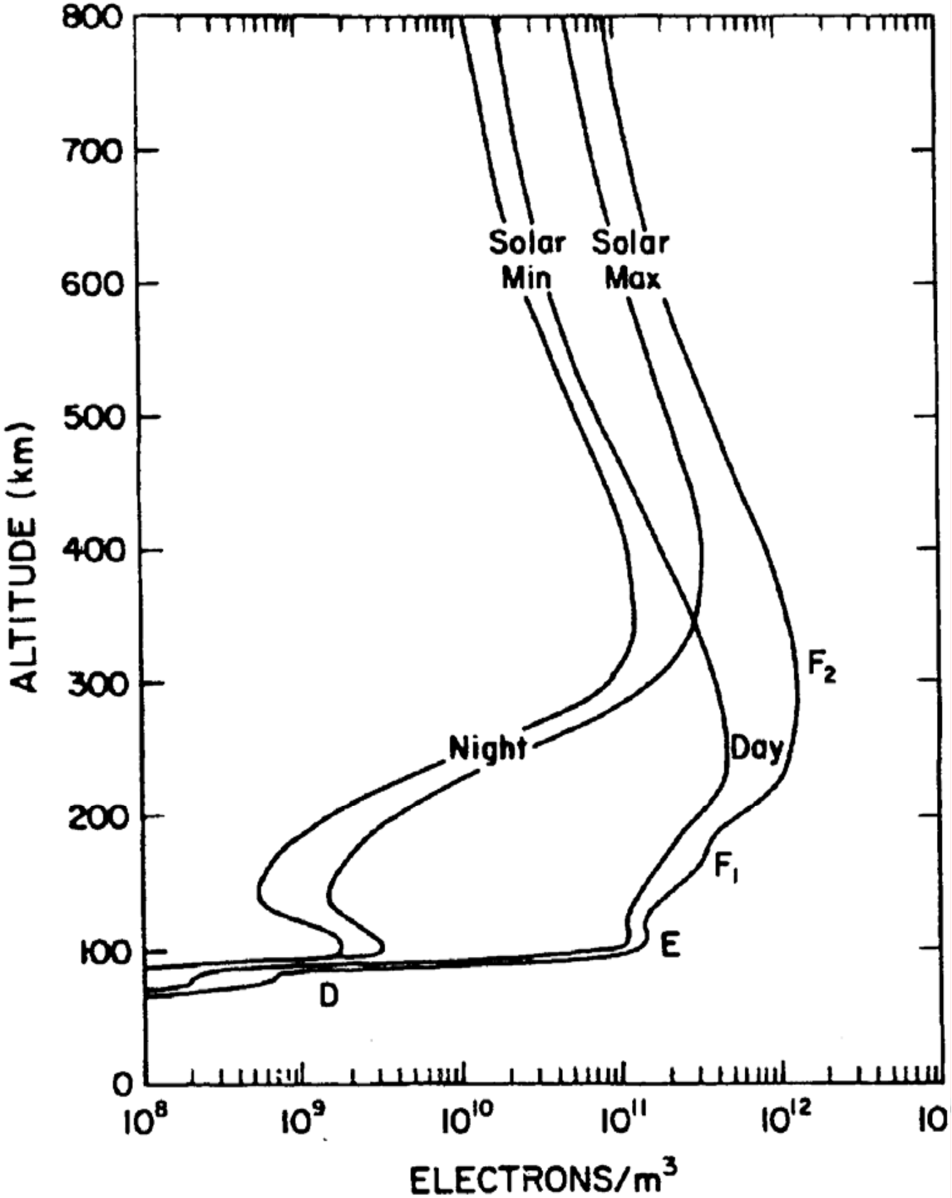
Naval Space Heritage (1946)


Ionospheric Effects
UFO
FLTSATCOM
GFO
Altimetry
Refraction
Time Delays
Phase Shifts
Faraday Rotation
Dispersion
GPS
Scintillation
Reflection
HF Comm.
OTH Radar
1098

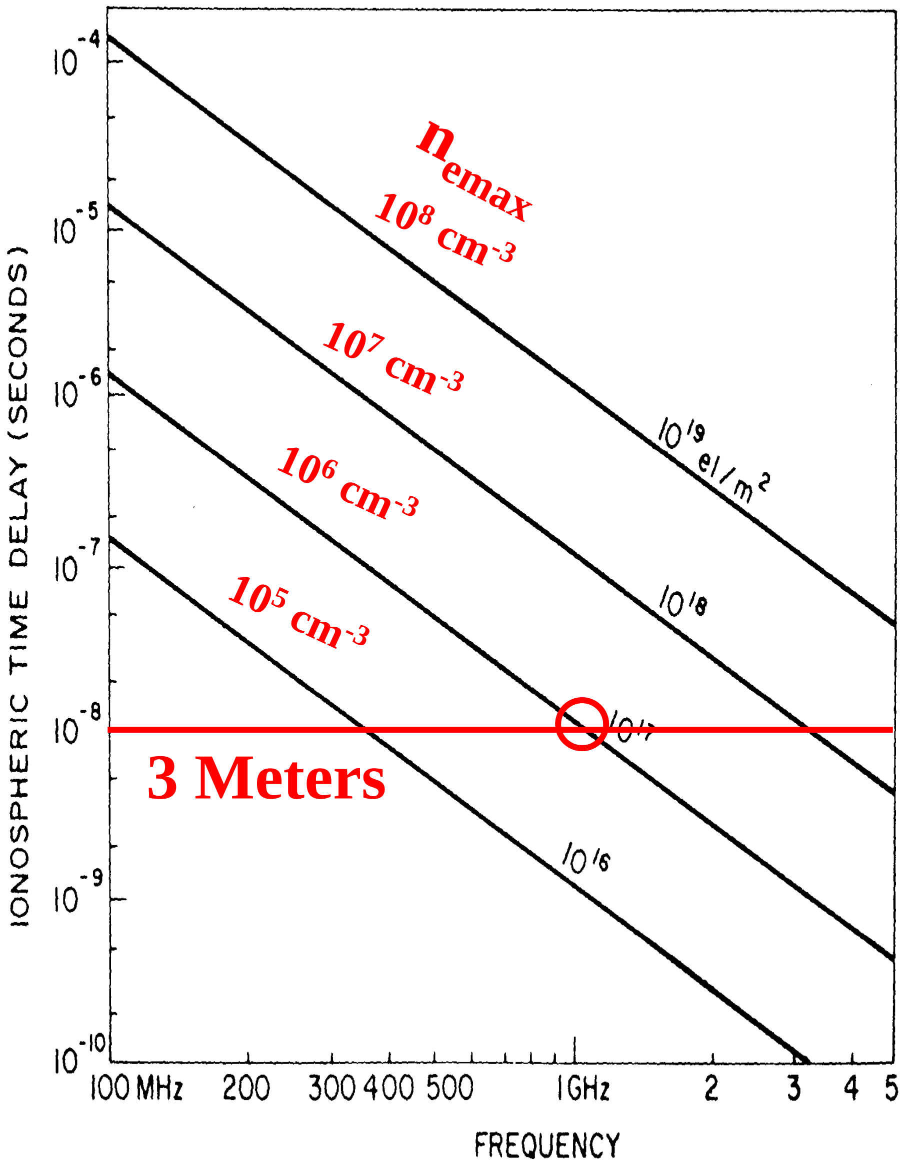

GPS Navigation Error Budget
Selective Availability
Ionosphere
Troposphere
Multipath
Orbit &
Clock
Noise
Largest single
source of error


Ionospheric &
Scintillation Effects on
Naval Systems
Message Updates
During Loiter Phase
TLAM
20-50 min Message
Delays at Solar Maximum
5-10 Min.
Message Delays
UHF Controller
93 km
Forward
Element
Fire Control
GPS
TMD
15-100 m Errors;
Loss of Lock
NAV
Range Errors
1098


Precision Geolocation of RF Emitters
Higher
Frequencies
Ionosphere
HF
Naval Information
Warfare Activity (NIWA)
Geolocation
Error Ellipse



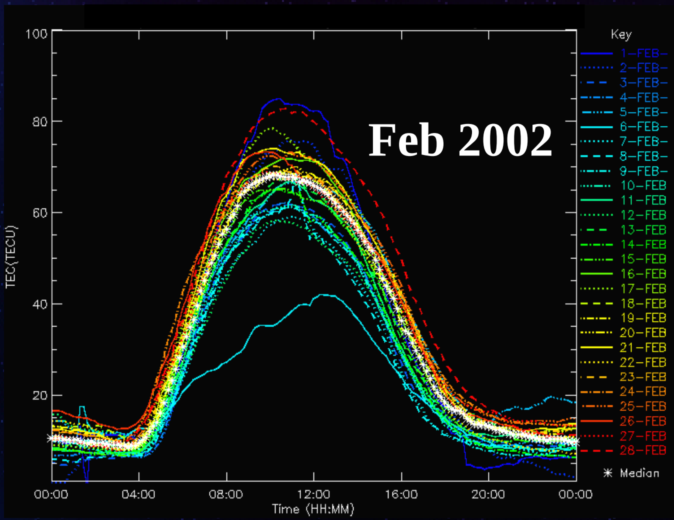
Solar Min
Solar Max
Night
Day
F2
F1
E
D
ALTITUDE (km)
ELECTRONS/m3

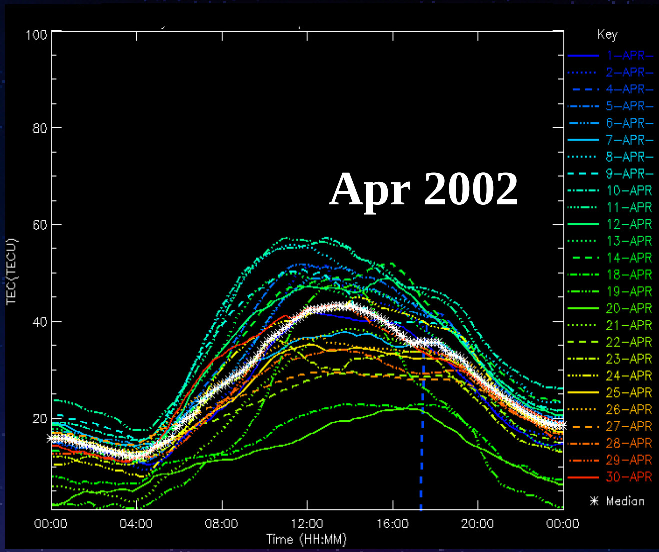


nemax
10^8 cm-3
10^7 cm-3
10^6 cm-3
10^5 cm-3
10^19 el/m2
10^18
10^17
10^16
3 Meters
IONOSPHERIC TIME DELAY (SECONDS)
FREQUENCY

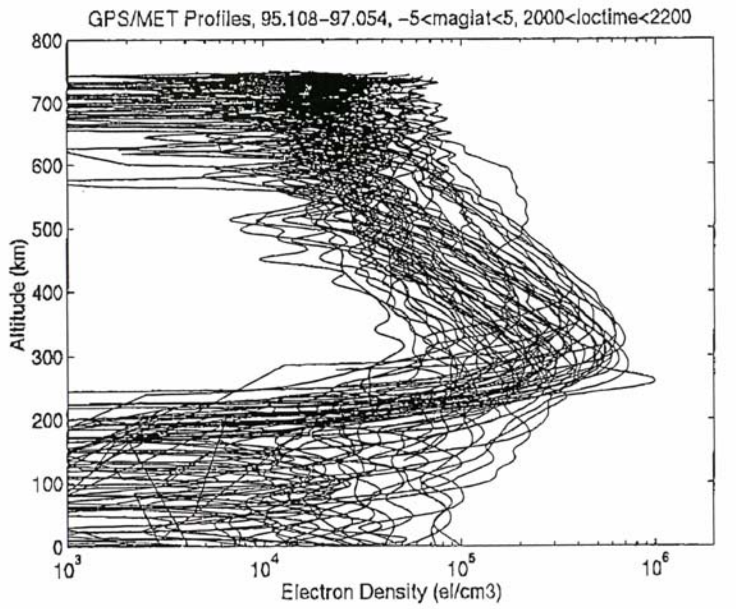
Difficulties for Ionospheric Models

TEC e cm^{-2}





Daily Measured Values



Variability: Daily, Seasonal, Solar Cycle

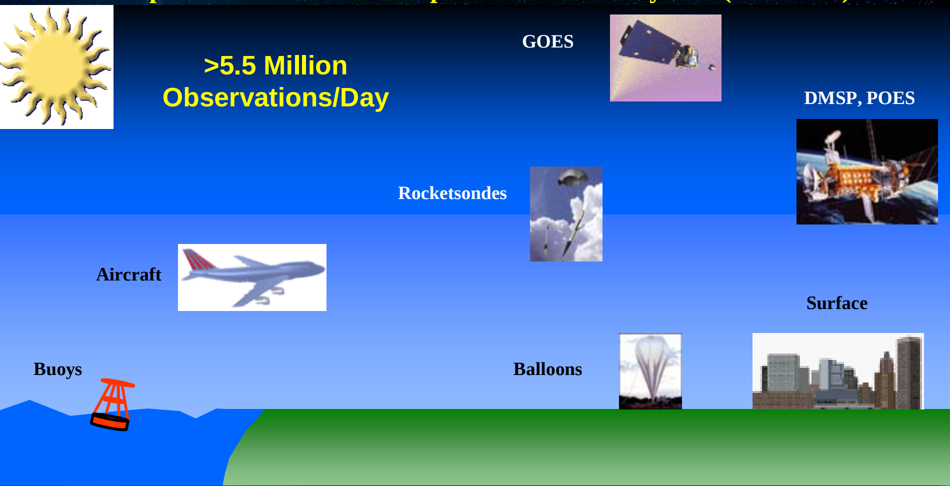
Forcing:

Solar EUV, X-ray, Solar Wind, Winds, Fields, Tides, Convection, Dynamics

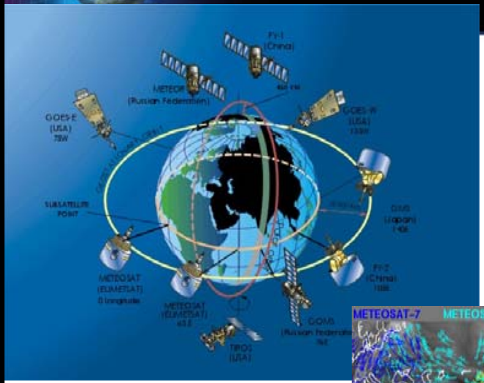
"Weather"

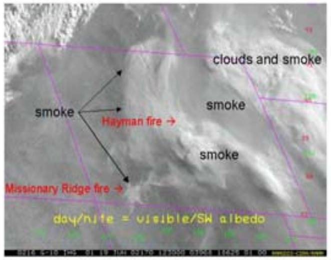
Meteorological Weather Specification & Forecast
Basic Physics Algorithms + Continuous Observations

Naval Operational Global Atmospheric Prediction System (NOGAPS)



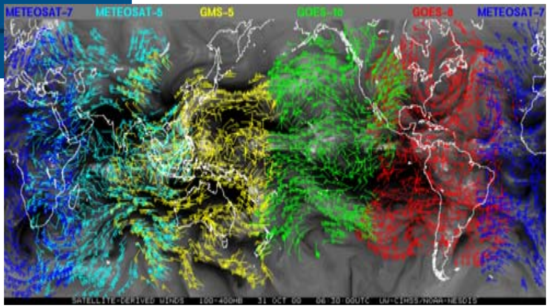
Observations: Global Satellite Systems





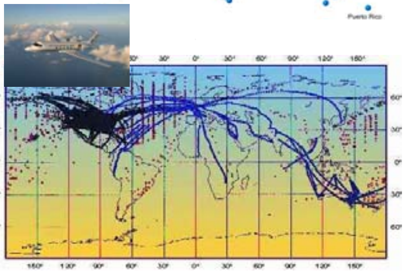
Colorado forest fires – 19 June 2002 1230 UTC (morning)

Winds from five geos are being processed every six hours to produce vectors of comparable accuracy (hi winds compare within 7 m/s of raobs); GOES and Meteosat winds are being produced every three hours on most days

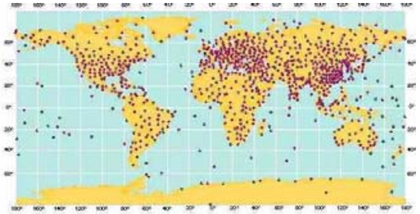


Regional Observations: Atmosphere

158 Operational sites, providing humidity, reflectivity information, in a 250 mile radius around each site

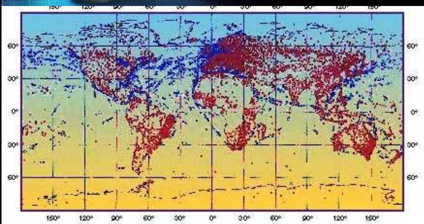


Over 3000 aircraft provide reports of pressure, winds and temperature during flight.

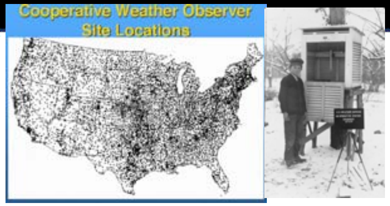


From a network of roughly 900 upper-air stations, radiosondes, attached to free-rising balloons, make measurements of pressure, wind velocity, temperature and humidity from just above ground to heights of up to 30km

Regional Observations: Surface and Hydrological

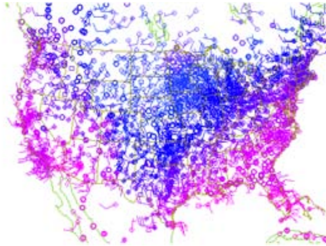


The backbone of the surface-based sub-system continues to be about 10,000 stations on land making observations of meteorological parameters such as atmospheric pressure, wind speed and direction, air temperature and relative humidity.

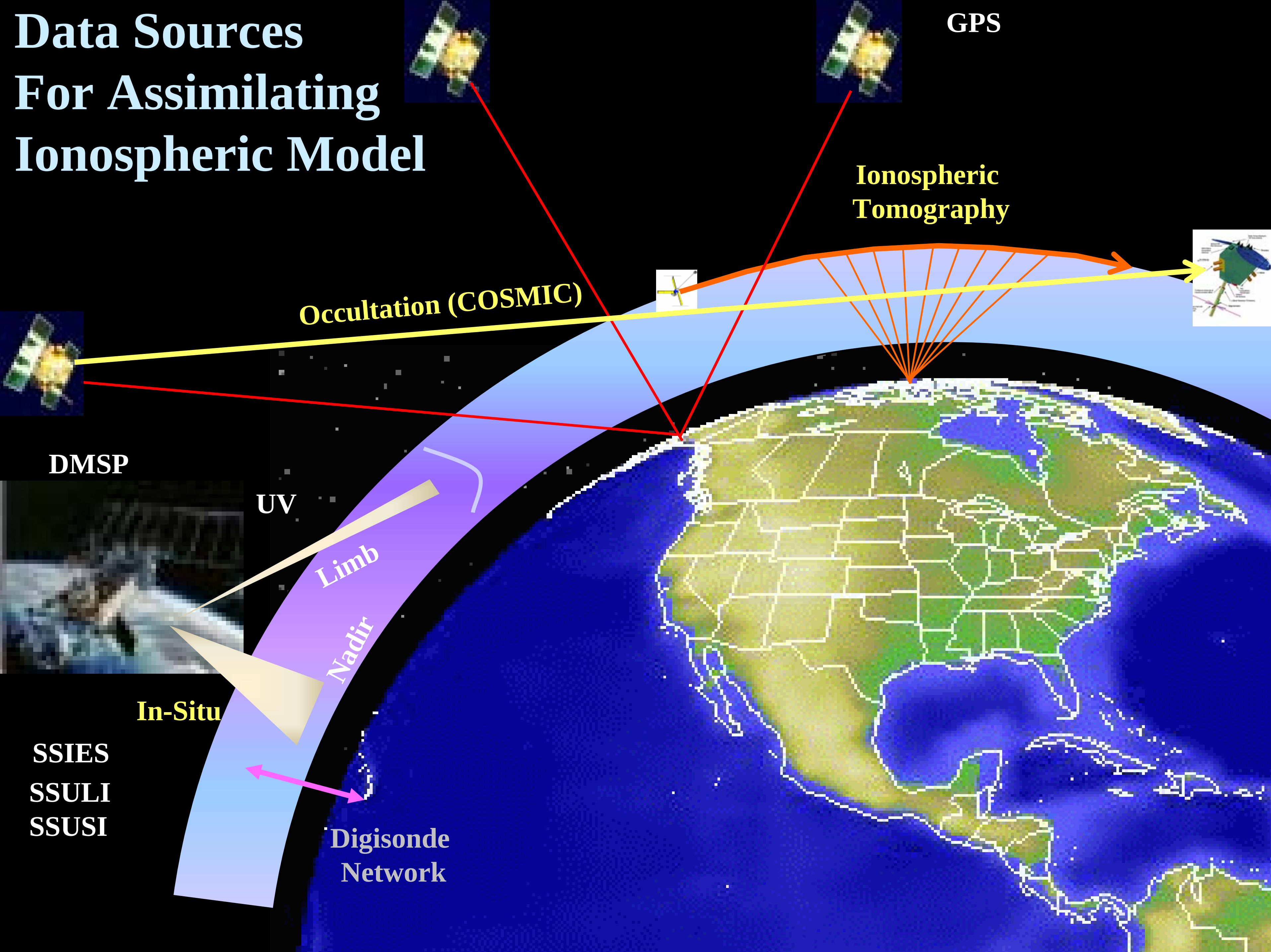


Cooperative Observer Network: 11,400 volunteer observers provide 24 hr max/min weather observations which include: temperature, precip, snow, and hydrology at non-airport locations

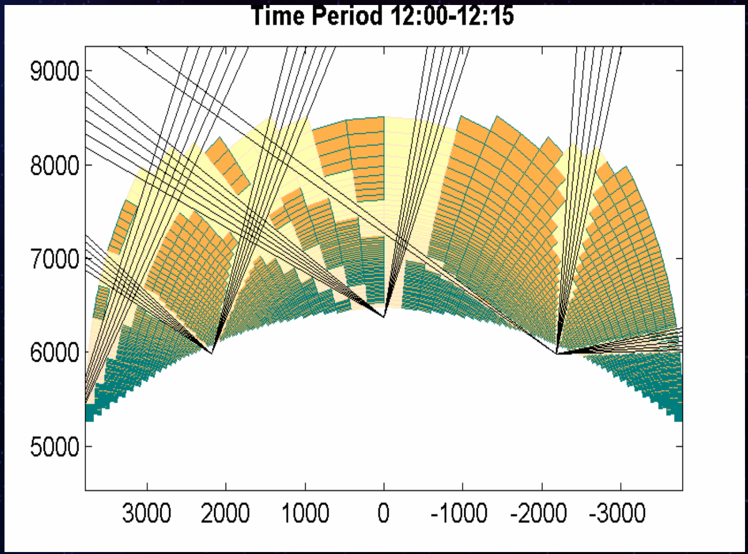
Automated Surface Observing System provides weather observations which include: temperature, dew point, wind, altimeter setting, visibility, sky condition, and precipitation up to approx 10,000 ft. 569 FAA-sponsored and 313 NWS-sponsored ASOSs are installed at airports throughout the country

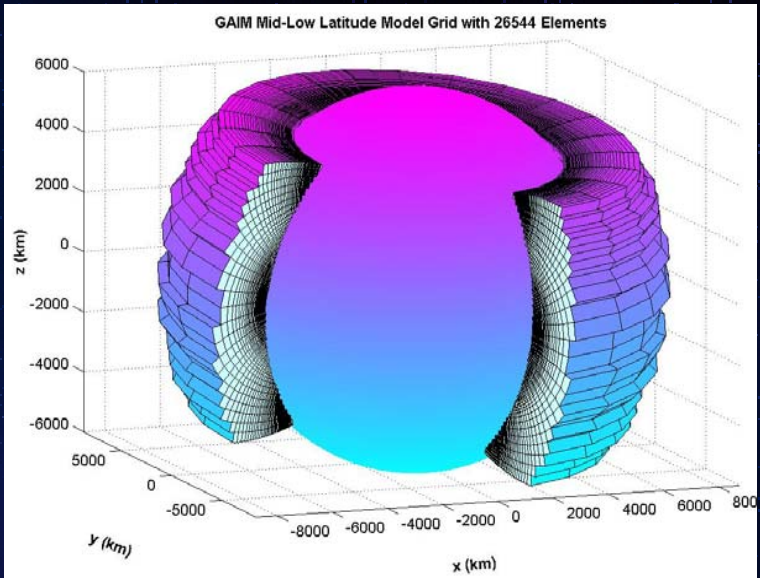


Courtesy Marie Colton


Data Sources
For Assimilating
Ionospheric Model
GPS
Ionospheric
Tomography
Occultation (COSMIC)
DMSP
UV
Limb
Nadir
In-Situ
SSIES
SSULI
SSUSI
Digisonde
Network

Assimilating Ionospheric Model

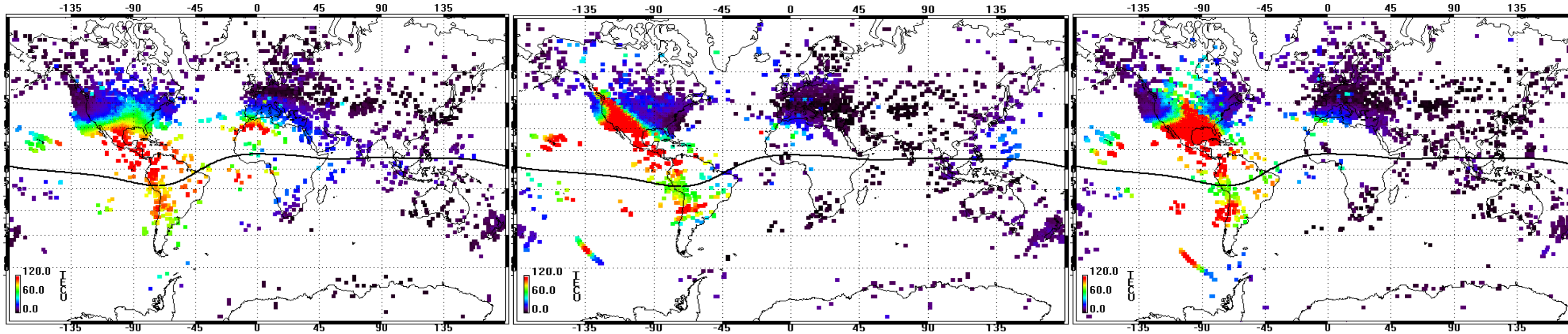




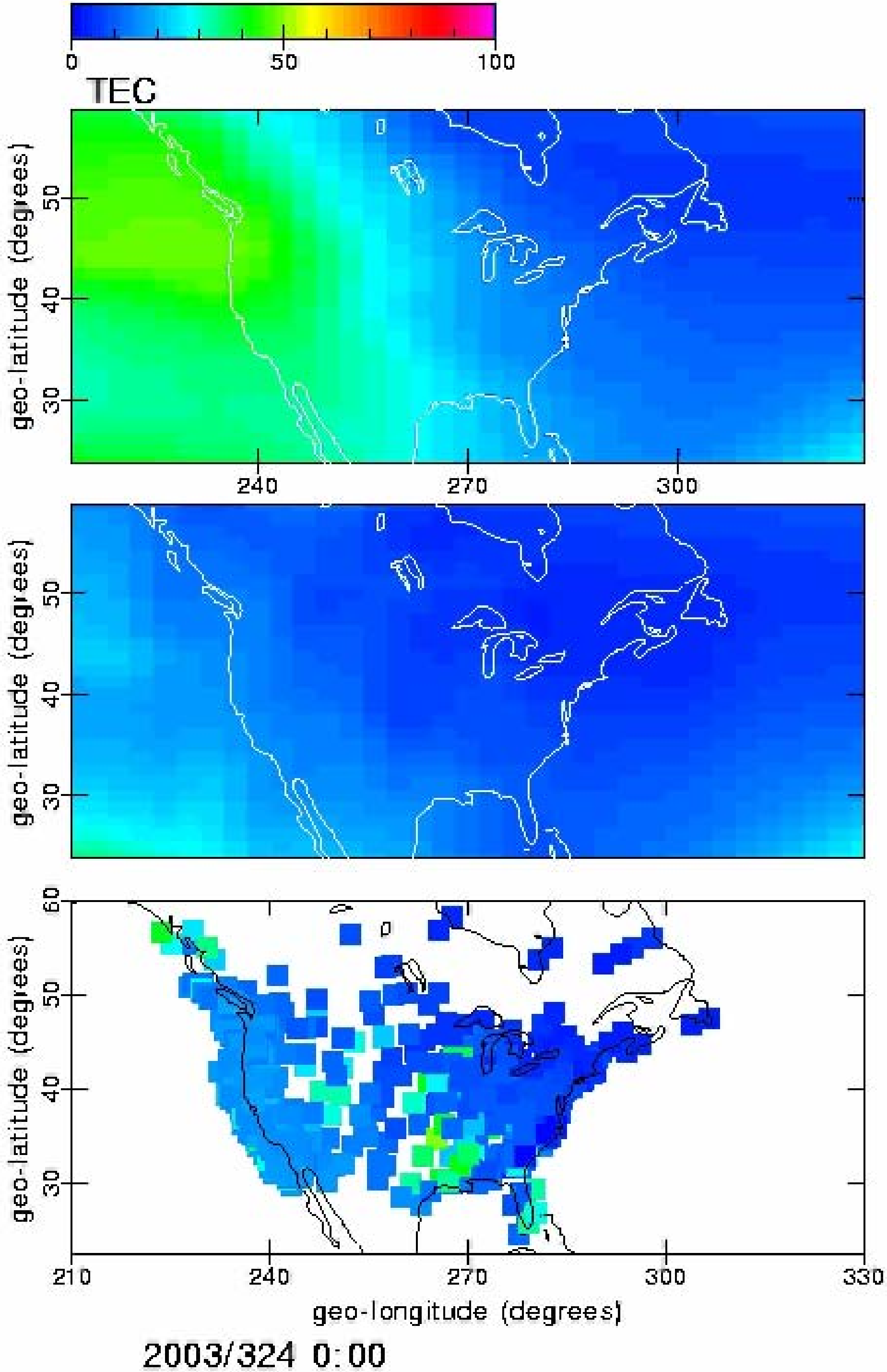
- First Principles Physics
- Multiple Data Sources
  - GPS, UV, In-situ, Digisondes, CIT, GPS Occultation, C/NOFS
- 3-D Time-Dependent Parameters
  - NO^+, O_2^+, N_2^+, O^+, T_e, T_i
- Adaptive Grid System
  - Global, Regional, Localized, 90-1600 km
- Plasmasphere Model
  - H^+: 1,600 - 30,000 km
- 1999 Multidisciplinary University Research Initiative: USU, USC, UC, UTD, UW/APL
- Dec 2006 : Global Assimilation of Ionospheric Measurements (GAIM) Operational at AFWA

Halloween Storm Oct 2003

1915 UT   2025 UT   2215 UT



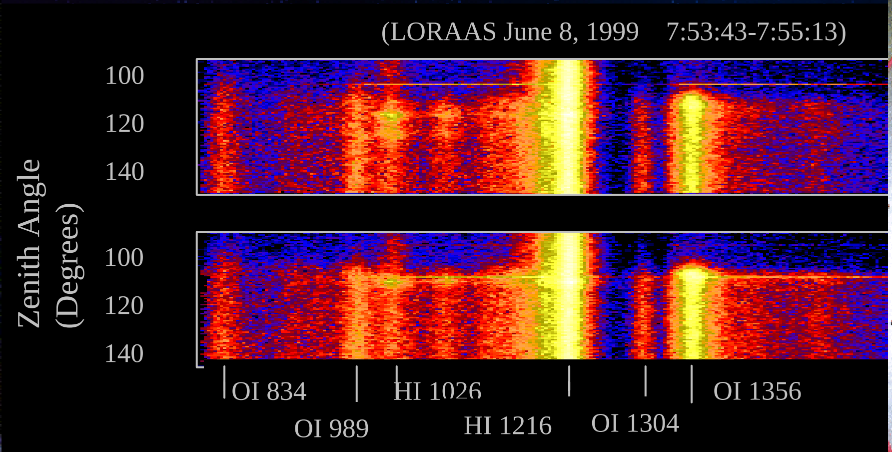
- **Storm Enhanced Density (SED) Plumes**
  - **– Illustrated by Total Electron Content (TEC) from 900+ GPS Receivers & TOPEX (Southern Hemisphere)**
  - **– Penetration of Magnetospheric Electric Fields into Midlatitude Ionosphere**
  - **– Shut Down $4.5B FAA WAAS System for 30+ hours**

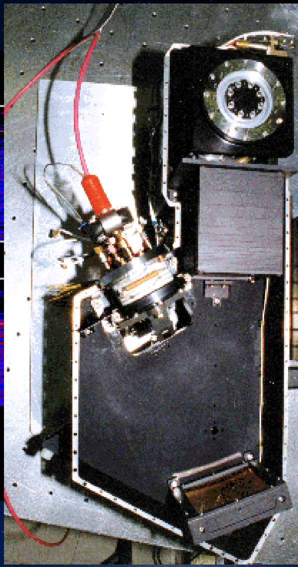


0
50
100
TEC
geo-latitude (degrees)
30
40
50
240
270
300
60
210
330
geo-longitude (degrees)
2003/324 0:00

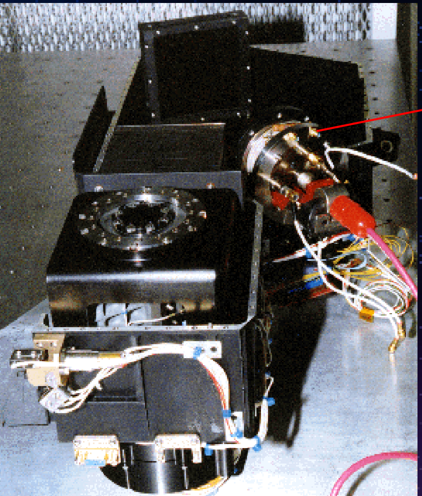
SSULI

Special Sensor Ultraviolet Limb Imager

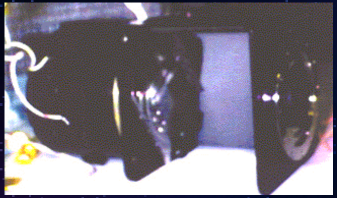




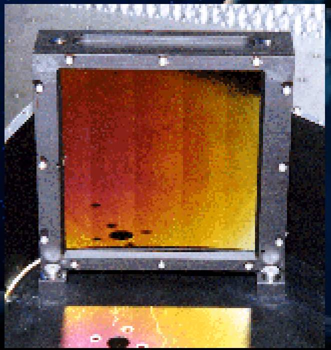
Spectrograph w/Collimator



Detector

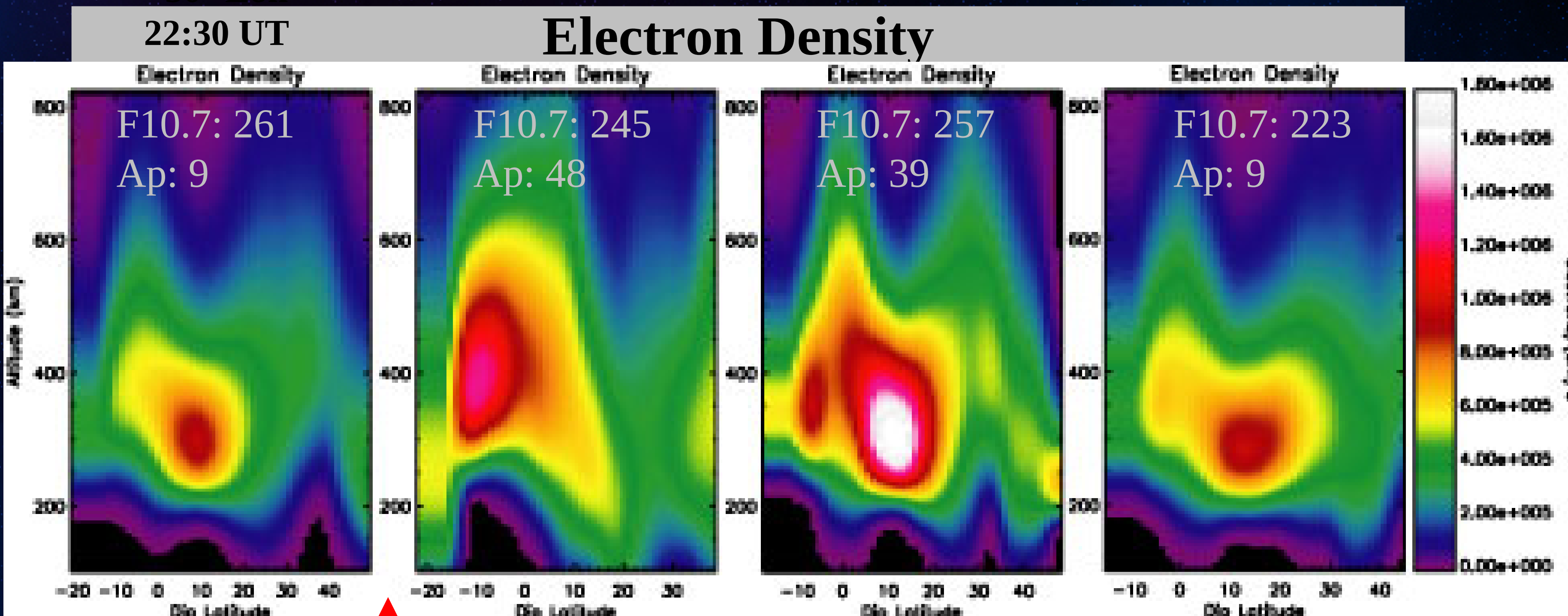


Scan Mirror



Grating

Storm Effects: 29 March – 03 April, 2001

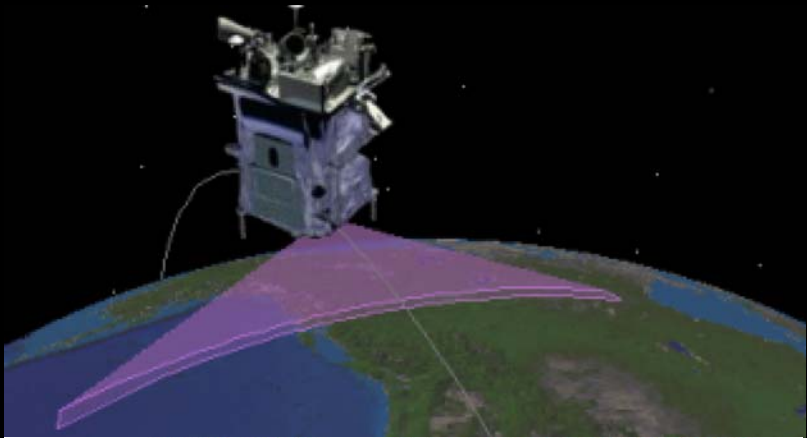


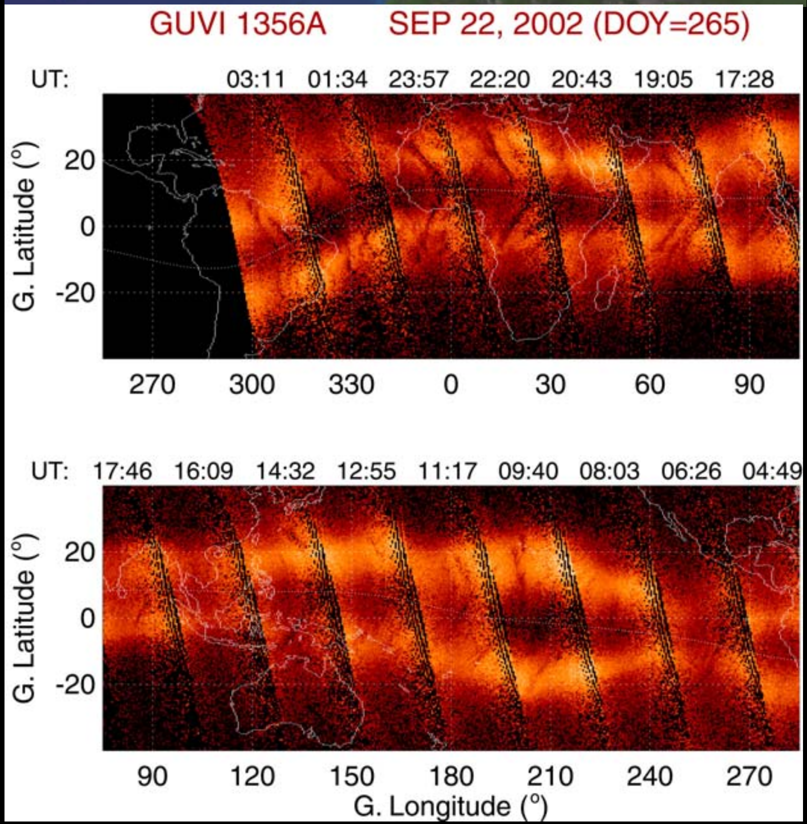
29 Mar | 31 Mar | 01 Apr | 03 Apr

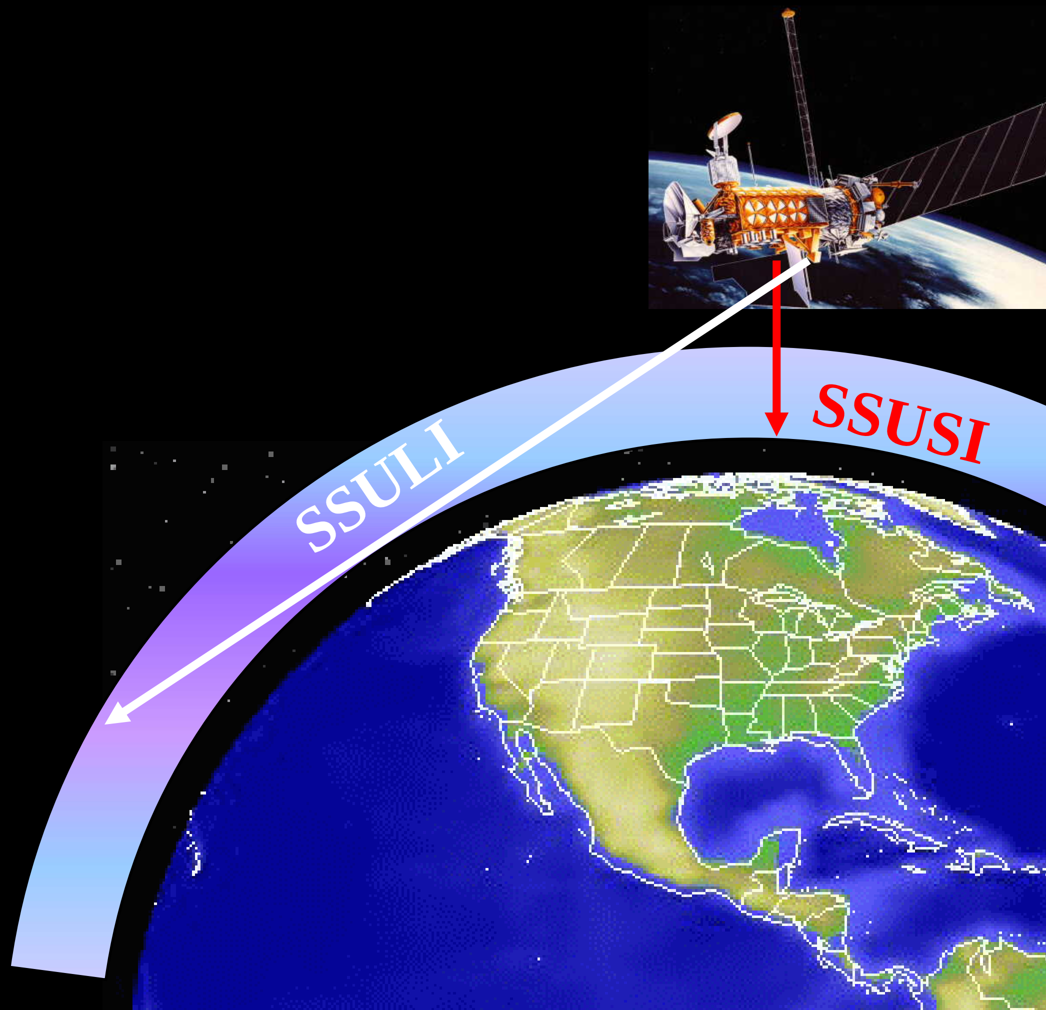
Storm 3/31 00:51 UT – 4/01 09:00 UT

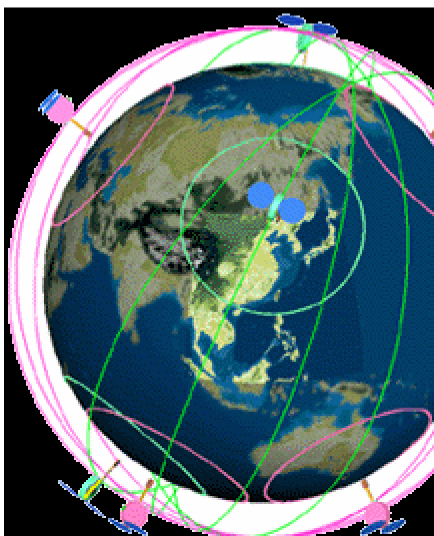
These images show the changes in the electron densities in the equatorial anomaly region before and after the Geomagnetic Storm that commenced on 31 March 2001. All images represent the region near +50° Longitude at 22:30 UT.

GUVI Nightside Ionospheric Imagery







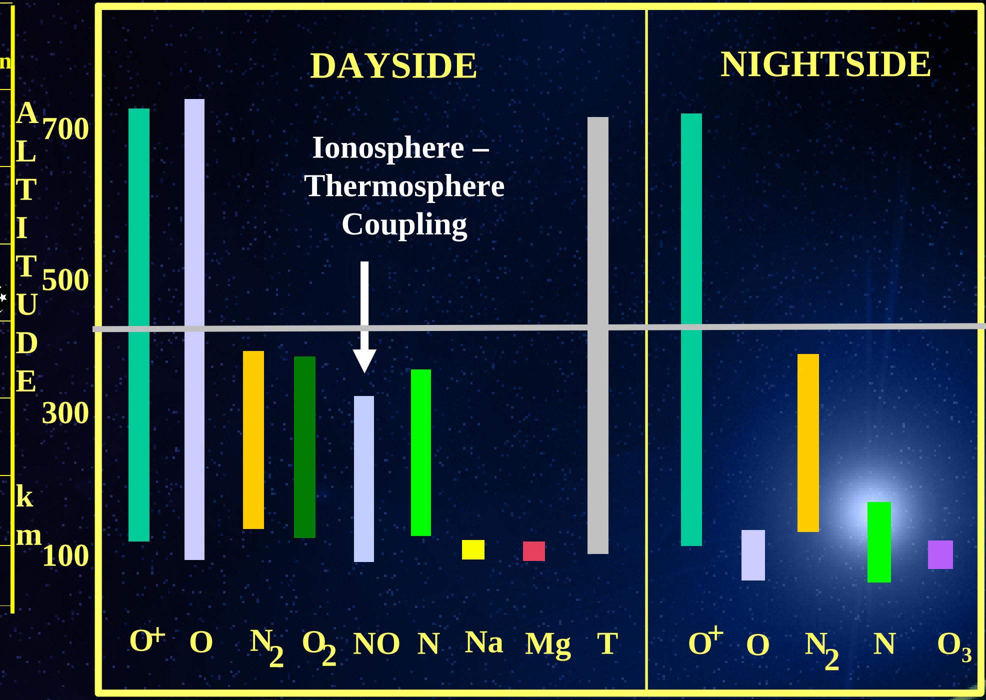


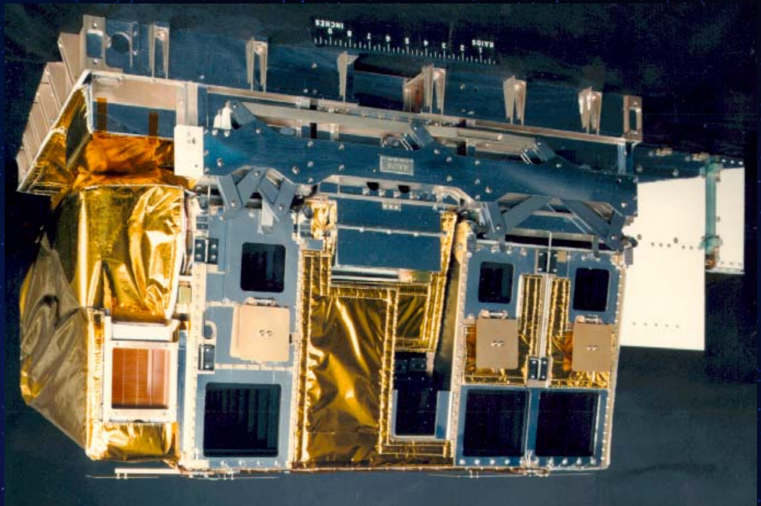
COSMIC launch picture provided by Orbital Sciences Corporation

RAIDS

Remote Atmospheric and Ionospheric Detection System

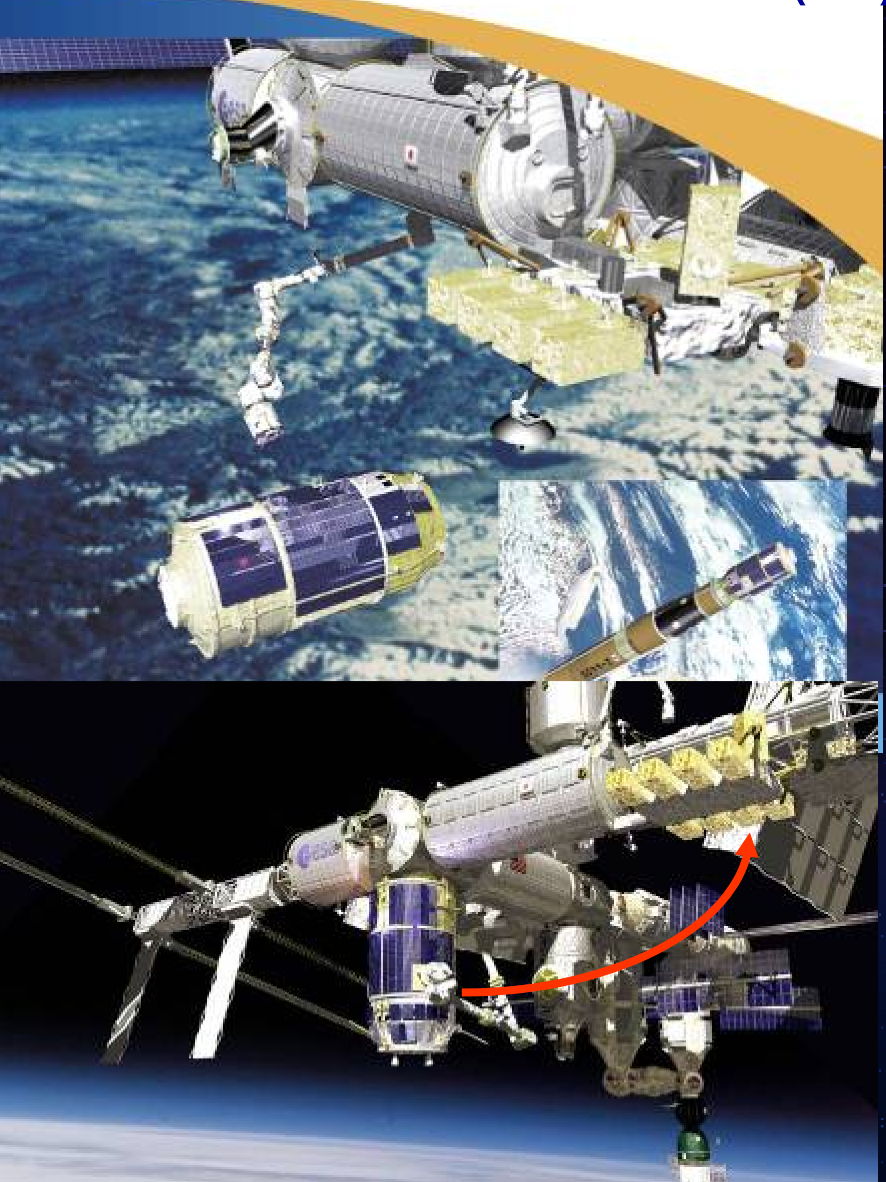
☀ Dayside ☾ Nightside	O^+	O	N_2	O_2	T	Photo-electrons	Aurora	Odd Nitrogen
EUV Spectrograph 550 - 1100 Å	☀ ☾	☀	☀		☀	☀	☀ ☾	
FUV Spectrograph 1300 - 1700 Å		☀ ☾	☀	☀	☀	☀	☀ ☾	
MUV Spectrometer 1900 - 3200 Å		☀ ☾	☀	☀	☀ ☾	☀	☀ ☾	☀ ☾
NUV Spectrometer 2950 - 4000 Å		☀ ☾	☀		☀ ☾	☀	☀ ☾	
NIR Spectrometer 7400 - 8700 Å	☾				☀ ☾		☀ ☾	
6300 Å Photometer	☾			☾			☾	
7774 Å Photometer	☾						☾	
5890 Å Photometer	Na ☀ ☾							





Key Payload Elements

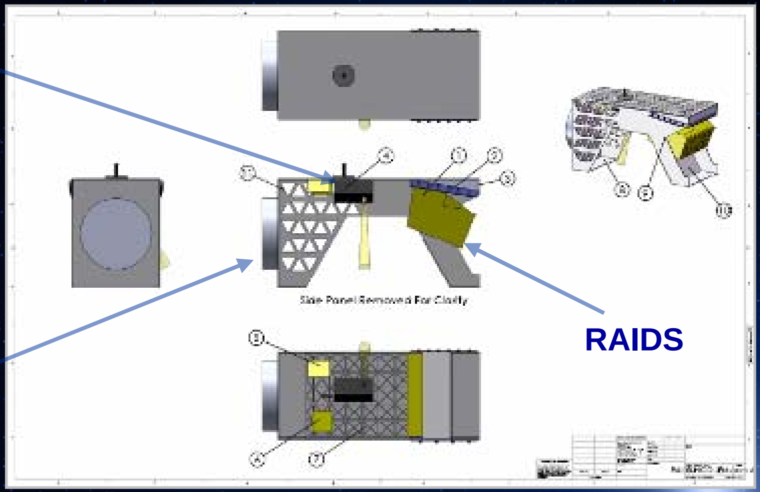
JAXA H-II Transfer Vehicle (HTV)



RAIDS/HICO JEM Configuration

HICO

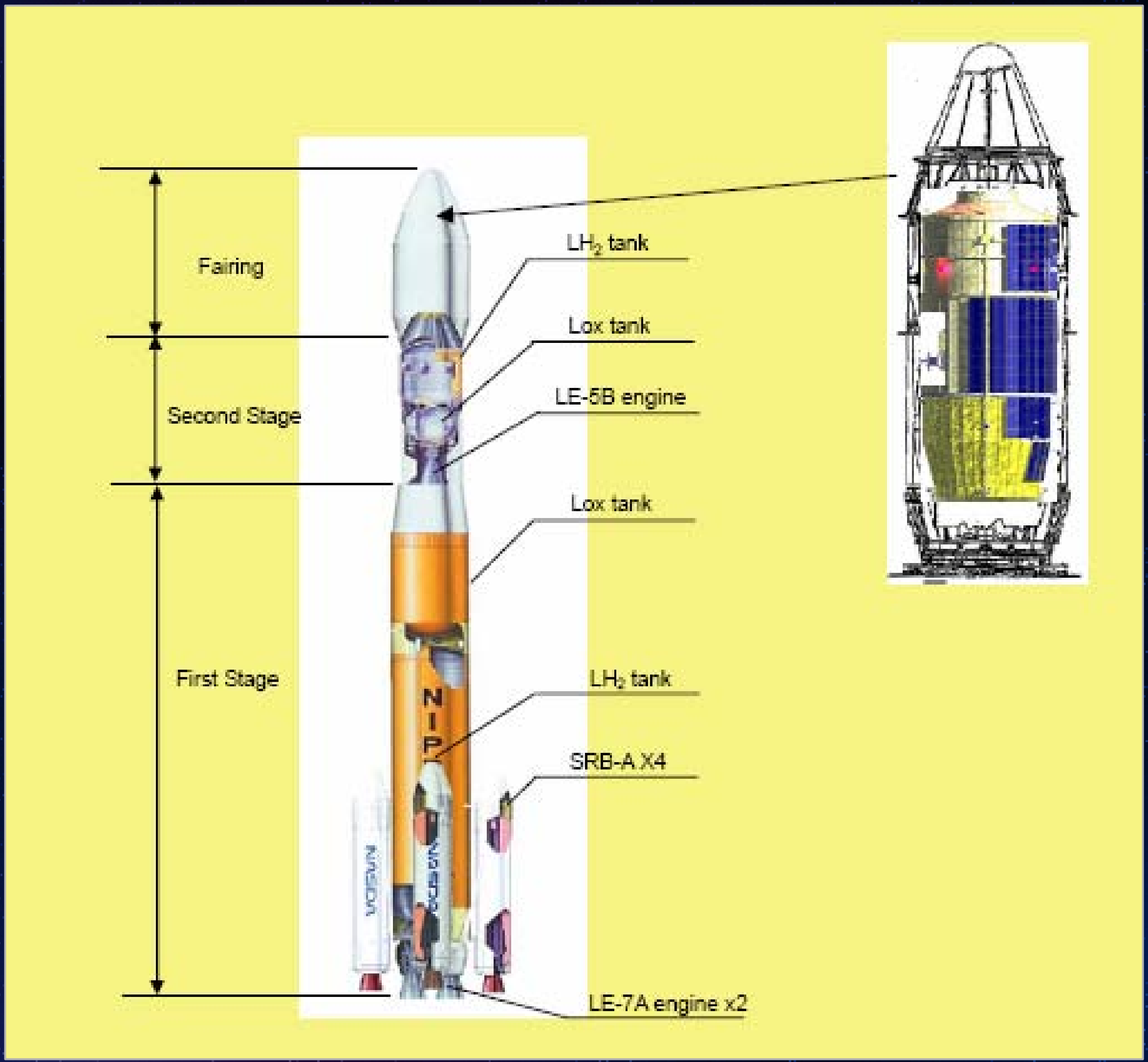
Interface to JEM-EF



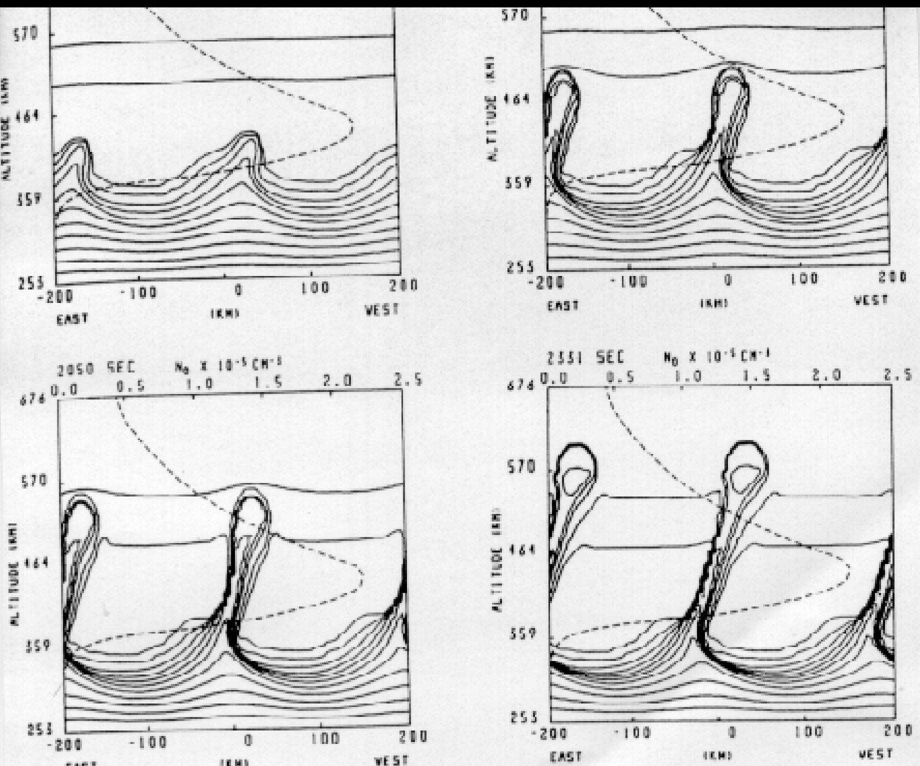
RAIDS

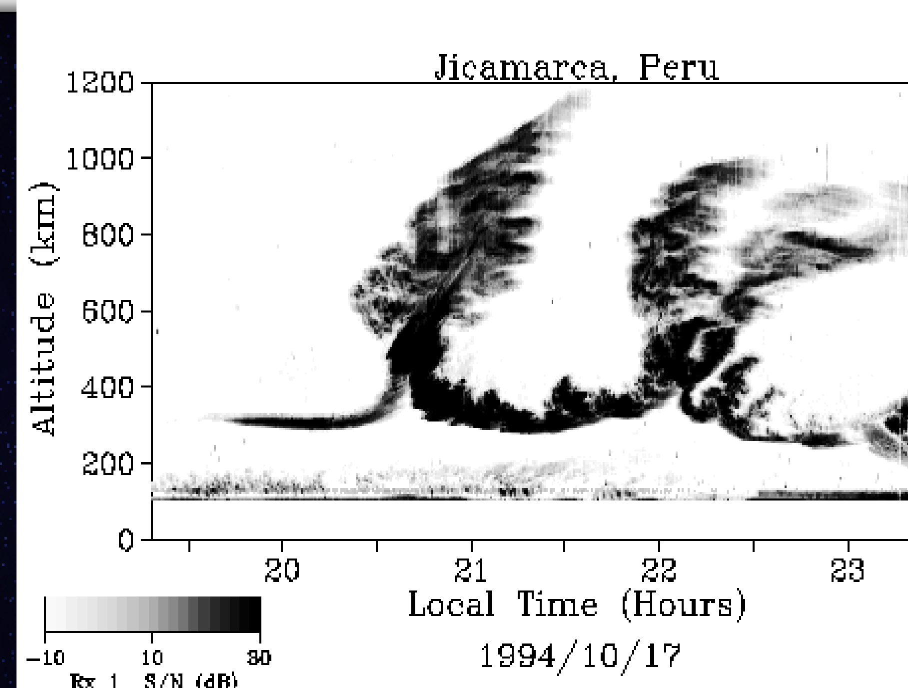
JEM Exposed Facility (Typical)

H-IIB/HTV Integrated Launch Configuration



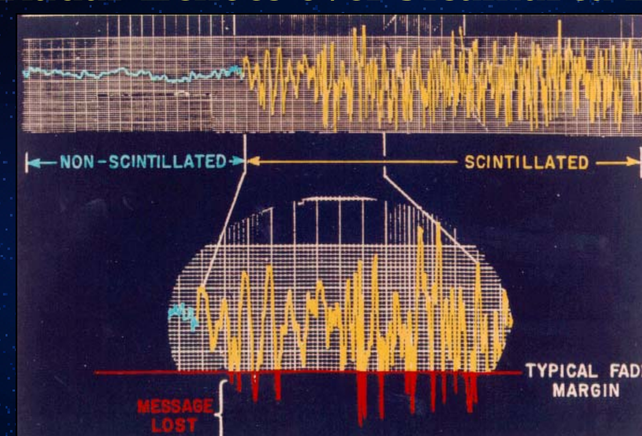
Ionospheric Bubbles & Scintillation



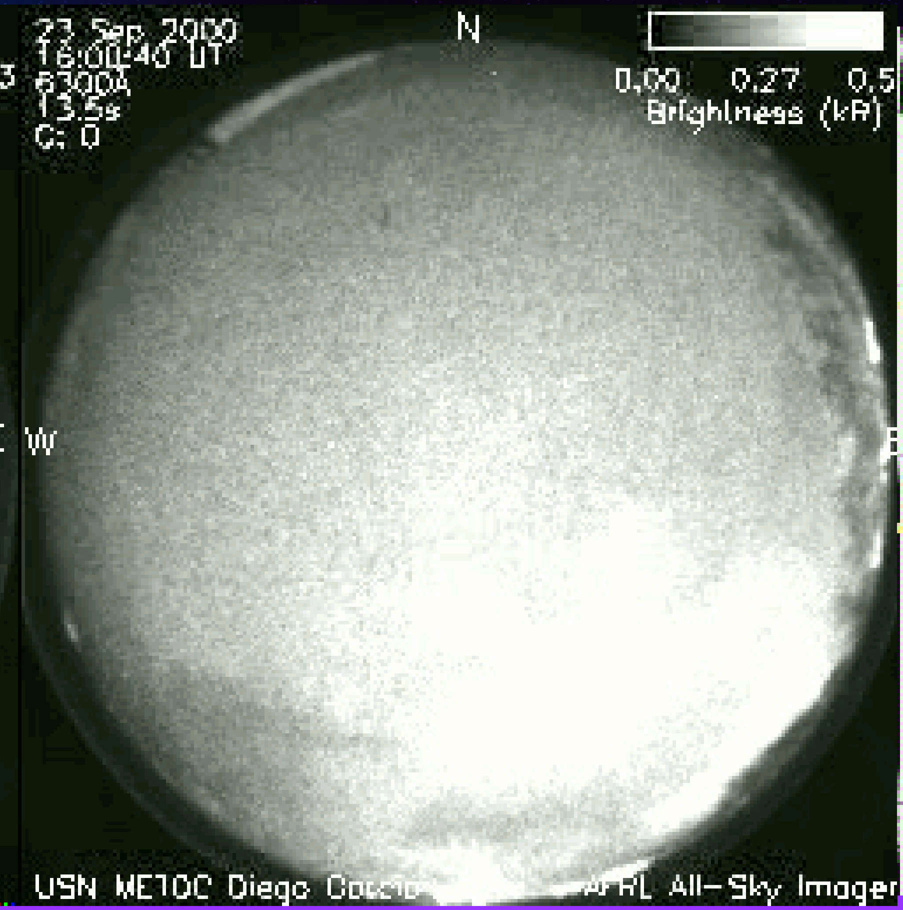


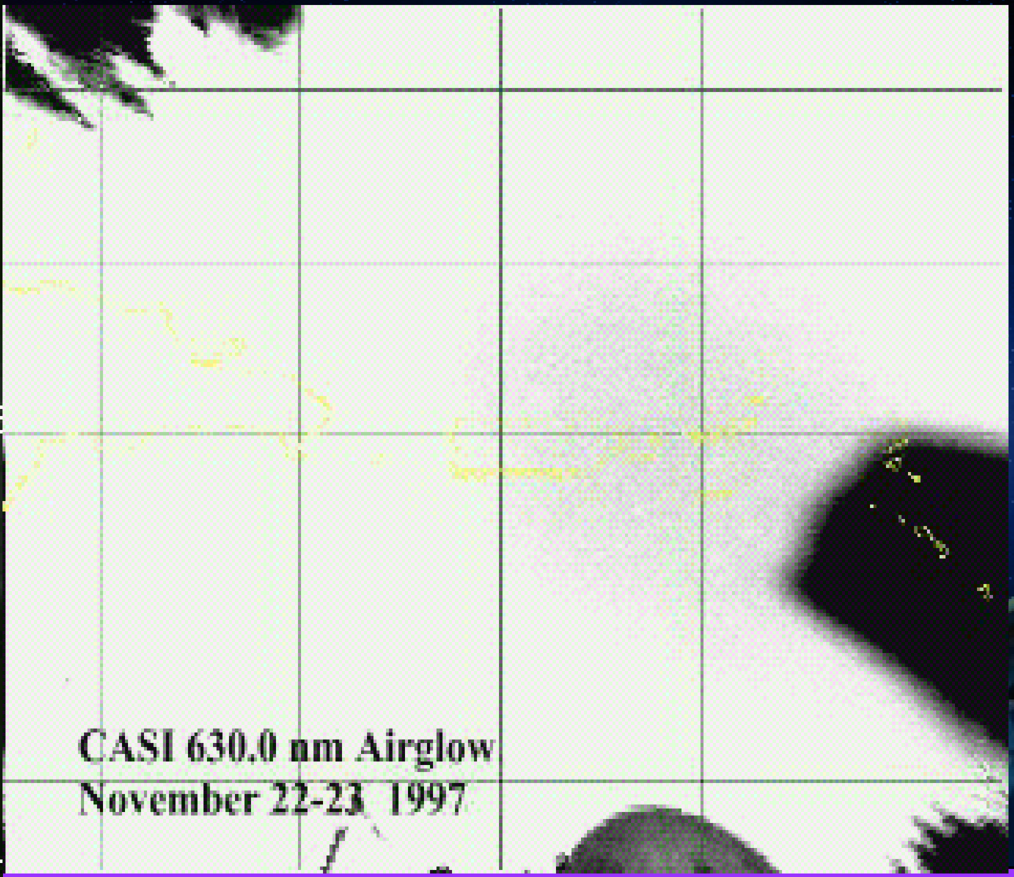
NRL Model Simulation of the Development Of An Ionospheric Bubble Leading to Ionospheric Scintillation

Radar Echoes over Jicamarca Peru



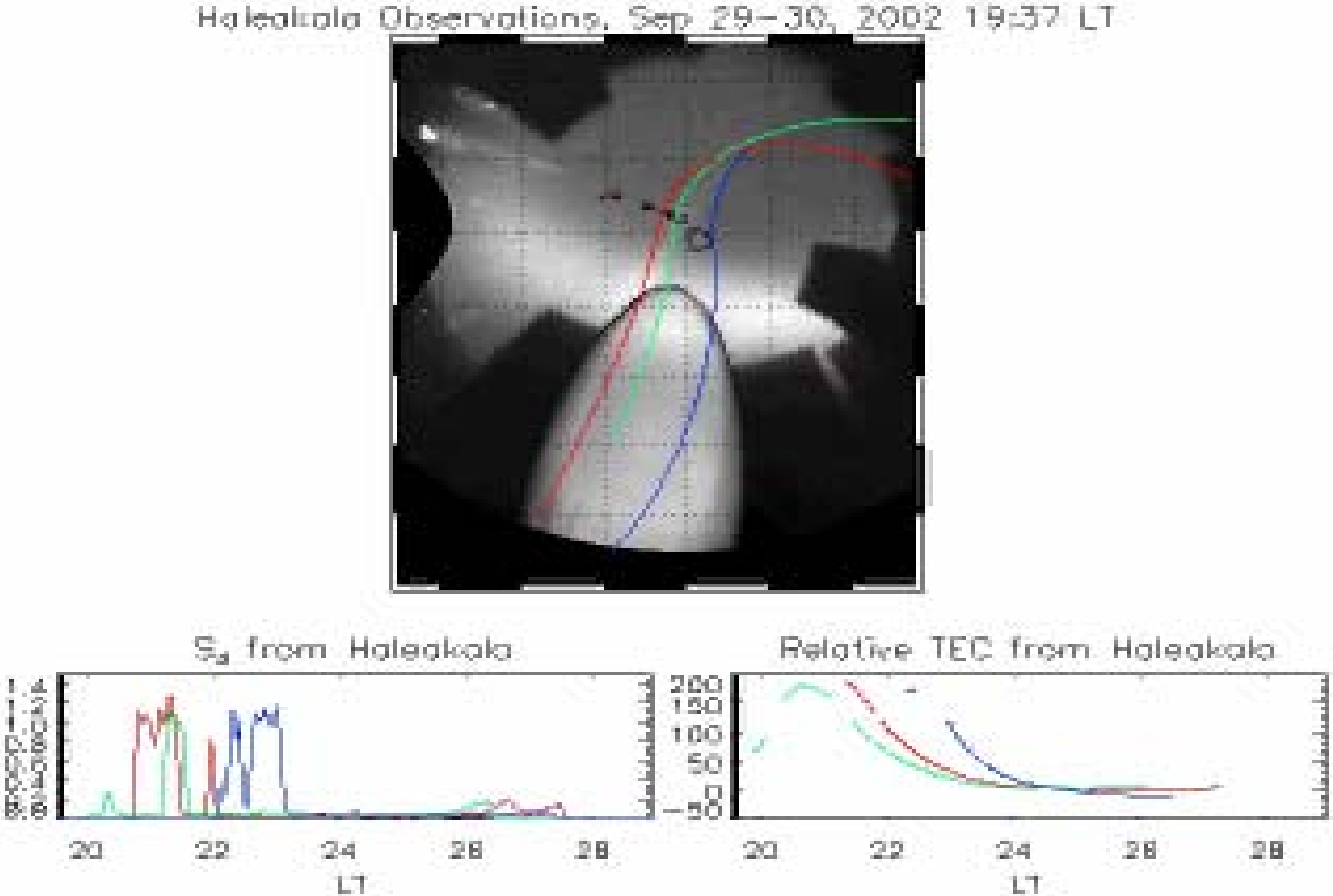
High Space/Time Resolution Ionospheric Imaging





Low Latitudes (Diego Garcia)

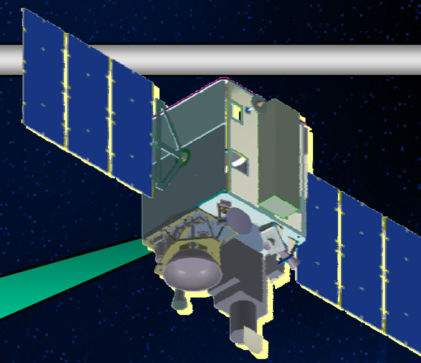
Mid Latitudes (Puerto Rico)



Haleakala Observations, Sep 29-30, 2002 19:37 LT
S4 from Haleakala
20
22
24
26
28
LT
Relative TEC from Haleakala
200
150
100
50
0
-50
20
22
24
26
28
LT

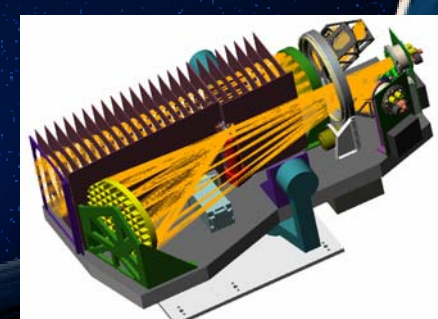
High Space/Time Resolution Ionospheric Imaging

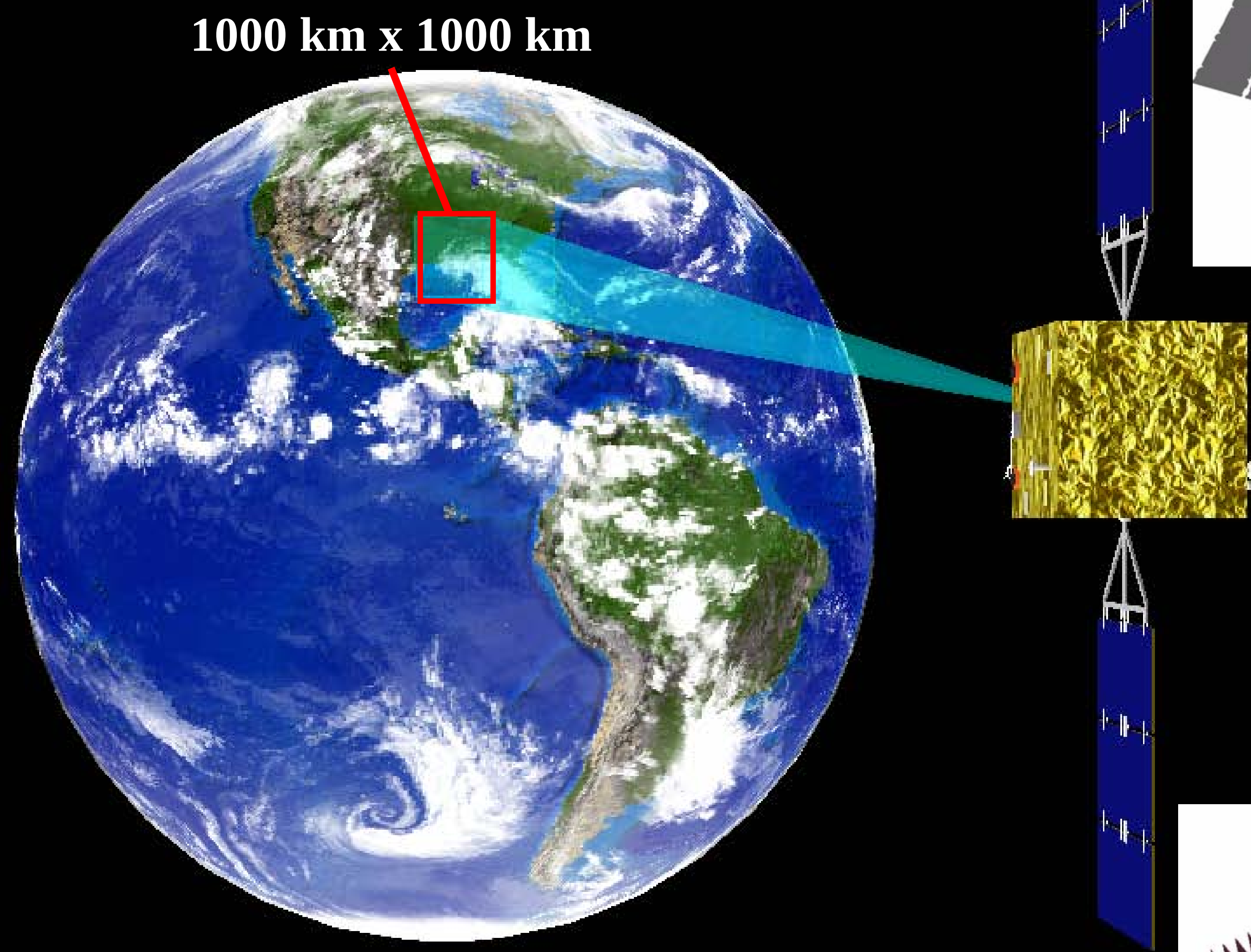
Apollo 16 UV Image of the Ionosphere from the Moon

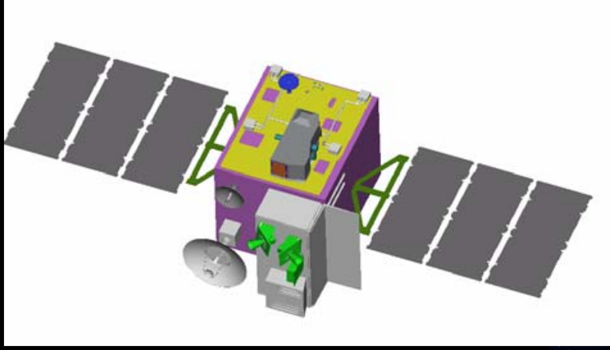


Geostationary UV Imager
1000 x 1000 km
10 km x 10 km Resolution
100 sec

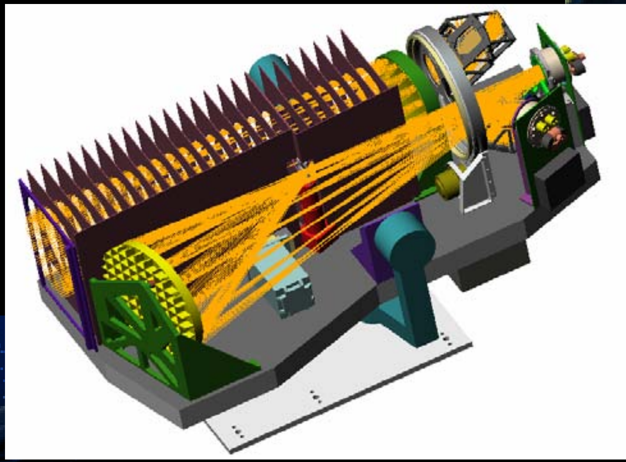
Ionospheric Mapping And Geocoronal Experiment (IMAGER)







Ionospheric Mapping and Geocoronal Experiment (IMAGER)



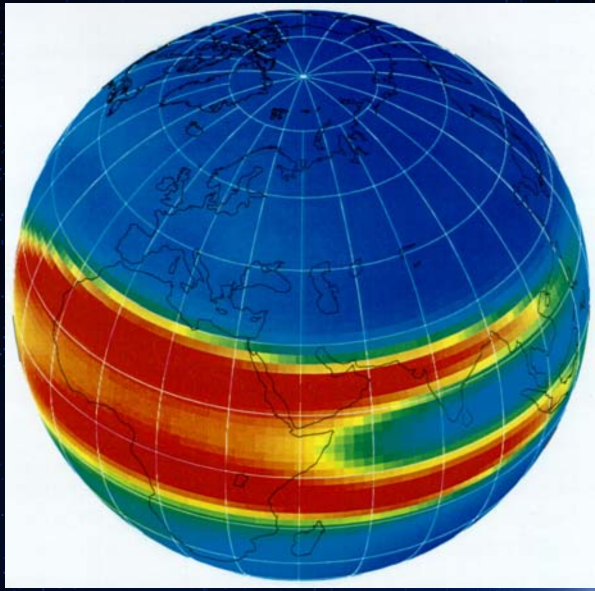
Extreme and Far-Ultraviolet Camera

- **1000 km by 1000 km field of view**
- **10 km by 10 km spatial resolution**
- **100 second temporal resolution**

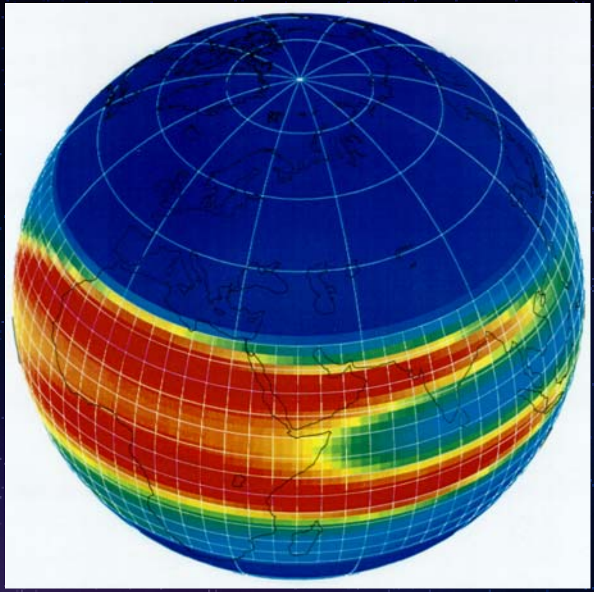
83.4 nm, 135.6 nm
130.4 nm 142.0 nm

Assimilating Model Grid Sizes For GAIM

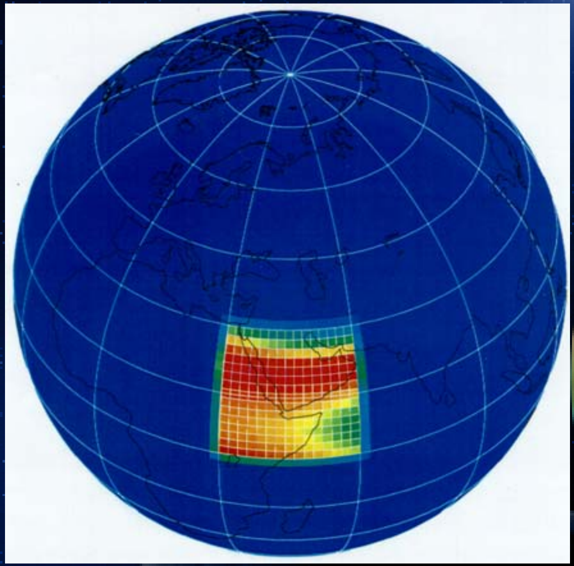
Global Grid



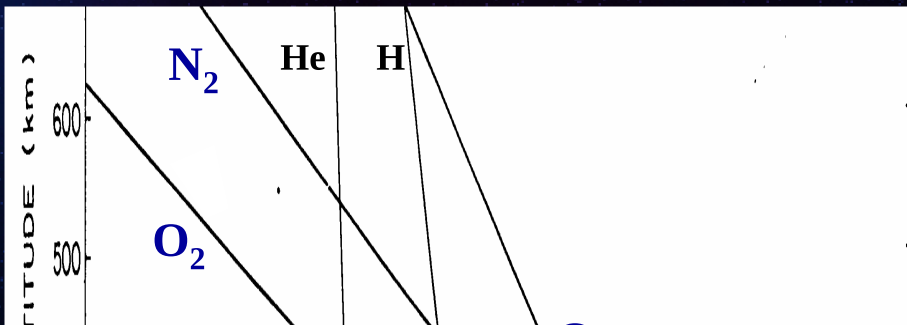
Regional Grid

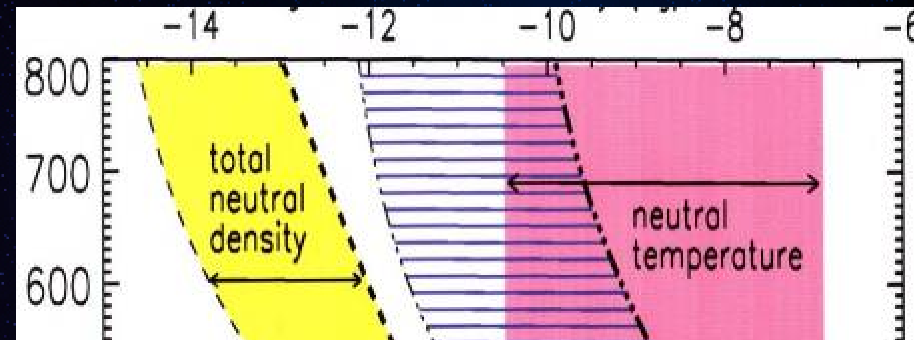


Synoptic Grid



Upper Atmospheric Neutral Density



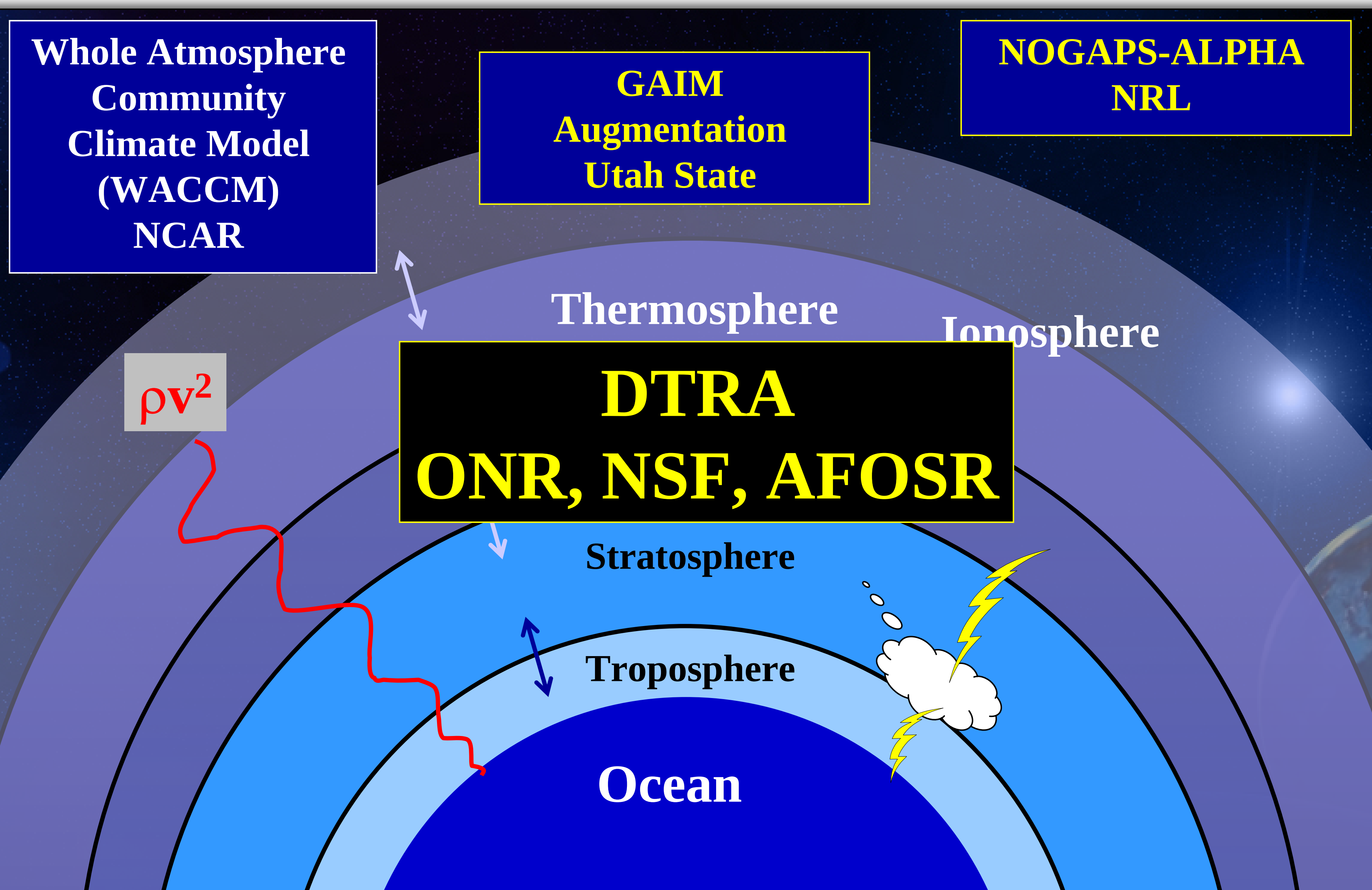


Recent Results Highlighting the Need for a Data-Driven Assimilation Neutral Density Model:

2006 Fall AGU:

- **X-Ray occultation measurements of thermospheric density near 150 km differ from models by 50% - 100% (DTRA/ONR)**
- **2000 ONR Primer (Keating GWU) result verified; thermosphere cooling at rate ~5K/decade (NCAR press conference)**

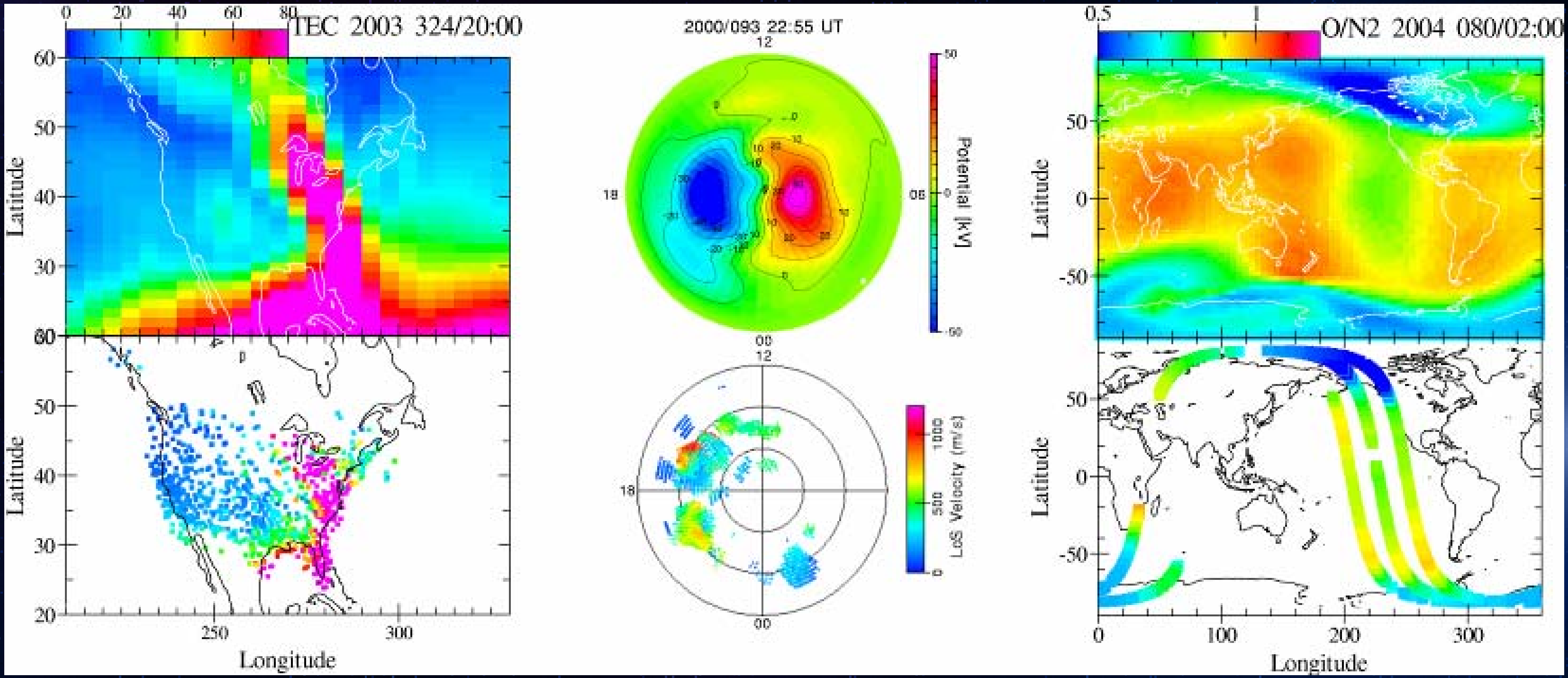
New Modeling Initiative: Ocean to Space



Atmospheric Neutral Density Prediction
2007 AFOSR MURI TOPIC

- Specific areas of interest include, but are not limited to, the following:
  - (a) The physics of solar and geomagnetic quiet time conditions
  - (b) Coupling of solar events and magnetosphere-ionosphere conditions into atmospheric effects
  - (c) A model of high latitude energy, including partitioning of that energy between winds and heating, and its impact on the atmosphere
  - (d) Determination of the effect of other thermospheric energy sources, including solar electromagnetic radiation and upward propagating tides and waves
  - (e) Determination of the response time from prediction or observation to a change in atmospheric density
  - (f) Development of physics-based energy indices to replace the proxy indices now in use
  - (g) An understanding of the physics of drag and precise determination of satellite drag coefficients in the 200-100 km altitude region with an orbiting object transitioning from free molecular flow to slip flow
  - (h) A method to validate model improvements based on results of this effort

DRI Approach to Ionospheric Forecast

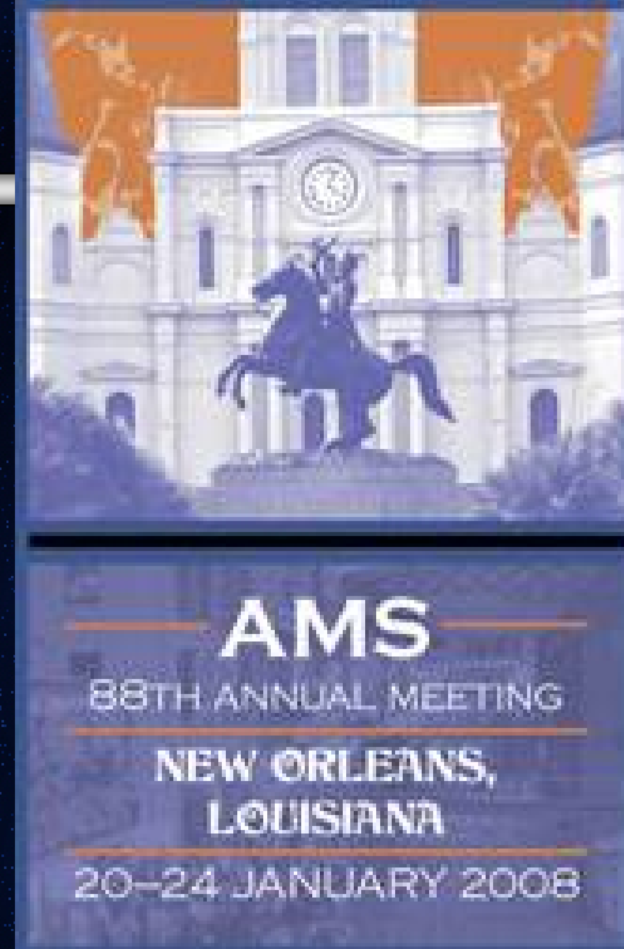


Low & Mid-latitude Ionospheric Drivers

High Latitude Drivers

Neutral Atmospheric Drivers & Variability

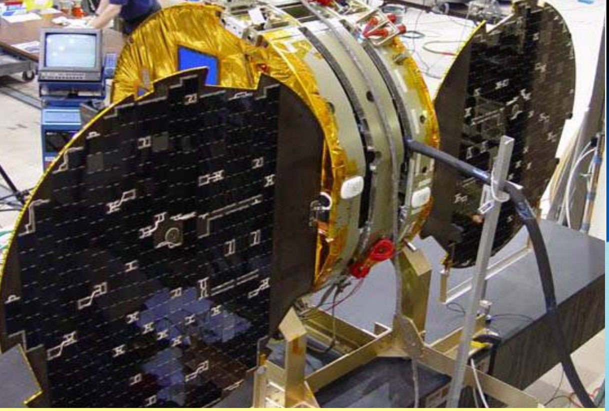
Use Satellite Neutral & Ionospheric Data

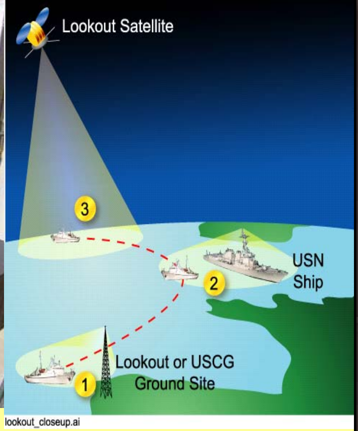


5th Space Weather Symposium
American Meteorological Society
20 – 24 January 2008
New Orleans, Louisiana

Innovative Naval Protot
(INP)
Tactical Space

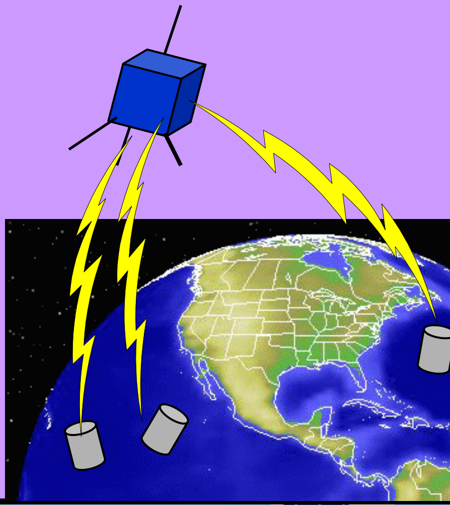
TacSat Initiated by Office of Force Transfor
State of Industry – Not State of the Art
$20M = Rocket + Bus + Payload
1 Year Start to Launch
Transition to Operational Responsive Space



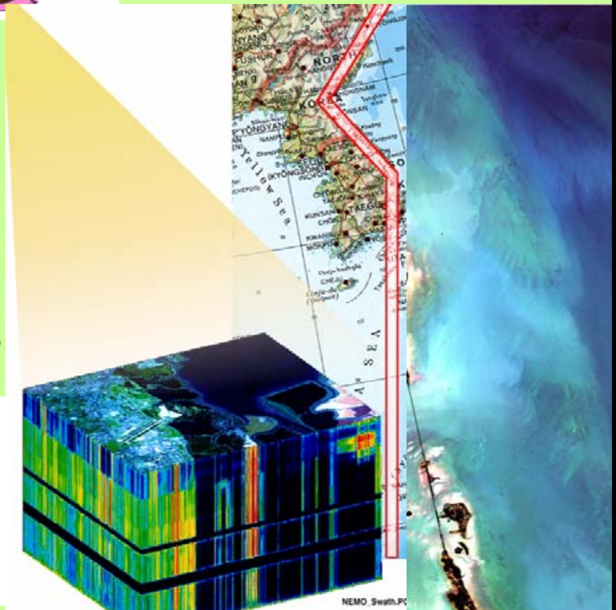


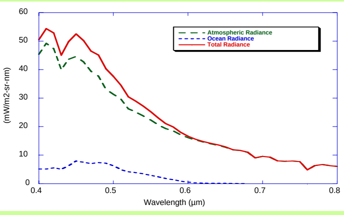
1) TIE (Ship Tracking) = ELINT + SEI + AIS

2) ODTML Data Exfiltration

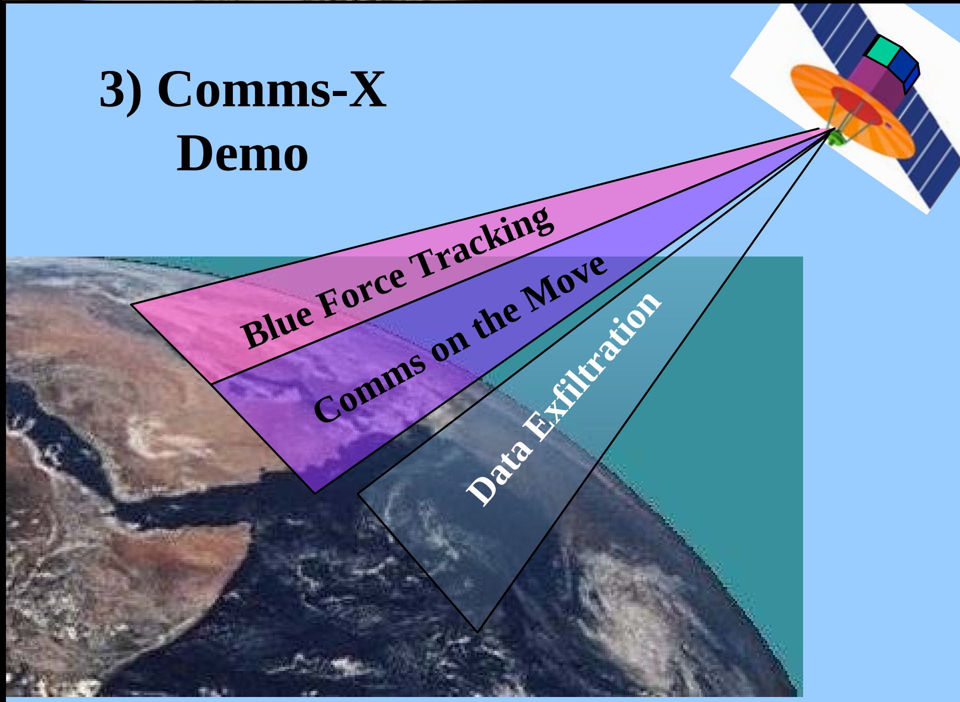


4) Maritime Hyperspectral Imaging (MHSI) HICO & COIS



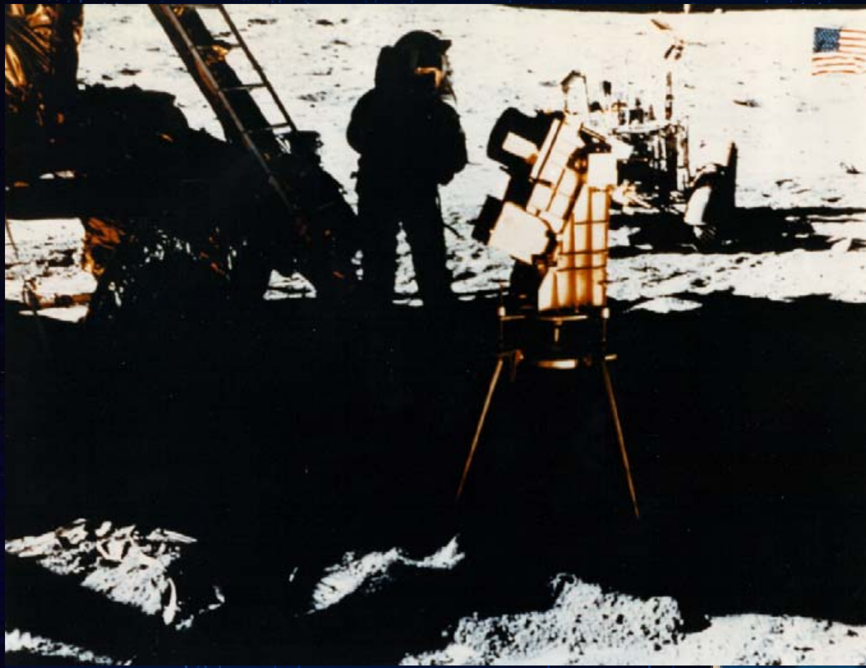


3) Comms-X Demo

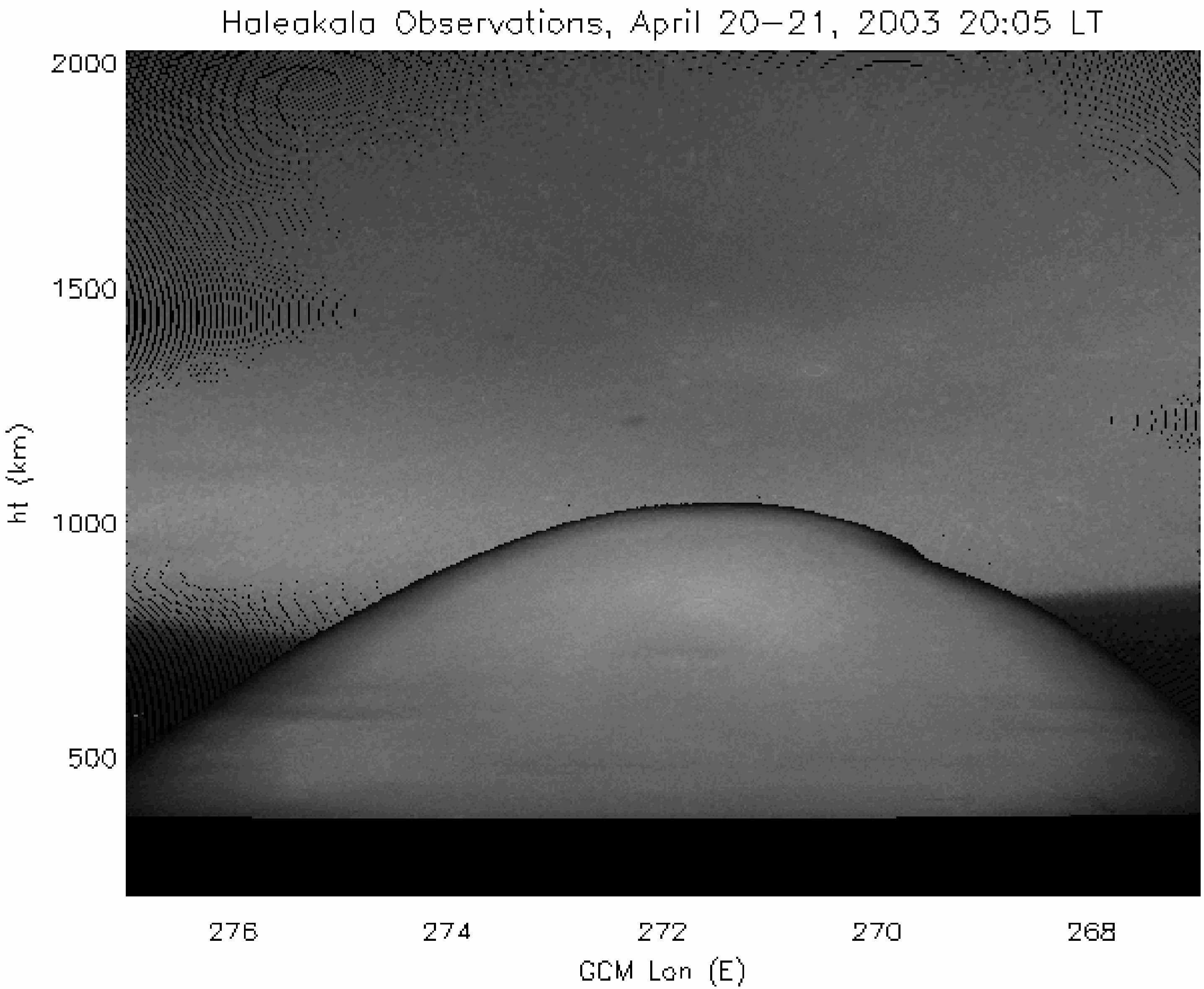


Backup

Far UV Image of the Earth from the Lunar Surface

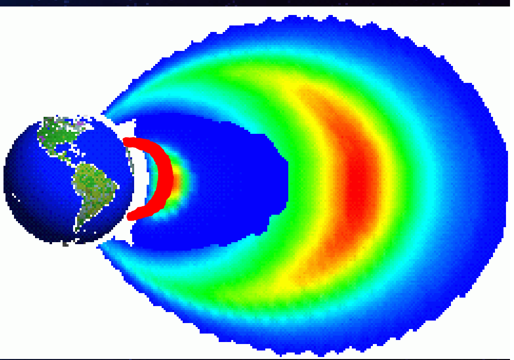


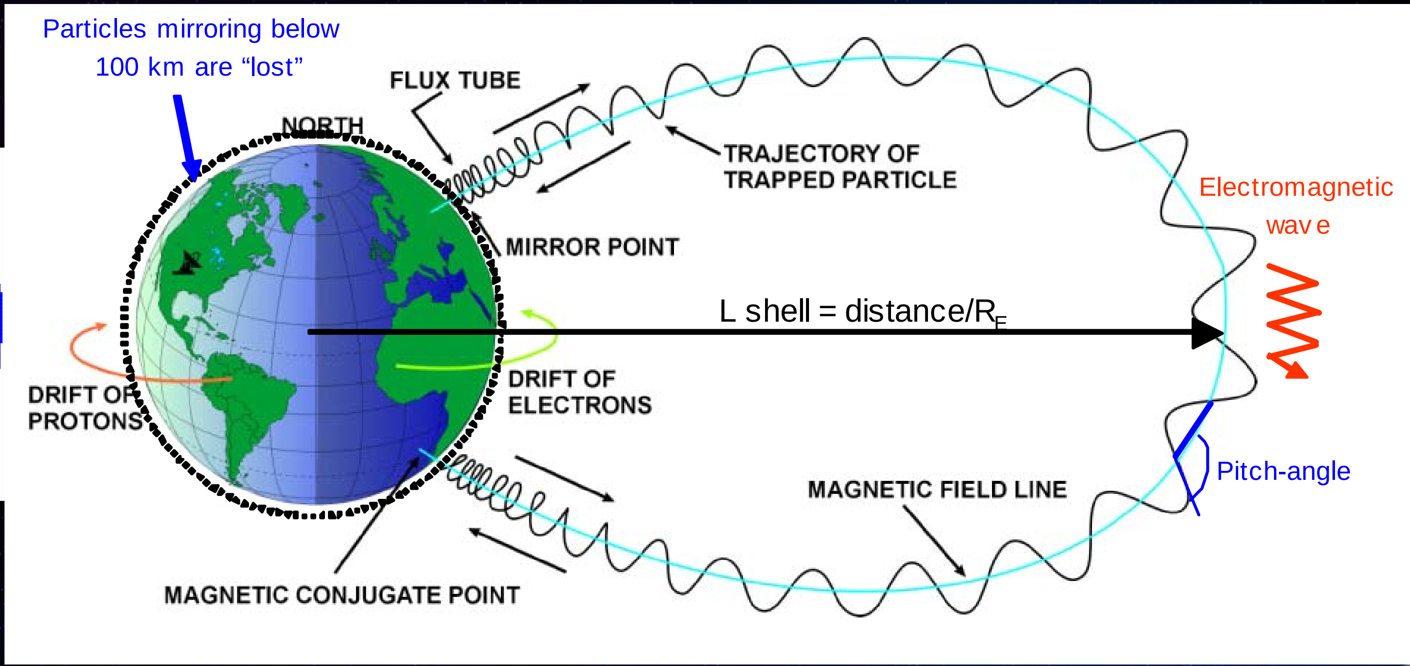
Apollo 16 (1971)
PI: Dr. George Carruthers
NRL



Haleakala Observations, April 20-21, 2003 20:05 LT
2000
1500
1000
500
ht (km)
276
274
272
270
268
GCM Lon (E)

Radiation Belt Dynamics and Energetics
2007 Joint ONR/AFOSR MURI Topic





ORANGE
3.8 MT at 43 km

TEAK
3.8 MT at 76.8 km

KINGFISH
__ MT at __ km

CHECKMATE
__ MT at __ km

STARFISH
1.4 MT at 400 km

Reconstructing the Ionosphere with the Long Wavelength Array

Christopher Watts

University of New Mexico

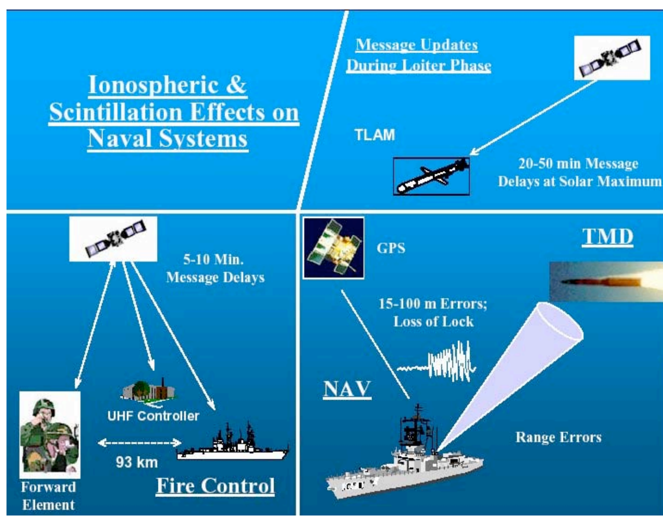
LWA Kick-off Meeting

20 Sept. 2007

http://lwa.unm.edu

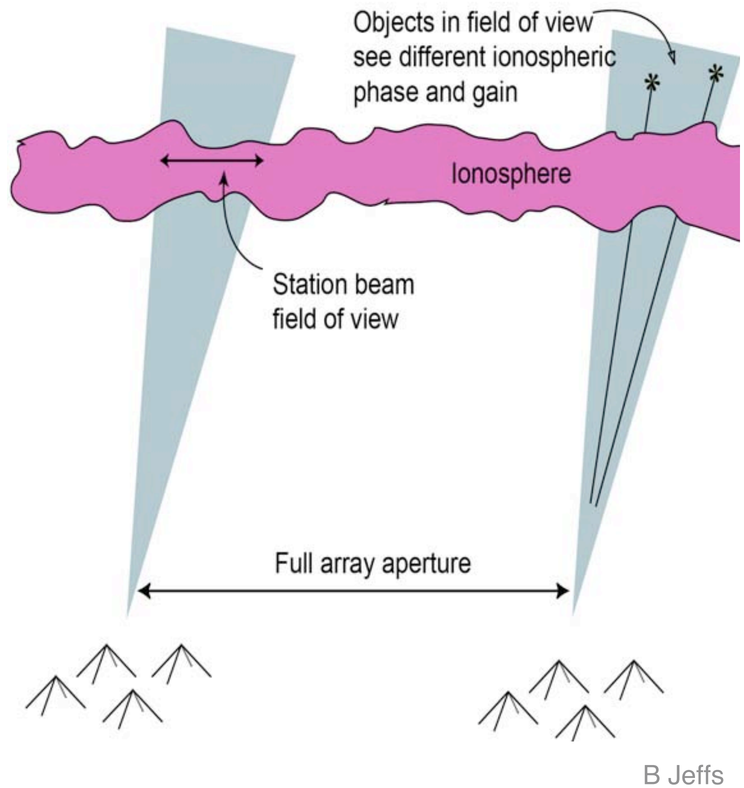
Space Weather Motivation for the LWA

- Ionospheric physics on fine spatial and temporal scales
  - Waves and turbulence, esp mid-latitude and equatorial region
  - Couple of ionosphere & neutral atmosphere
- Improvement of global data assimilation models
- Reliability of GPS & communications systems
- Space weather predictive capability for "events"
- The LWA is funded through ONR
- Ionospheric microstructure affects a wide variety of operations:
  - Communications
  - Navigation
  - Geolocation
  - Satellite operations

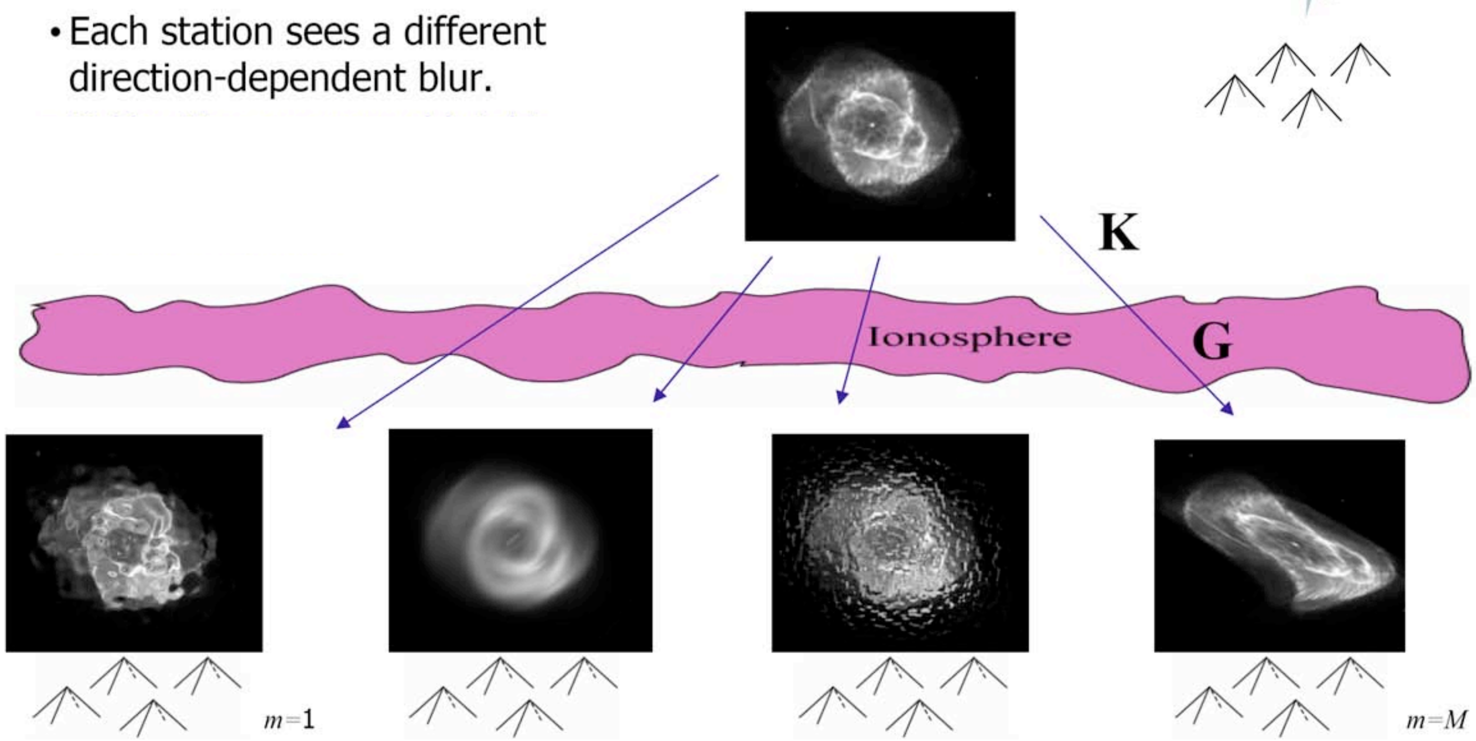


Ionosphere Problem for the LWA

- Ionospheric effects severely limit resolution & sensitivity
- Spatial variations in the ionosphere across each station beam distort the image



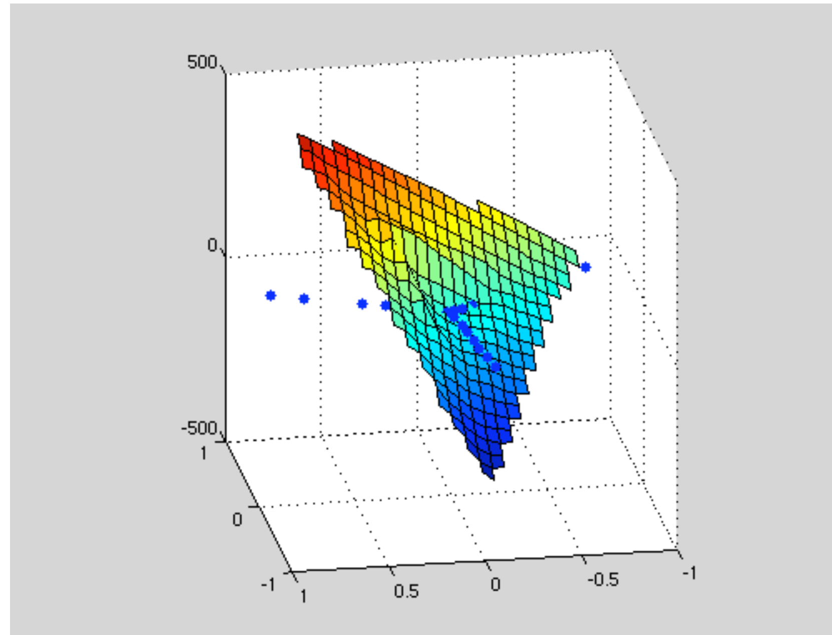
- Each station sees a different direction-dependent blur.



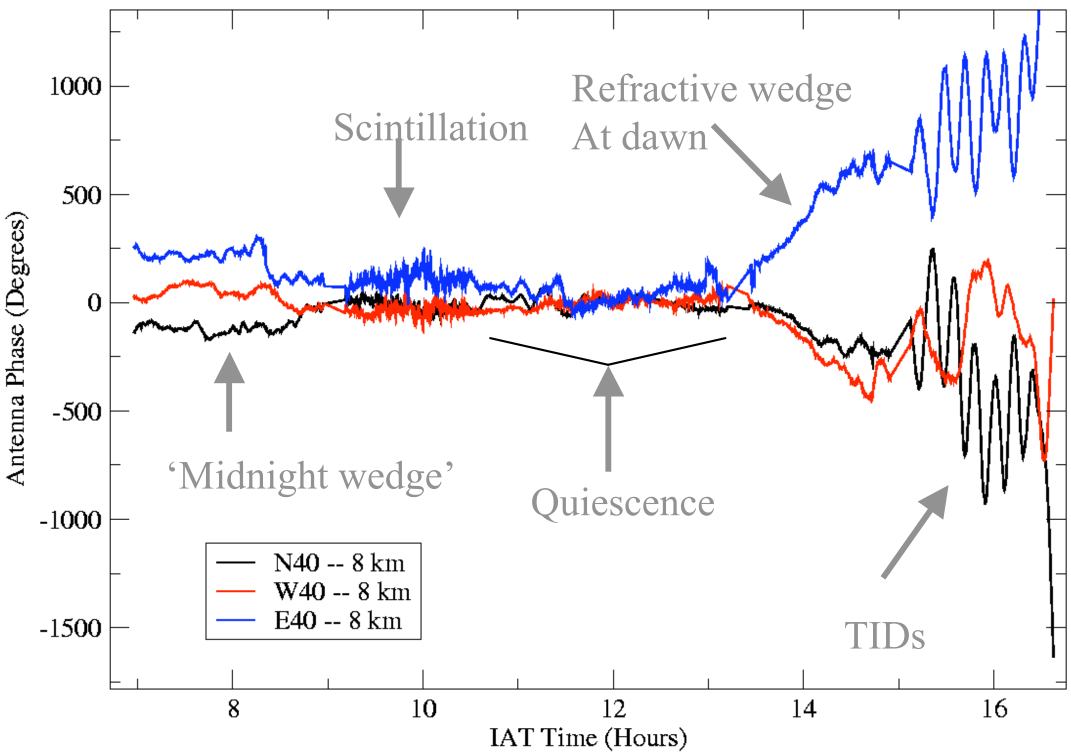
Ionospheric Phase Corruption

- HF/VHF arrays are extremely sensitive to ΔTEC (for example, VLA)
  - VLA probes ΔTEC variations to ~100 m, ~1 min, over 20° FoV
  - Current VLA has ΔTEC precision ≤ 10^{-3} TECU [1 TECU ≡ $\int n_e dl \sim 10^{16}$ m^{-2}]

Δphase over VLA

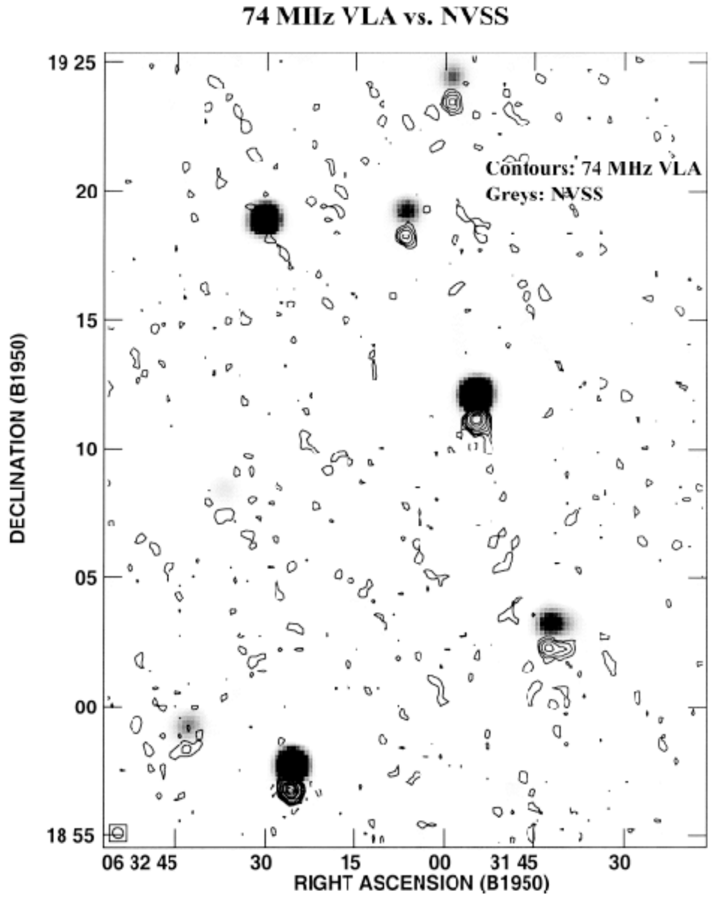


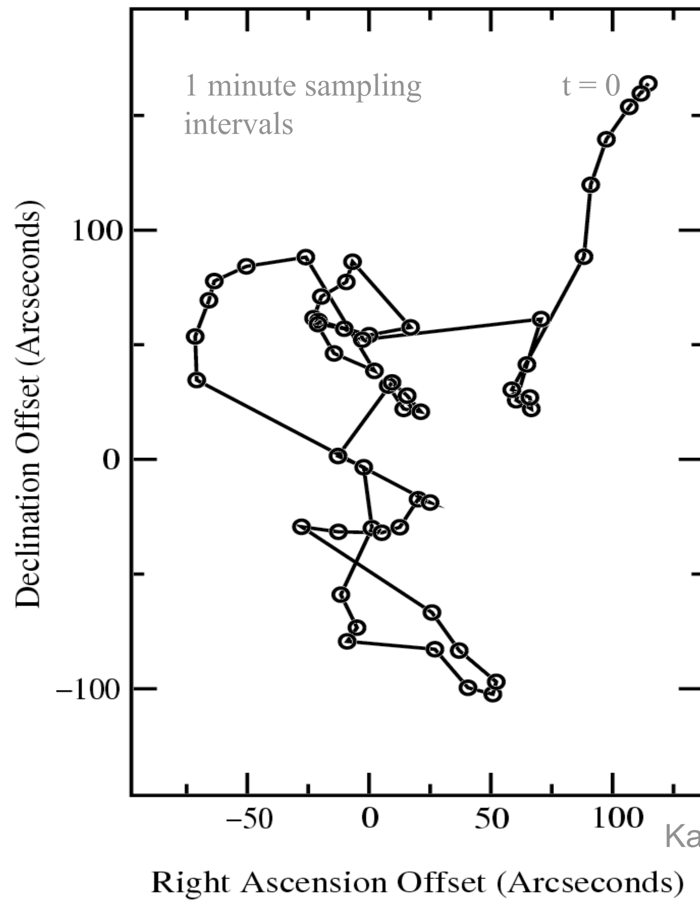
19 Jan 2001
Mike Montgomer



Kassim et al. 2007

0th Order Correction: Refractive Wander



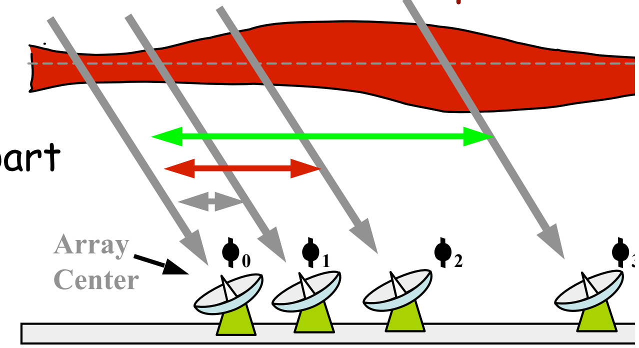


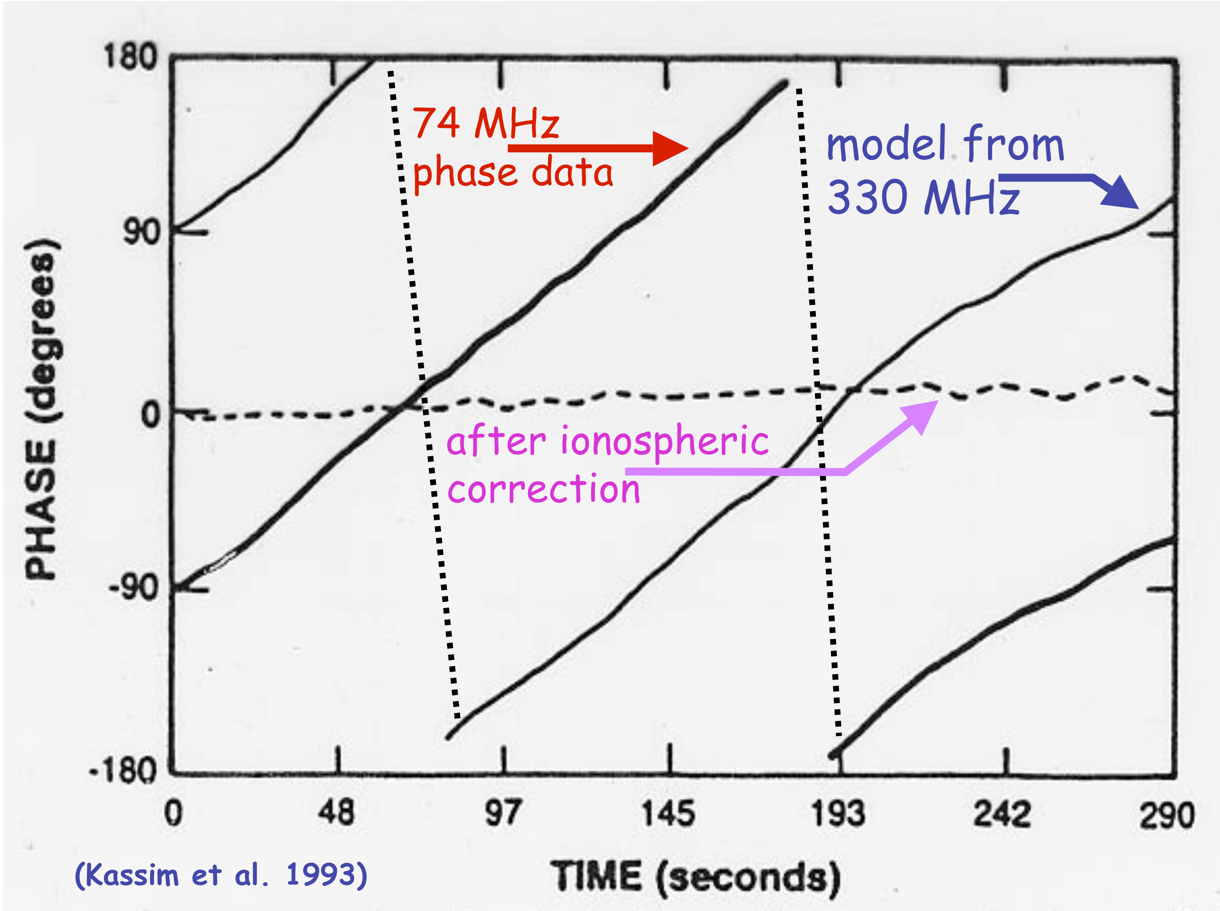
Kassim et al. 200

- The large-scale ionospheric refraction shows considerable variability
  - Shown at the left 74MHz referenced to 1400MHz images
- Large Scale Ionospheric Structure -> simple phase shift
- Solution – use known phase centers to shift images to compensate

1st Order Correction: Phase Transfer

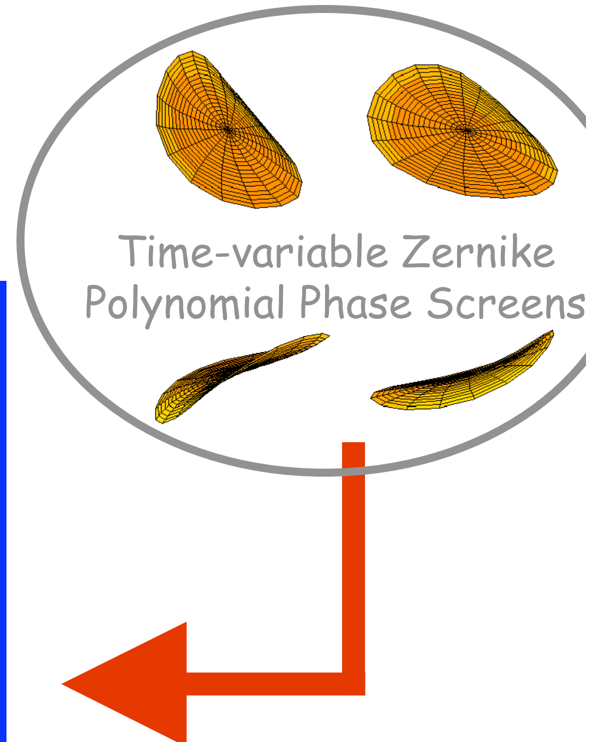
- Distortions can be removed by observing the same source and two different frequencies
- Example: Traveling Ionospheric Disturbance (TID)
  - 1% perturbation in TEC , 30 km wavelength, 100 km/hr
  - Causes a phase offset of 10 radians between antennas 30 km apart
  - Phase changes 1 rad/min.
- Self-calibration can remove residual effects.
  - Uses the target as the phase reference

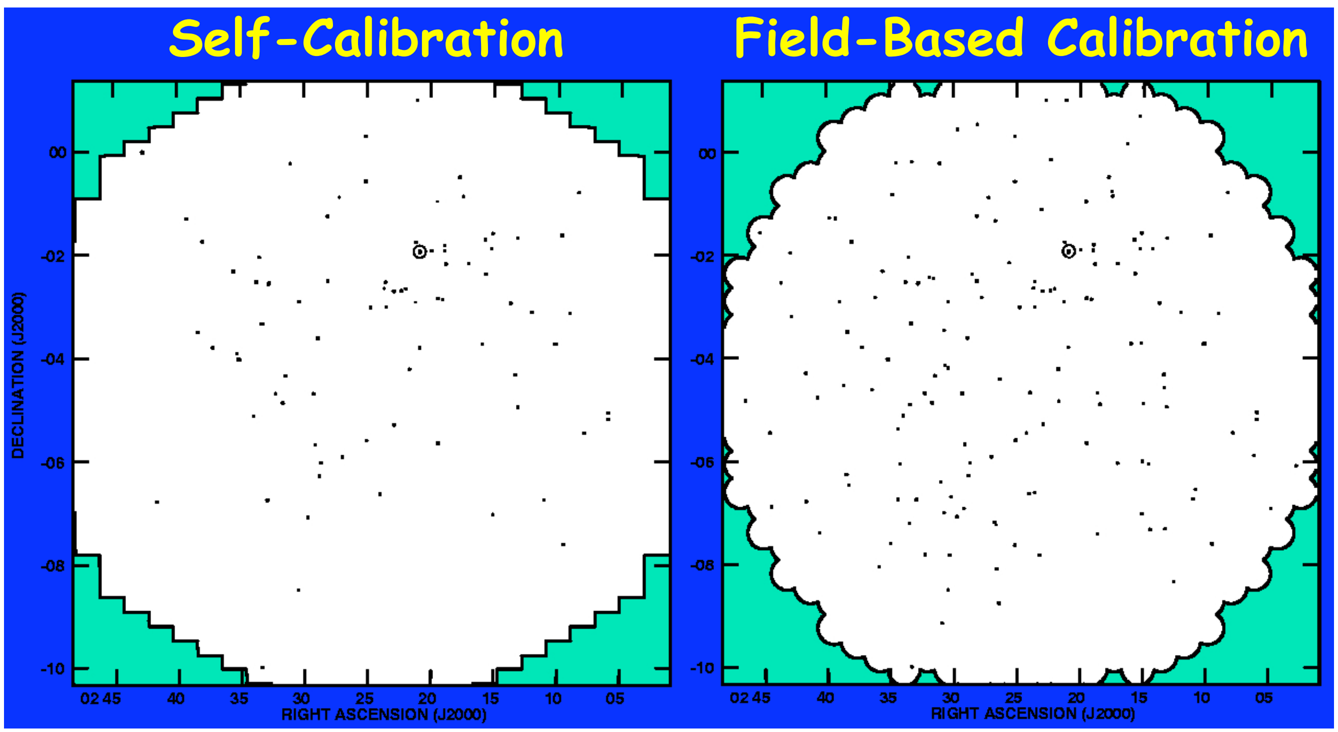




Field Based Calibration

- Take snapshot images of bright sources; compare to known positions
- Fit Zernike polynomial phase delay screen for each time interval.
- Apply time variable phase delay screen to produce corrected image.
  - Slice by slice fit - NO physical continuity in time
  - Fit limited to 2nd order (practical considerations of the VLA)
  - Barely adequate for VLA and VLSS survey





Non-uniform sensitivity

Uniform sensitivity

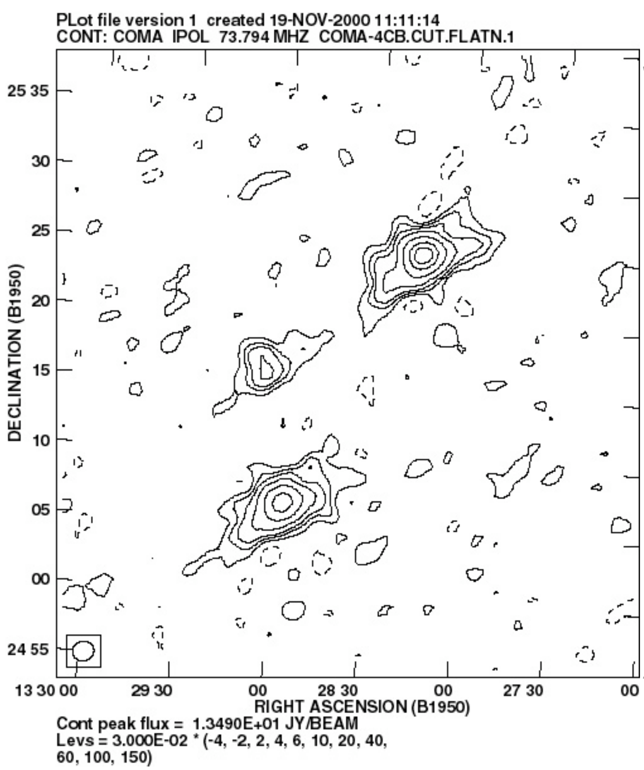
black dots ≡ radio sources

Improved calibration yields more detections & uniform distribution

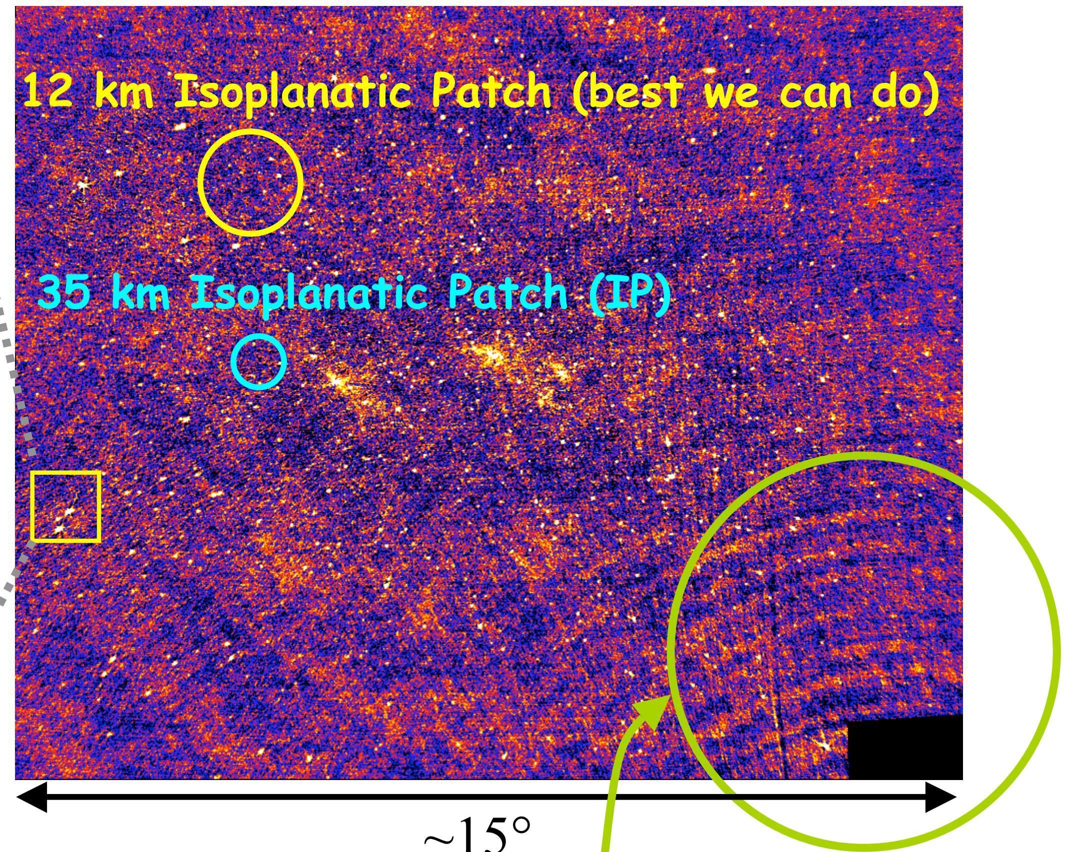
Cohen et al. 2007

Limits of Current Ionospheric Corrections

- Current adaptive optics (AO) cannot support full-field mapping on baselines > 12 km.
- Longer baselines (for improved resolution) require higher order phase solutions.

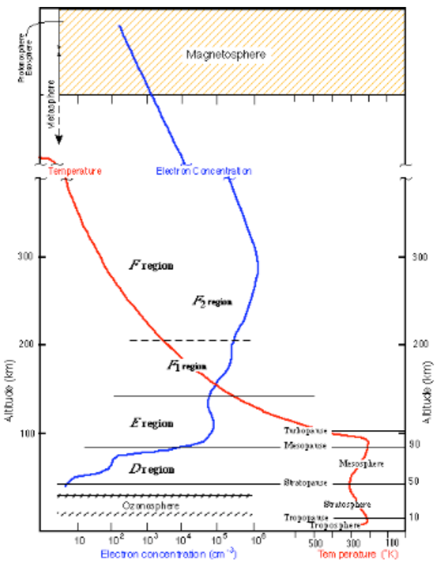


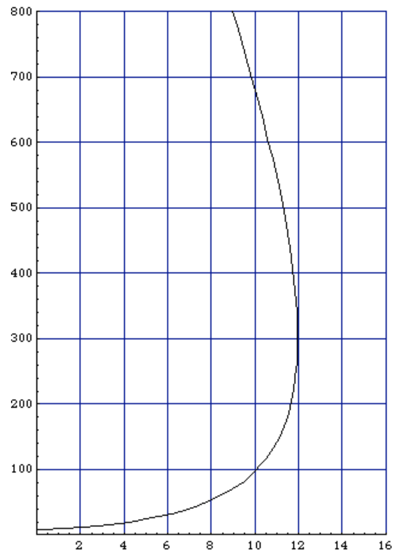
Away from best correction patch, images are distorted and intensities are reduced.



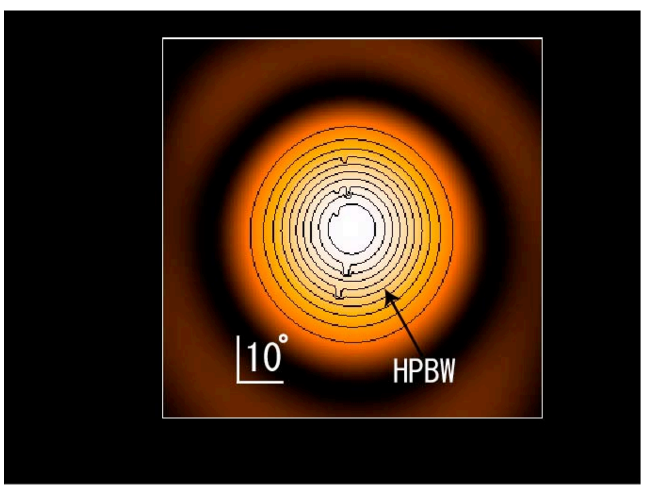
Striping, due to sidelobe confusion from a far-off source in a completely different IP, dominates signal-to-noise

Modeling the Ionosphere's Effect

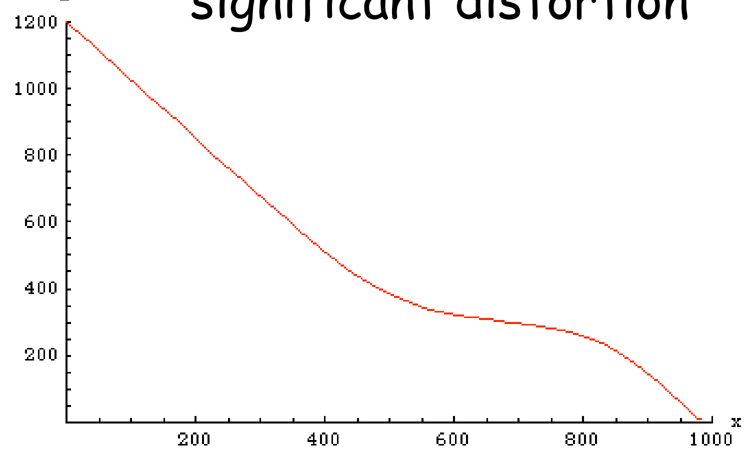




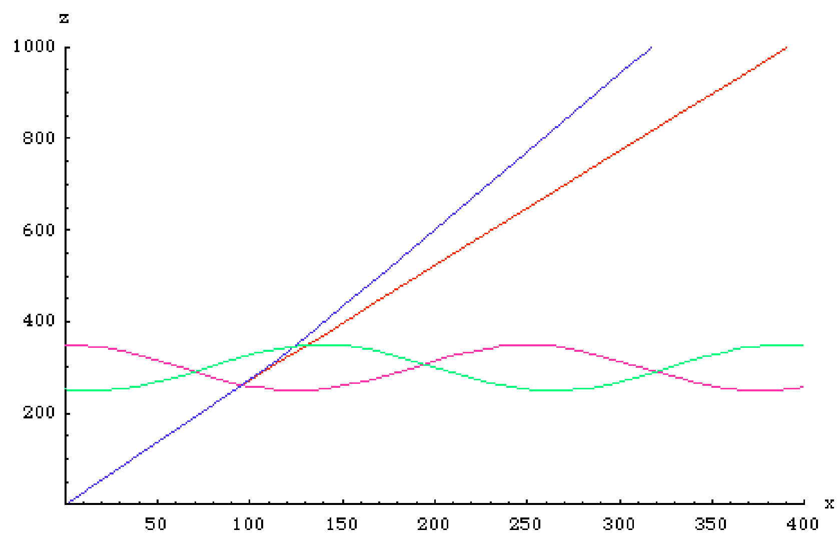
- Use ray tracing code to understan
  ionosphere effect on beam patter
  - Cold plasma model with magnetic fiel
  - Refractive and Faraday rotation effects
- Code check: simple laminar ionosphere
- No effect on Station beam patter
  - Note: ray @ 10MHz travels ~300 km horizontally
  - Nonuniform, curvature, will cause significant distortion



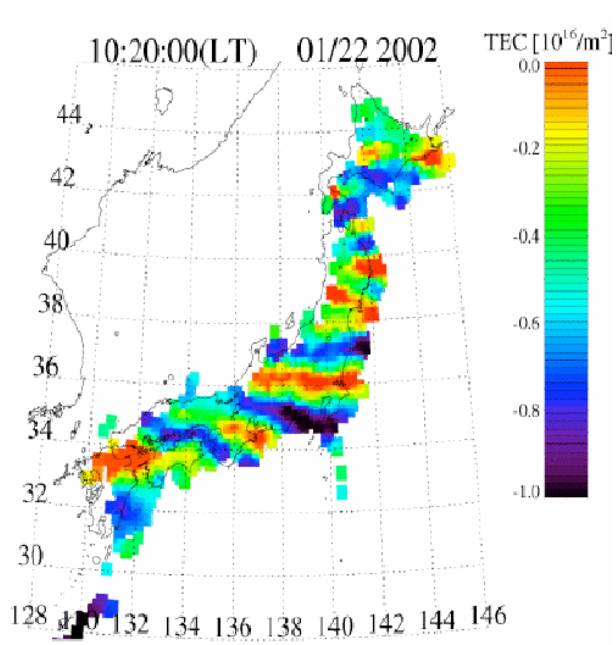
Beam pattern @ 70° from 50 sources

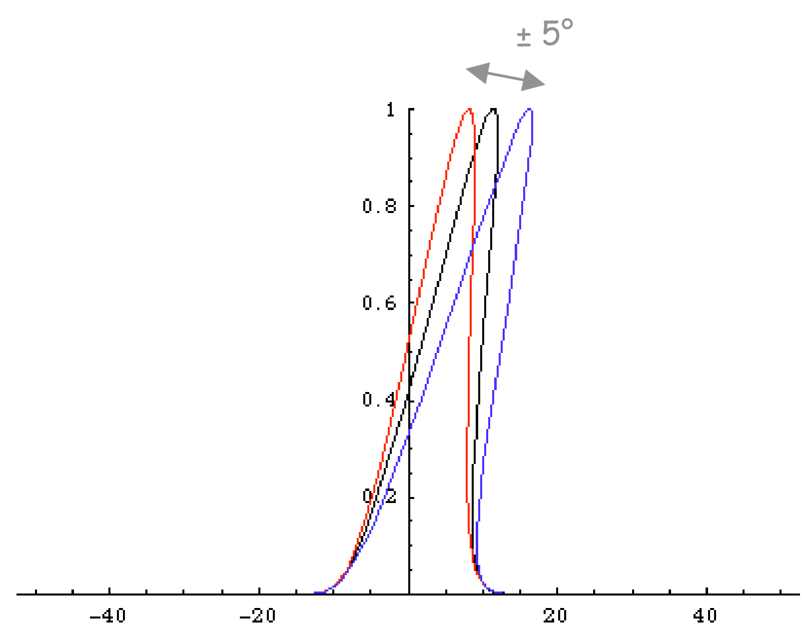


TID Effect on Station Beam



- Now add traveling ionospheric disturbance (TID)
  - Parameter mimic VLA measurements at 74 MHz
  - Use 10.5 MHz for worst case
- Significant beam deviation and distortion
  - 70 ± 5° shift in beam direction
  - Beam broader





LWA Technical Specifications: Ionosphere Impact

	Required	Desirable
Frequency Range:	20 MHz to 80 MHz	9 MHz to 88 MHz
Angular resolution:	θ ≤ [8,2]″	θ ≤ [5,1.4]″
LAS at [20,80] MHz:	= [4,1]°	= [8,2]°
Baseline range:	100 m to 400 km	50 m to 600 km
Sensitivity [20,80 MHz]:	σ ≤ [0.7,0.4]	σ ≤ [0.5,0.1]
Dynamic r		
$\Delta\nu_{max}$ (per		
$\Delta\nu_{min}$:		
Temporal		
Polarization:	dual circular > 10 dB	dual circular > 20 dB
Sky Coverage:	Z ≥ 64°	Z ≥ 74°
Primary Beam [20,80] MHz:	= [8,2]°	≥ [8,2]°
# of beams:	2 fully independent	≥ 2 fully independent
Configuration:	2D array, N = 53 stations	2D array, N≥53
Philosophy:	User-oriented, open facility; proposals solicited from entire community	
Mechanical lifetim		

Angular resolution/point accuracy → electron density 0.0003-0.003 TECU

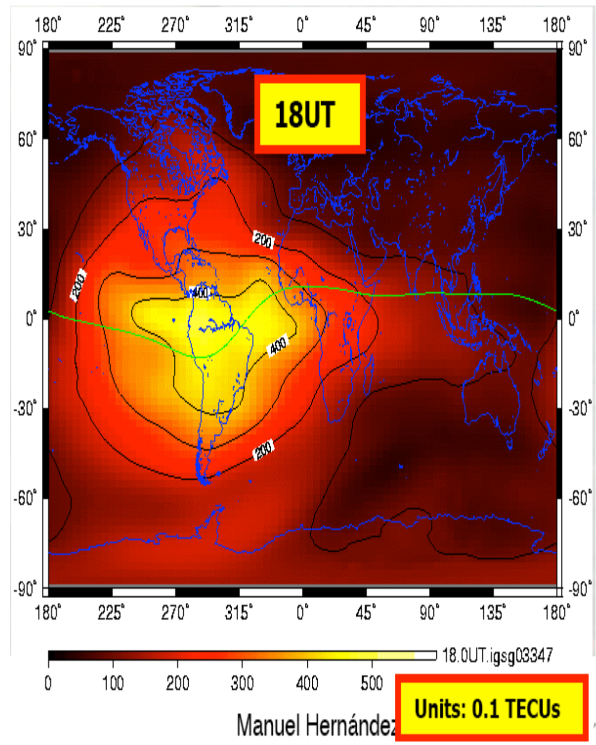
Resolve geomagnetic storms → temporal resolution ~ $\Delta\tau \leq$ 1 msec (GPS uses 50 Hz)

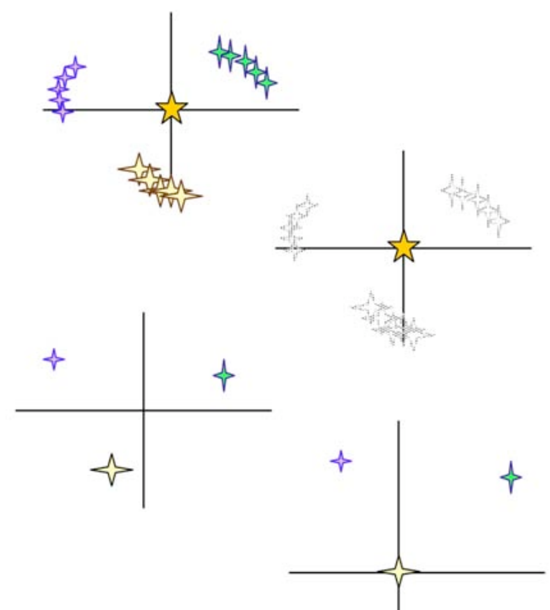
Faraday rotation (1°) → B along path ~ 1%

Input from ionospheric community very much needed

Addressing the Ionospheric Issue

- Uses global GPS station network
  - ~100 stations
  - TECOR might provide 0th order correction
- High density GPS receiver network at each LWA station
  - Multiple pierce points for high resolution TEC measurements
  - Use other beacon satellites, too
- Passive "radar" from RFI sources
  - FM and TV stations
- Self-calibration methods
  - Peeling algorithm: successive calibration on brightest source
  - Direct least-squares: using all bright sources
- Ionospheric Modeling
  - Gaim & IDA3D incorporate data

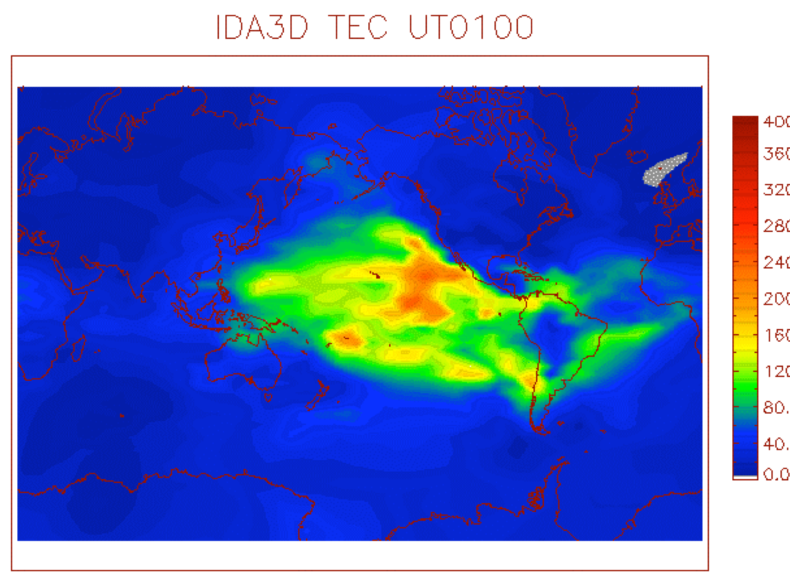


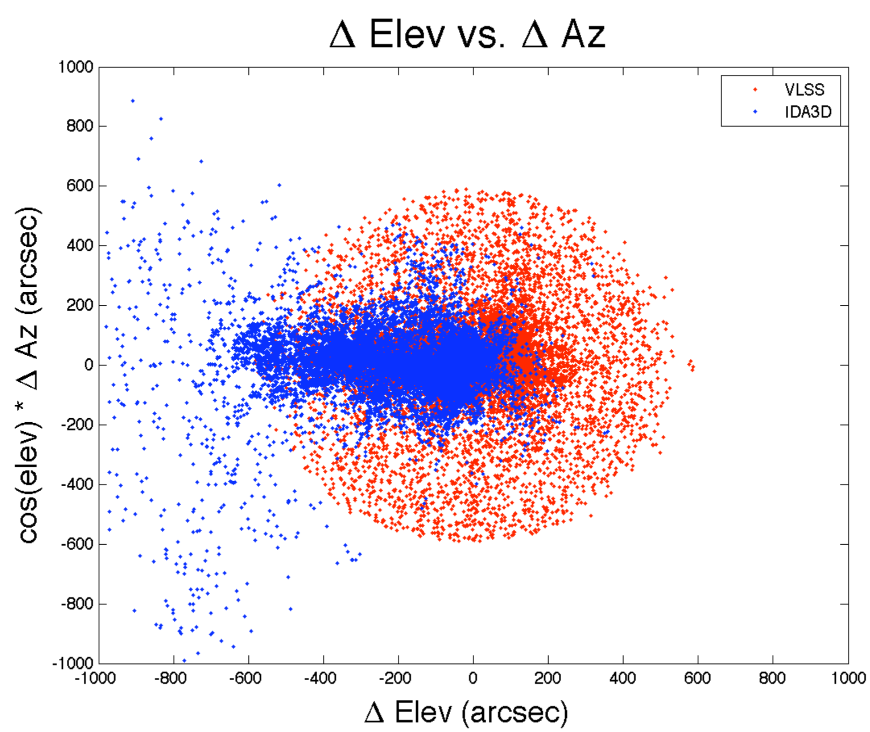


B Jeffs

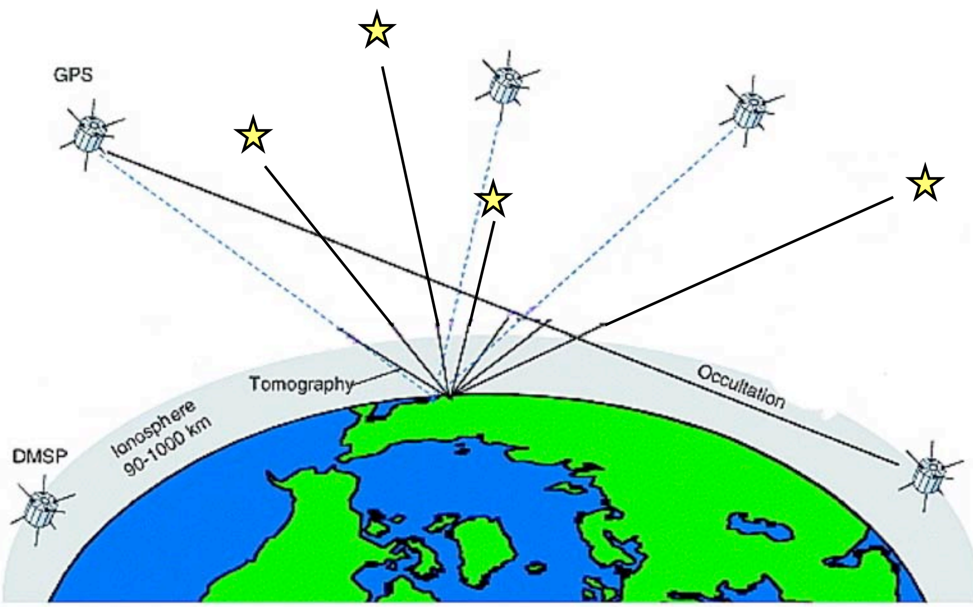
Modeling with Real Data

- IDA3D assimilative model used by ARL
  - Model incorporates data from GPS, GPS occultation (GOX), oversatellite electron content (OSEC)
- Use ray tracing to obtain apparent position of sources
- Compare with VLSS and known positions
  - Field calibration does reasonable job in correcting ionosphere.
  - Nighttime is better than daytime,
    - but much of daytime is still useful.



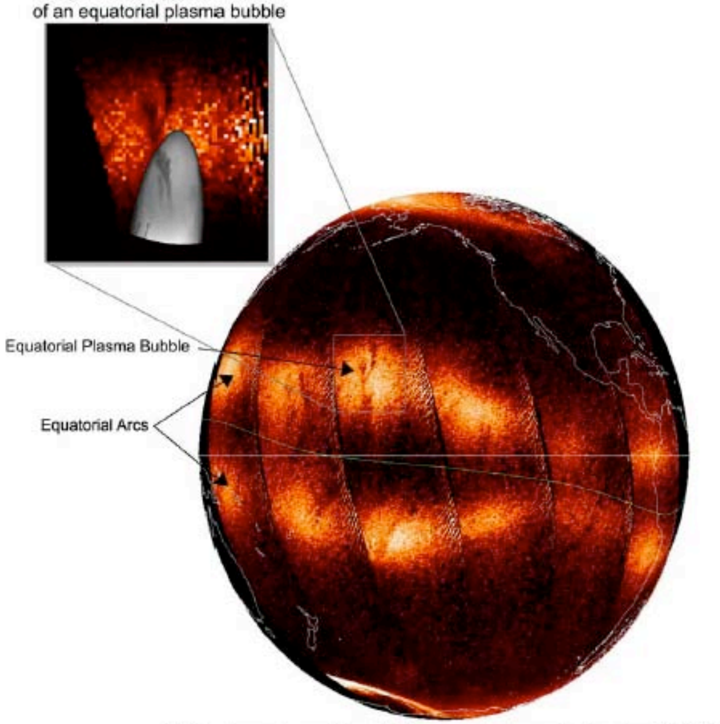


Current LWA Ionospheric Experiments



- Beacon/VLA experiment for 3D tomography over the VLA
- Use 4 measurements
  - GPS Occultaton for horizontal chords
  - Satellite radio beacons for vertic chords (COSMIC, OSCAR, DMSP)
  - VLA phase during observation of astronomical sources
  - Satellite-borne air glow measurements (TIP) at night
- Data just this past weekend …
- HAARP Moon bounce
  - Use LWA prototype antennas
  - Detect at 9.8 and 7.8 MHz
  - Proposal just submitted

New Challenge: Fine Scale Structure



GUVI observations of the 135.6-nm emission on September 22, 2002

- VLA 74 MHz Archive
  - Fine-scale structures in the VLA 74 MHz data.
  - Data since the 74 MHz system was installed in 1998.
  - Observing periods are concurrent wit significant space weather events (e.g Halloween storm of 2003).
  - Data are archived by NRAO
    - index is maintained by Aaron Cohen at NRL.
- Space physics community encourage to investigate data further

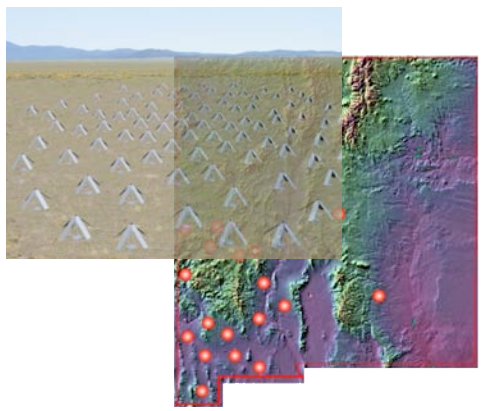
LWA Ionospheric Research Contributions

- LWA HF/VHF data will provide unprecedented spatial & temporal ionospheric imaging
  - Continuous monitoring (not limited to night) for study of e.g.:
    - Evening collapse of F-region & onset of depletions & enhancements (bubbles).
    - Ionospheric response to penetrating electric fields during solar & geomagnetic storms
    - Coupling of neutral atmosphere & ionosphere
  - High 2D spatial resolution probes fundamental physical understanding
    - F-region correlation lengths
    - Wave formation & attenuation

- ΔTEC Measurements with extraordinary accuracy
  - Validation of alternate measurement techniques such as airglow & GPS
  - Possible separation of ionospheric layers (TEC – F (airglow) = E + D regions)

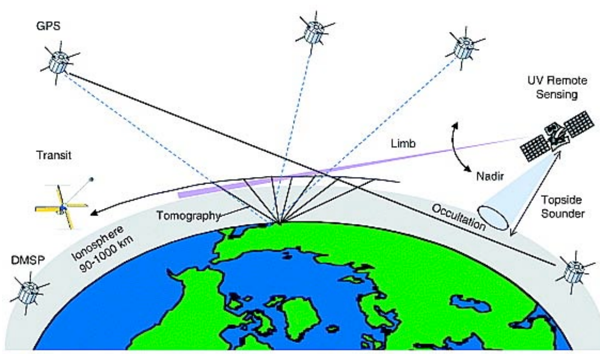
Summary

- Astronomer's nightmare is Ionospheric Scientist fantasy
- Success will require multifaceted approach
  - Modeling
  - GPS and related instrumentation
  - LWA use of coherent and incoherent sources (FM, scatter radar)
  - LWA self-calibration
- Astronomers and ionospheric physicists must work closely together from the start

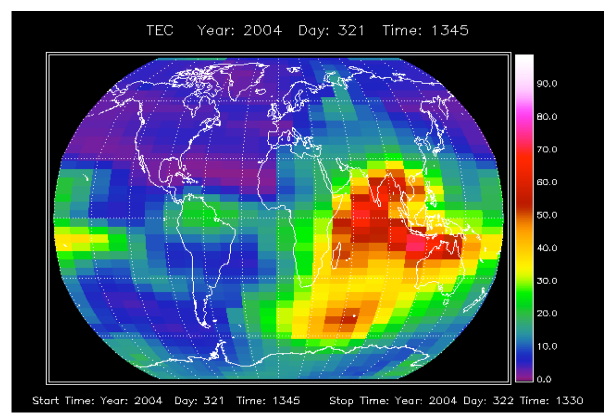


Long Wavelength Array

Will require significant investment, but will produce significant rewards!



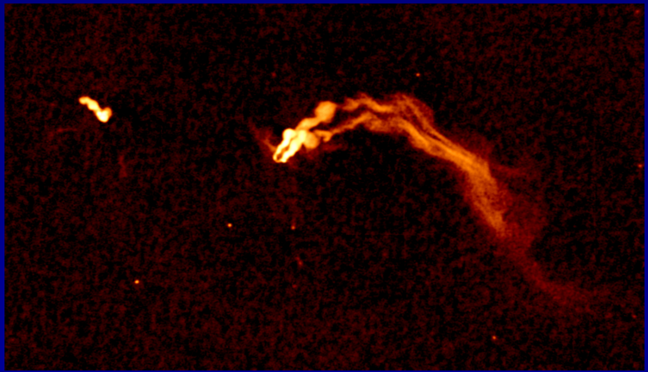
Multiple sensor input to modeling

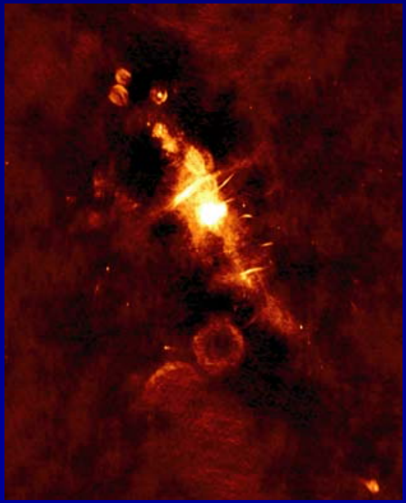


GAIM dynamic TEC model

The Long Wavelength Array

Namir Kassim
LWA Project Scientist
Naval Research Laboratory





Long Wavelengths ≡ LW ≡ 20-80 MHz

LWA Science Case

1. **Plasma Astrophysics & Space Science**
   - Ionospheric waves & turbulence
   - Solar, Planetary, & Space Weather Science
   - Acceleration, Turbulence, & Propagation in the interstellar medium of the Milky Way & normal galaxies
2. **Acceleration of Relativistic Particles**
   - Supernova remnants (SNRs) in normal galaxies ($E < 10^{15}$ ev)
   - Radio galaxies & clusters at energies ($E < 10^{19}$ ev)
   - Ultra-high energy cosmic rays ($E \sim 10^{21}$ ev?)
3. **Cosmic Evolution & the High-z Universe**
   - Evolution of Dark Matter & Energy by differentiating relaxed & merging clusters
   - Study of the 1st black holes
   - H I during the Dark Ages?
4. **Exploration & Discovery**

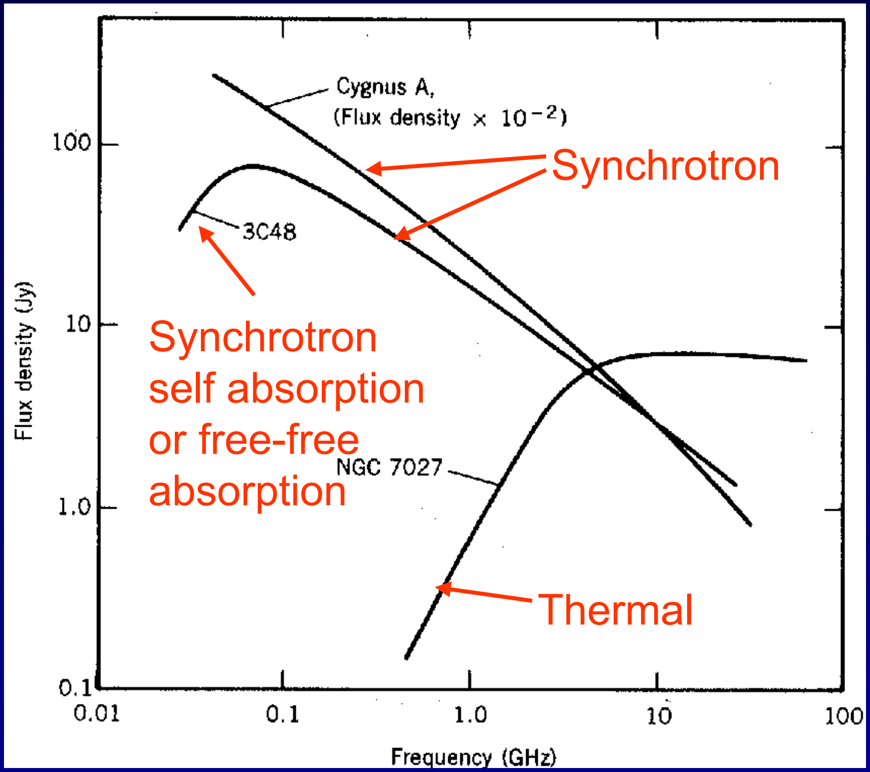
LWA science plan recommended in National Academies' Astronomy Decadal Report":

" ... will dramatically improve knowledge of the universe …"

Thermal vs. Synchrotron Emission

- Thermal Emission (Bremsstrahlung)
  - Best observed at cm λ (ν > 1 GHz)
  - Coulomb force between e^- & ions
  - Temperature dependent, Blackbody spectrum
- Synchrotron Emission (nonthermal)
  - Best observed at m λ (ν < 1 GHz)
  - Relativistic e^- in magnetic field
  - Depends on the energy of the electrons and magnetic field strength
  - Emission is polarized
  - Can be either coherent or incoherent

$1\ \text{Jy} = 10^{-26}\ \text{Watts m}^{-2}\ \text{Hz}^{-1}$

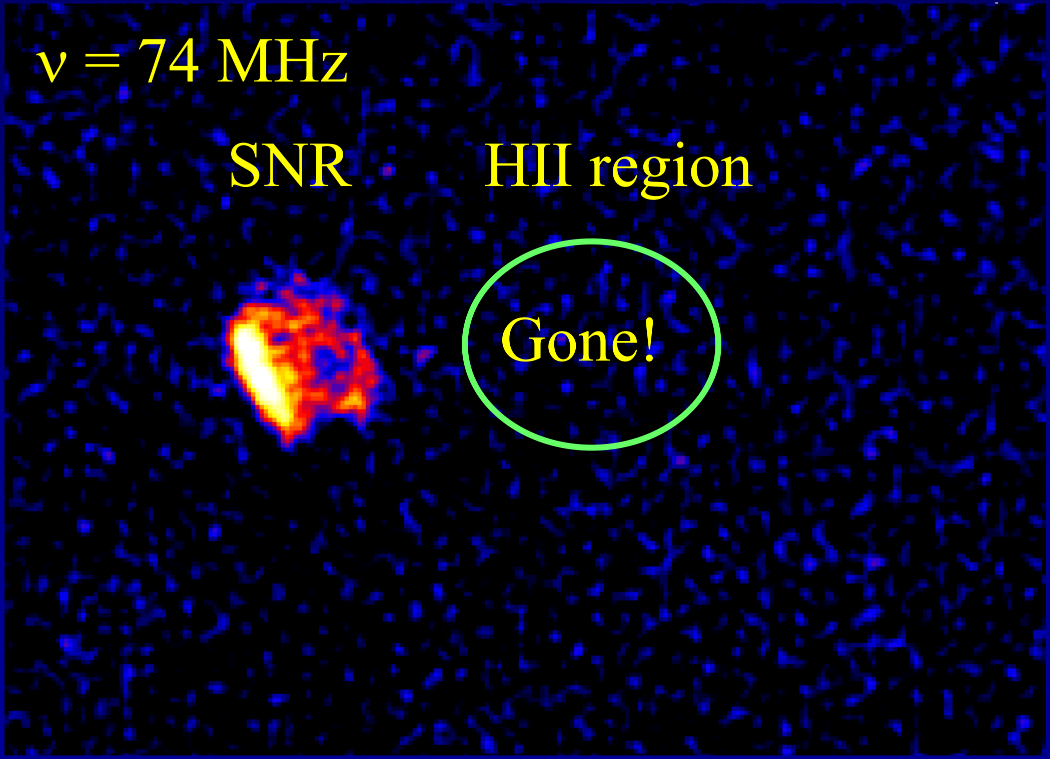


Thompson, Moran, & Swenson

- **LW: least explored region of the spectrum**
  - Consequence of <u>poor angular resolution & sensitivity</u>
    - Due to ionosphere
  - Favors studies of nonthermal sources - intrinsic link to shock physics, high energy phenomena – MeV, Gev electrons
  - Unique insights into thermal & nonthermal interaction, self-absorption processes – distance information
  - Large field of view, high surface brightness sensitivity - often an advantage

Thermal vs. Nonthermal Emission

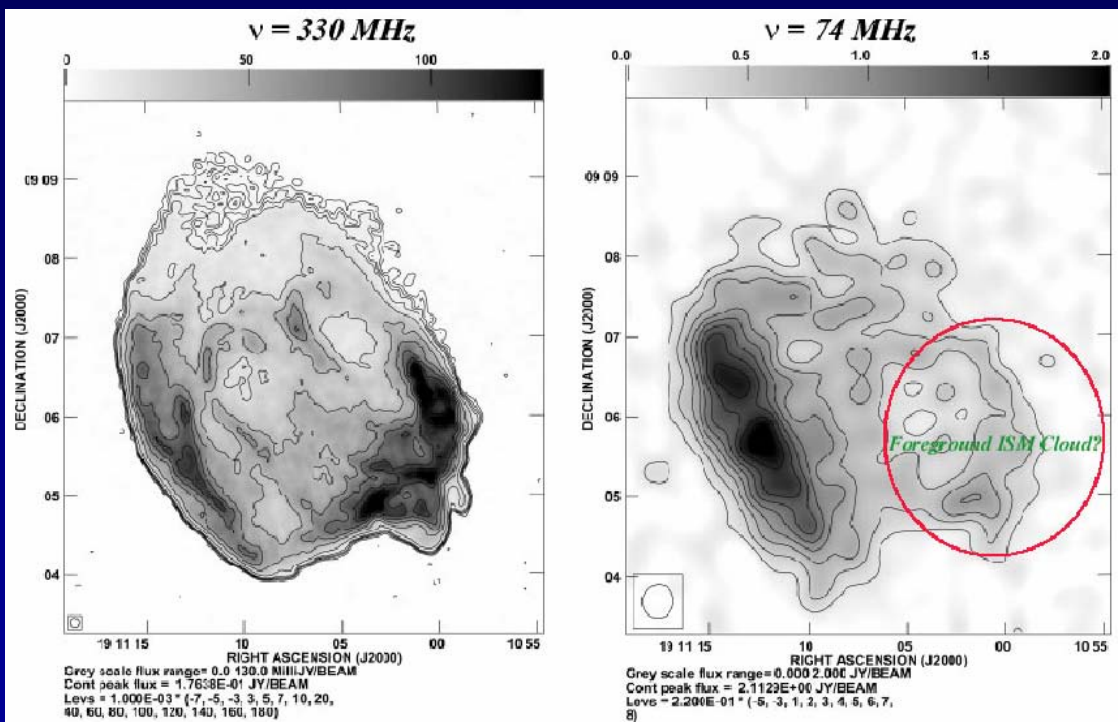
SNR≡ supernova remnant => nonthermal
HII ≡ ionized hydrogen => thermal



(Note large field of view)

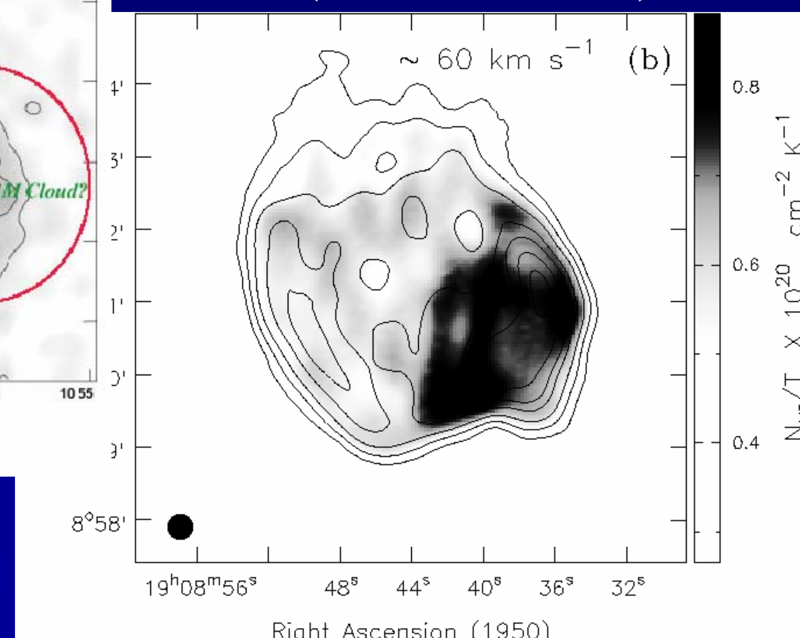
SNR

Plasma Astrophysics: ISM Thermal Absorption



Lacey et al (2001)

HI (ν = 1.4 GHz)

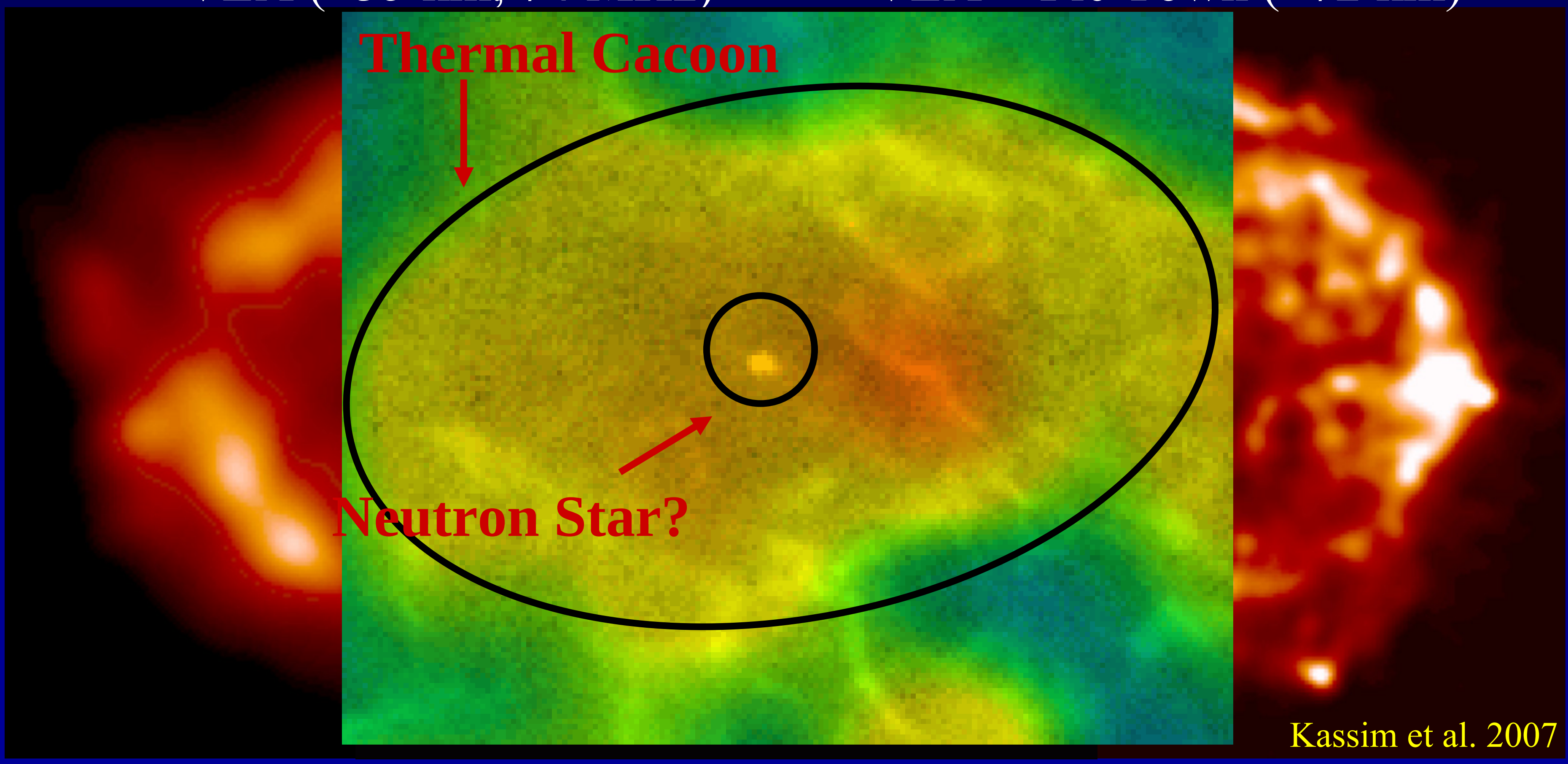


1st example of resolved thermal absorption in the interstellar medium

Brogan & Troland (2001)

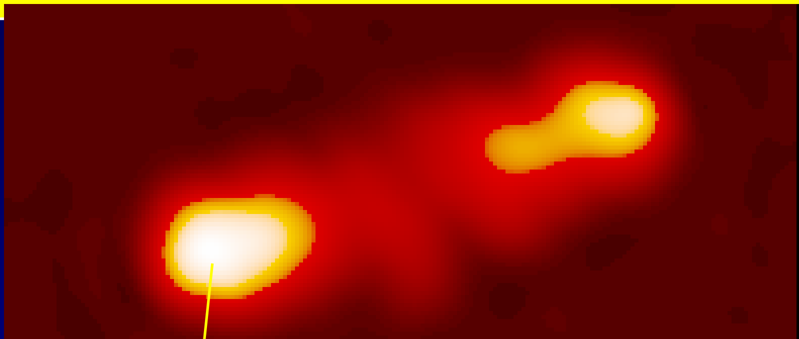
Acceleration: SNR Blast Physics

VLA (~35 km, 74 MHz) VLA + Pie Town (~72 km)

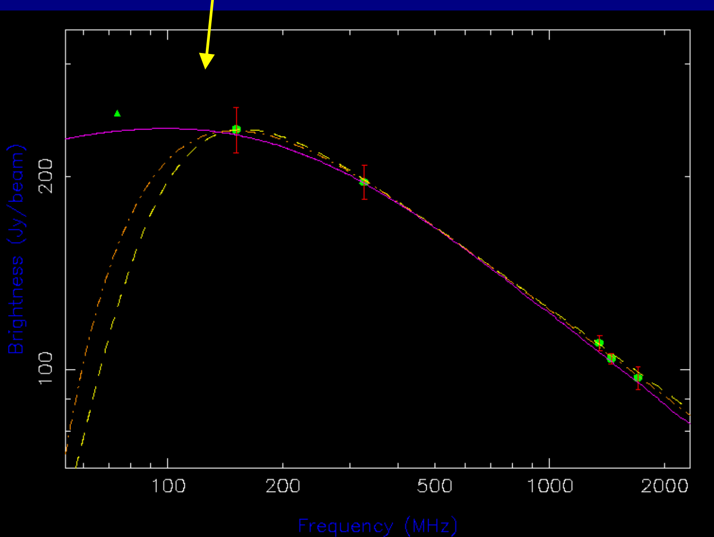


T. Delaney, PhD Thesis, UMN

Acceleration: in Radio Galaxies



~ 10" angular resolution



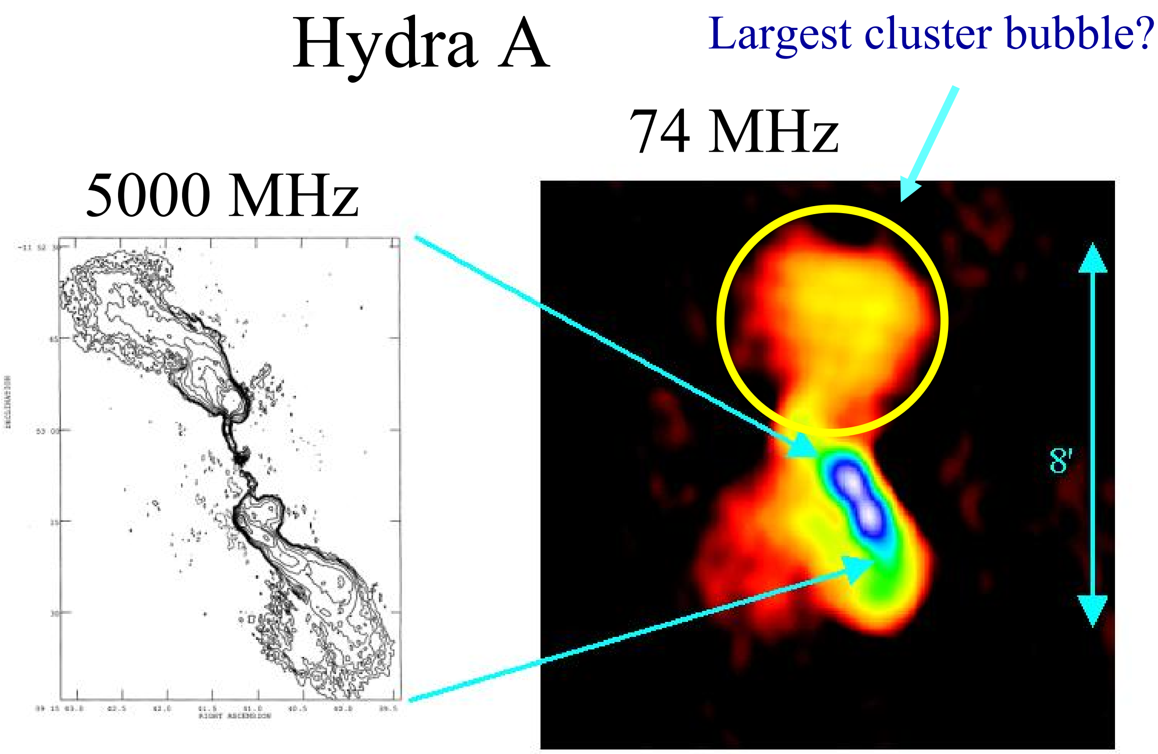
Cygnus A: The case of the missing hotspots (Lazio et al.)

Highest angular resolution LW imaging

- Carilli et al. (1991) suggested a low energy cutoff in electron energy spectra in hot spots.
- PT-link data confirm this.

PT antenna, 70 km distant ⇒

Acceleration: What is the real size of radio sources?

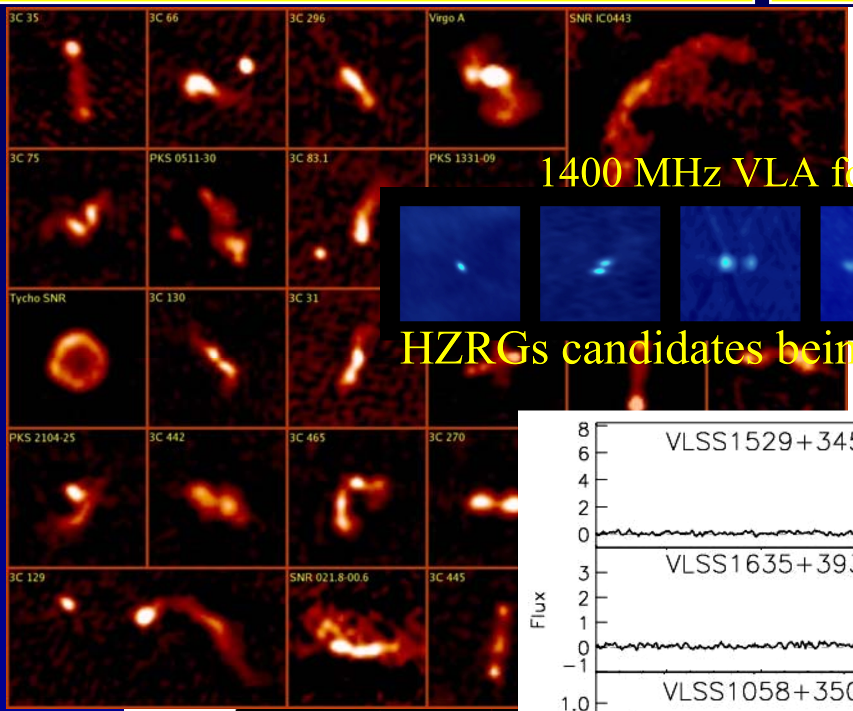


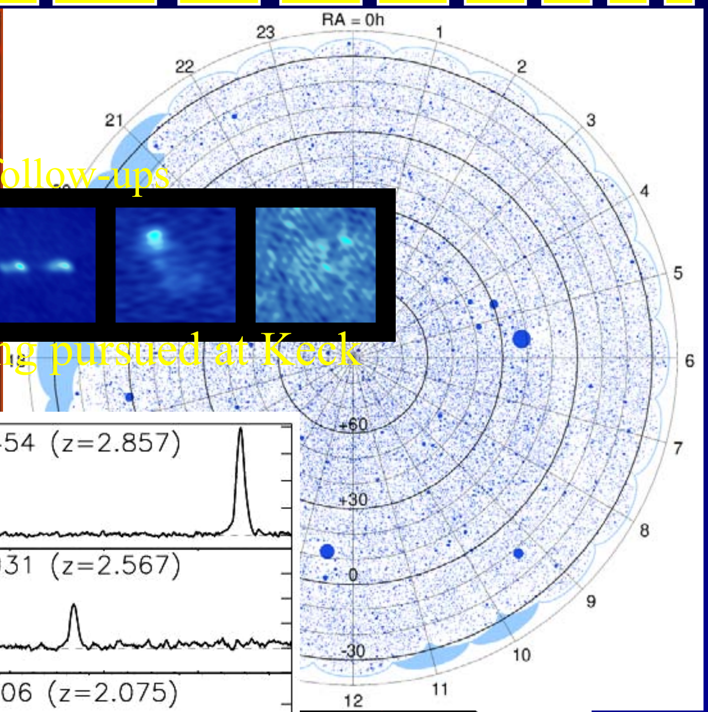
Lane et al. 2004

74 MHz VLA reveals this powerful radio galaxy is substantially larger than previously thought.

Important for understanding radio source energy budget, AGN lifecycle, & impact on IC physics.

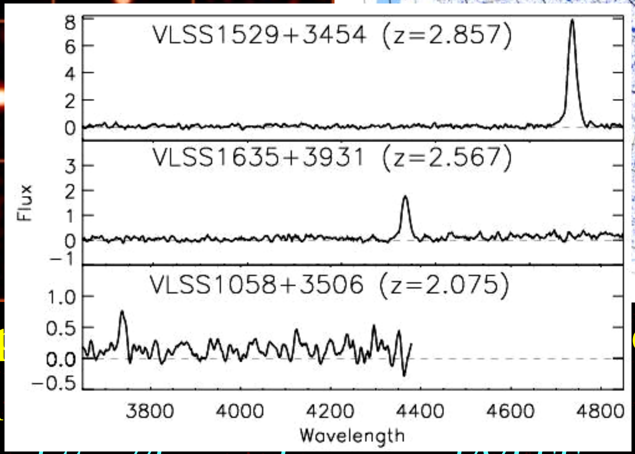
Cosmic Evolution: In search of the first black holes





1400 MHz VLA follow-ups

HZRGs candidates being pursued at Keck



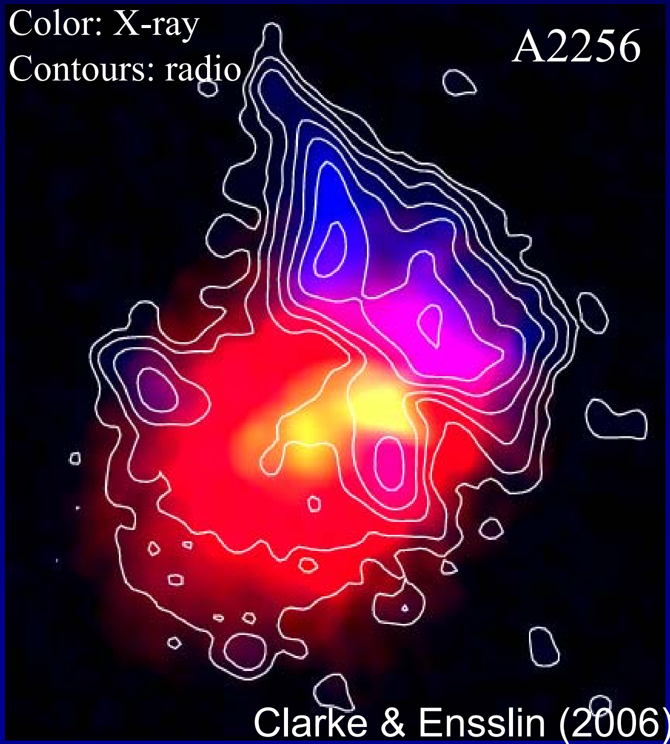
- One of most p... ey to date.
- Important cal...

http://lwa.nrl.navy.mil/VLSS

Cohen et al. 2007

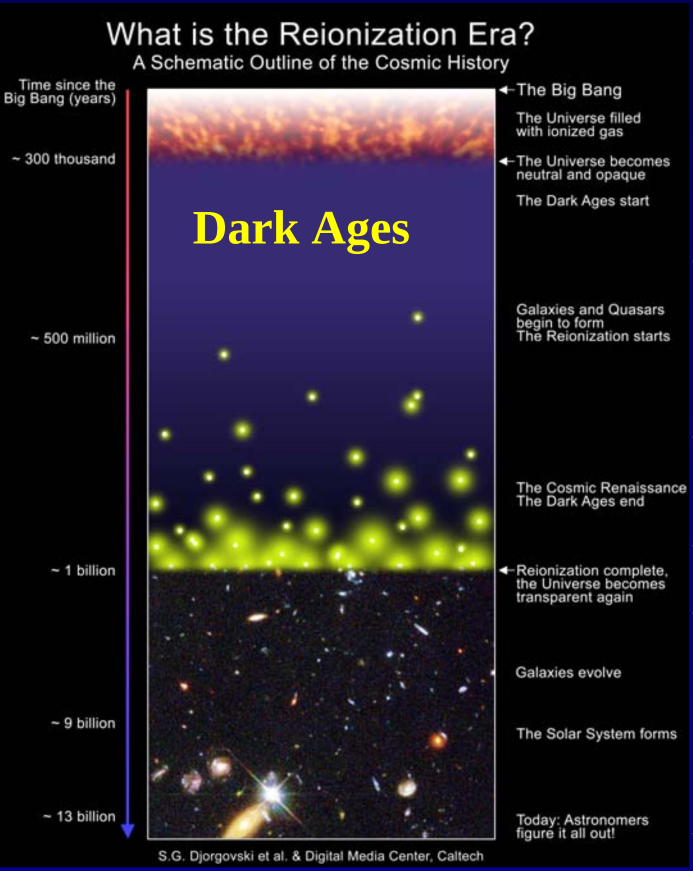
Cosmic Evolution: Dark Matter Studies

- Clusters form through mergers which heat the IC gas, compress magnetic fields & accelerate relativistic particles
- Studies of the associated halo & relic emission allow us to probe the dark matter potentials
- Wide-Angle-Tailed (WAT) radio galaxies also serve as signposts for dark matter potentials (Blanton et al. 2003) over a wide range of redshifts



- LWA surveys of clusters could identify merging systems over a range of redshifts to study the evolution of the dark matter potentials.
- Arcsecond resolution all-sky surveys could detect steep-spectrum WATs tracing cluster potentials

Cosmic Evolution: Peering Into the Dark Ages



$\nu < 100$ MHz (Dark Ages)

$100 < \nu < 200$ MHz (EOR=Epoch of Reionization))

> 200 MHz

- The MWA & LOFAR will search for radiation from the first stars & galaxies
  - Targeting the EOR at ~ 150 MHz
- Will be observed directly by NGST at IR wavelengths
- Observations below 100 MHz are the only ones capable of looking further back into the “Dark Ages”
  - Theory abounds with predictions of Dark Ages signatures for the LWA

LWA frequencies the only way to see into the Dark Ages

Thinking Outside the Box: Full Potential of LW Radio Astronomy

(inspired by R. Ekers)

- Thinking beyond key science drivers:
  - Most major discoveries in science are not predicted
    - Serendipity
  - The greatest scientific discoveries often follow technical breakthroughs.
    - De Solla Price: *most scientific advances follow laboratory experiments.*
    - Martin Harwit: *most important discoveries result from technical innovation.*
  - The greatest astronomical discoveries have accompanied the opening of new, or poorly explored, regions of the spectrum.
    - Many examples from radio astronomy (RA)
      - Discovery of RA, Quasars, Pulsars (Nobel prize), CMB (Nobel prize) ….
      - Many at long wavelengths …

74 MHz VLA demonstrates the technological breakthrough to open the last poorly explored spectral window.

Discovery Space – what is left?

- √ New wavelengths - just about finished
  - *The region below 100 MHz is the last, poorly explored one.*
- √ Angular resolution & sensitivity
  - *The LWA will increase both the angular resolution and sensitivity by more than two orders of magnitude compared to previous LW instruments*
- √ Volume of space sampled
  - *An area where low frequency instruments, with their intrinsically large fields of view, will naturally thrive – LWA, LOFAR, MWA.*
- √ New observing paradigms: multi-beaming
  - *Natural capability of the new, electronic, low frequency arrays*

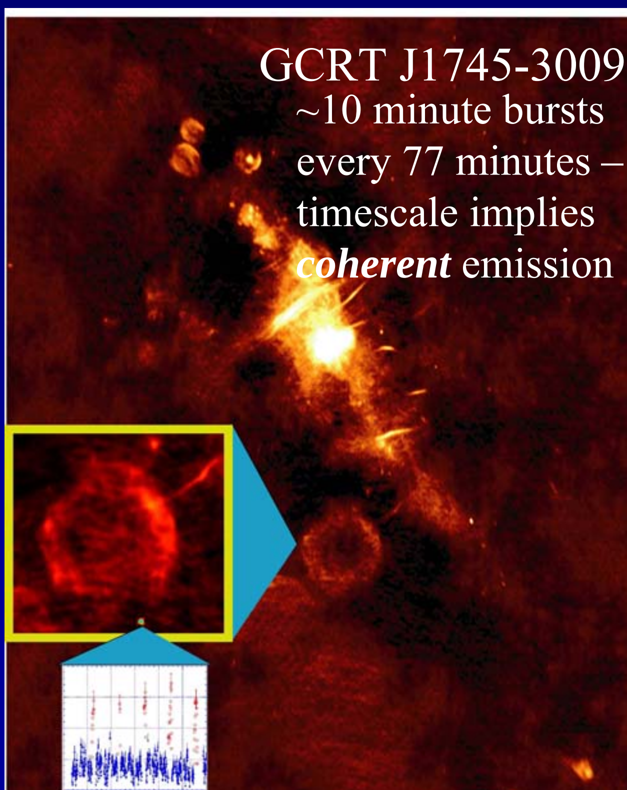
The LWA efficiently exploits the last remaining areas of discovery space for radio astronomy.

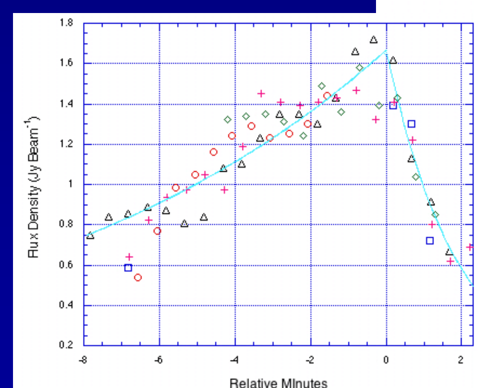
Discovery Space: Things that go bump in the night

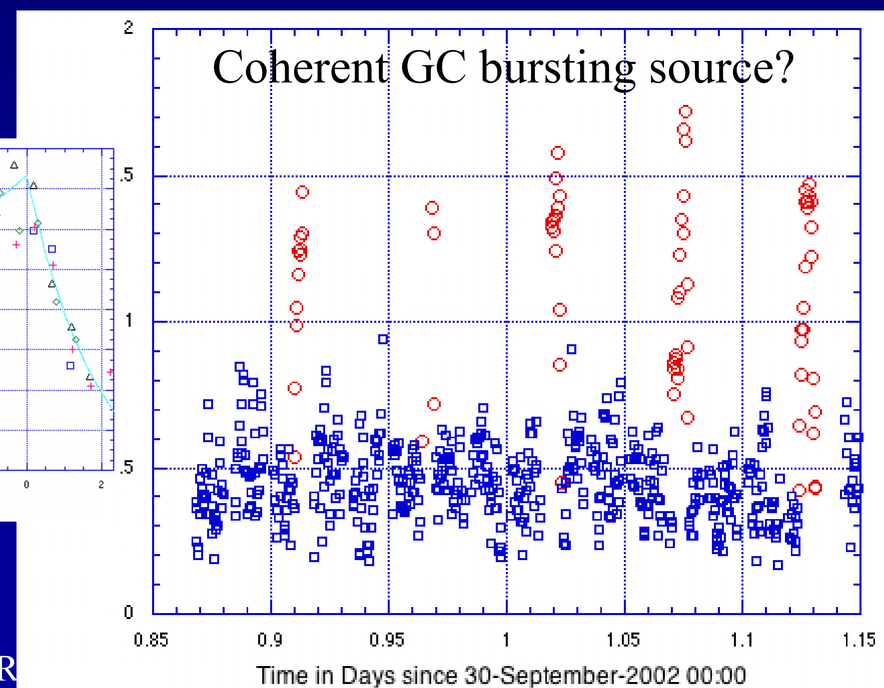
- LOFAR/MWA/LWA/ETA (etc) all-sky monitoring opens window to previously unexplored transient universe.
- Unanticipated coherent emission sources?
  - Well known in solar system, but very rare beyond that (e.g. pulsars, mazers)

330 MHz VLA Discovery: New candidate coherent emission source

(Hyman et al. 2005, 2006, 2007)

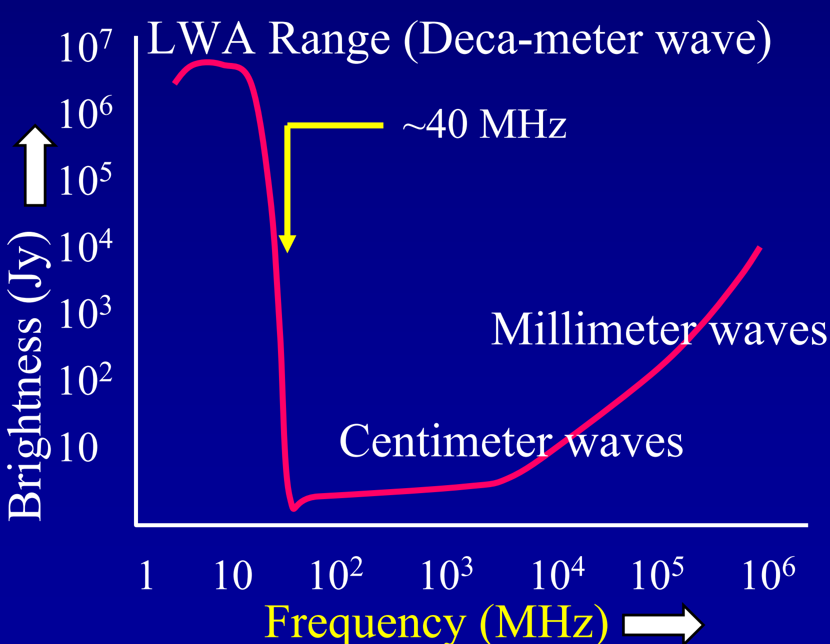


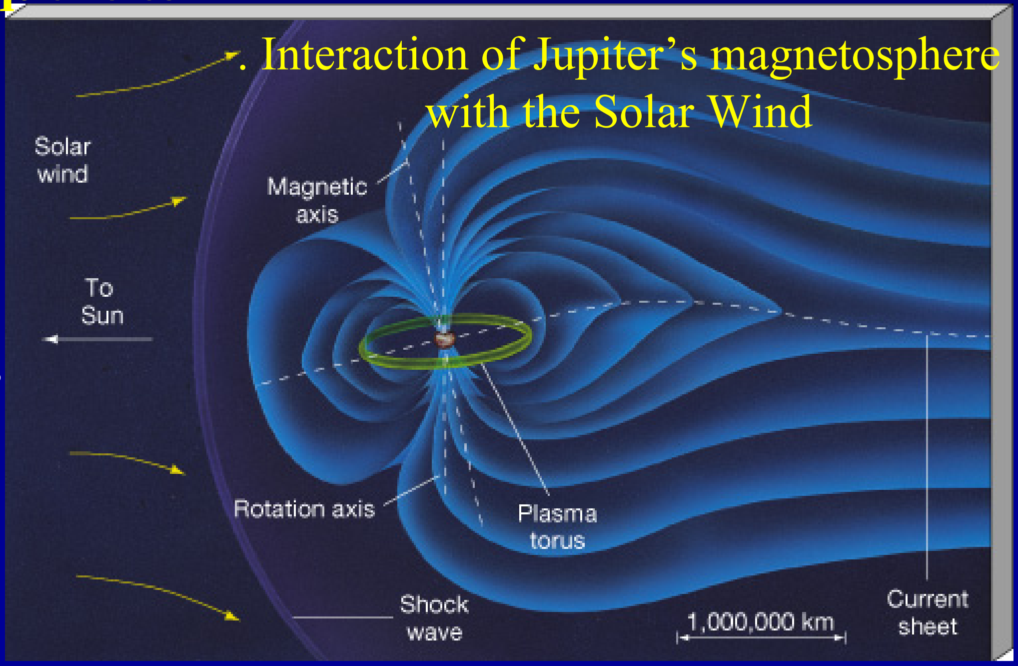




LWA-1 Transient Science: Extra-solar planets

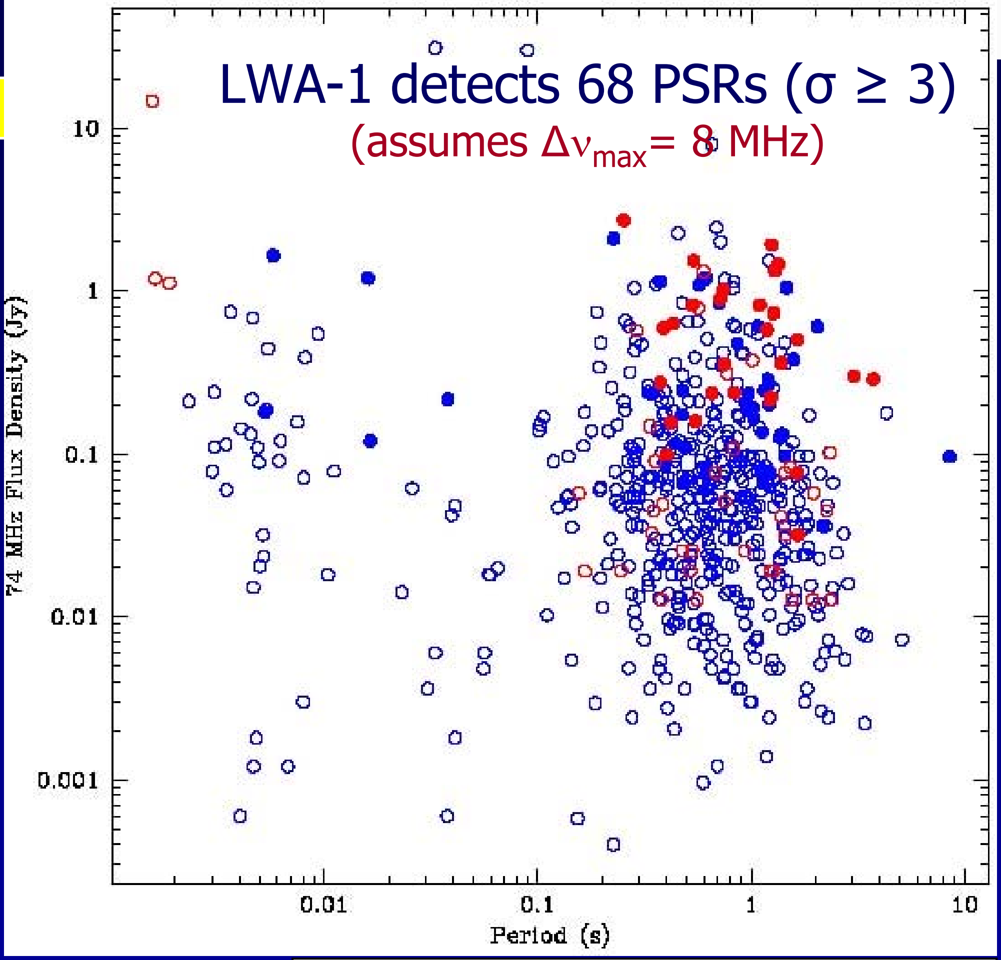
- Below 40 MHz, Jupiter, when bursting, is brightest object in solar system
- LWA might detect emission from extra-solar “Jupiters”
  - Independent verification of planetary systems & proof of magnetosphere
- LWA-1 pathfinder observations – advantage over current VLA searches through **longer integrations at lower frequencies**





LWA-1 Science: *Feasibility of Detecting Pulsars*

- Target nearby pulsars
- Source list developed from knowledge of flux density & scattering
- LWDA "Pilot search" now underway for B0329+54
  - LWA-1 much more sensitive due to greater collecting area & bandwidth

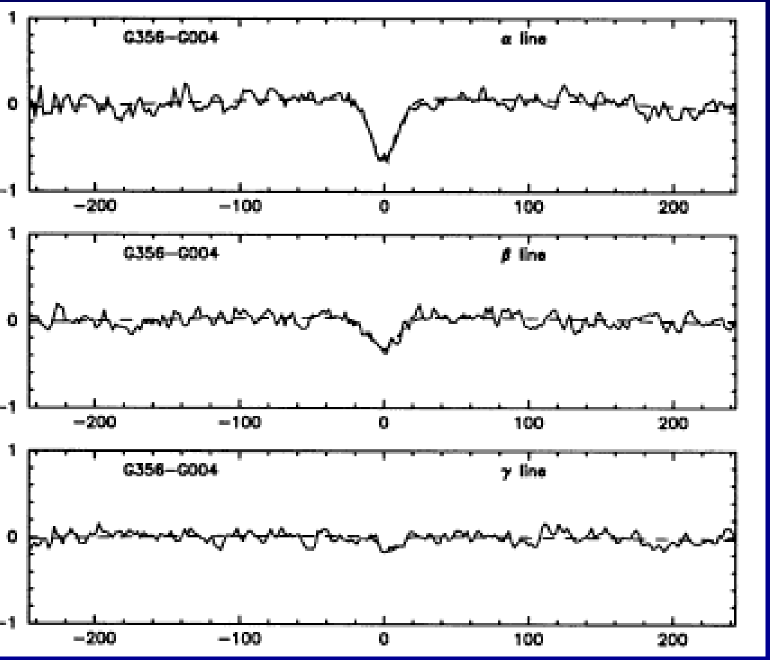


- ● Measured ≤ 102 MHz – detected
- ● Extrap. from 400 MHz – detected
- ○ Measured ≤ 102 MHz – not detected
- ○ Extrap. from 400 MHz – not detected

Over 60 PSRs detectable with LWA-1!

LWA-1 Science: ISM Studies using RRLs

Averaged profiles of carbon lines seen towards inner galaxy.



Erickson et al. 1985

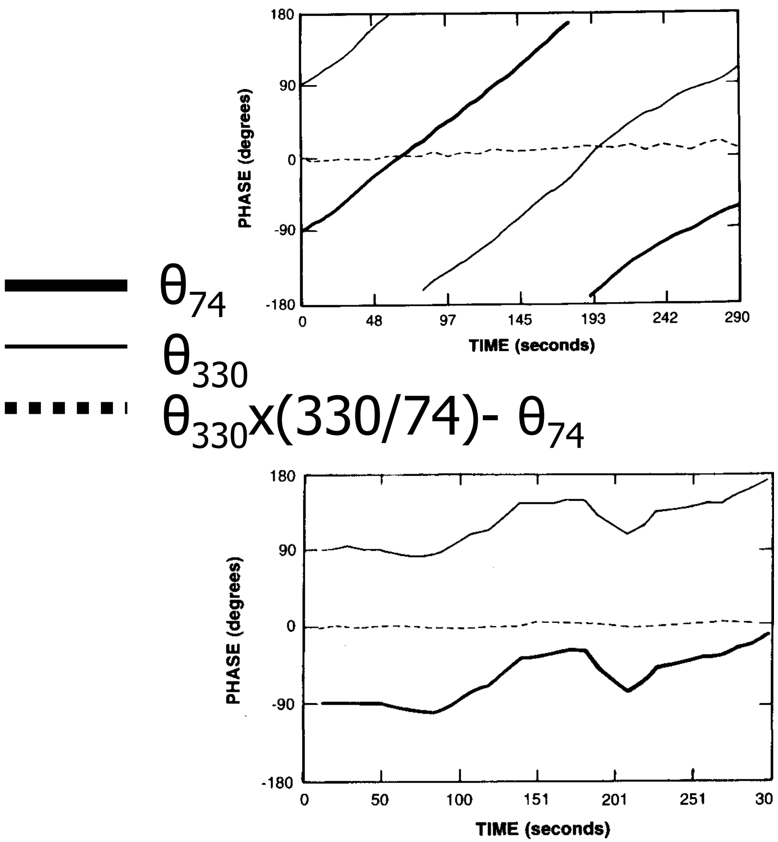
- LW Carbon & Hydrogen Radio Recombination Lines are unique diagnostics of the cold ISM
- LWA-1 will push beyond Parkes - a Galactic plane survey (student thesis?) is very feasible.
- Challenging test of our ability to do sensitive work
  - Prove we can we work in the RFI environment of the SW US
  - Surveys with LWA-1 would make excellent student thesis projects

LWA-1 will improve over current capabilities.

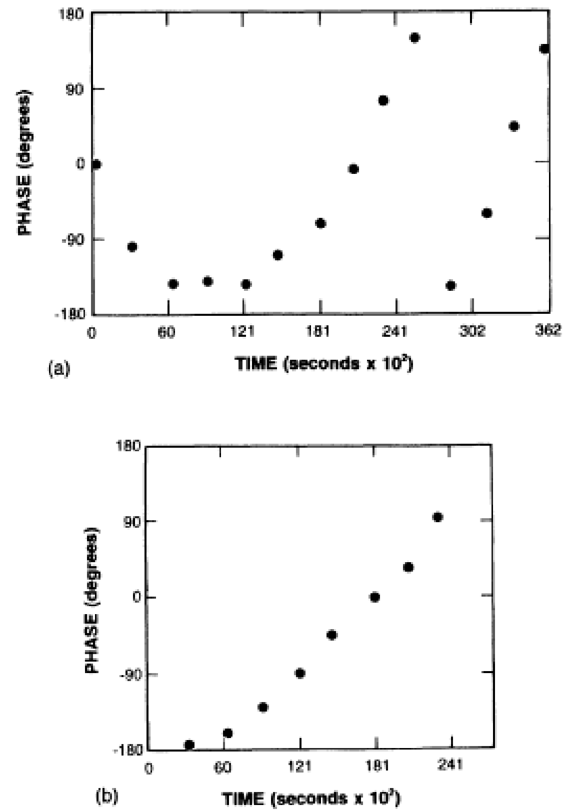
Science with LWA-1+: Ionospheric Measurements

- Building blocks of LWA measurements are phase measured between two stations
  - As soon as LWA-2 is available, we can start exploring those kinds of measurements
- Example - how well do ionospheric phases & phenomena scale with frequency?
  - Crucial tool for future calibration schemes
  - Ionospheric weather statistics, e.g. frequency of scintillations, etc

5 minutes



10 hours



"Phase transfer" works on time-scales of few minutes, but over many hours "mystery drift" sets in – what causes it?

Can't explore how phenomena scale without access to large frequency range

Technical Specifications: Summary

	Required	**Desirable**
Frequency Range:	20 MHz to 80 MHz	9 MHz to 88 MHz
Angular resolution:	$\theta \leq [8,2]''$	$\theta \leq [5,1.4]''$
LAS at [20,80] MHz:	$= [4,1]^{\circ}$	$= [8,2]^{\circ}$
Baseline range:	200 m to 400 km	100 m to 600 km
Sensitivity [20,80 MHz]:	$\sigma \leq [0.7,0.4]$	$\sigma \leq [0.5,0.1]$
Dynamic range:	$DR \geq [1x10^3,2x10^3]$	$DR \geq [2x10^3, 8x10^3]$
$\Delta\nu_{max}$ (per beam):	$\Delta\nu \geq 8$ MHz	$\Delta\nu =$ full RF
$\Delta\nu_{min}$:	$\Delta\nu \leq 100$ Hz	$\Delta\nu \leq 10$ Hz
Temporal Res:	$\Delta\tau = 100$ msec	$\Delta\tau \leq 0.1$ msec
Polarization:	dual circular > 10 dB	dual circular > 20 dB
Sky Coverage:	$Z \leq 64^{\circ}$	$Z \leq 74^{\circ}$
Primary Beam [20,80] MHz:	$= [8,2]^{\circ}$	$\geq [8,2]^{\circ}$
# of beams:	2 fully independent	≥ 2 fully independent
Configuration:	2D array, N = 53 stations	2D array, N≥53
Philosophy:	User-oriented, open facility; proposals solicited from entire community	
Mechanical lifetime:	≥15 years for potentially long lifetime	

SUMMARY

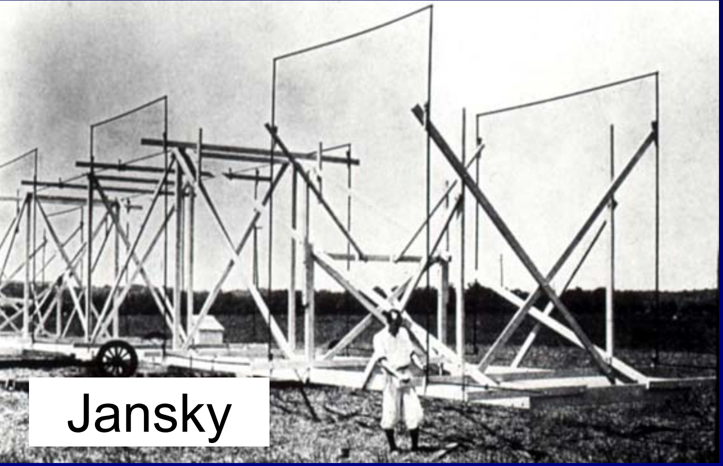
- LWA will open a new window on the last, most poorly explored region of the EM spectrum
  - Multi-beam electronic array will herald revolutionary approach to ionosphere, space science, & astronomical observations
- Key science drivers:
  - Plasmas from the Earth's Ionosphere to the Interstellar Medium of Galaxies.
  - Cosmic Evolution from the Dark Ages to the Present
  - Acceleration of cosmic rays
  - Exploration of the unknown
- LWA-1+ a modest start, but interesting science available immediately

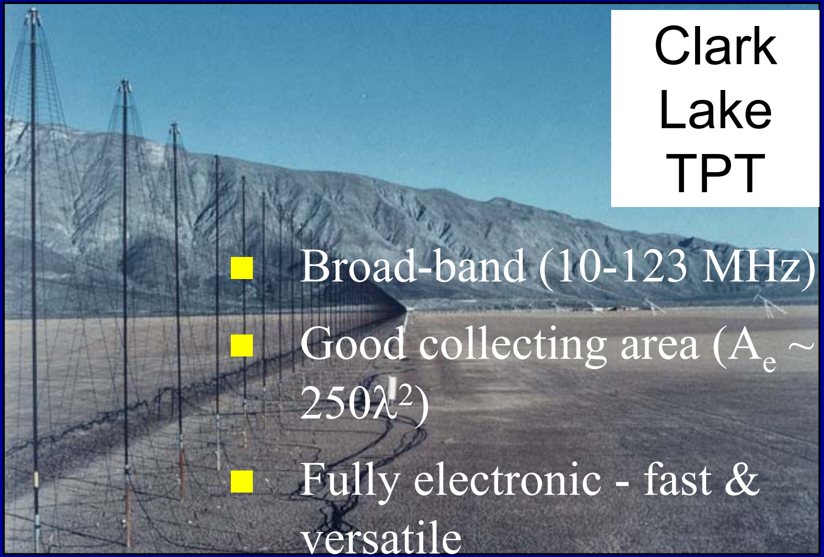
Frontier science: new discoveries expected in unexplored regime

Backup/History

Historical Perspective: Why now?

- Jansky first detected celestial radio emission at LW: 20 MHz
- LW stimulated much of modern astronomy
  - Non-thermal emission, Pulsars, Quasars, …
- Many large telescopes built
  - Clark Lake TPT: to be surpassed in sophistication only by instruments like LWA



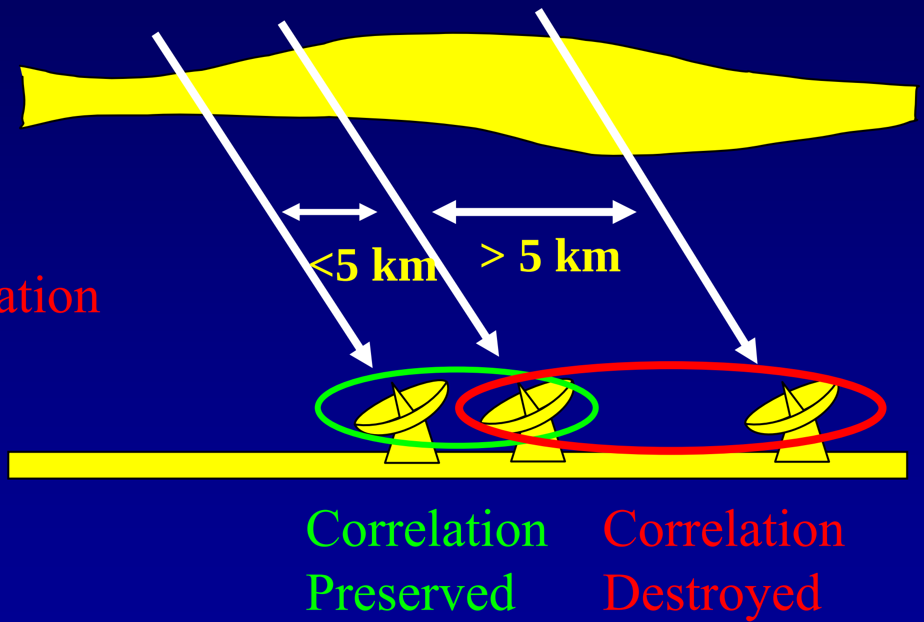


- Broad-band (10-123 MHz)
- Good collecting area ($A_e \sim 250\lambda^2$)
- Fully electronic - fast & versatile

Why Has Low Frequency Astronomy Languished?

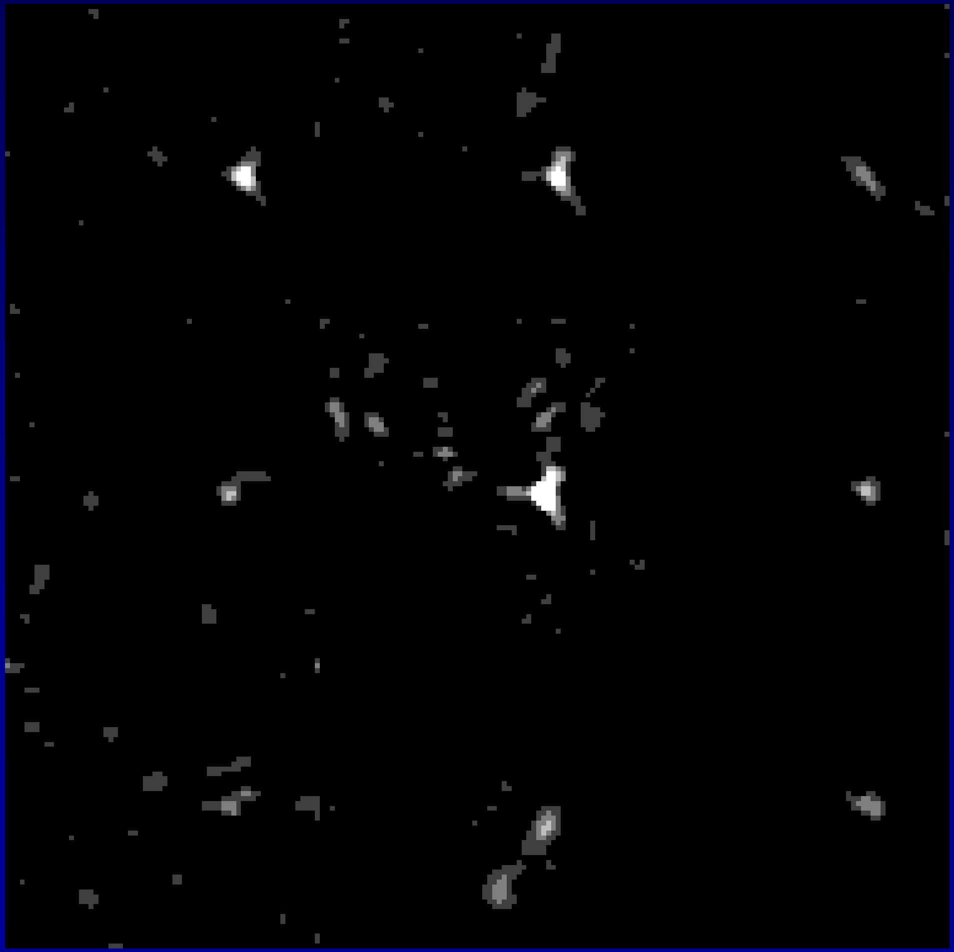
Key reason: λ/D (angular resolution)

- CLRO TPT
  - D ~3 km baselines
  - ~900" resolution at 30 MHz
    - » 1"≡1 arc-second ~5x10^{-6} radians
  - ~1000 mJy rms with infinite integration (confusion limited)
- VLA
  - D ~35 km baselines
  - ~2" resolution at 1400 MHz
  - ~0.5 mJy in 1 minute



Astronomy is difficult when you are nearly blind.

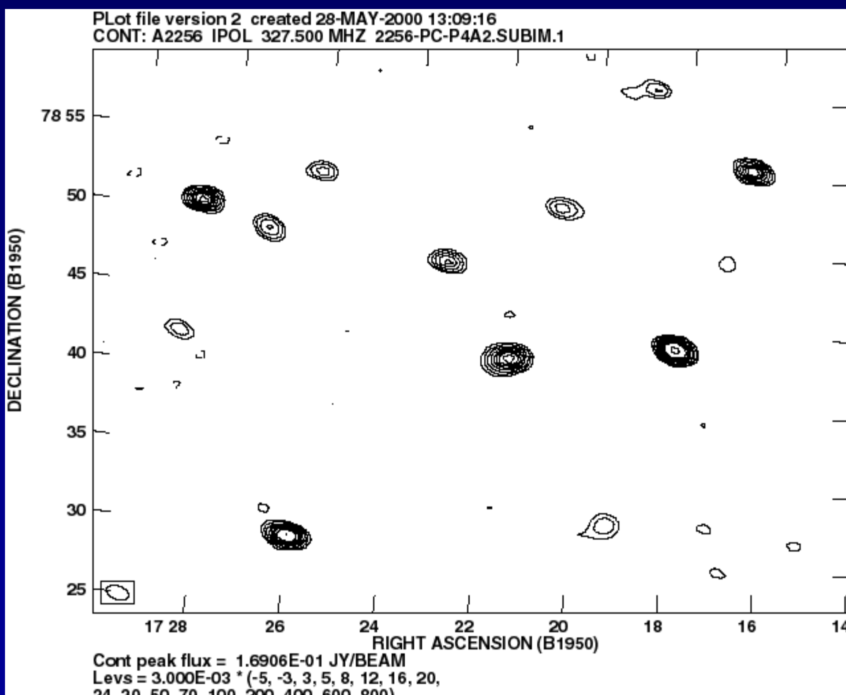
Ionospheric Phase Effects (among other challenges)

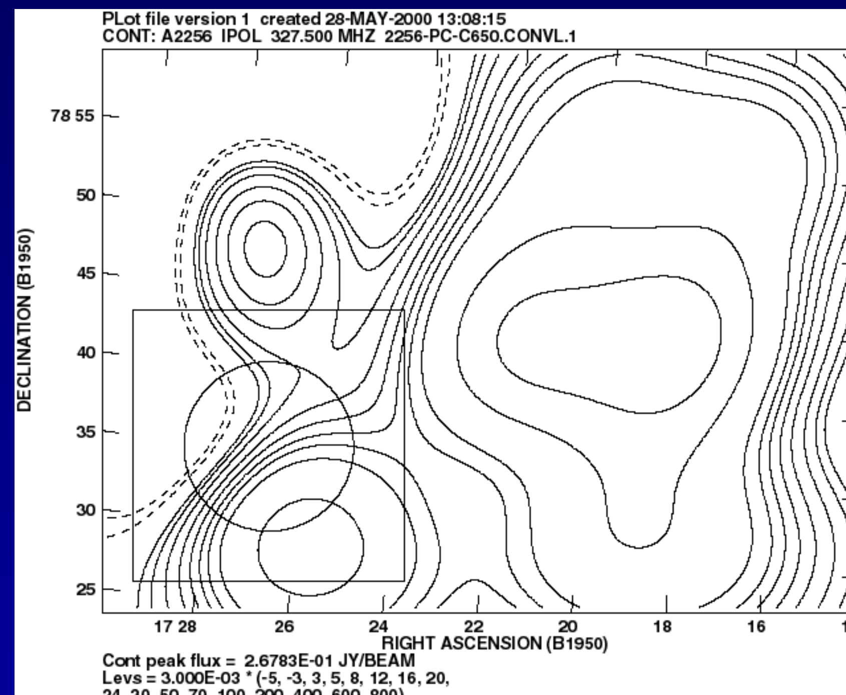


- The ionosphere limited the maximum baseline of interferometers below 100 MHz to ≤ ~5 km.
- As main-stream radio astronomy went to high resolution and sensitivity (e.g. VLA), LW radio astronomy was left behind.
- Other problems: RFI. 3D imaging – computational tedium only recently manageable

Low Angular Resolution: Limits Sensitivity due to Confusion

θ ~ 1’, rms ~ 3 mJy/beam θ ~ 10’, rms ~ 30 mJy/beam

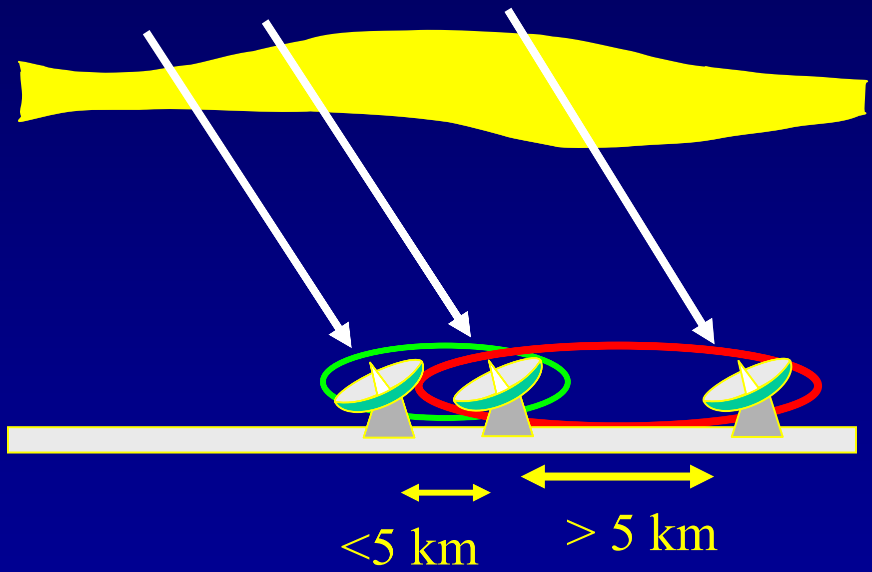




$$\theta = \lambda / D$$

NRL-NRAO 74 MHz Very Large Array

- Early 1980s: development of *self-calibration*
  - Data driven
  - Solve for N antenna phases using N(N-1)/2 observed interferometric phase differences
- Early 1990s: 8-antenna prototype
- 1998: All 27 antennas outfitted (Kassim et al. 2007)



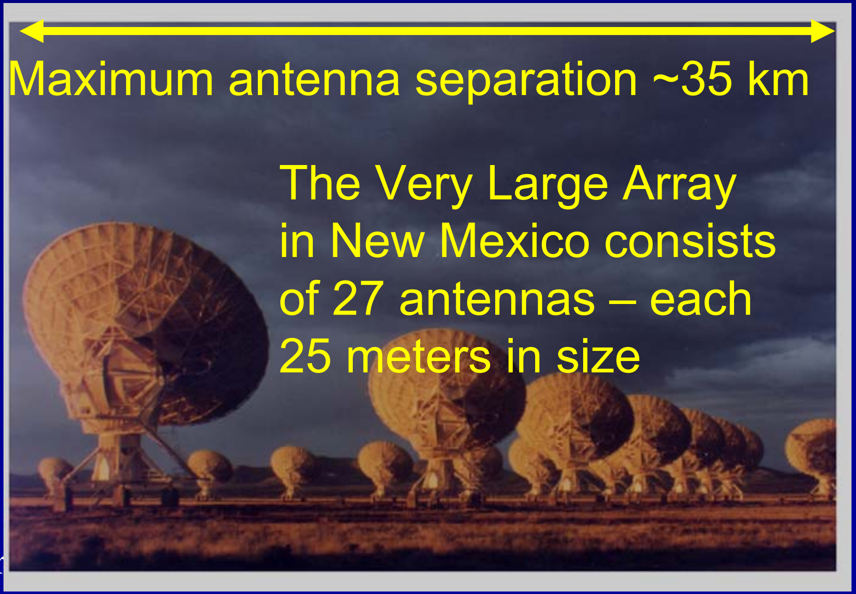
Prior to 74 MHz VLA

Enabled after 74 MHz VLA

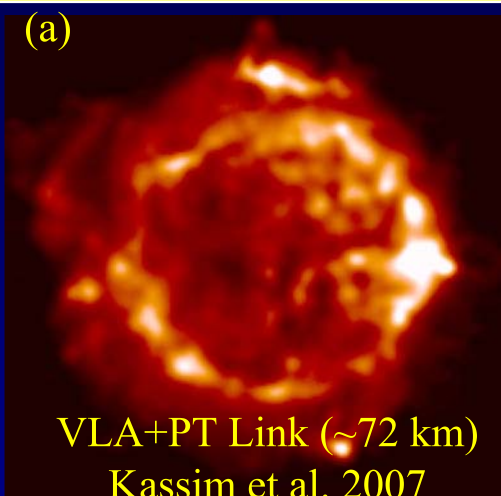
NRL – NRAO Very Large Array LW System

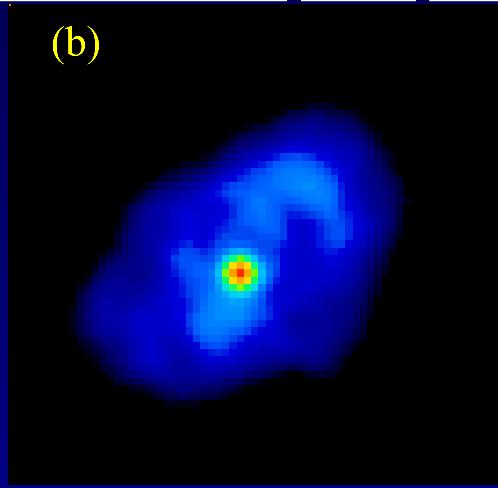
Very Large Array LW receiving elements
(operates at 74 MHz = 4 meters)

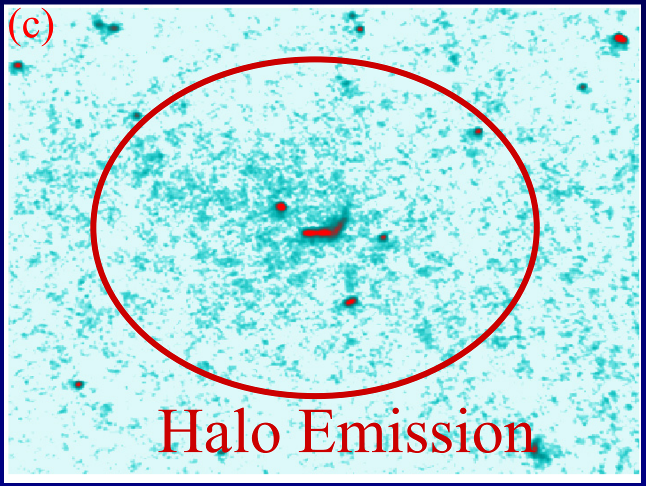
Kassim et al. 1993

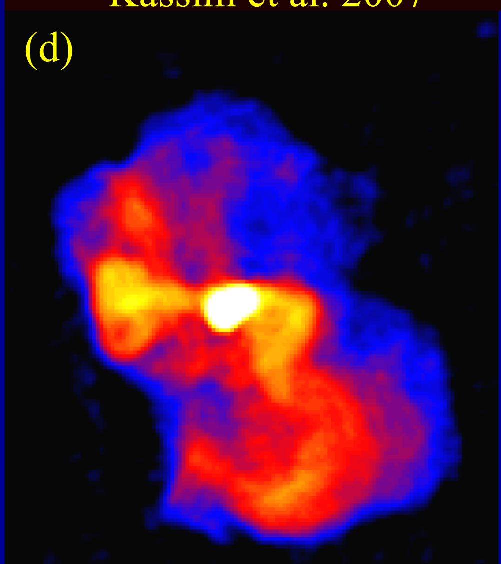


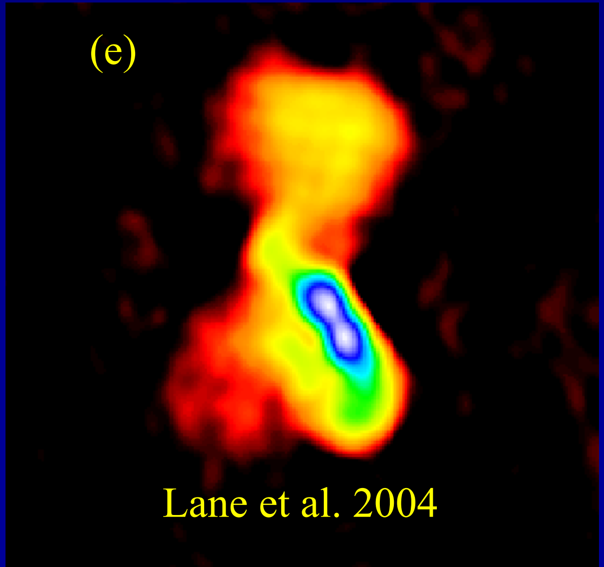
Results from 74 MHz VLA: Dramatic proof that we can finally build large LW arrays











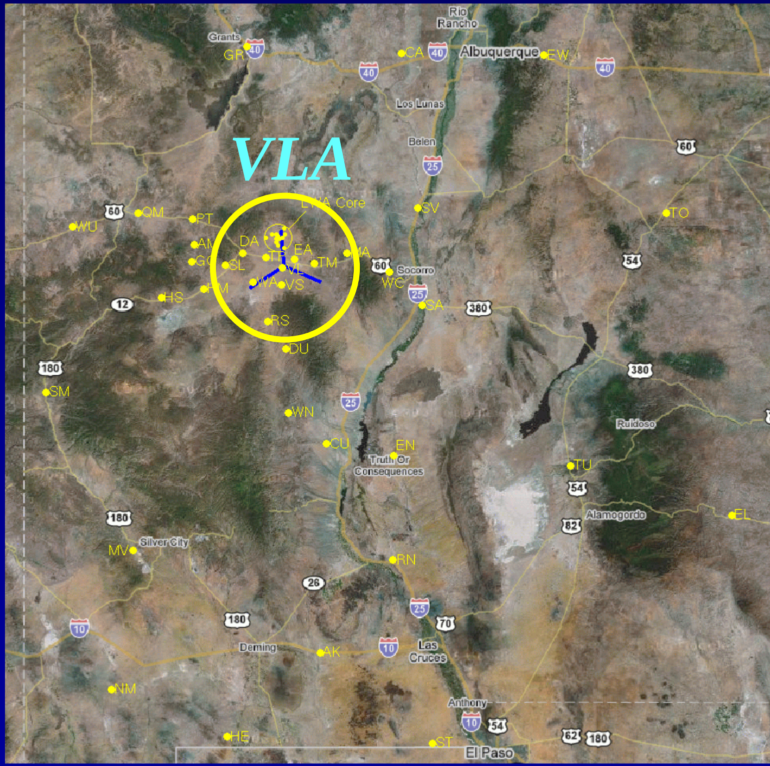
These are some of the most famous cosmic sources – previous LW images would show them as “unresolved” point sources.

(a): Cassiopeia A; (b): Crab Nebula; (c): Coma Cluster; (d): Virgo A; (e): Hydra A

Long Wavelength Array (much larger than VLA)

- 20–80 MHz
- Dipole-based array stations – 256 antennas each
- 50 stations across New Mexico
- 400-km baselines ⇒ arcsecond resolution

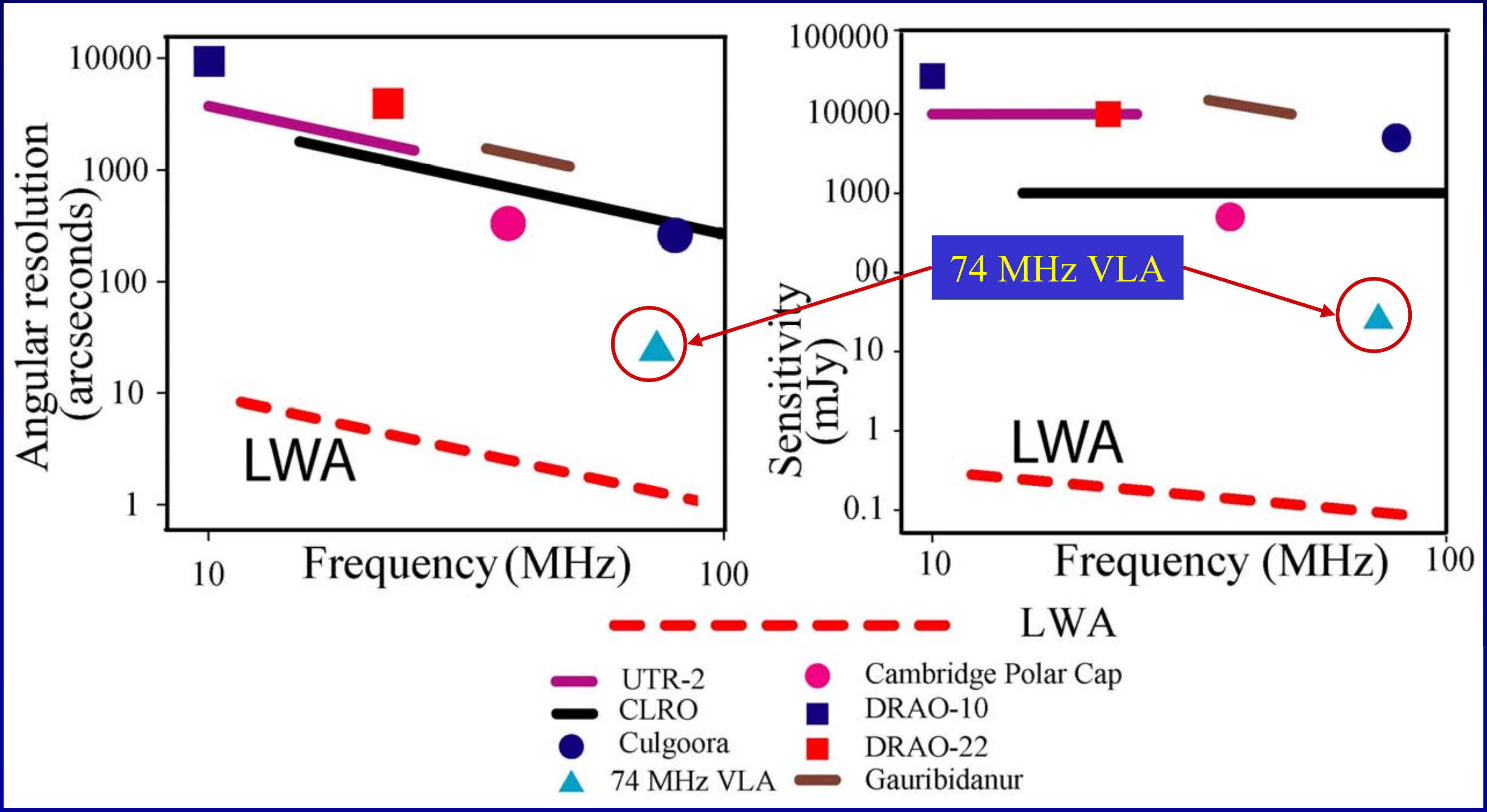
● LWA Stations



400 km

Long Wavelength Array
A New Window on the Universe

Angular resolution Sensitivity



Backup

On the Path to the LWA: LWA-1+

- **Plasma Astrophysics & Space Science**
  - Building block ionospheric phase measurements – over wide frequency range
    - » Statistical measure of ionospheric phase stability – good vs. bad weather, scintillations, etc.
  - RRL – e.g. detect in ~ [5,25] hrs @ [≤40,74] MHz, $\Delta\nu$=0.1 kHz (1-2 km/s @25 MHz)
  - Solar bursts – e.g. study fast (50 ms) narrow-band (<10 kHz) structures
  - Jupiter decametric bursts – e.g. fine temporal and spectral structure seen by Voyager
  - ISM tomography – e.g. single pulse studies
- Acceleration of Relativistic Particles in:
  - UHECR
- Cosmic Evolution & The High Redshift Universe
- **Exploration Science**
  - ***bright transients – e.g. GCRT J1745-3009: ≥ 5σ detection if $\alpha \leq$ -1***
  - ***nearby pulsar spectra – e.g. detect 68 bright, low DM pulsars***

- ***Significant engineering and commissioning experience***
- ***Insight into limitations for deep integrations***
- ***Combination with 74 MHz VLA expands science of both instruments***

On the Path to the LWA: LWIA (9 stations)

Opens ability to self-calibrate and image bright sources (Cohen, Clarke, & Lazio 2007)

- 74 MHz VLSS gives 362 LWIA targets – e.g. 5 SNR, 5 halos/relics, 8 cooling core, 100's of extragalactic radio sources
- more than 4800 targets possible using BW smearing techniques
- science limited mainly to compact emission regions.

- **Plasma Astrophysics & Space Science**
  - Ionospheric Turbulence – e.g. hundreds to thousands of ionospheric pierce points
- **Acceleration of Relativistic Particles in:**
  - Radio Galaxies – e.g. low frequency spectra
- **Cosmic Evolution & The High Redshift Universe**
  - HzRG – e.g. compact steep-spectrum sources with no optical counterparts
- **Exploration Science**
  - ***"Deep Spot" Surveys – e.g. deep fields around bright sources***
  - ***Fainter Transients & Pulsars – e.g. follow-up spectra***

On the Path to the LWA: LWIA + core (16 stations)

Addition of 6 core stations widens science to mapping of diffuse emission in LWIA target lists. Expands science potential of LWIA list.

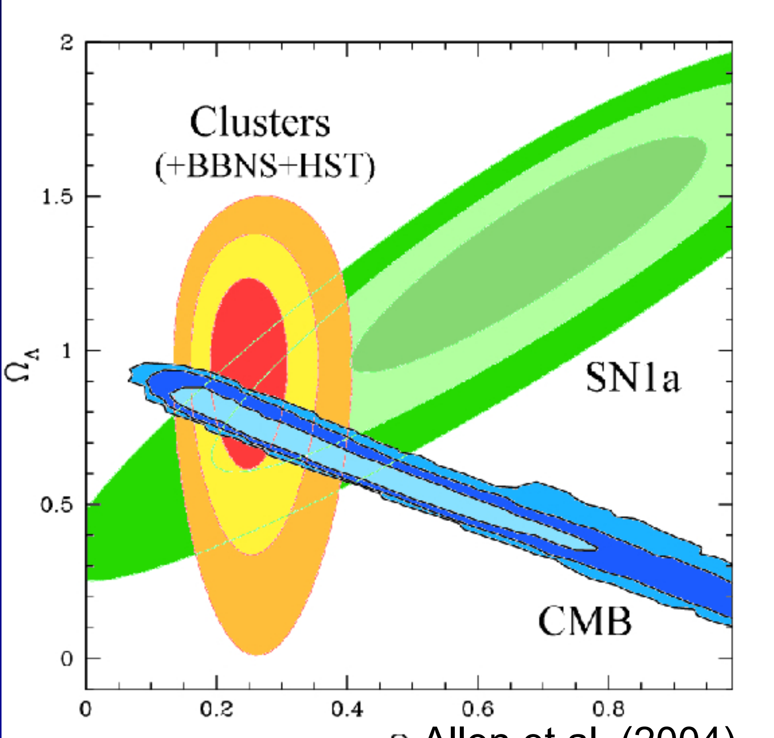
- Cosmic Evolution & The High Redshift Universe
  - LSS – e.g. explore DM & DE with available cluster
- **Acceleration of Relativistic Particles in:**
  - galaxy clusters – e.g. mapping diffuse radio halo/relic emission + spectral studies
  - SNR – e.g. mapping extended and filamentary structure + spectral studies
- **Plasma Astrophysics & Space Science**
  - Solar – e.g. CME's
- **Exploration Science**
  - Regime expanded to include weaker phenomena with extended structure

Cosmic Evolution: Dark Energy Implications

• Clusters probe Dark Energy (DE) through the geometry of the Universe & structure formation

• DE studies require cluster Mass or Temperature assuming hydrostatic equilibrium - scaling relations influenced by mergers (Ricker & Sarazin 2001)

• Low frequencies serve as "mergo-meter" - powerful tool to study the dynamical state of clusters by searching for merger-related halos & relics (Clarke et al. 2005, Sarazin 2006)

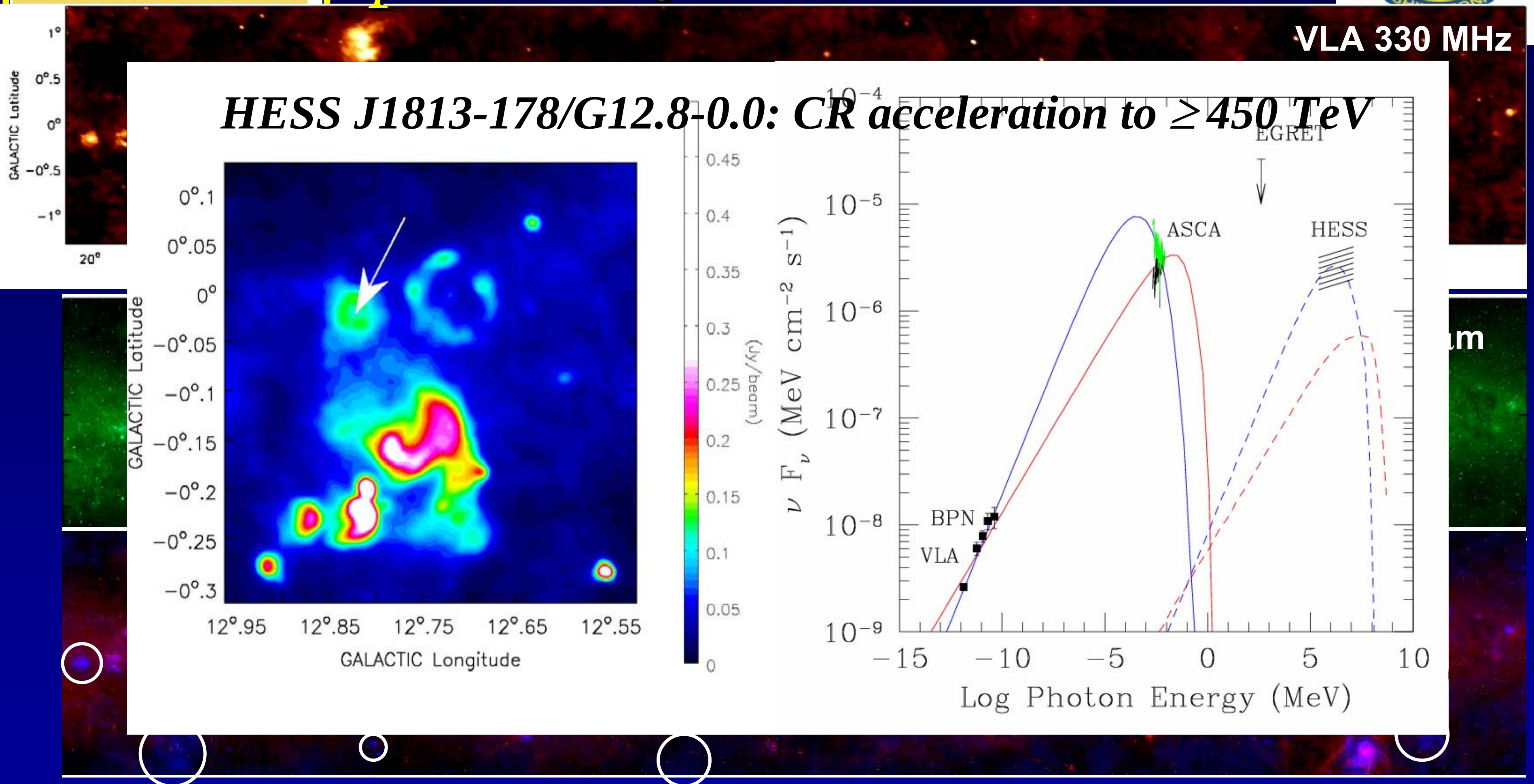


Allen et al. (2004)

• LWA surveys could identify merging systems to remove from DE sample

• Derive corrections allowing merging clusters to be included in the DE sample

Acceleration: Complete SNR census - with distances!



2 Color Image:
Red: MSXat 8 μm
Blue: VLA 330 MHz

Tripled (19=> 54) known SNRs in survey region!

(Brogan et al. 2006)

LWA Scientific Specifications

	Required[#]	**Desired[#]**
Frequency Range	20 MHz to 80 MHz	10 MHz to 88 MHz
Spatial resolution	$\theta \leq$ [8,2]”	$\theta \leq$ [6,1.5]”
Largest Angular Scale	[8,2]°	>[8, 2]°
Baseline range	107 m to 470 km	<107 m to 535 km
Sensitivity [20,80 MHz]: (1 hr, 4 MHz, dual pol.)	σ = [1.0,0.5]	σ < [1.0, 0.5]
Number of Stations	52 x 256 stands	>52 x 256 stands
Dynamic range:	10^4	>10^4 (per channel)
$\Delta\nu_{max}$ (per beam)	32 MHz (R<0.5 km) 8 MHz (R>0.5 km)	Full RF
$\Delta\nu_{min}$	0.1 kHz	0.01 kHz
Temporal Res ($\Delta\tau$)	1 msec	1 ns
FoV [20,80] MHz	[8,2]°	> [8,2]°
Polarization:	Dual orthogonal	Dual orthogonal
Sky Coverage	$z \leq 74°$	$z \leq 80°$
Simul. Beams	3 spatial & frequency	> 3

#: parameter range calculated for [20,80] MHz

Discovery Space: Predicted Transients

GASE: Gamma-ray All-Sky Spectrometer Experiment

LWA-type dipoles deployed in MIT-NRL experiment to detect transient radio emission from GRBs – observations triggered by SWIFT γ-ray satellite.

Hewitt, Ray et al.

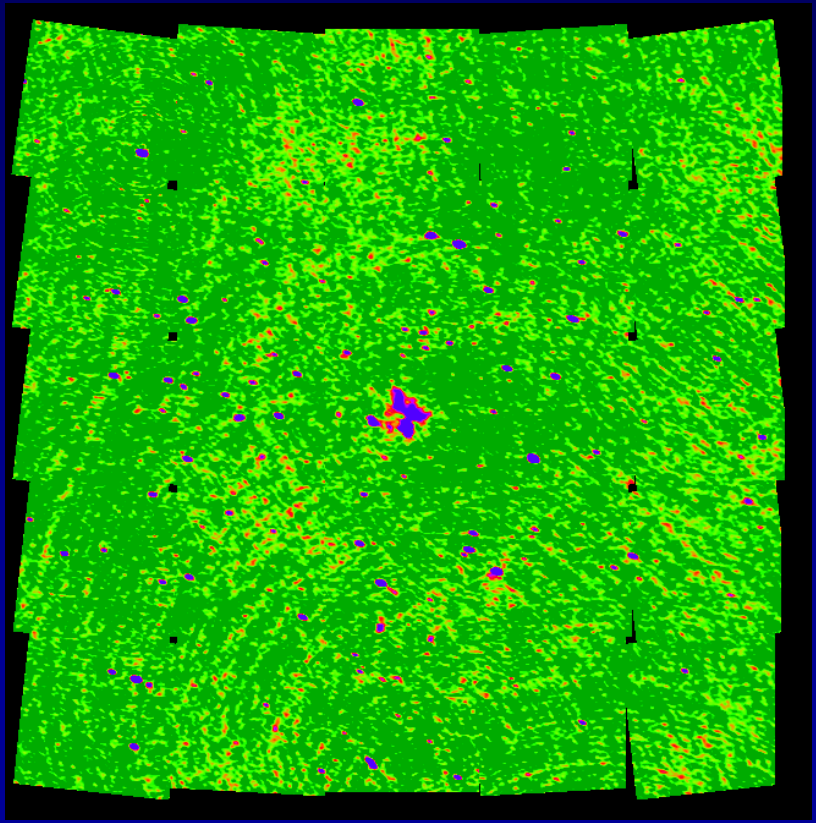
The Clark Lake TPT

- Broad-band (10-123 MHz)
- Reasonable collecting area ($A_e \sim 250\lambda^2$)
- Fully electronic - fast and versatile

Will be surpassed in sophistication only by the emerging new LW arrays

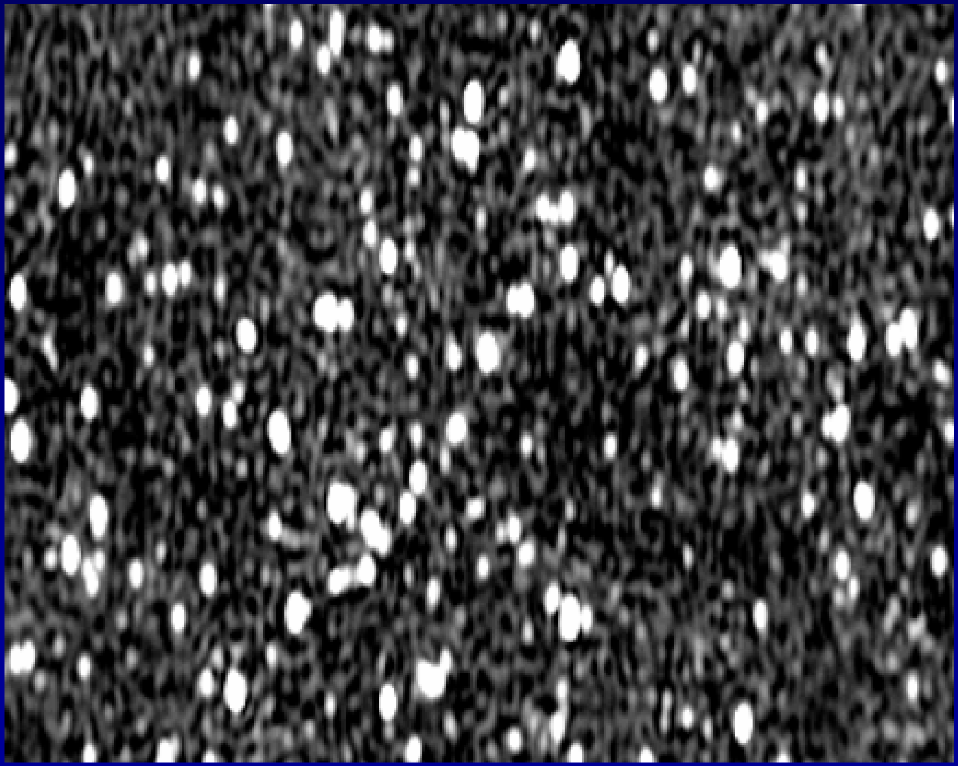
Confusion

Sidelobe Confusion



VLA 330 MHz

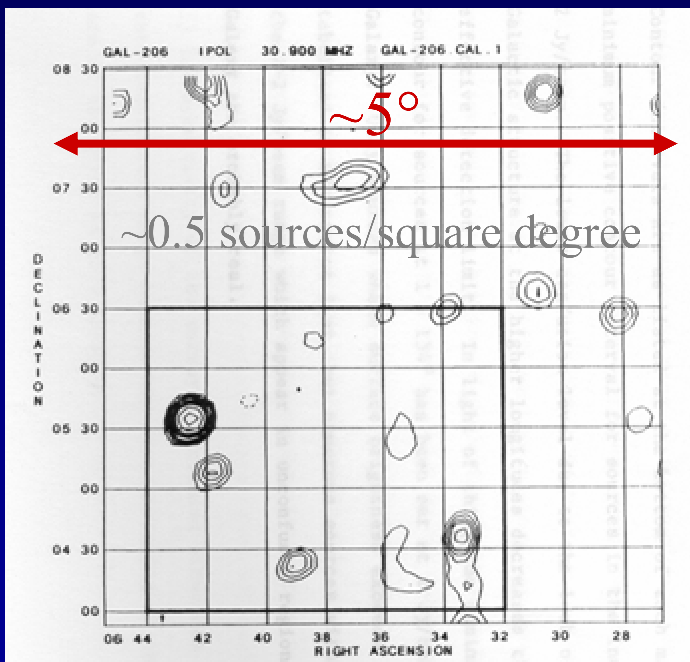
Classical Confusion



WSRT 330 MHz

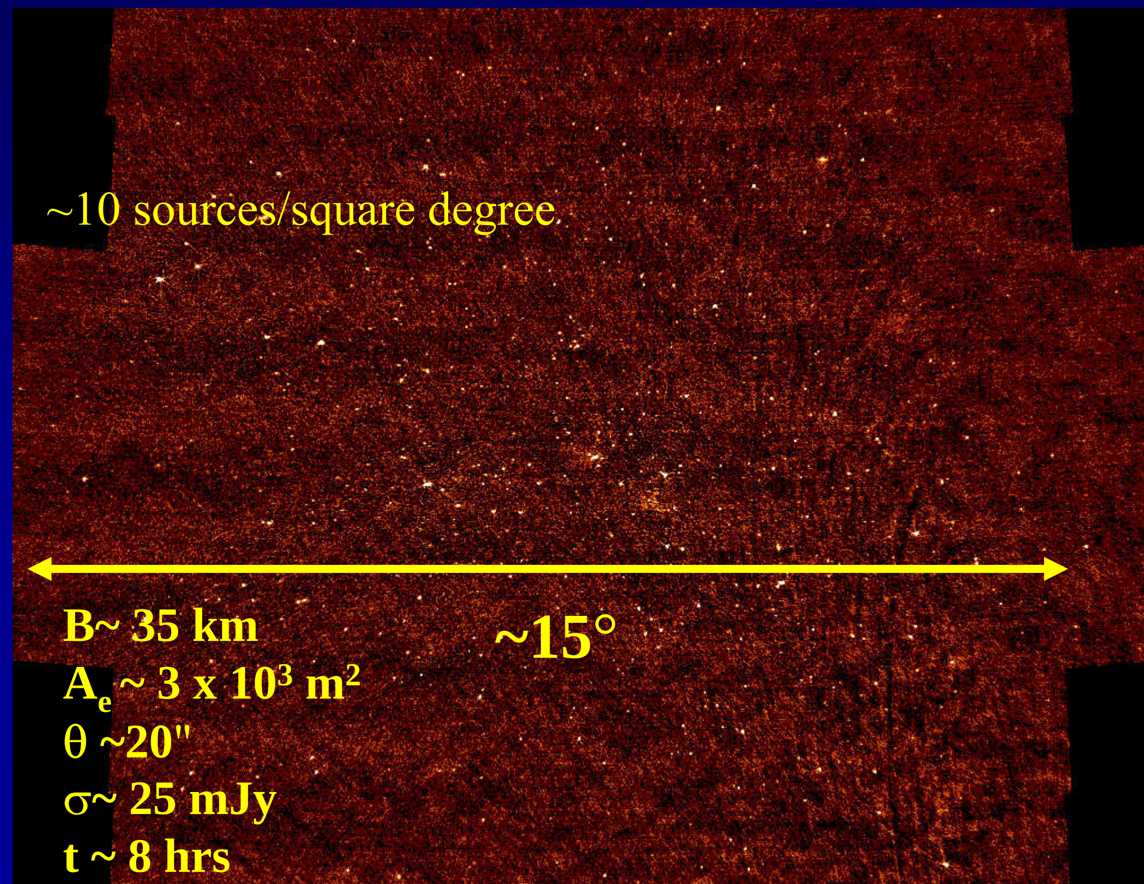
Comparison of the Clark Lake TPT to the 74 MHz VLA

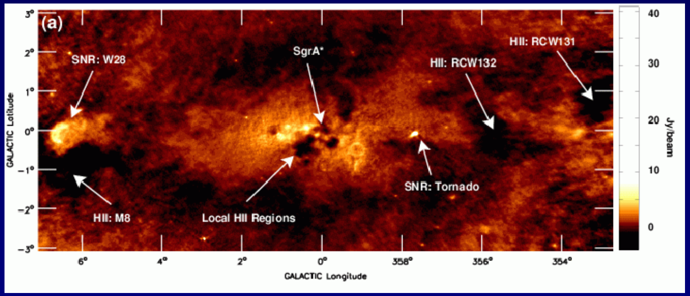
Clark Lake (30 MHz)

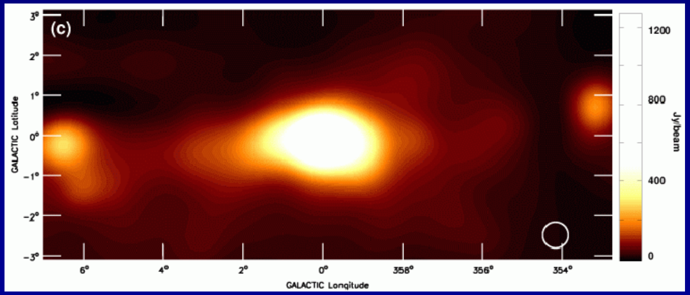


- **B ~ 3 km**
- **A_e ~ 3 x 10^3 m^2**
- **θ ~ 900"**
- **σ ~ 1000 mJy**
- **t ~ ∞**

VLA (74 MHz)




(a)
SNR: W28
SgrA*
HII: RCW132
HII: RCW131
SNR: Tornado
HII: M8
Local HII Regions
GALACTIC Latitude
GALACTIC Longitude
Jy/beam

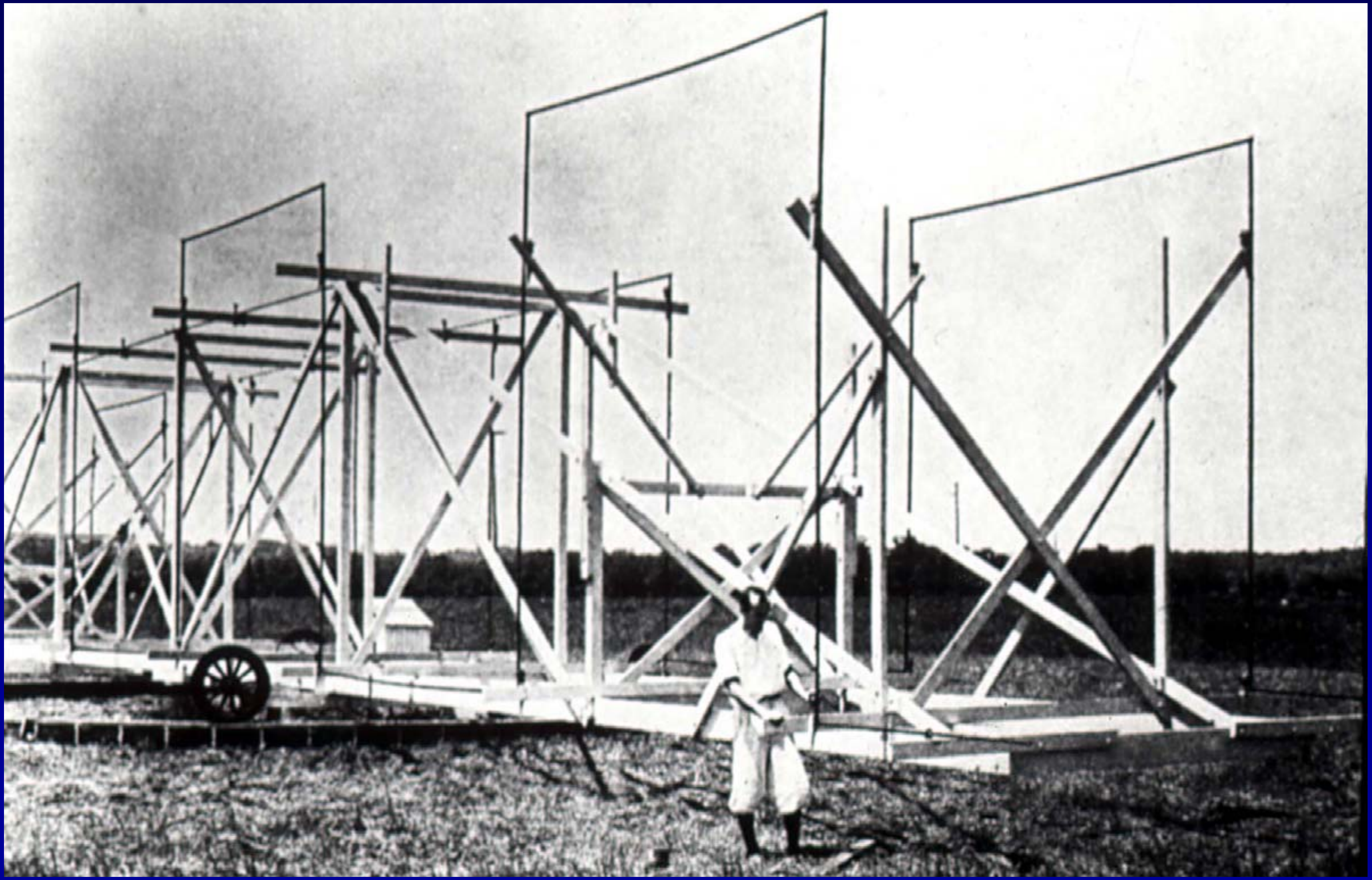

(c)
GALACTIC Latitude
GALACTIC Longitude
Jy/beam

History of Long Wavelength Astronomy

- *1931-35: Discovery of cosmic radio waves, **birth of radio astronomy** (Jansky)*
- *1935-40: **Discovery of nonthermal emission** (Reber, Henyey, Keenan)*
- *1942: Discovery of solar radio emisson (Hey)*
- *1946: **First radio interferometers** (Pawsey et al., Bolton et al., Ryle)*
- *1946-50: **Discovery of discrete cosmic radio sources** (Hey, Bolton et al.)*
- *1946-51: Discovery of radio galaxies & SNRs (Ryle et al.)*
- *1955: First all-sky surveys (Kraus, Mills, Baldwin, others)*
- *1955: **First detection of planetary radio emission** (Burke, Franklin, Shain)*
- *1962-63: First widely used radio catalogue (Bennett – 3C)*
- *1963: **Discovery of quasars** (Hazard, Schmidt, Sandage, Greenstein, others)*
- *1967: First VLBI fringes*
- *1968: **Discovery of pulsars***

The First LW Radio Telescope

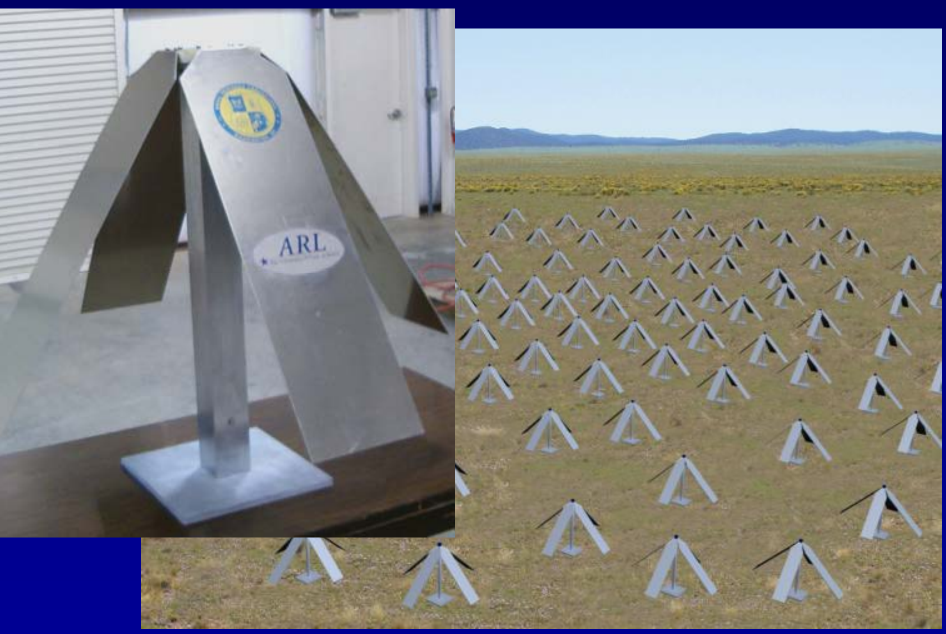
(Karl Jansky Bell Telephone Laboratory 1933)



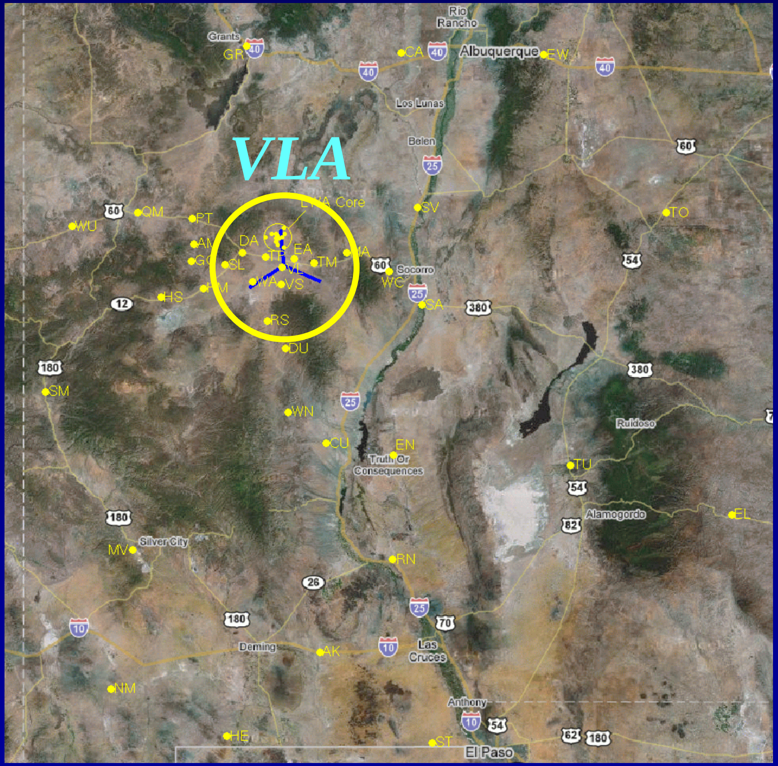
Opportunity: Long Wavelength Array (LWA) Much larger than 74 MHz VLA

One LWA Station = 256 antennas

20 ≤ ν ≤ 80 MHz, 1 sqr km @20 MHz



Full LWA: 52 stations spread across NM

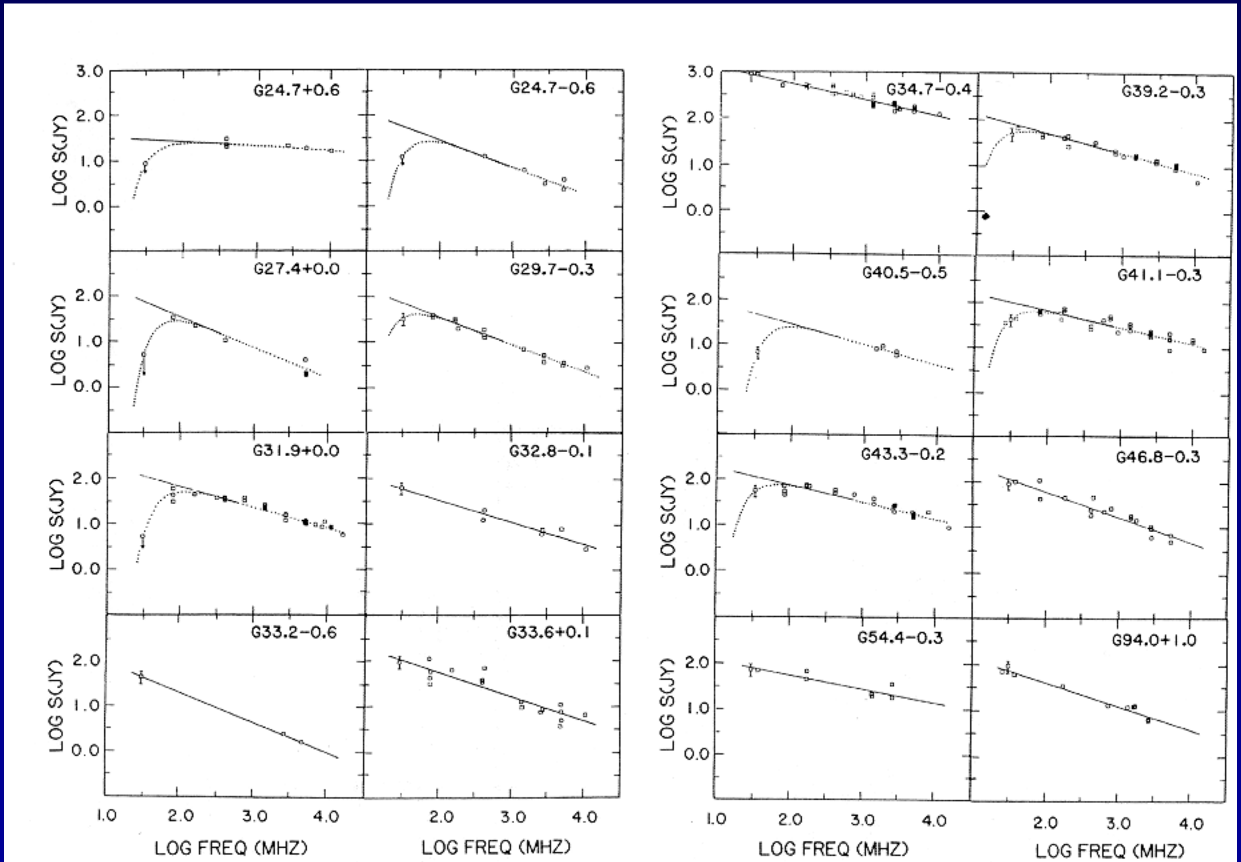


SW part of New Mexico

100 m

400 km

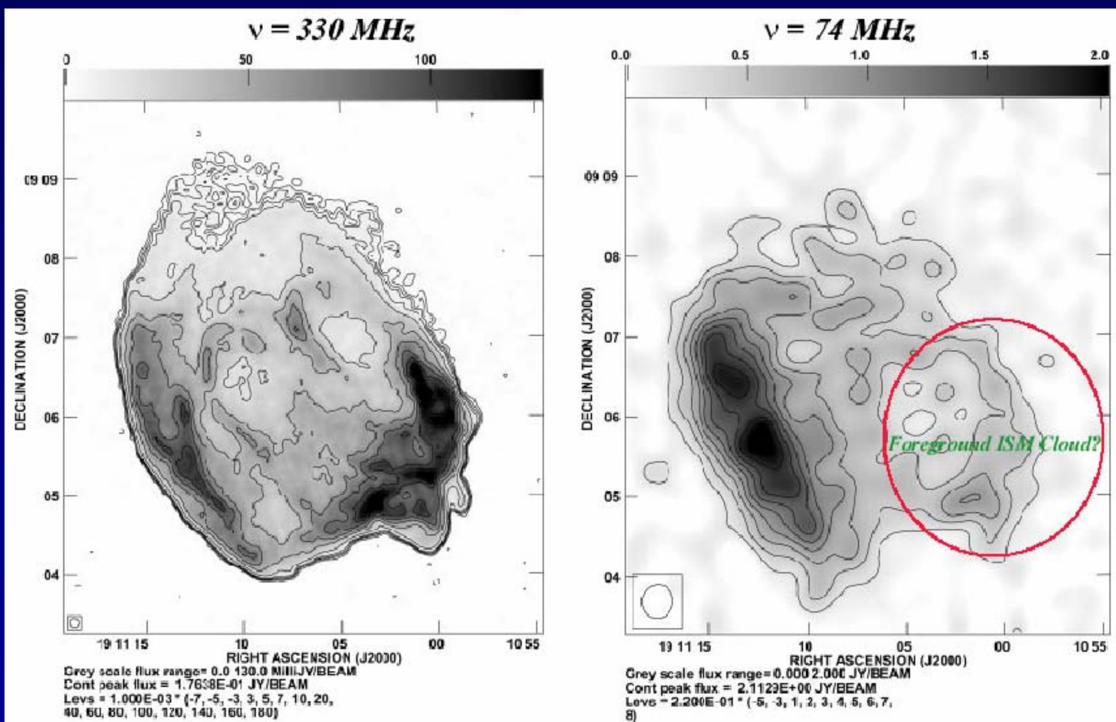
Plasma Astrophysics: Thermal Absorption from the ISM



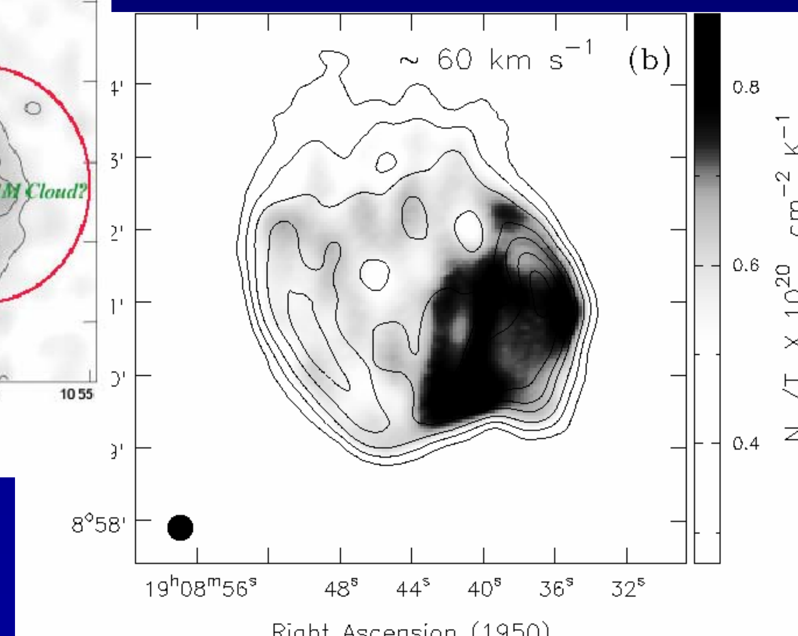
(Kassim 1989)

- Many, but not all, SNRs show LF continuum turnovers.
- Previous studies limited to integrated spectra by poor angular & resolution & sensitivity.
- LOFAR & LWA will revolutionize & expand to extragalactic sources for intrinsic & extrinsic absorption & scattering studies.

Plasma Astrophysics: Resolved ISM Thermal Absorption



HI

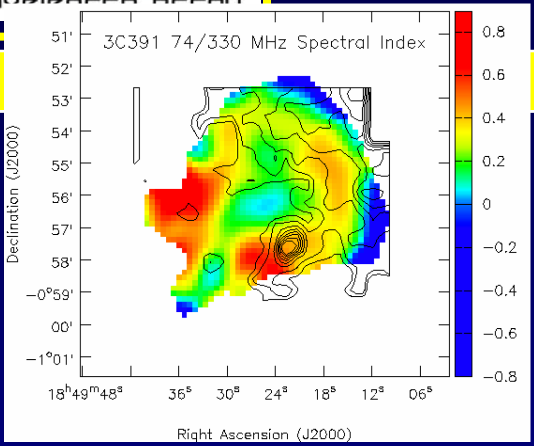


Lacey et al (2001)

Radio Recombination line H134α observed at ~65 km/s (*Downes & Wilson 1974*)

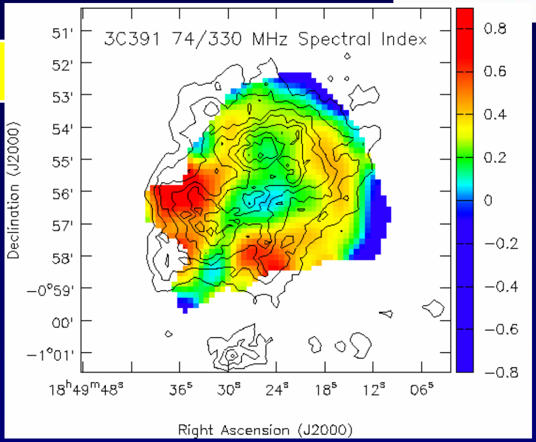
Brogan & Troland (2001)

Plasma Astrophysics: Thermal/N-Thermal Source Interactions

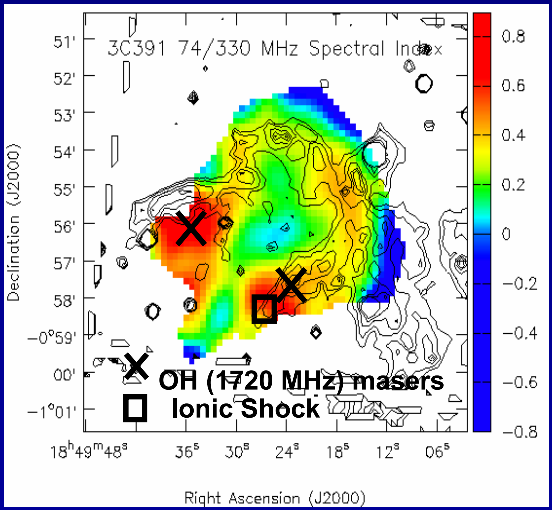


CO (2-1) integrated emission tracing MC (*Reach & Rho 1999*).

74 MHz absorption delineates sheath of absorbing ionized gas residing in the SNR/ molecular cloud shock boundary.



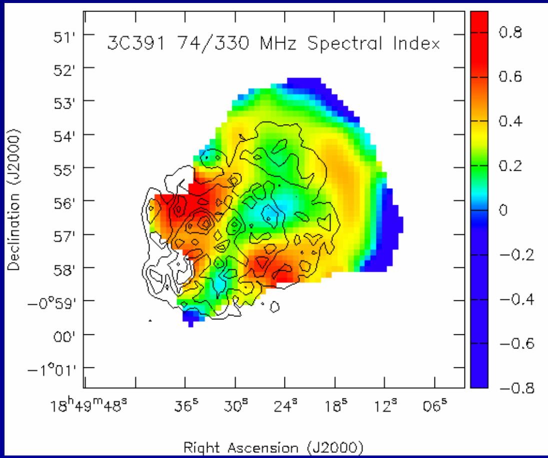
HARD X-rays showing full extent of SNR (*Chen & Slane 2001*)



IR emission from 12-18 μm tracing shock boundaries (*Reach et al. 2002*).

Thermal absorption couples the power of kinematic (HI) ***distances*** to Galactic nonthermal sources.

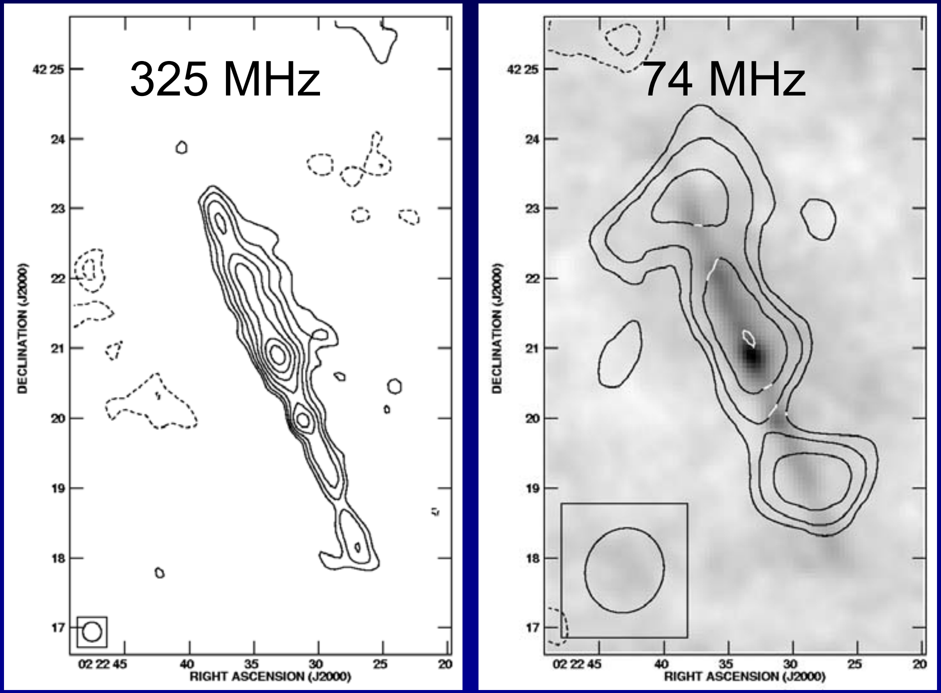
(Brogan et al. 2005a)



SOFT X-rays showing X-ray absorption (*Chen & Slane 2001*)

Plasma Astrophysics: Resolved Extragalactic Absorption

NGC 891: POSS II image

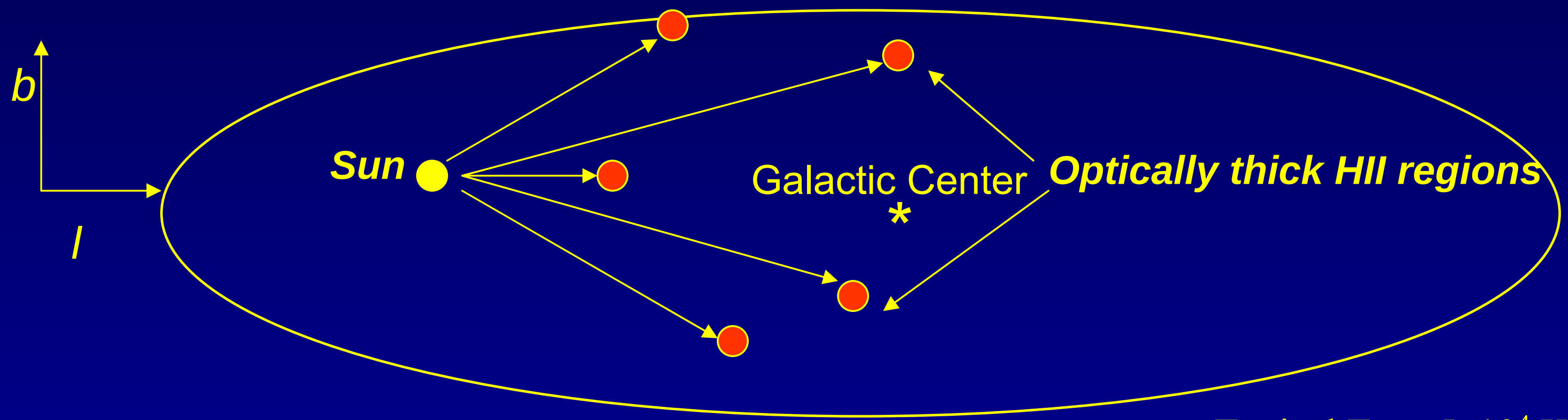


Cohen, Israel & Kassim, 2004

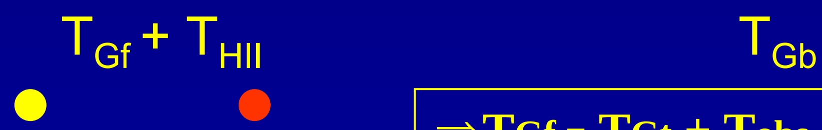
Resolved Spectral Turnover in NGC 891 - spectrum flatter in disk – need LOFAR or LWA to confirm!

Acceleration: Galactic Cosmic Ray Tomography

- CR energy ~ energy in starlight, gas pressure, and Galactic magnetic field



Typical T_{Gb} ~$5x10^4$ K
Typical T_{HII} ~$8x10^3$ K

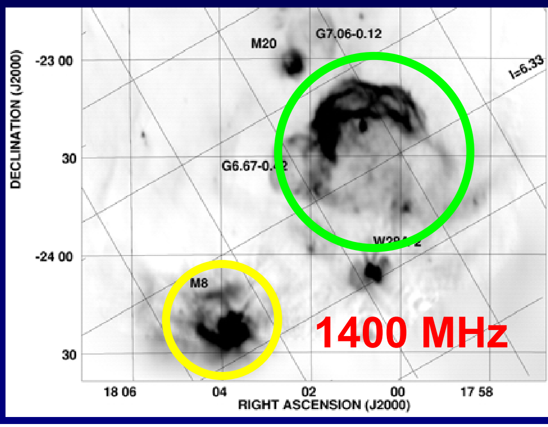


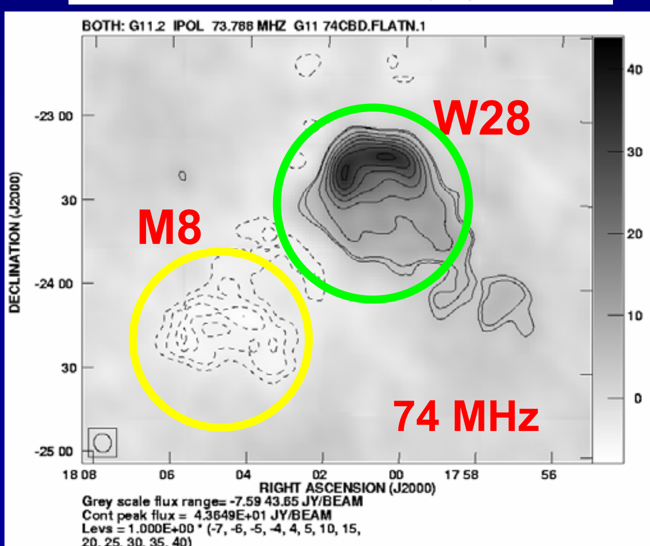
$\Rightarrow T_{Gf} = T_{Gt} + T_{obs\_i} - T_{HII}$

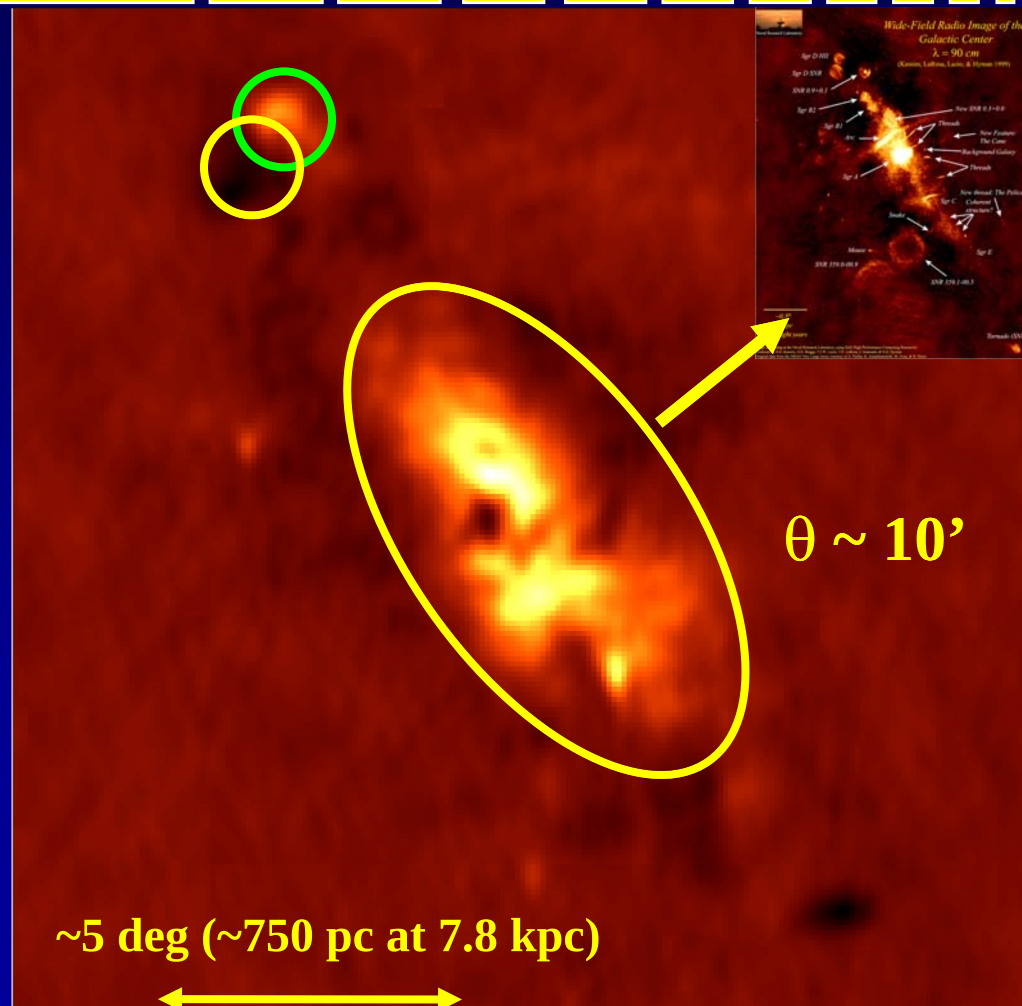
$\Rightarrow$Emissivity= T_{Gf}/D

- ➢ Galactic cosmic ray spectrum & origin
- ➢ Galactic magnetic field morphology

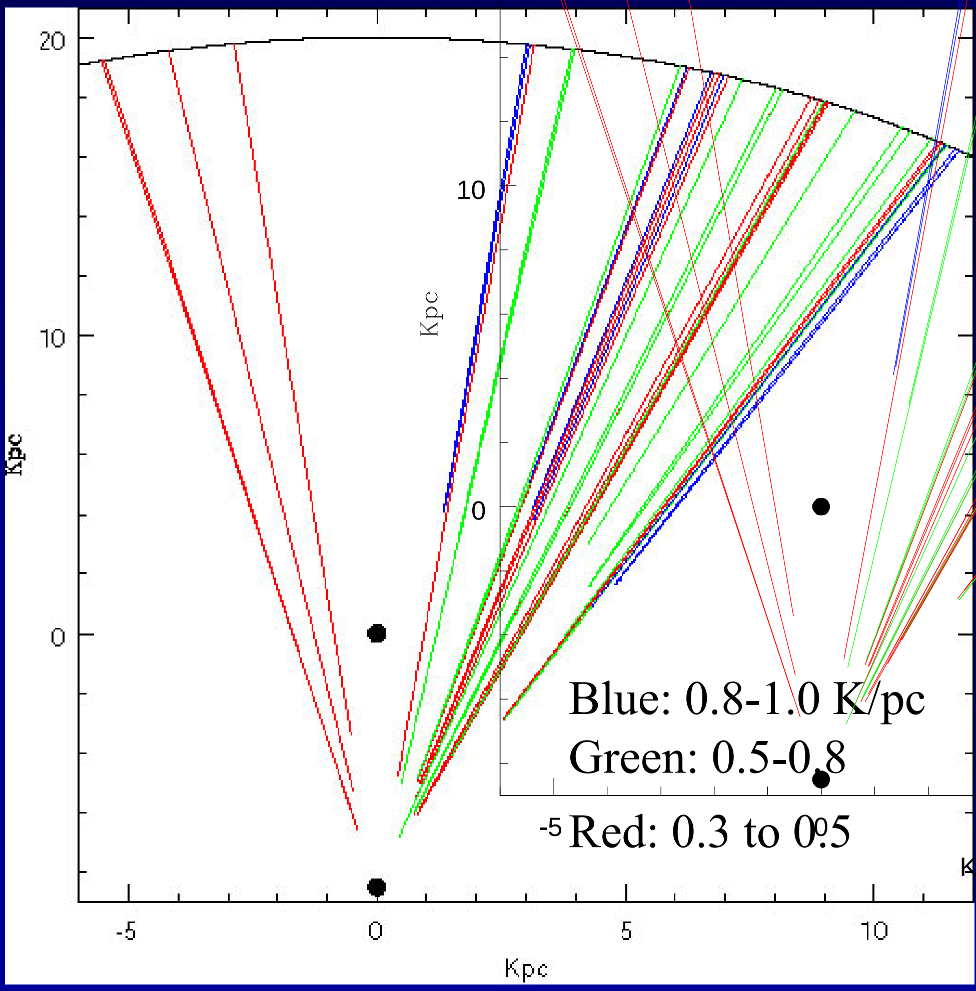
Acceleration: Galactic Cosmic Rays







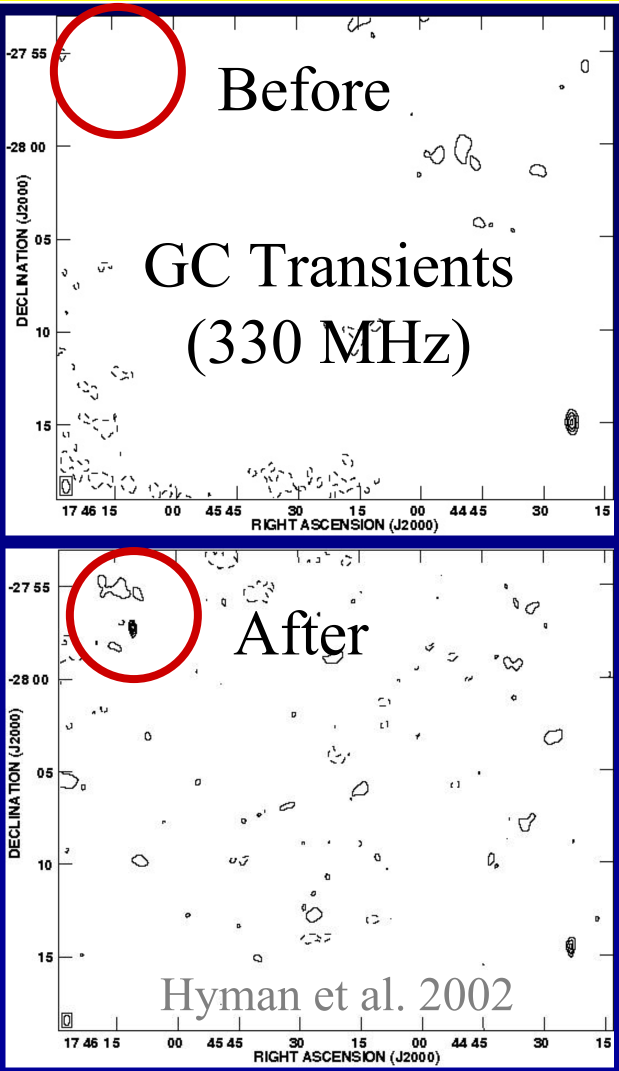
Acceleration: Galactic Cosmic Rays



- First quantitative results (~ 100 HII regions) imply paucity of CR emission within 2 kpc of GC.
- LWA can push to many more HII regions and get CR spectrum from multi-frequency measurements

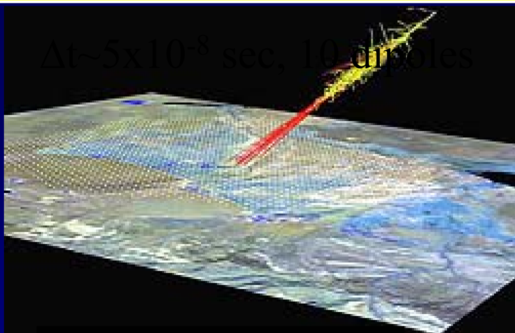
Nord et al. 2006

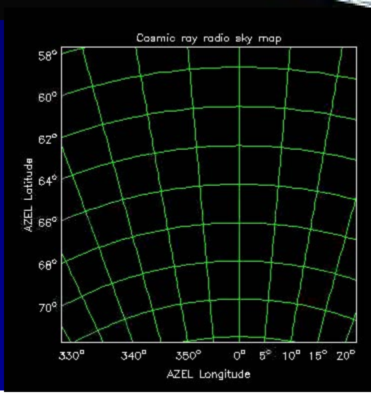
Acceleration: Transients



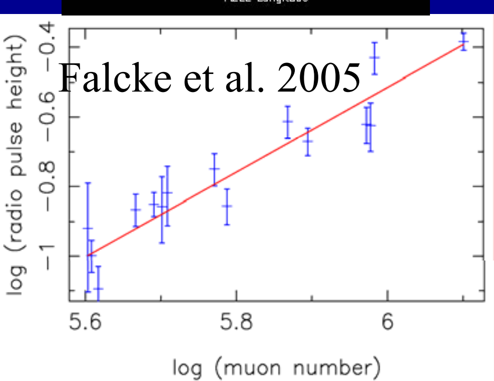
- Radio afterglows (GRBs, SNe, magnetars, …)
- Prompt GRB and/or SNe emission
- Giant pulses from pulsars
- Coherent burst emission (stars, planets)
- Microquasars
- AGN flares
- Microlensing events
- Cosmic-ray showers
- LIGO events
- Evaporating black holes
- …

Acceleration (Transients): Cosmic Ray Air Showers





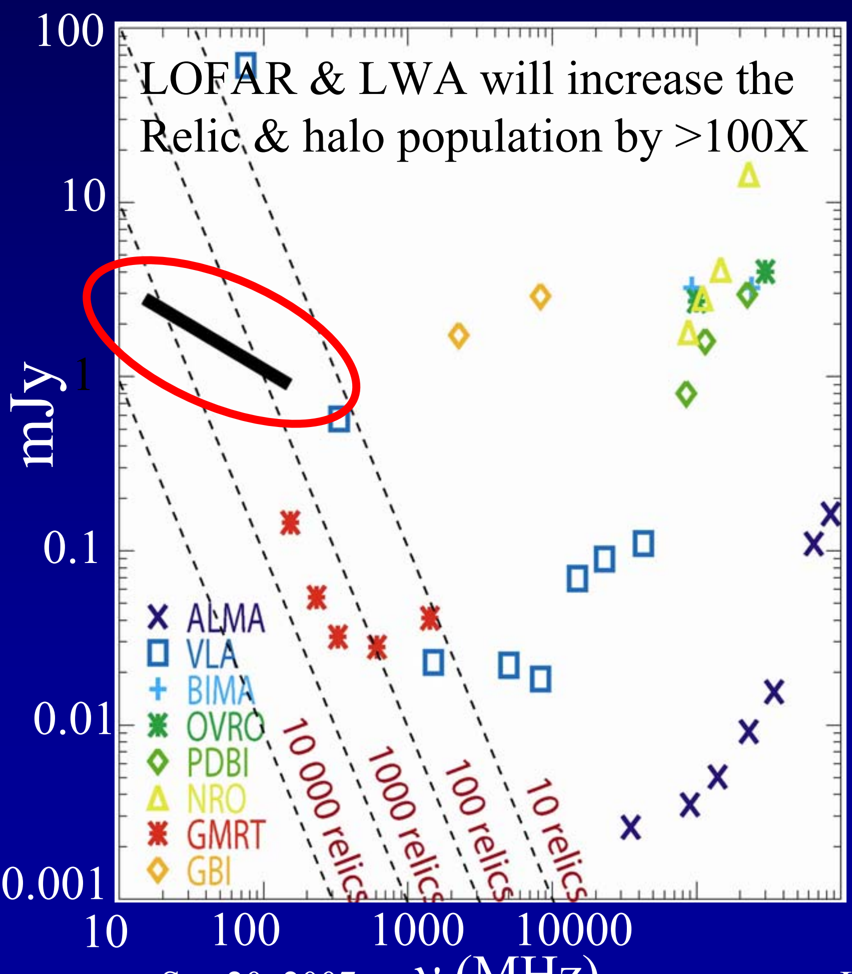
~10°

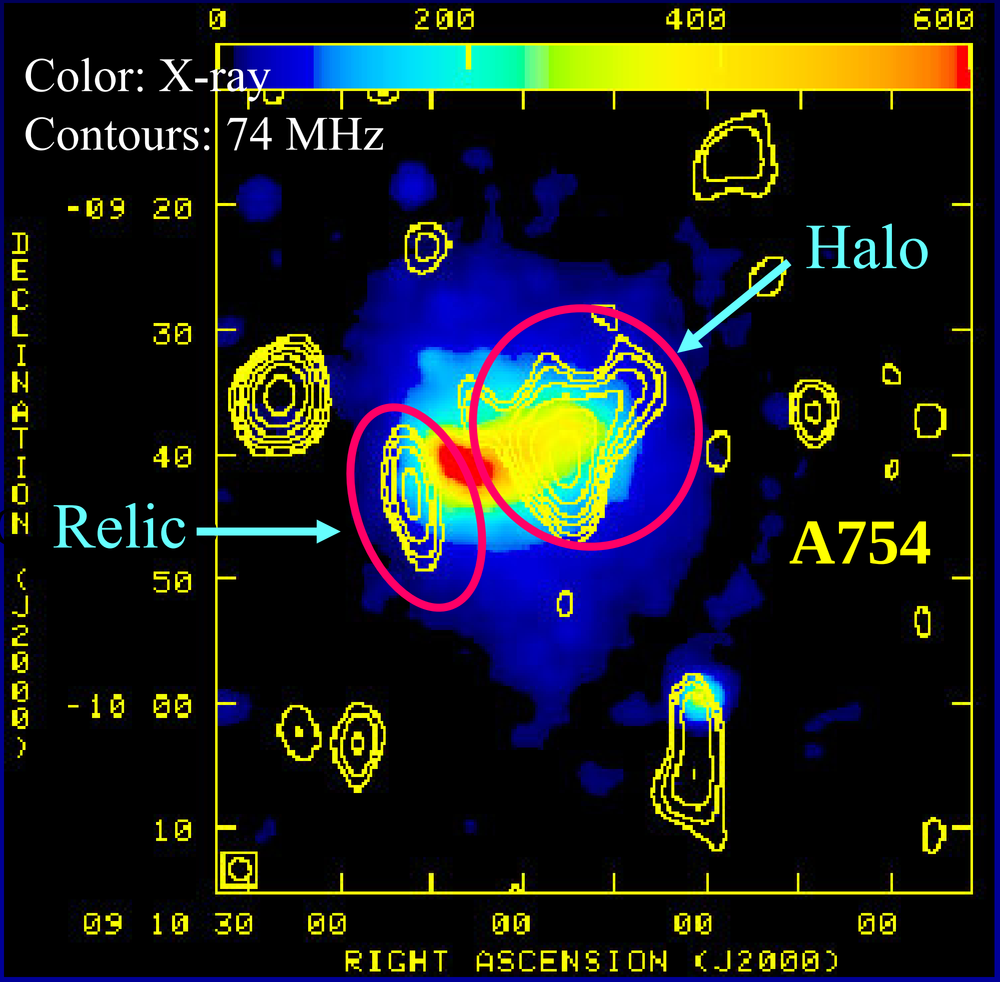


Falcke et al. 2005

- Highest Energy Cosmic Rays
  - Energy ≥ 10^{19} eV – unique signature at low frequencies
    - Fundamental unsolved problem in high energy astrophysics: Origin? New fundamental particles? M87?
  - High energy cosmic rays cause cascade of secondary particles in atmosphere
    - Coherent gyro-synchrotron emission
    - Brightest sources in the sky for μsec
    - Complimentary info to conventional scintillation detectors
      - Only measure particles arriving on the ground.
      - Comparing two methods should help identify composition and nature of the primary particles.

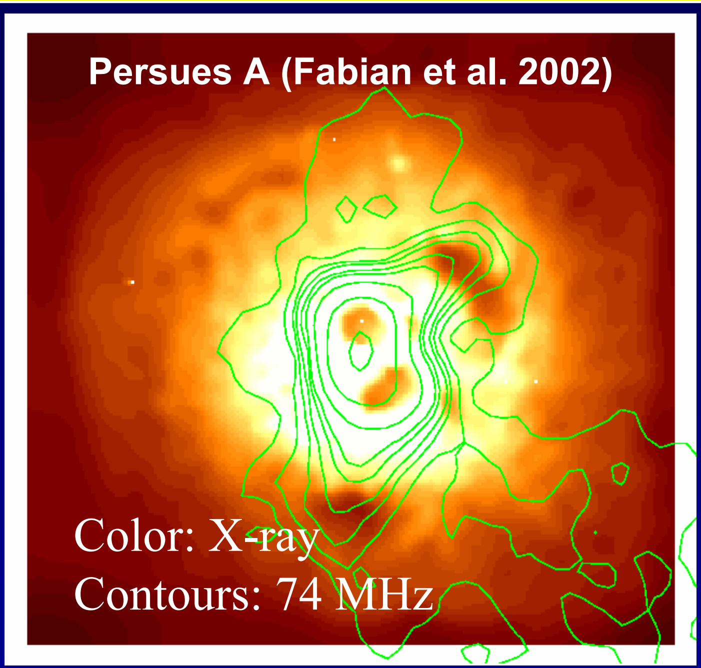
Acceleration: Cluster Mergers: Relics & Halos

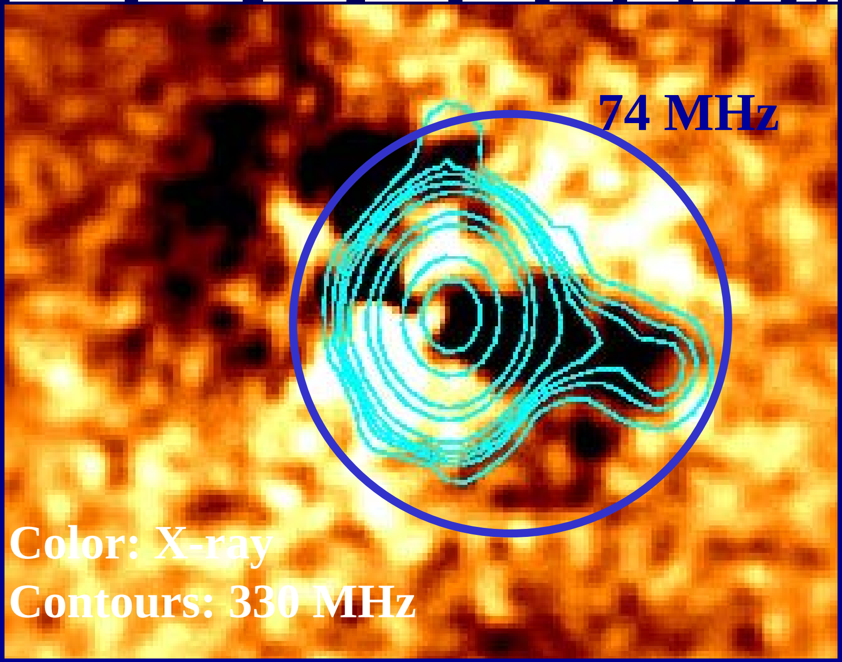




Kassim et al. 2001

Acceleration: Bouyant bubbles in clusters

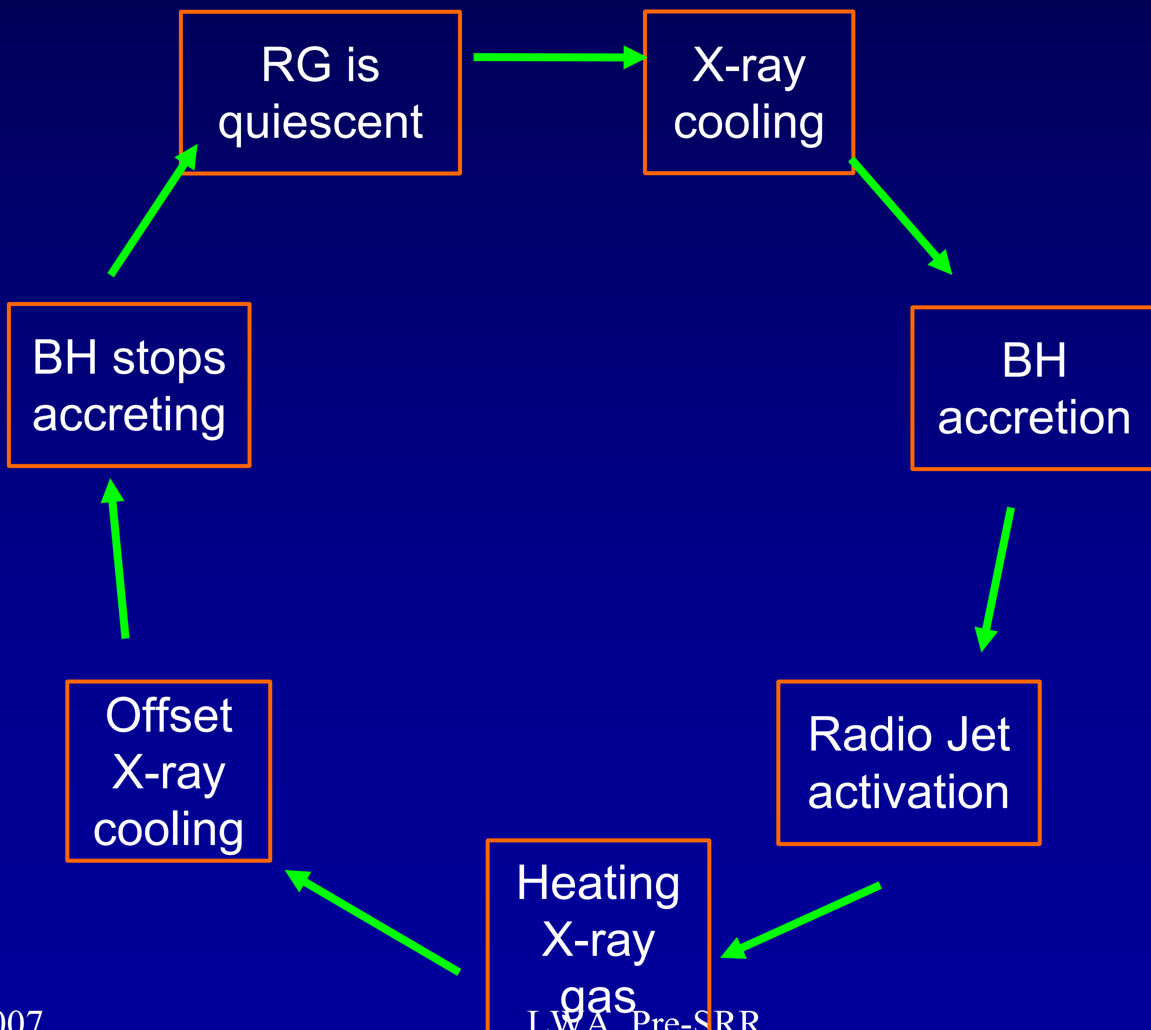




A2597

- Low frequencies trace bouyant bubbles of relativistic plasma –
  - Explain X-ray & radio morphology
  - Provide source of heat to solve “cooling flow crisis”
  - Provide means of transporting B-fields from AGN accretion disk to cluster periphery
  - Trace AGN lifecycle & influence of black holes on IC environment

Acceleration: AGN Lifecycles



Extending Ionospheric Calibration through Physics-based Models

P. Colestock, S. Close, Larry Cox, W.Junor,
Los Alamos National Laboratory
and G. Bust, ASTRA

Los Alamos
NATIONAL LABORATORY
EST. 1943

What are we attempting to do?

- Provide an accurate means of determining ionospheric corrections to LWA data
- Remove all systematic phase distortions on 10-1000 km wavelength scales
- Determine optimal conditions for LWA observations

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AGW as drivers for coherent ionospheric disturbances

- Atmospheric gravity waves determine structure for TID's – coupled by neutral winds
- AGW propagate horizontally for large distances – ducting may be significant
- May be generated by thunderstorms as well as from convection

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AGW Dispersion Relation

$$k_z^2 = \frac{\omega^2 - \omega_A^2}{c_s^2} + k_x^2\left(\frac{\omega_B^2}{\omega^2} - 1\right)$$

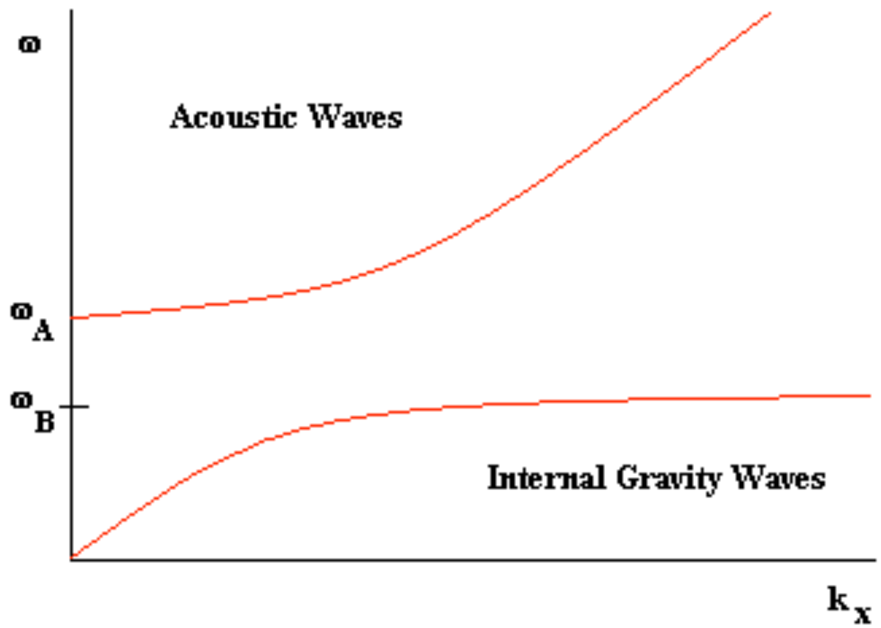
Ref: R. Hunsucker, Encyclopedia Of Earth Sciences, Vol. 1, Academic Press (1992)

$$\omega_A \equiv \frac{\gamma g}{2c_s}$$

Acoustic cutoff frequency

$$\omega_B \equiv \frac{(\gamma - 1)^{1/2} g}{c_s}$$

Brunt-Vaisala frequency



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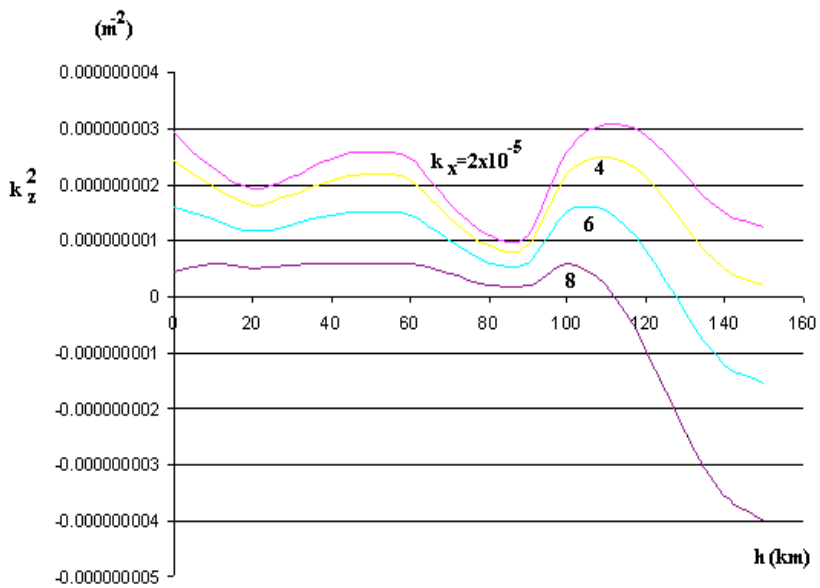
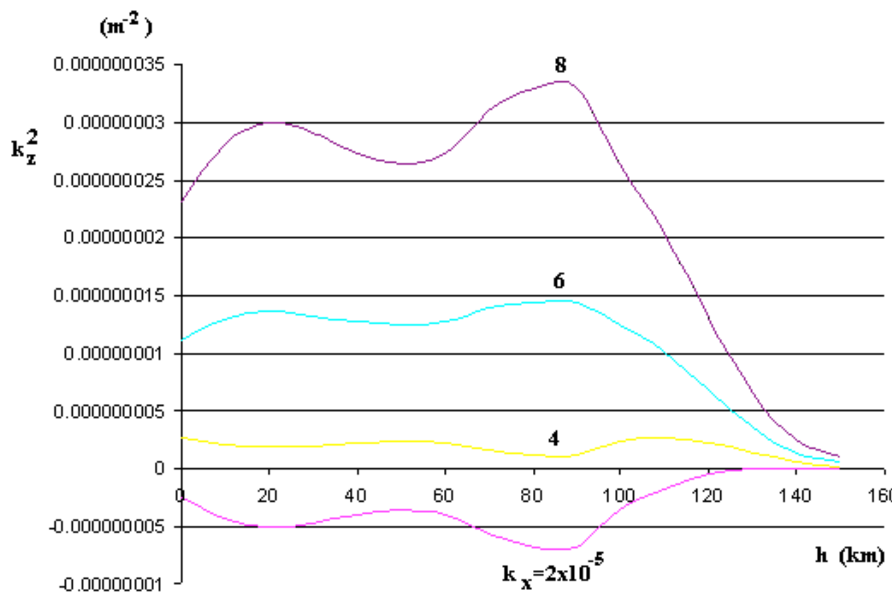
AGW Index of Refraction shows Ducting and Horizontal Propagation

Acoustic Gravity Waves
ω=.03 Hz



Internal Gravity Waves
ω=.01 Hz



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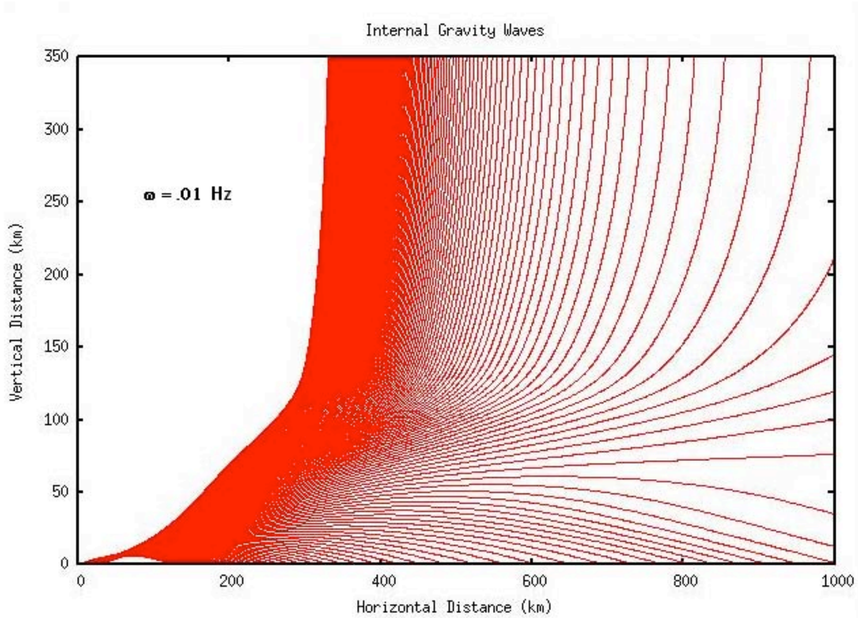
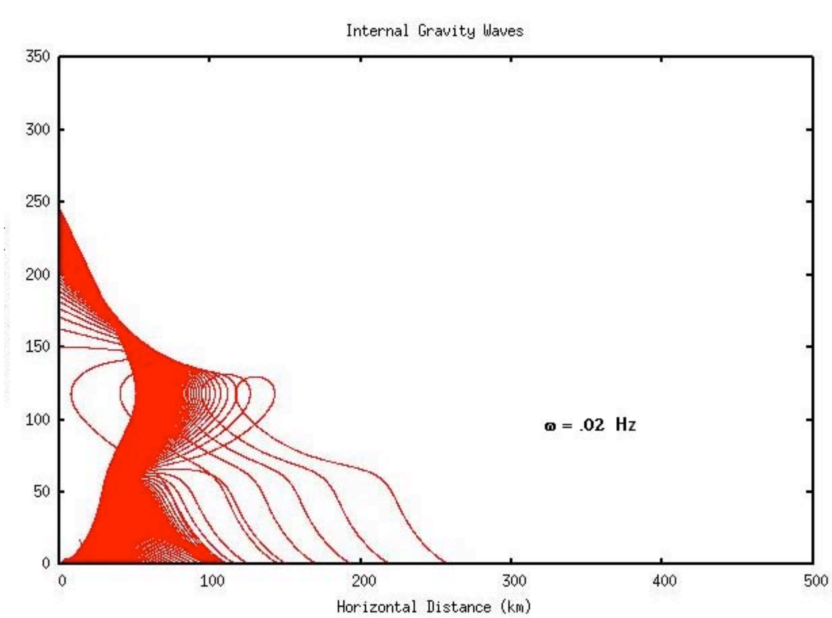
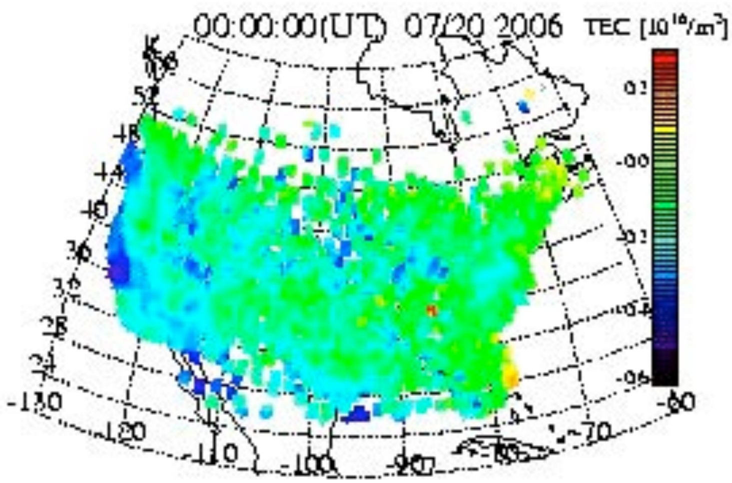
Ray Model of AGW Propagation

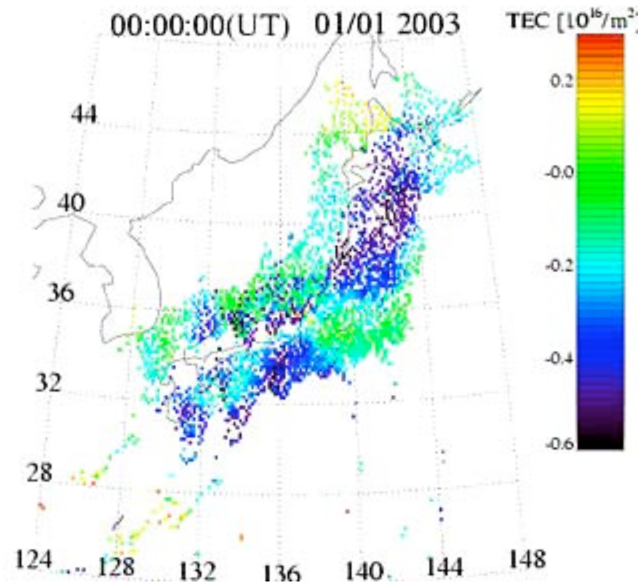




Internal gravity waves exhibit upper frequency cutoff for long distance propagation.

MSTID from GEONET





http://stdb2.stelab.nagoya-u.ac.jp/member/tsugawa/GPS/IGS/MAP/

Kotake et al., EPS, 2007

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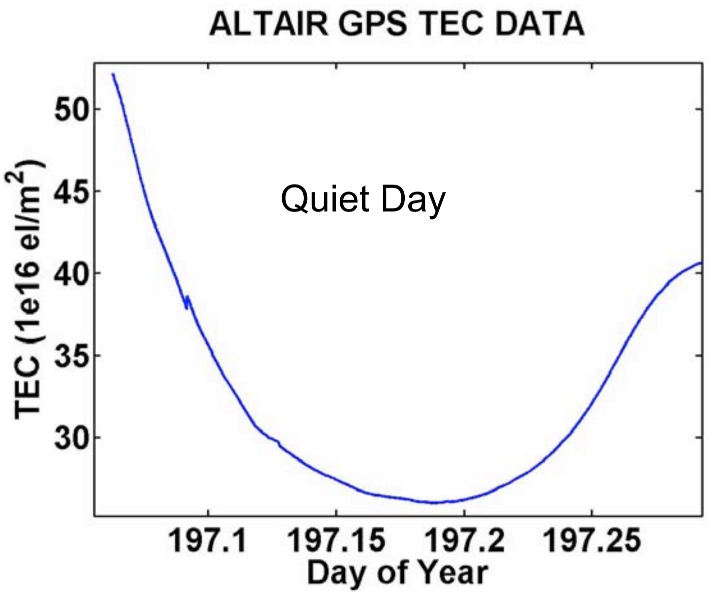
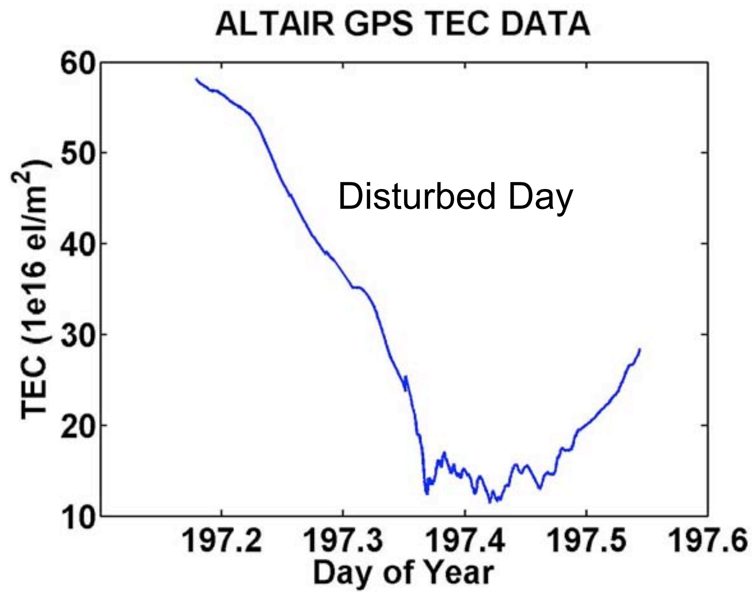
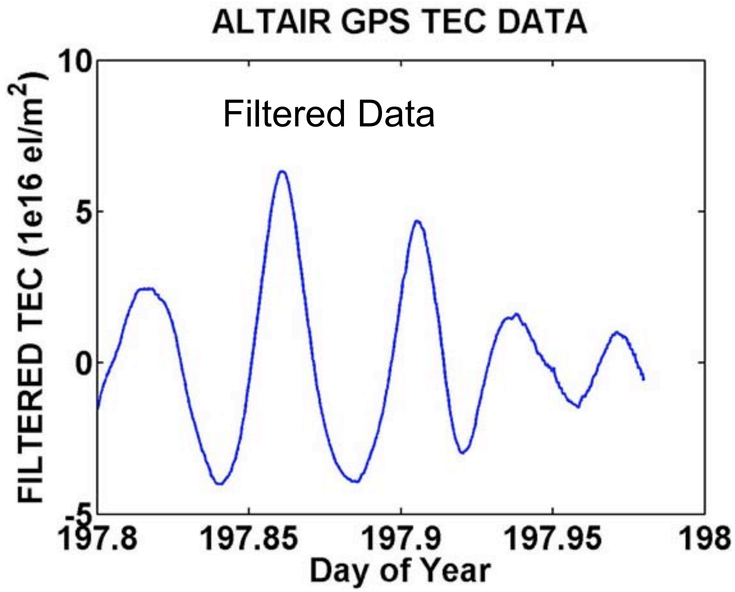
Data from ALTAIR







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Research Plan

- Incorporate complete dispersive model of AGW's ref: S. Vadas, JGR,**112**, A06305 (2007)
- Determine coupling to TEC fluctuations
- Identify AGW signatures in GPS data
- Formulate feed forward algorithm based on distributed TEC measurements
  - Determine error basis
  - Specify algorithm requirements

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The Long Wavelength Demonstrator Array

David Munton

ARL:UT

Tracy Clarke, Paul Ray

Naval Research Laboratory

Sept 20, 2007

LWDA Team

NRL

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Dan Wood

UNM

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Walter Gerstle
Ylva Pihlstrom
John Dickel

ARL/UT

David Munton
J.A. Banks
John Copeland
Tom Gaussiran
Aaron Kerkhoff
Charlie Slack
Jonathan York
Mike Montgomery

LANL: Bill Junor, Sigrid Close

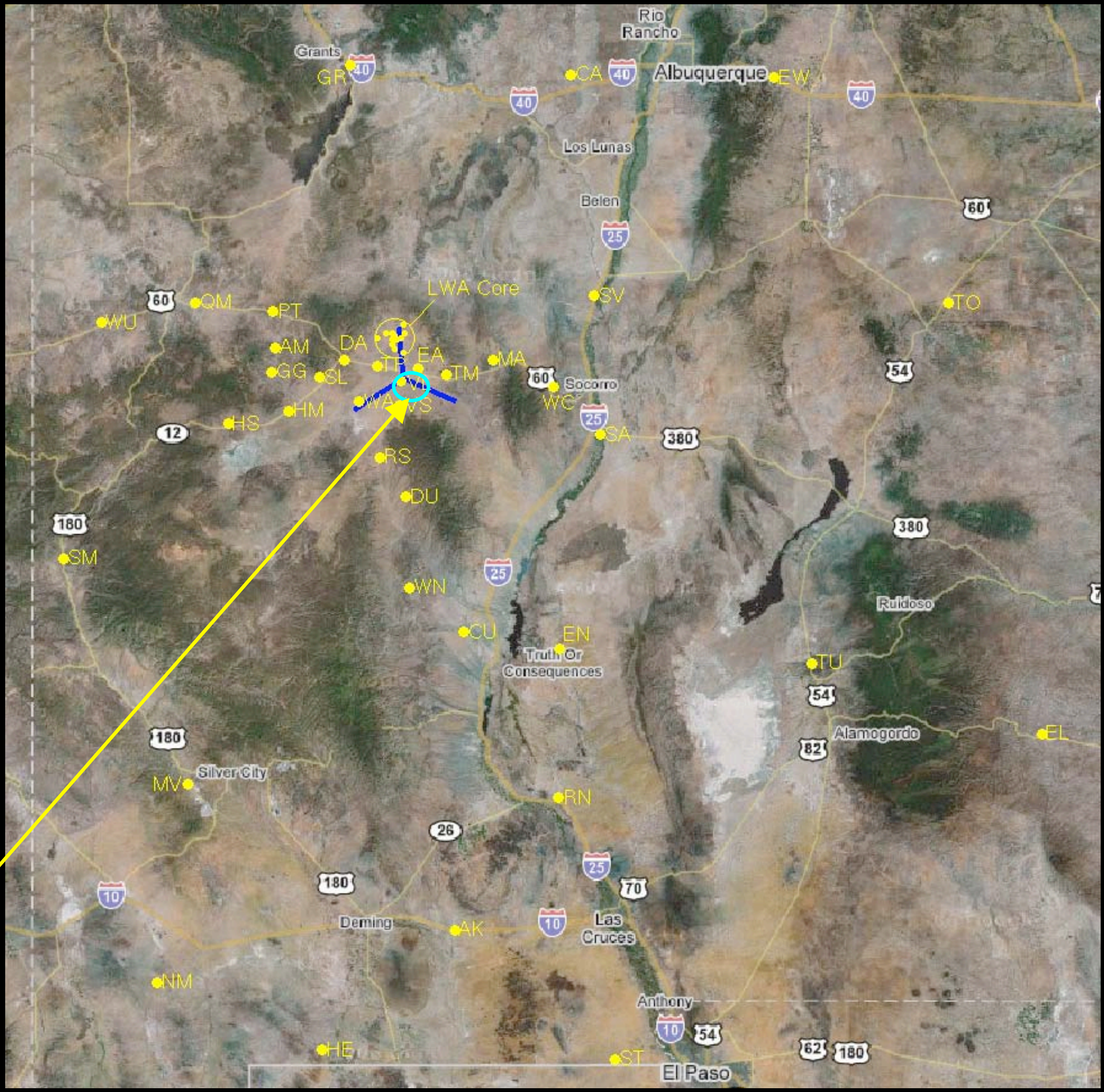
VA Tech: Steve Ellingson

We gratefully acknowledge assistance from NRAO staff members.

LWDA Location

- Built by the Southwest Consortium: UNM, LANL, UT-ARL, NRL
- Situated in south western New Mexico near the VLA
- Potentially a future LWA station location
- 120 m by 120 m area
    - Power
    - Communications,
    - Working area

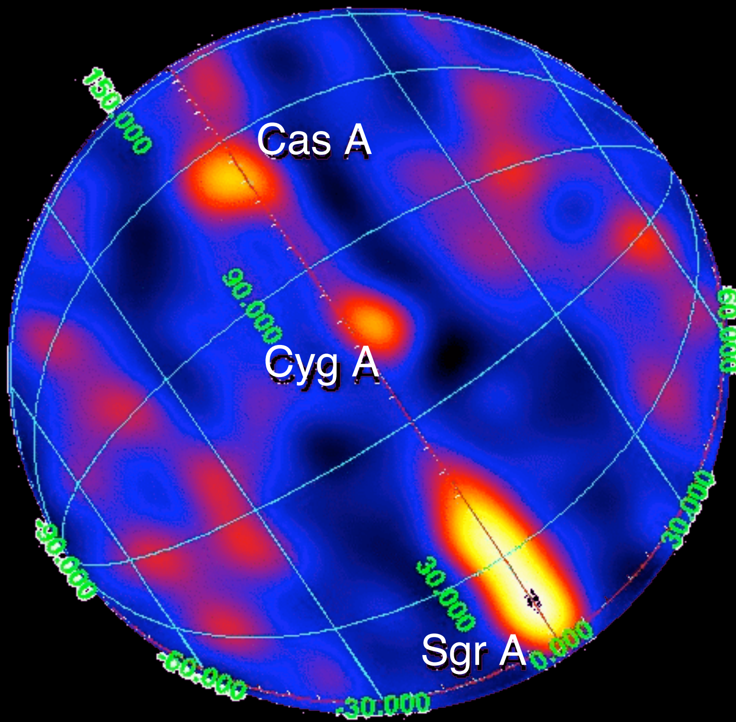
Long Wavelength Demonstrator Array (LWDA)



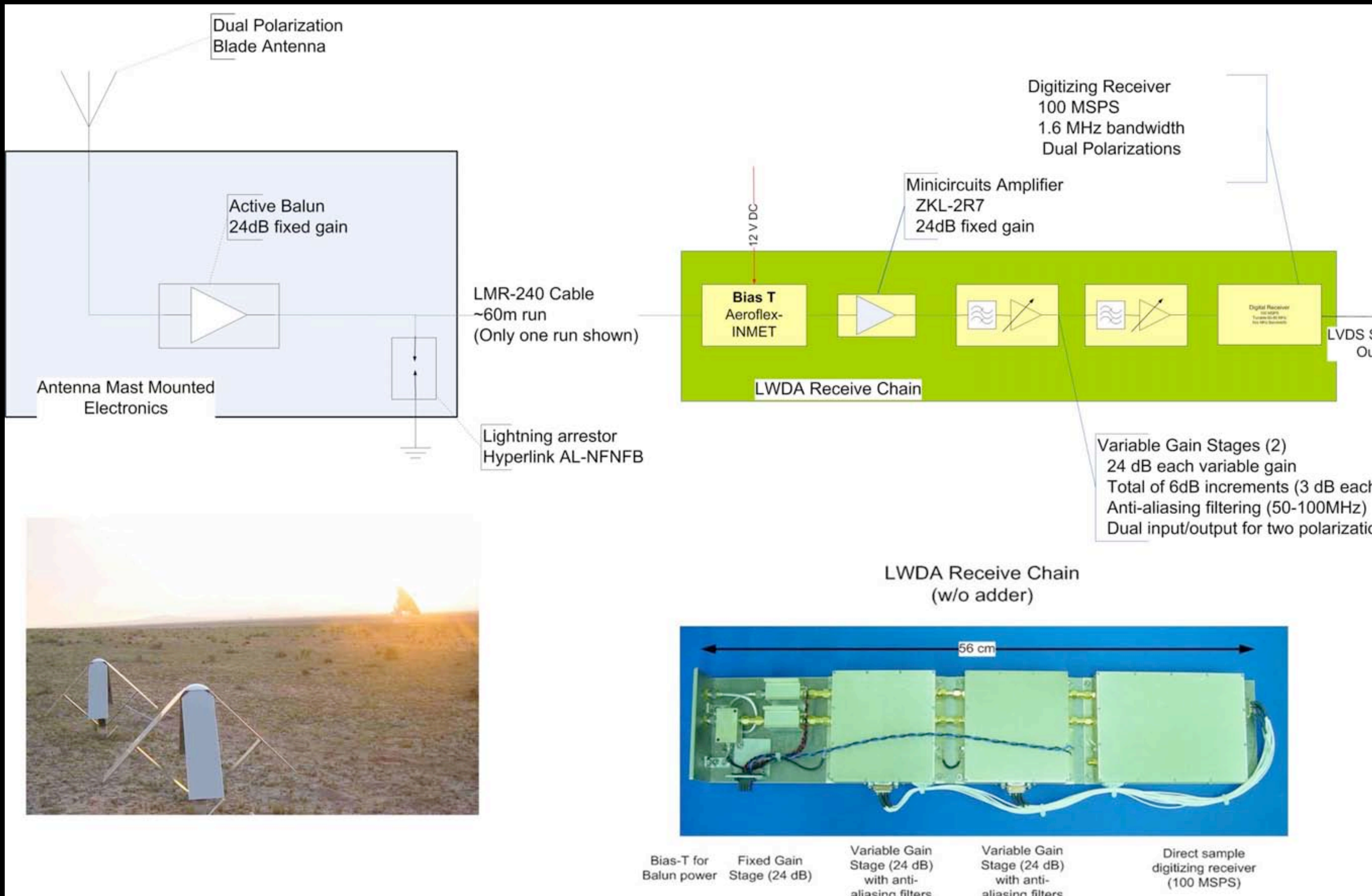
← 400 km →

LWDA

- 60-80 MHz, internal baseline of 20 m
  - Expanded with addition of outlier element
- Capabilities
  - Digital delay beamforming
    - Two independent beams of 1.6 MHz
  - All-sky monitoring
- Dual orthogonal linear polarizations
- First-light on October 23, 2006



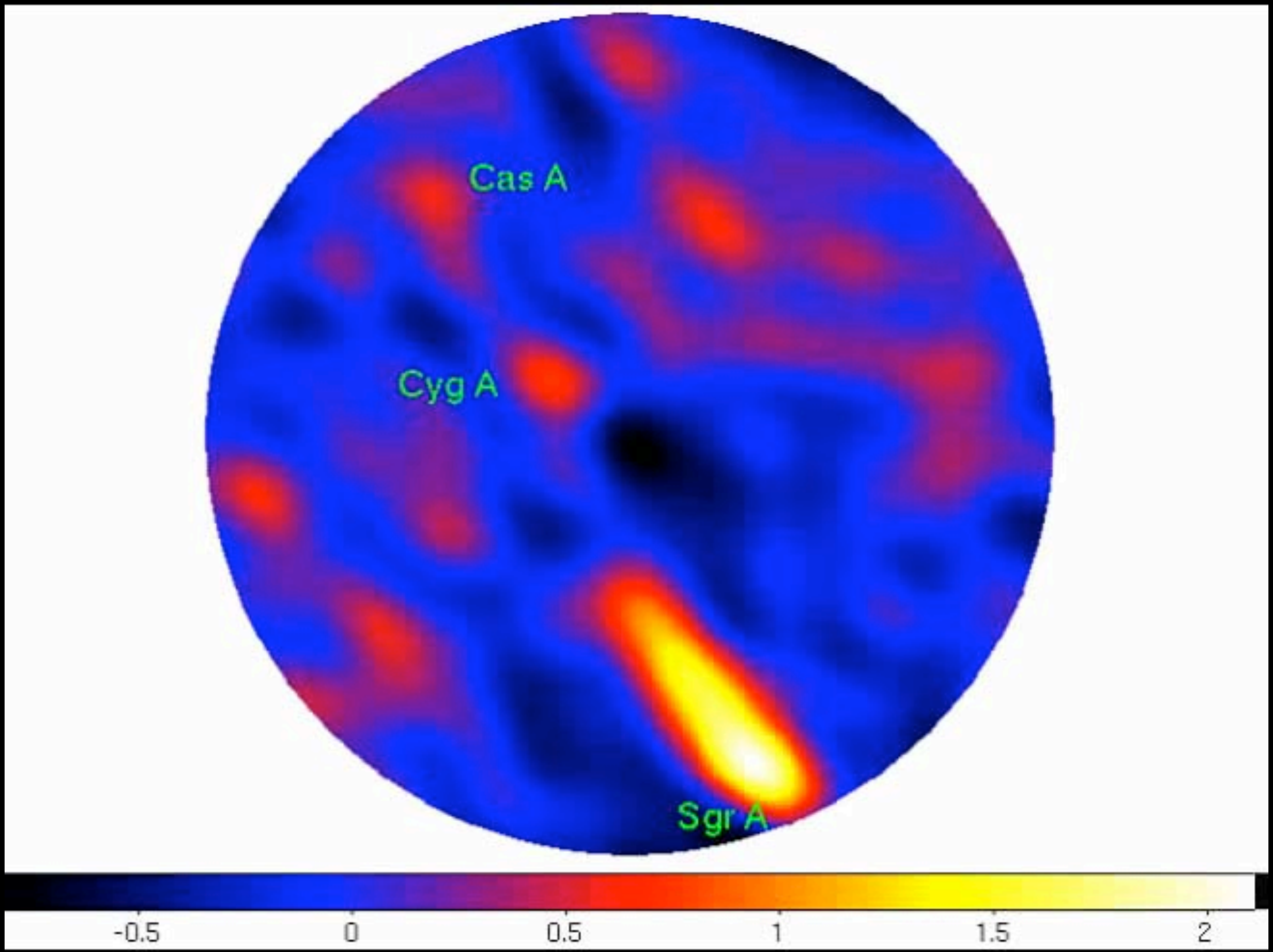
LWDA Signal Chain



LWDA First Light Movie

- Acquisition mode
  - Cycled over 120 pairs of dipoles (at ~50 ms per baseline),
  - Correlating the signals from each.
  - Phase and gain calibrations, applied to each of the visibilities.
- Data written in FITS IDI format
  - Read into AIPS
  - Processed using automated pipeline script developed for astronomical transient searches
- Movie has dirty images (no deconvolution)
  - Every 5 minutes over 24 hour period on Oct. 28, 2006
- LWDA observing at zenith in all-sky monitoring mode
- Cas A, Cyg A, Galactic Plane, and Sun are clearly visible.
  - Also detect North Polar Spur and Loop III (not shown).

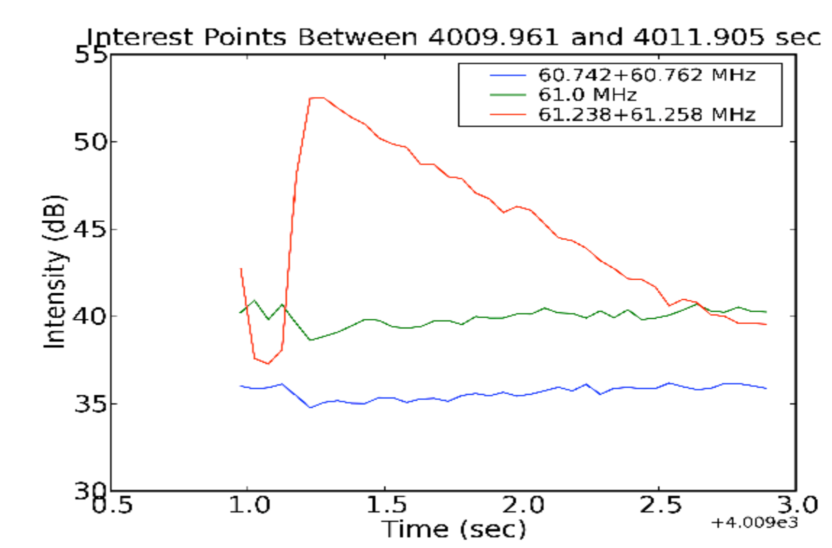
LWDA First Light Movie

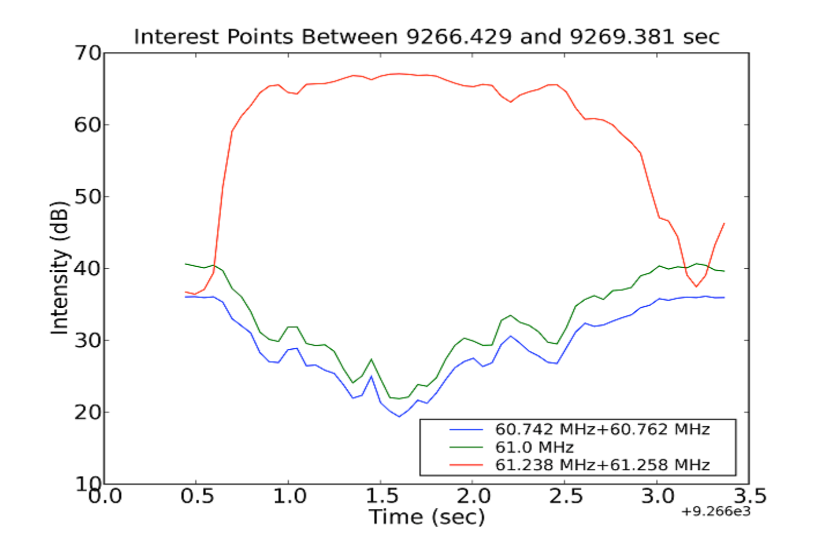


North Up, East Left

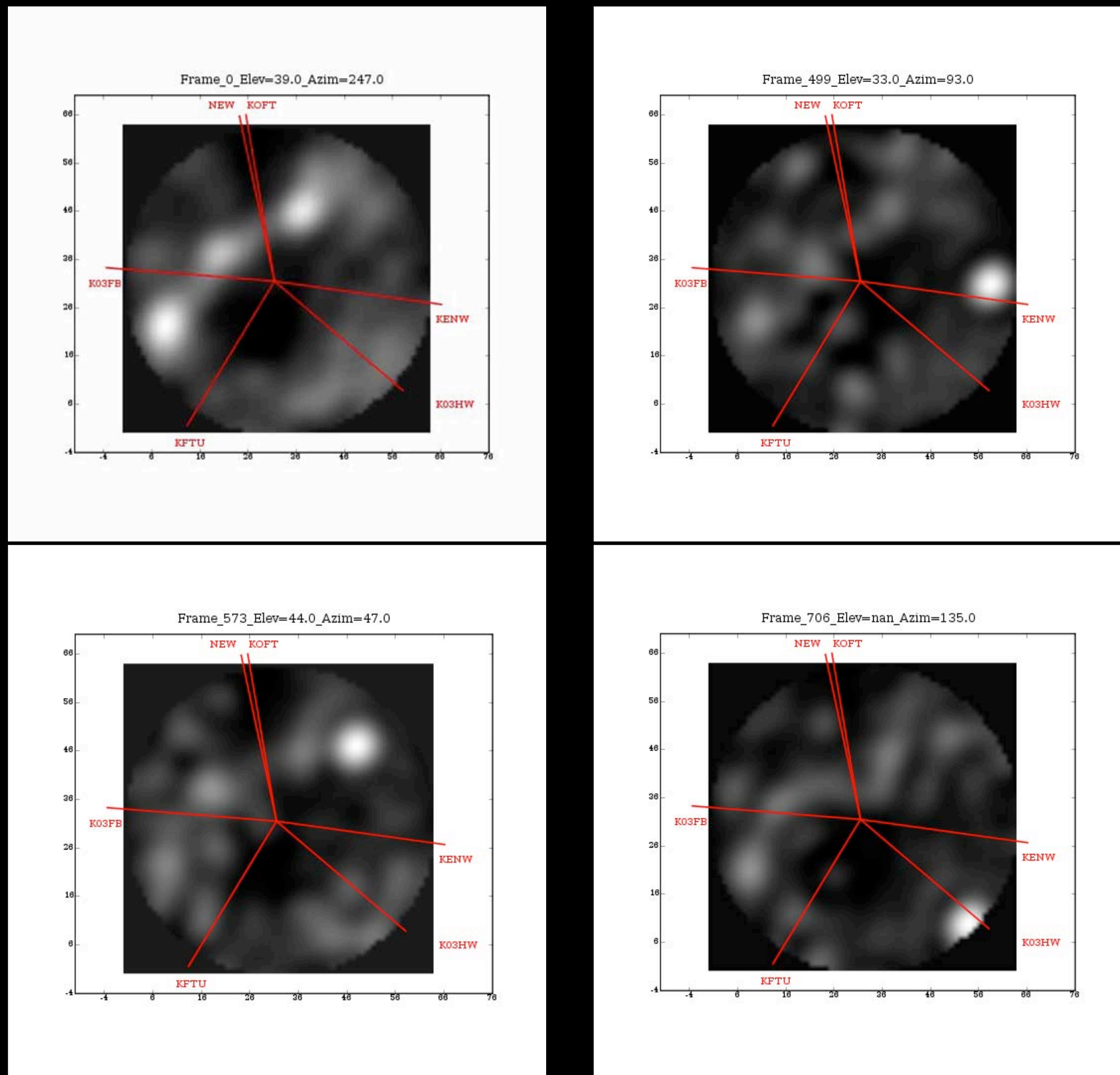
Leonid Meteors & Meteor Scatter November 18, 2006

- Tuned to 61.0 MHz
  - TV Ch 3
  - Video carrier at 61.25 MHz
- Simultaneous 1-bit data from all antennas
- Post-processed with single lag 1-bit software correlator
- Single antenna power vs time





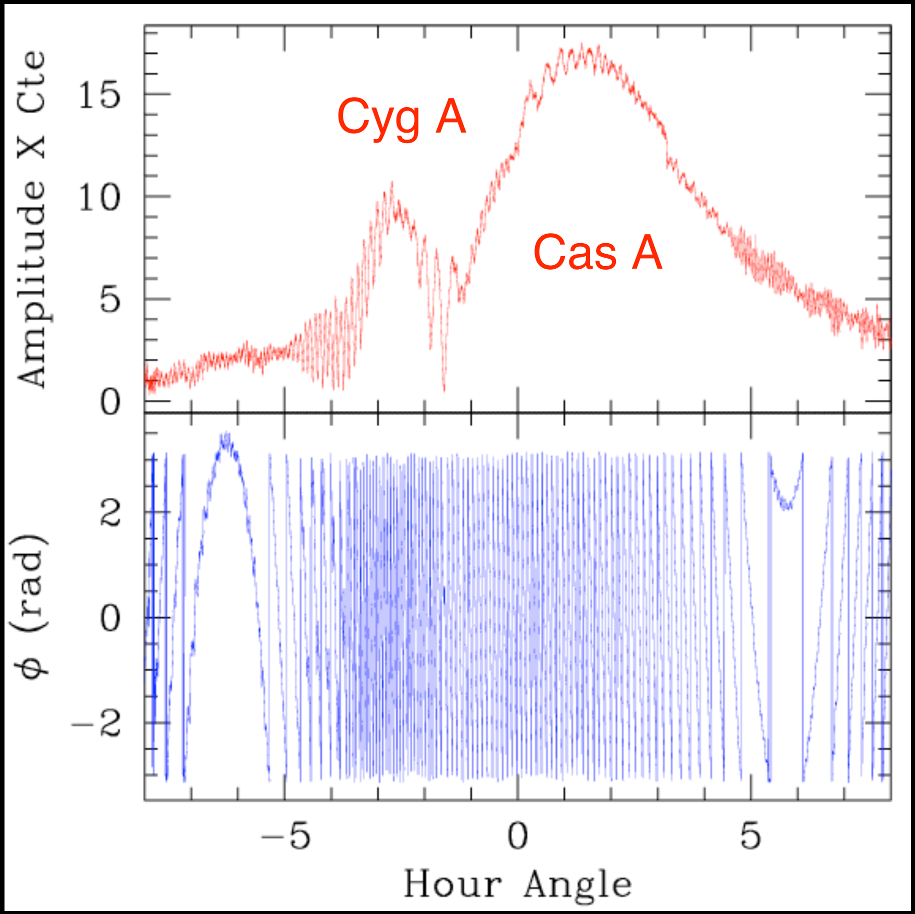
Leonid Meteors – The Movie



North Up, East Right

LWDA Interferometer

- Outrigger Big Blade antenna set up for interferometer measurements with phased-array LWDA
- Astronomical observations used to precisely measure baseline length and position angle
- Initial applications include Solar flux monitoring, transient searches, and measurements of the phased- array beam pattern



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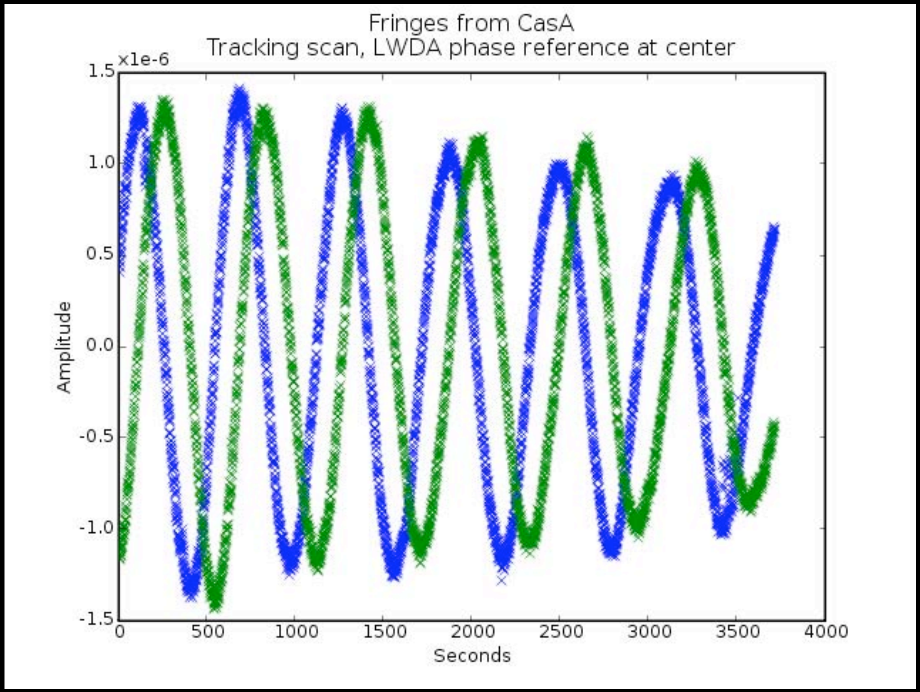
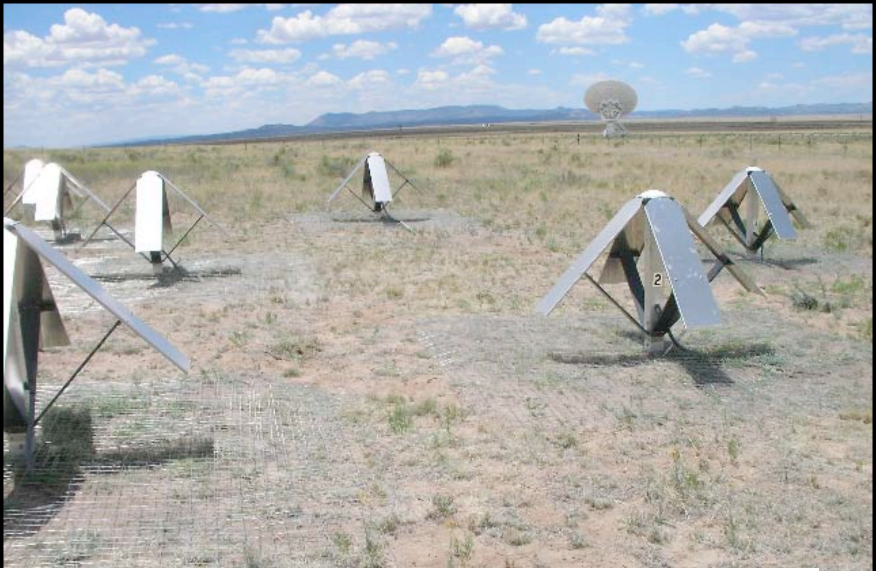


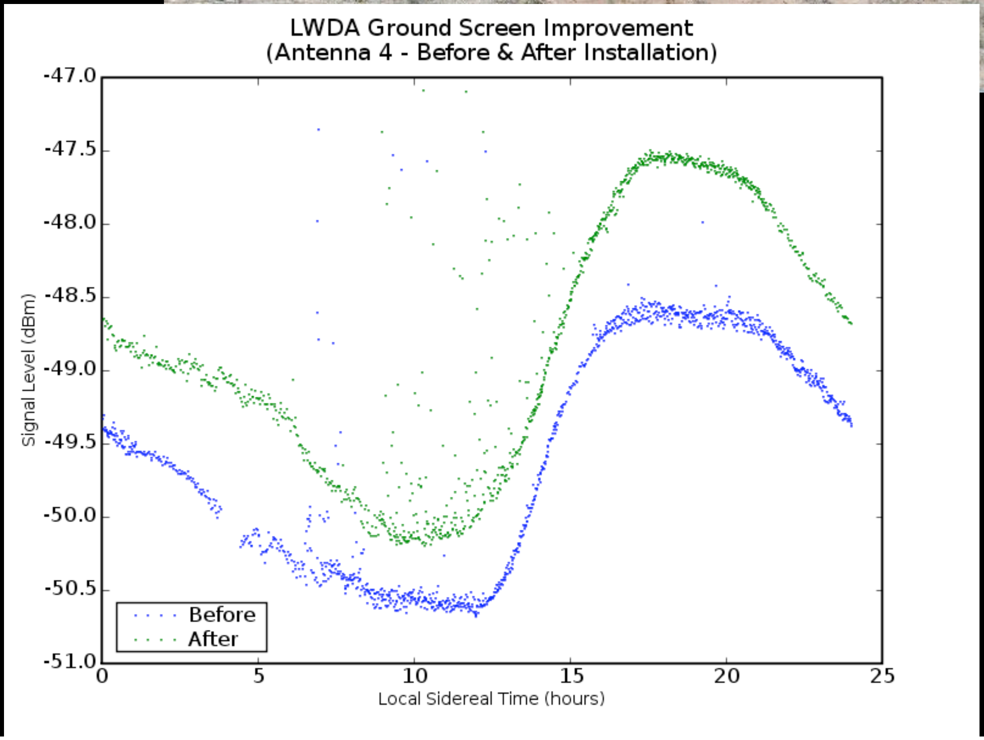
The Impact of Ground Screens

- Ground Screens installed this spring

- Simulations predict improvement between ~ 1.1 and 1.9 dB
  - Depends on f, moisture content of soil.

- Measurements taken show total power increase ranging from 0.5-1.6 dB
  - Dependent on both the antenna and local sidereal time.



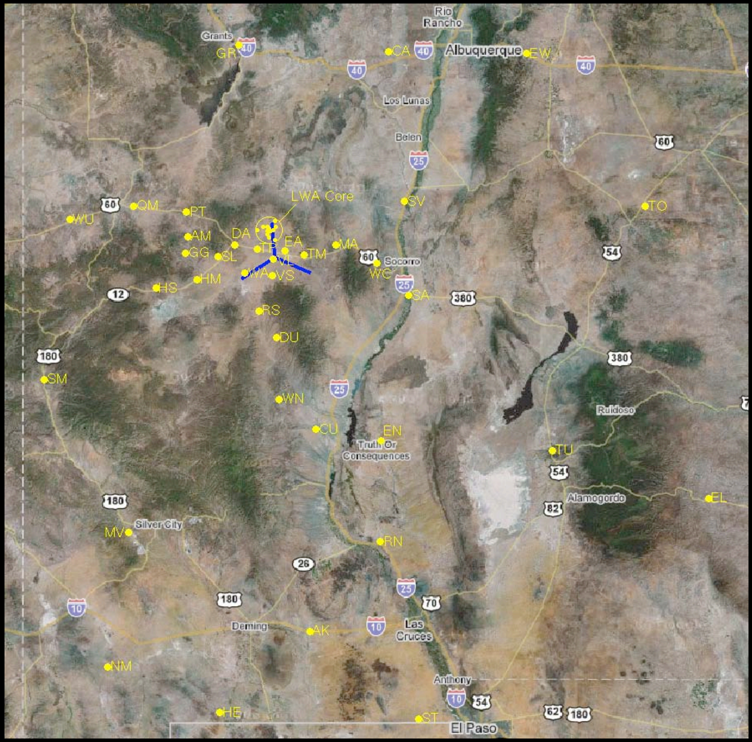


Lessons A Year After First Light

- The LWDA has provided a number of interesting lessons
  - Logistics
  - Maintenance
  - Ground screens matter
  - Moving large quantities of data
  - Software considerations
  - Communications across institutions

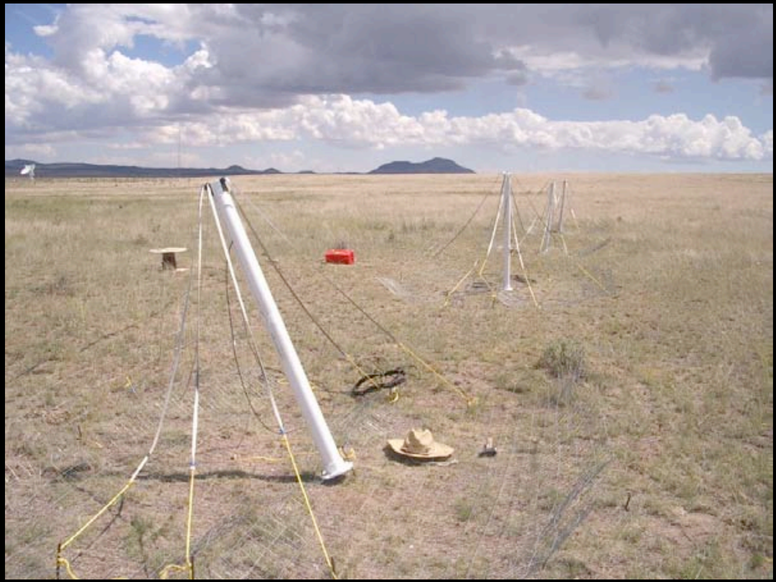
Logistics

- Getting things out to the sites takes time – plan for it.
  - If you have to ship something, two days is not enough.
- If you forgot it, you'll have to do without (or borrow it).
  - Long drive back to Albuquerque
- Shipping costs money
  - Find nearby vendors for large purchases
- **Plan your trips carefully!**



Maintenance

- Things break when least expected
  - Have spares available – plan for them!
- Large animals wreak havoc
  - Fence or enclose all equipment
- Power can go out - there are no redundant power lines
  - Be aware of all contact numbers
    - Power
    - Security
    - Medical



Communications

- With many institutions involved, who do you talk to and when?
  - Miscommunication will happen
  - Clearly established POC's
    - Known contact numbers
  - All site visits are coordinated through the program office
- Sites have owners or other tenants
  - LWDA site is under the oversight of NRAO
  - North arm site is lease by ranchers
  - Post contact numbers at each site

Moving Data

- For some modes, the LWDA produces too much data to move over existing communication link.
- LWA1 will easily best the output data rate of LWDA
  - What data transfer rates can we achieve from the site?
  - What on-site reduction does this require?
- Strategies:
  - Reduction in place
    - Can we afford the computer power?
    - Do we have the software ready?
  - Sneaker net transport of disks – Costs time and money.
    - LWDA solution

Software Effort

- Software must be a consideration from the beginning
  - Control
    - LWDA daily concept of operations changed (for the better)
    - What will LWA operations look like?
  - Post-processing
    - Converting raw data into a suitable format took more effort than expected.
    - Limitations of the traditional astronomical software related to all-sky imaging.
- Strategies
  - Develop a daily concept of operations.
  - Identify software that will need to be written early.
  - Develop and finalize an output data format as early as possible
    - Including telemetry and other observation specific data.

Summary

- LWDA has been collecting data since October, 2006
  - Successfully demonstrated
    - All sky mode
    - Interferometry wtih outlier antennas
  - More science to come!
- LWDA has provided many lessons
  - Keeping these lessons in mind should help us plan
  - LWA1+ will provide new challenges

LWDA Science Observations

- Low freq. spectra of bright pulsars
- Giant pulse monitoring of the Crab pulsar
- All-sky monitoring for bright continuum transients
- Solar burst observations with high spectral and temporal resolution
- GRB prompt radio counterpart searches
- Blind searches for narrow, dispersed pulses
- Bistatic radar observations of the ionosphere

LWA Technical Concept

Kickoff Meeting, Albuquerque, NM
September 20, 2007

Steve Ellingson
LWA Interim Systems Engineer
Virginia Polytechnic Inst. & State University
ellingson@vt.edu

Goal Instrument

Technical Drivers:

10-88 MHz tuning range

Baselines up to 400 km for resolution [8,2]'' @ [20,80] MHz

52 "stations" - mJy-class sensitivity

Each station is an array of dipole-like elements in 100 m diameter aperture for FOV = [8,2]°

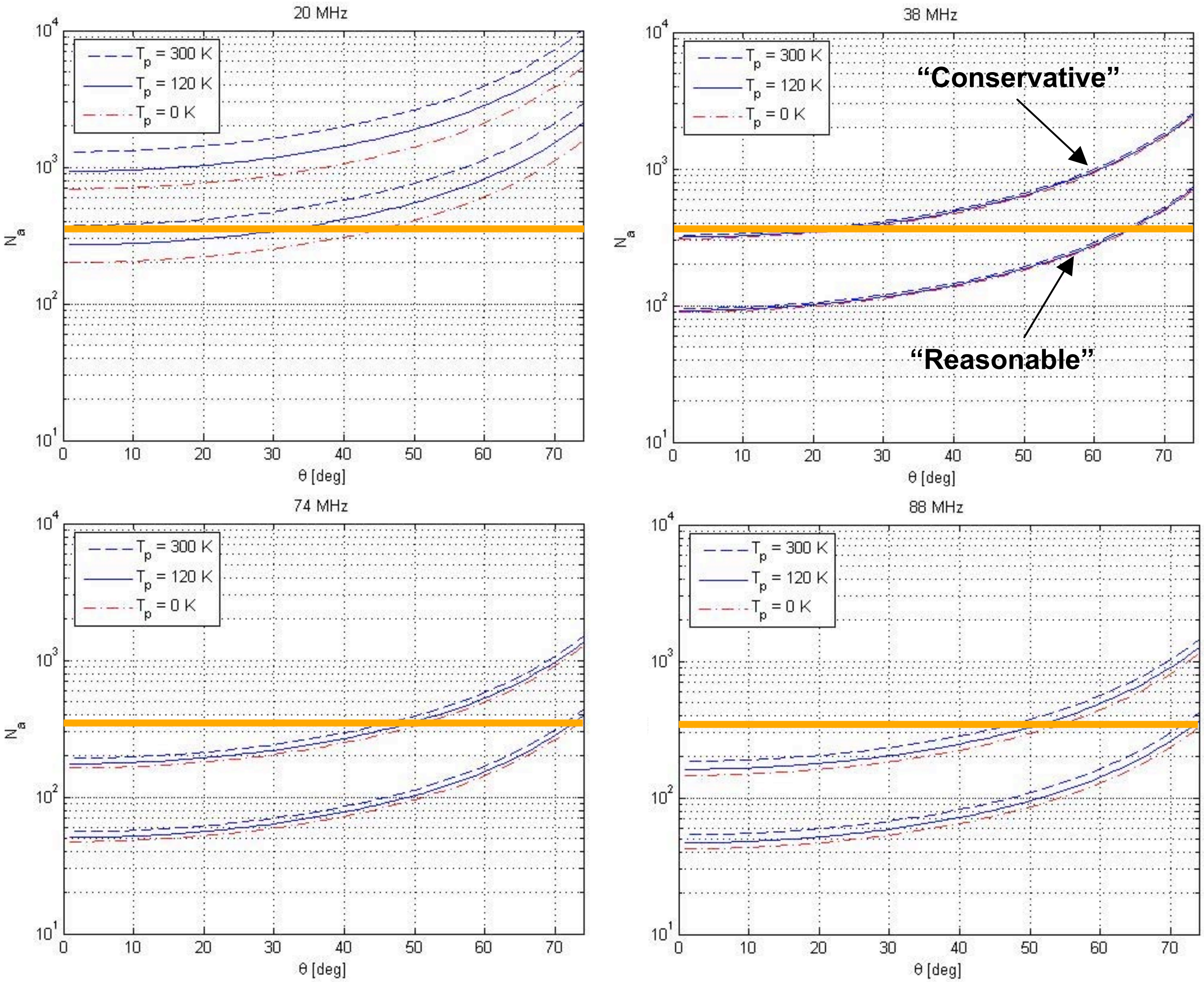
Access to Galactic Center (low gain antennas)

Phased Deployment

	First Station + Outriggers	High-Res Imaging (Self-Cal)	Goal System (Full-Field Cal)	
	LWA-1(+)	**LWIA**	**LWA**	**Remarks**
Freq Range	[10,88] MHz	→	→	
No. of Stations	1 (+2 small)	9* - 16	52	
Max Baseline	a few km	200 km	400 km	min: 100 m (core)
Image Resolution	(TBD)	[15,4]"	[8,2]"	
T_{sys}	G.N.D.*	→	→	9000 K @ 38 MHz
Sensitivity/beam	[40, 25] mJy	[3, 2] mJy	[0.8, 0.5] mJy	2 pol, 1 h, 8 MHz
sky coverage	$\theta < 74^{o}$	→	→	includes GC
FOV size	$[8,2]^{o}$	→	→	zenith pointing
Simult. beams	3	→	→	ortho. circ. pols.
Time resolution	1 ms (13 ns)	→	→	(raw sample mode)
Freq resolution	100 Hz	→	→	
Aggregate data rate	576 Mb/s	9.3 Gb/s	30 Gb/s	sum of stations; rough estimates

- LWIA-9 is sparse; LWIA-16 includes partial core
- G.N.D. = Galactic noise-dominated by at least 6 dB, preferably 10 dB
- All values subject to revision as science and technical requirements are currently in flux.

Stands Per Station



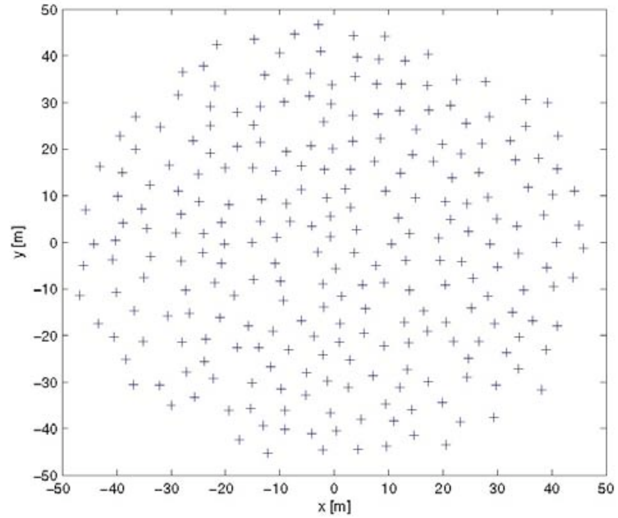
Each station needs to contribute sufficient collecting area to ensure calibratibility.

Estimates of # of dual-pol antenna elements (stands) required <u>per station</u>, extrapolating from VLA 74 MHz experience

***N_a* = 256 (baseline)**
Tough call!

LWA Memo 94

Station Geometry

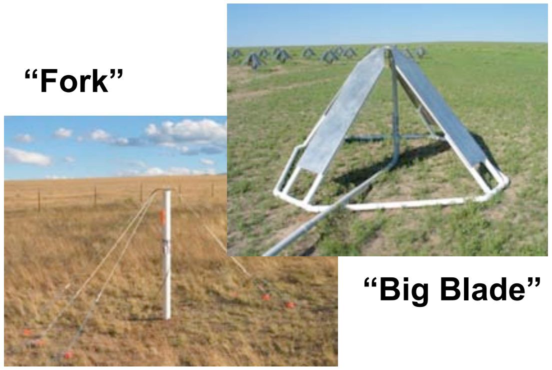


- Every element digitized to allow unconstrained pointing of beams
- Cost ∝ N_a, so prefer to minimize N_a
- Using 256 stands results in spacings 3 x Nyquist at 80 MHz
- Therefore, array has to be pseudorandom to mitigate against aliasing
- Have to depend on elements & front end noise temp. for broadbanding
- Some concern about pointing-direction dependent mutual coupling effects arising from irregular spacing

Antennas & Front Ends

Antenna Candidates

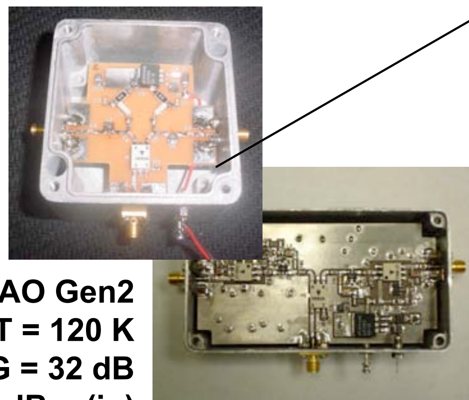
"Fork"



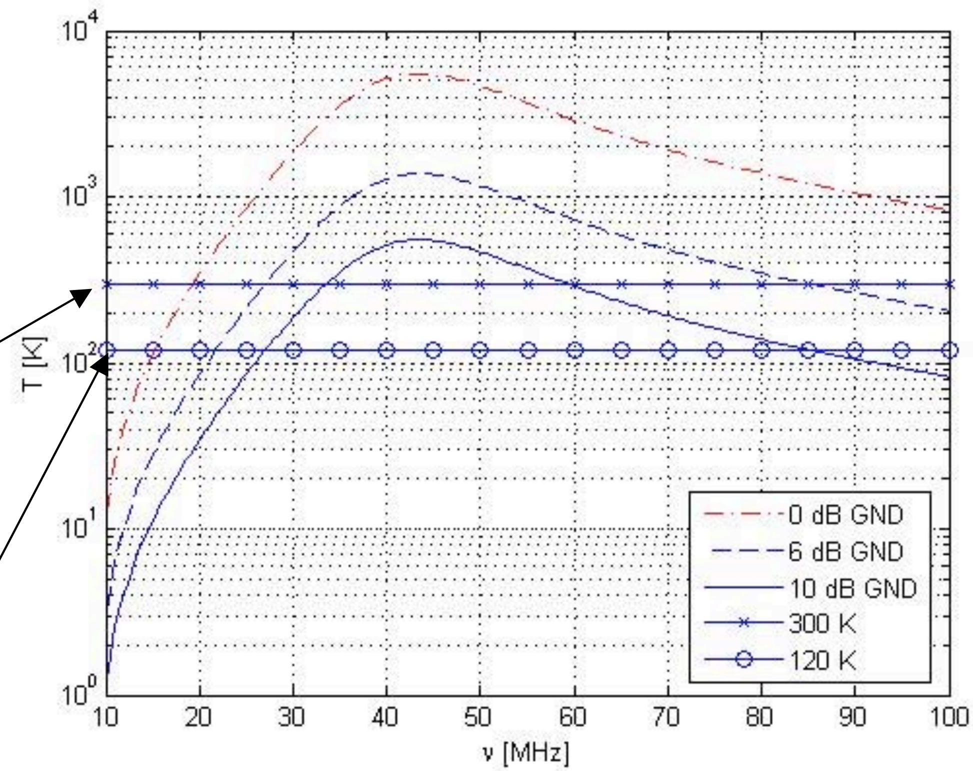
"Big Blade"

Front End Candidates

NRL Gen1
T = 250 K
G = 24 dB
P_{1dB} = -5 dBm (in)

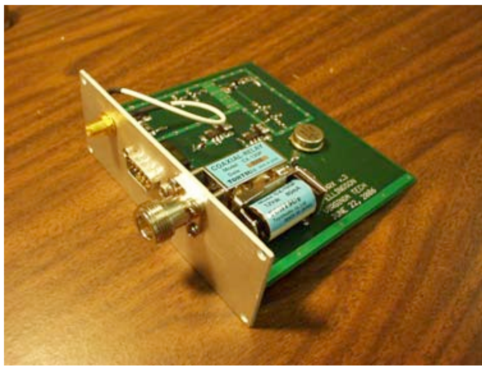


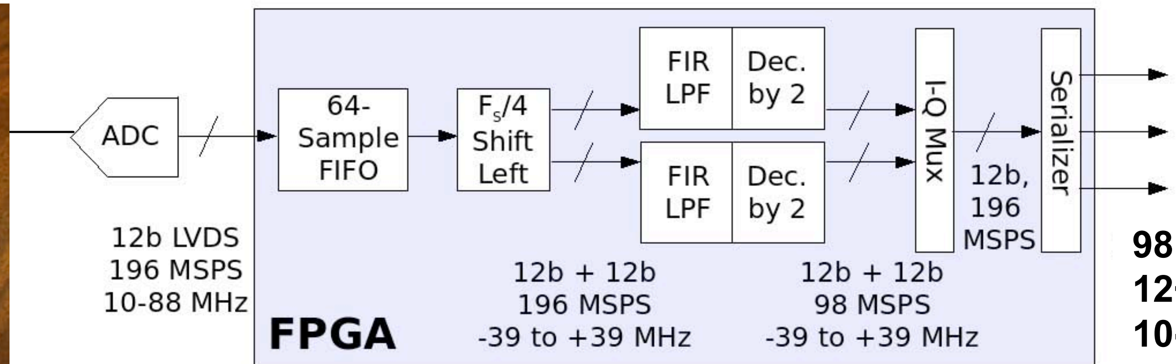
NRL/NRAO Gen2
T = 120 K
G = 32 dB
P_{1dB} = -14 dBm (in)



- Primary challenge is to maintain Galactic noise-limited sensitivity over frequency and zenith angle – proven, but left with optimization problem
- Relevant theory: LWA Memo 22. Progress reported in subsequent memos.

Receiver / Digitizer





98 MSPS
12+12 bit
10-88 MHz
(78 MHz BW)

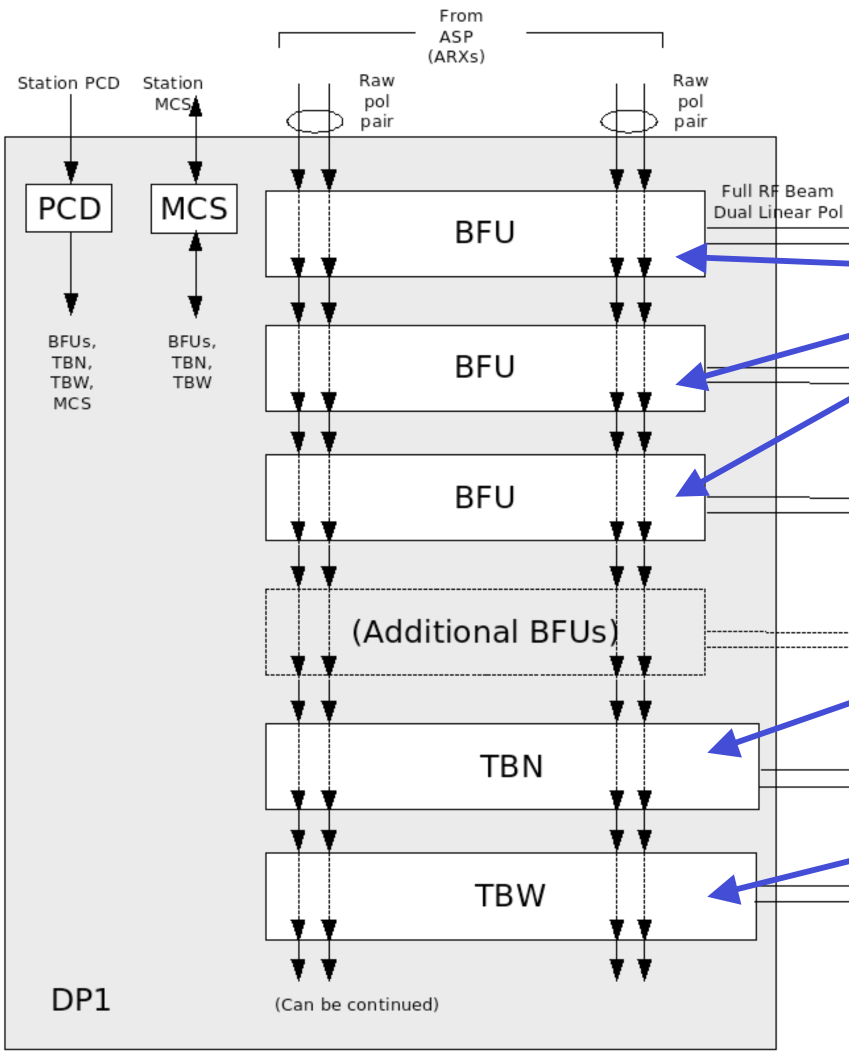
Analog Receiver (ARX)
29-47 MHz ETA ARX
(Memo 46)
20-80 MHz Mod.
(Memos 82,89)

196 MSPS
10-12 bit
(Memos 100,98)

10-88 MHz BW ADC Postprocessor
Fits in $50 FPGA
(Memo 101)

- Above repeated 512 times (!)
- Efforts underway to upgrade ETA ARX to LWA specifications, Evaluate/select ADC, develop interface specs

Station Electronics – DP1



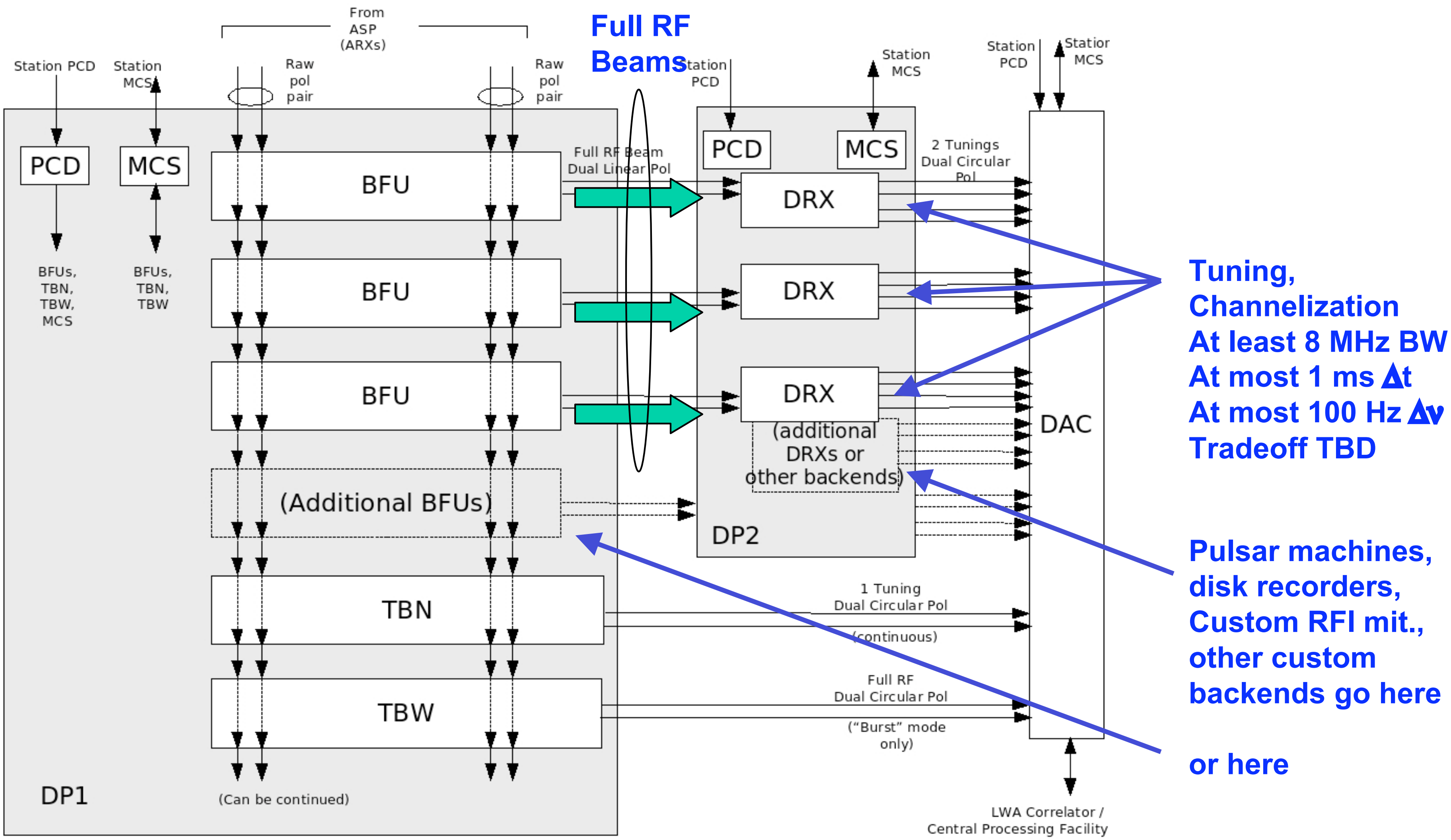
Full-RF Interpolated Delay & Sum Beamformers

"Transient Buffer-Narrowband" (continuous)

"Transient Buffer-Wideband" (Full-RF, Burst Mode; 13 ns Δt)

(Station Architecture Document, ver. 0.5)

Station Electronics – DP2 / DAC



(Station Architecture Document, ver. 0.5)

Open Interfaces

- Simple, openly-defined interfaces between subsystems
  - DP1 daisy chain (LVDS x 256 stands)
  - DP1-DP2 interconnect (LVDS x 1 per beam)
  - DP2 daisy chain (LVDS x 1 per beam)

- Seeking to encourage independent development and possible outsourcing of
  - Custom backends
  - Alternatives/upgrades to existing BFU, DRX, TBN, TBW, etc.

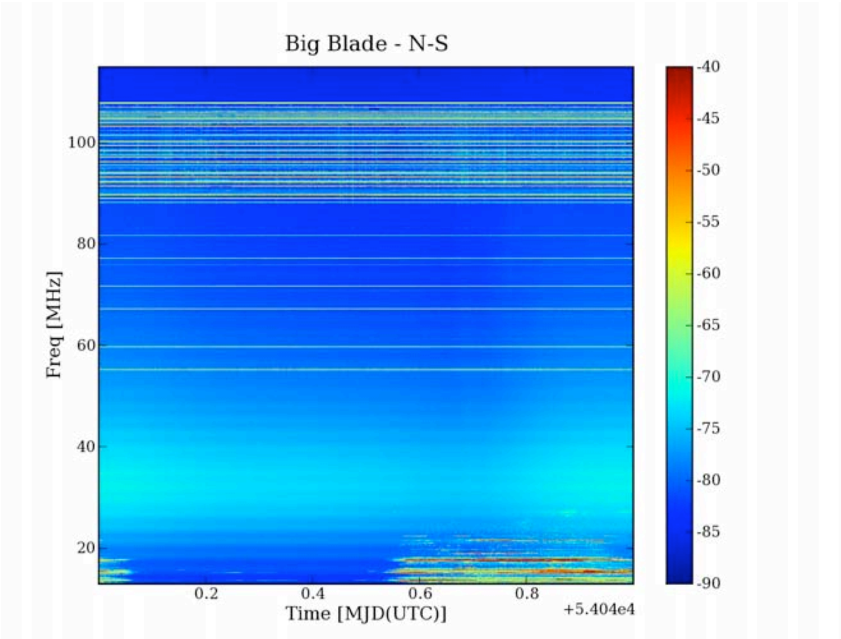
Towards LWIA

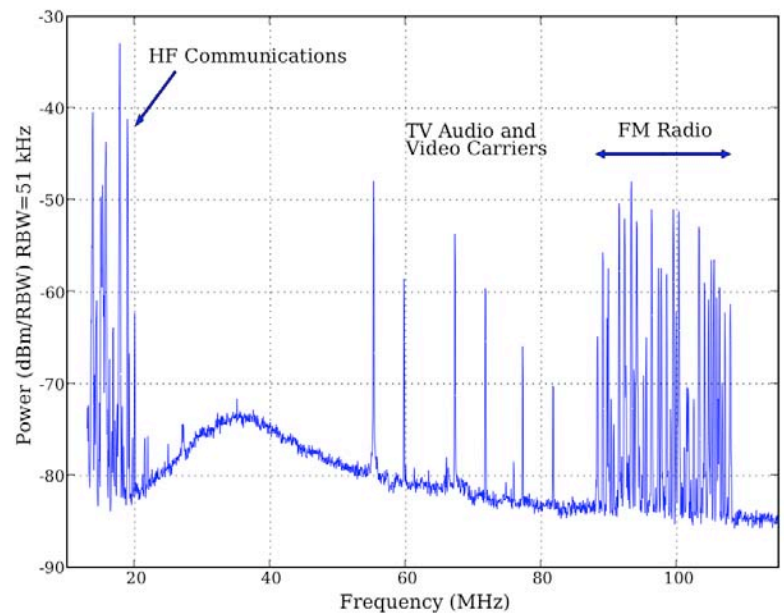
- Technical issues with multiple stations over long baselines
  - Correlator
  - Ionosphere
  - Distributed control and timing
  - Datacom (stations to correlator)

- The datacom problem can be bypassed temporarily using a sneakernet / software correlator approach. (This will not be satisfactory for very long, though.)

- Long baselines offer diversity against RFI

Radio Frequency Interference (RFI)





RFI is ALWAYS in the way.

Easier to deal with if:
- **Receivers stay linear,**
- **$\Delta t < 1$ ms,**
- **$\Delta \nu < 1$ kHz.**

T-F blanking + other techniques

Concerns:

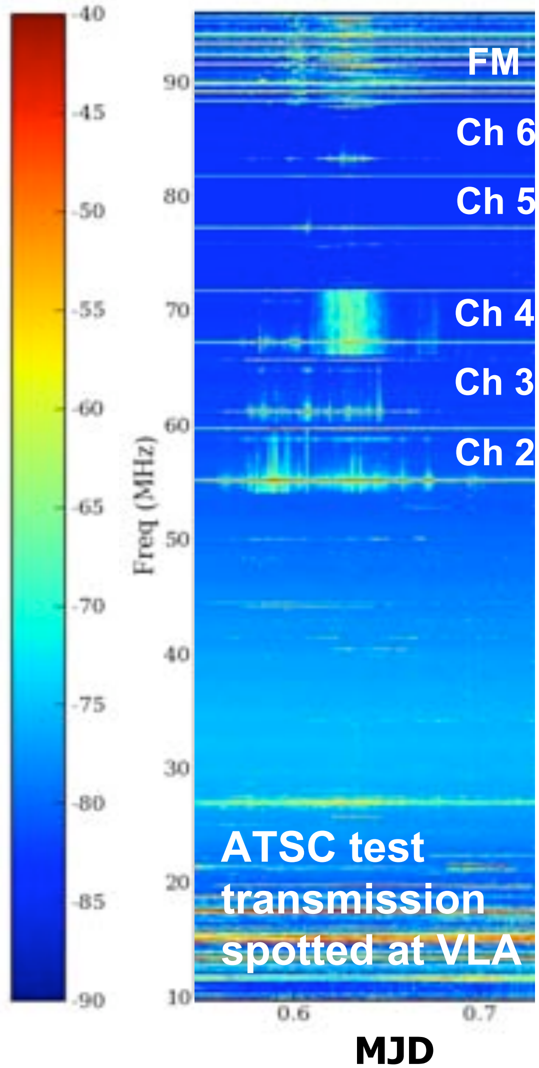
- **ATSC (digital TV)**
- **BPL – no problems observed (yet)**
- **Self-RFI**

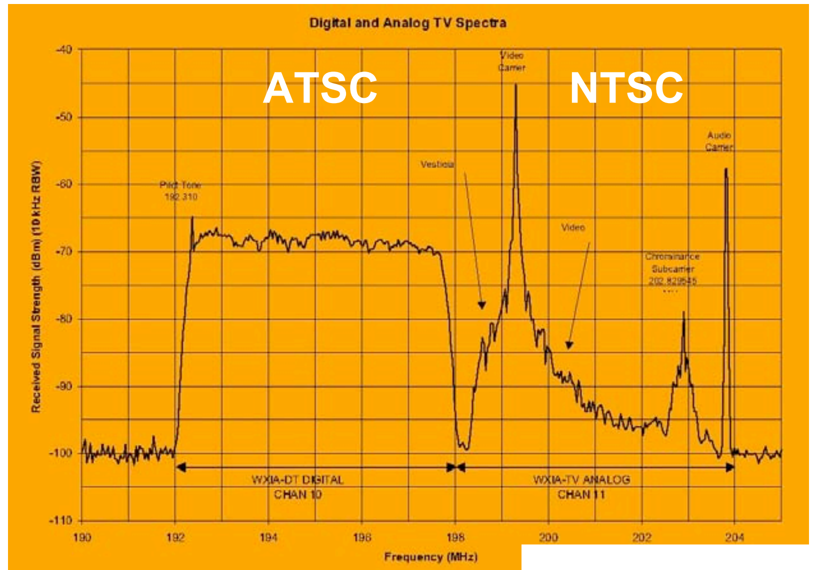
Now continuously monitoring: http://lwa.nrl.navy.mil/rduffin/

Real-Time RFI Mitigation

- High dynamic range front end & receivers
- ARX: Reconfigurable bandpass and gain control
- ADC post-processor: Asynchronous pulse blanking (APB)
- BFUs capable of space-time nulling, static or adaptive (may be effective against ATSC)
- DRX (or post-DRX): Time-frequency blanking, static or adaptive
- Custom canceling devices

ATSC

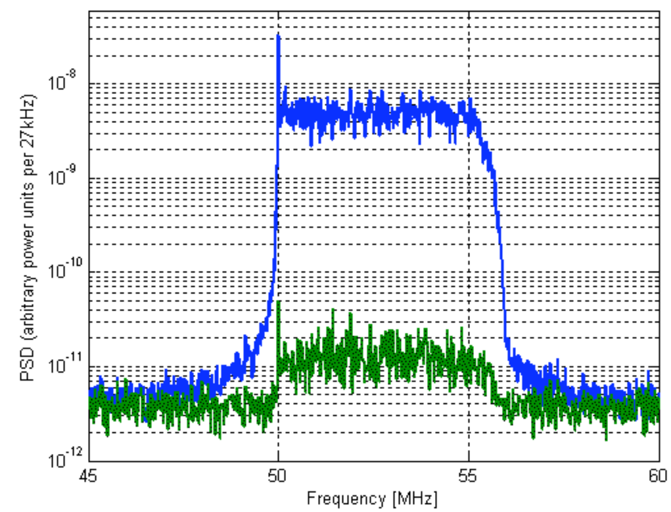




From Clegg briefing to CORF, 2006 Fall

Could loose portions of 54-72 MHz & 76-88 MHz at some sites (74 MHz is protected)

Experimental ATSC canceler:



Other RFI Mitigation Measures

- Station-to-station anti-coincidence (particularly important for transient science)
- Detection improvement via "reference signal relay" – esp. for canceling
- Good old-fashioned hand editing of visibilities; perhaps automated to some degree

Top Concerns Overall

- Sky coverage; especially toward Galactic center
- Mutual coupling-induced, pointing-direction-dependent effects
  - Difficult-to-predict variations in dipole-level calibration
  - Complicates polarization calibration in beamforming
- RFI; esp. ATSC, BPL, and self-inflicted
- Computing; esp. data reduction and archiving
- Long haul (stations to correlator) data communications
- Inadequate engineering staff, especially for PDR to CDR activities.

Concluding Remarks

- Reasonable technical risk in this design concept, which appears to be consistent with (perhaps even satisfies) science requirements.
- Much of the risk is associated with uncertainties such as RFI and mutual coupling which are difficult to assess before LWA1+ IOC
- For more information:
  - Station Architecture Document, currently Ver. 0.5 (email ellingson@vt.edu)
  - Memo Series (http://www.ece.vt.edu/swe/lwa/)
- Parts of the effort leading up to SRR are moving fast; keep an eye out for new memos and versions of system documents.

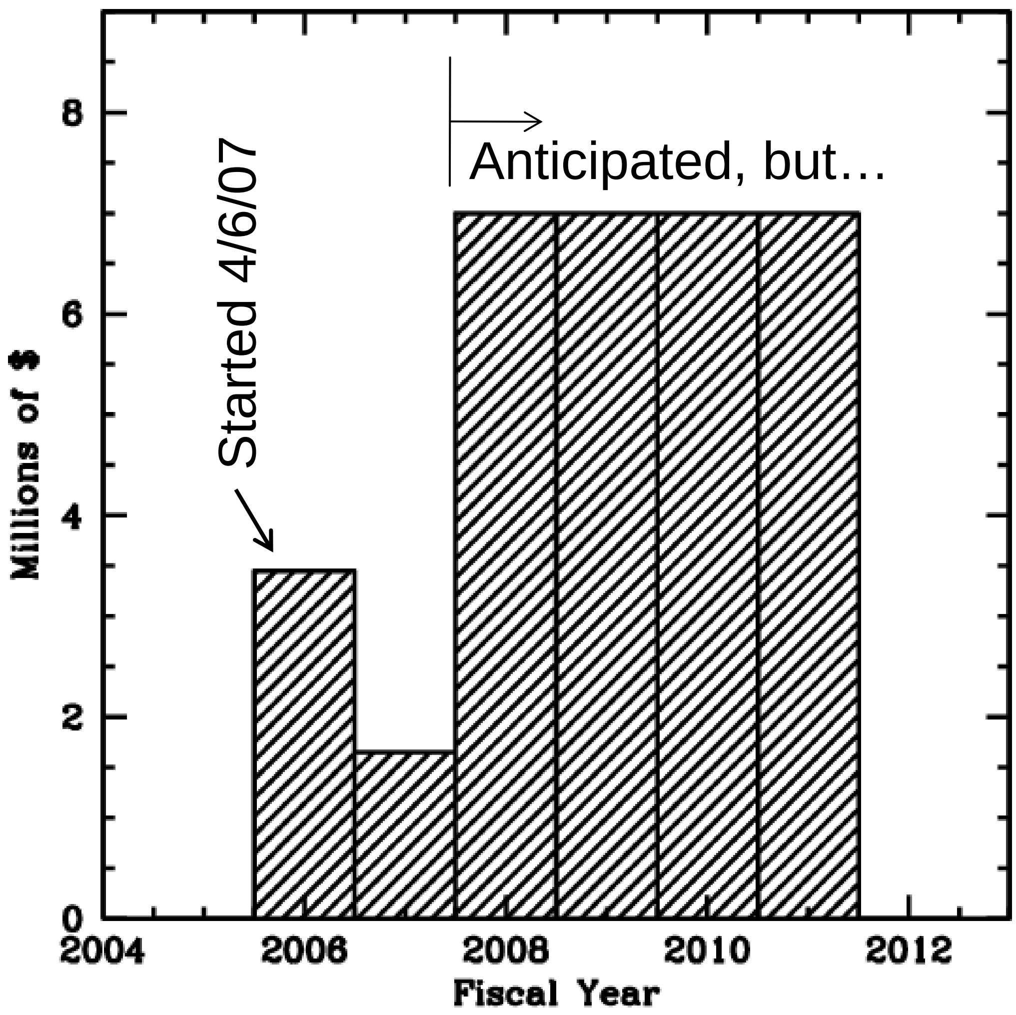
Thanks!

LWA Development Plan

Planning Difficulties

- Coordination across multiple institutions
  - Trying to adapt pre-existing capabilities to specific subsets of the technical problem.
    - E.g., NRL work on active antennas and instrumental calibration is drawn from internal development done for ONR as part of HF/VHF Adaptive Optics ARI.
  - Trying to jump-start technical work without (or in advance of) major growth in engineering staff on site.
- Iterative development of technical concept and program plan
  - Consequence of staggered funding among activities
- Uncertainty of overall flow-rate of funds

Projected Funding



Total = $33 M

Phased Development Plan

Date	Phase	Milestone Description	Acronym
To 2006	0	Existing 74 MHz VLA	VLA74
2006 Q4	Ia	NRL/ARL Long Wavelength Demonstration Array	LWDA
2007 Q4	Ia	System Requirements Review	SRR
2008 Q1	Ia	Preliminary Design Review for First LWA Station	LWA1+ PDR
2008 Q4	Ia	Critical Design Review for First LWA Station	LWA1+ CDR
2009	Ib	Long Wavelength Array Station #1 + Options	LWA1+
2009-2011	IIa	9 Station Long Wavelength Intermediate Array	LWIA-9
2011-2013	IIb	16 Station LWIA with Partial Core	LWIA-16
2013-2015	III	High Resolution LWA	LWA
2010-	IV	LW Operations and Science Center	LWOSC

First Stage: LWA1+

- Mostly: single station proof-of-concept for station-level design
- Advantages:
  - Much of design is likely to be consistent with development path for full LWA.
  - Have reasonable hardware design already drafted.
  - Provides stream of useful science data.
- Concerns:
  - Ability to deploy sufficient engineering FTEs (esp. digital); acquiring additional engineers may extend timeline too long.
  - RFI requirements set by EVLA may require longer development timeline.

Optional Additions: the '+' in LWA1+

- Optional additions could be pursued if permitted (or required) by costs.

- These include:
  - 'Outrigger' stations
  - More frequency beams
  - More capable transient detection system
  - More collecting area in single station

Currently prefer some combination of these two

Why an 'LWA-1+' IOC is a Worthy First Milestone

- It provides an important test of costing and scheduling.
- There are technical issues that can <u>only</u> be resolved with confidence by testing a <u>full-size, operational</u> station.
  - Antenna pattern determination (position dependent!)
  - Mutual coupling & station beam performance generally
  - Station calibration; Station-to-Interferometer calibration
  - Robustness to external and self-RFI; what is <u>really</u> required? ($!)
  - Expose the myriad other issues that we need to worry about, and which are hidden until we attempt to build/operate.
  - Identify the issues that are not so important, on which we are wasting money.
- There <u>is</u> good science to be done with LWA-1+.

LWA1+ is Important Subset of LWA Technical Capability

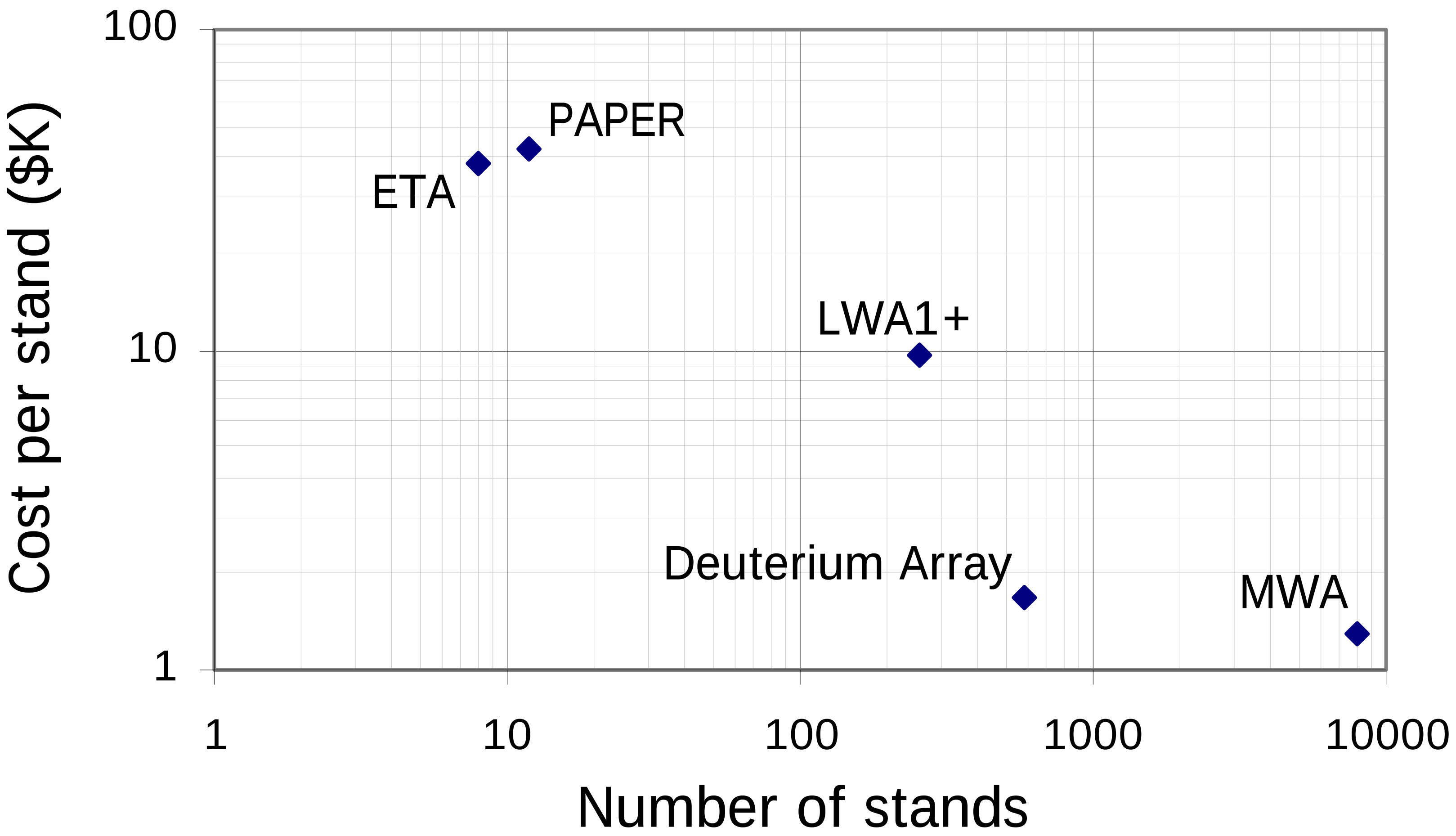
	LWA-1(+)	LWIA	LWA	Remarks
Freq Range	[10,80] MHz	→	→	[10,88] MHz ext.
No. of Stations	1 (+2 small)	16	52	
Max Baseline	(TBD)	200 km	400 km	min: 100 m (core)
Image Resolution	(TBD)	[15,4]"	[8,2]"	
T_{sys}	G.N.D.*	→	→	9000 K @ 38 MHz
Sensitivity/beam	[40, 25] mJy	[3, 2] mJy	[0.8, 0.5] mJy	2 pol, 1 h, 8 MHz
sky coverage	$\theta < 74^o$	→	→	includes GC
FOV size	$[8,2]^o$	→	→	zenith pointing
Simult. beams	3	→	→	ortho. circ. pols.
Time resolution	1 ms (5 ns)	→	→	(raw sample mode)
Freq resolution	100 Hz	→	→	
data rate	576 Mb/s	9.3 Gb/s	30 Gb/s	sum of stations

* G.N.D. = Galactic noise-dominated by at least 6 dB, preferably 10 dB

Benchmarking Cost/Schedule Realism

- PAPER
  - ~$0.3M (total) for 8 (soon to be 16) stands ($38K/stand)
  - Actually somewhat less because correlator much more expensive than beamforming (analogous to ETA's RCC)
  - ~2 years, 1 engineer, collaboration w/ATA, students
- ETA
  - ~$0.5K (total) for 12 stands ($42K/stand)
  - Minus operations, data archive, and RCC: $0.15K (total), $12K/stand
  - 1.5 years, 2 engineers, 2 students
- LWA1+
  - $4.94K for (currently) 256 + 2 x 128 stands ($9.6K/stand)
  - ~2 years, handful of engineers
- Deuterium Array
  - ~$1M (total) for 576 stands ($1.7K/stand)
  - 3 years, handful of engineers
- MWA (Underway with $4M in NSF money)
  - ~$10M (total) for 8000 stands ($1.3K/stand)
  - ~3 years, handful of engineers

Benchmarking Cost/Schedule Realism

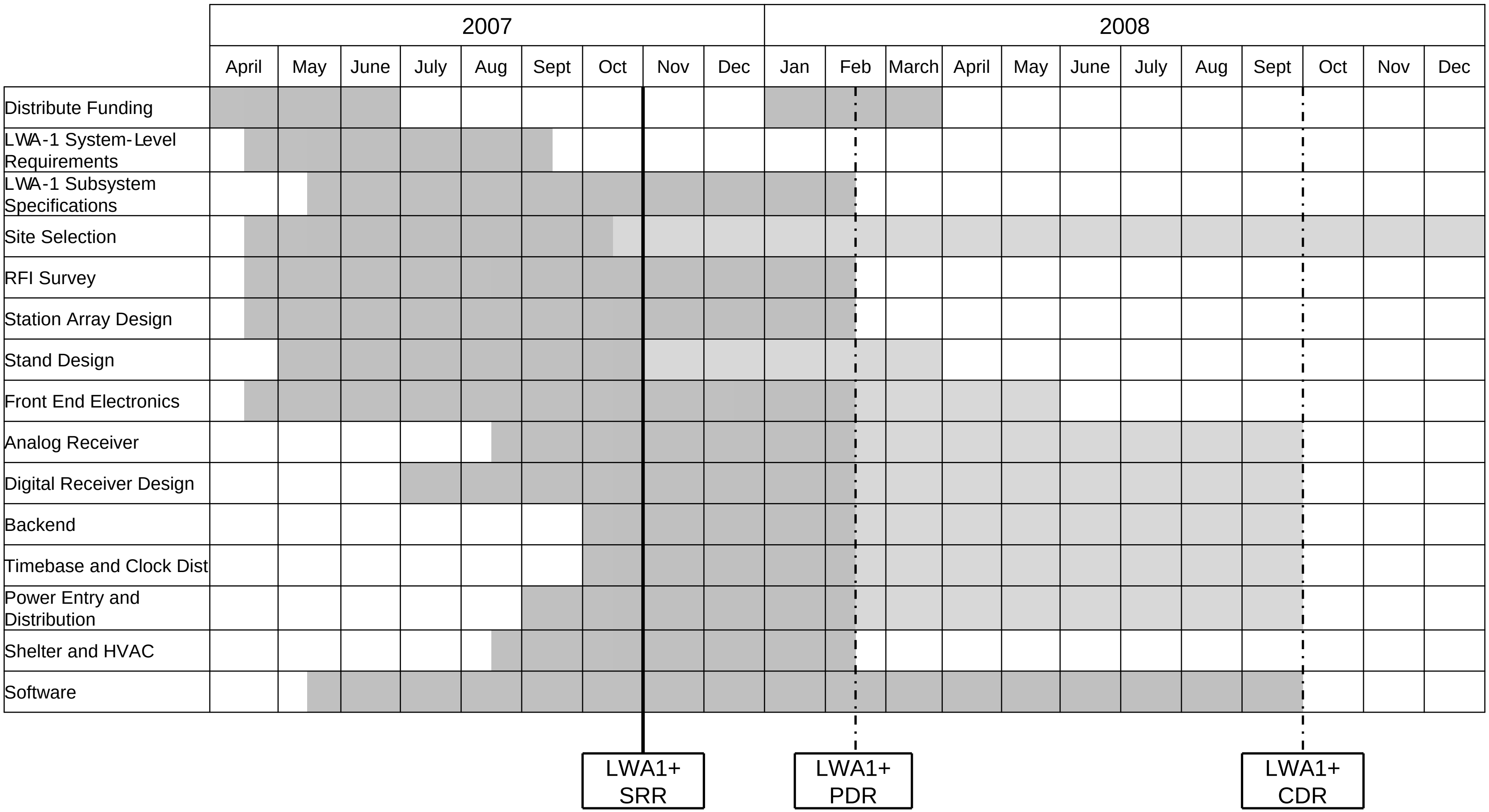


WBS Level One

Long Wavelength Array

- 1.1 Program Management
- 1.2 Array and Site Development
- 1.3 Stand
- 1.4 Shelter
- 1.5 Analog Signal Processor
- 1.6 Digital Signal Processor
- 1.7 Monitor and Control System
- 1.8 Data Aggregation and Communications
- 1.9 Control Building
- 1.10 Data Processing Software
- 1.11 Data Post-Processing and Analysis Software
- 1.12 Operations Plan
- 1.13 Maintenance Plan
- 1.14 Upgrade Plan

Rough Pre-Construction Schedule



Coming Milestones

- System Requirements Review: Oct – Nov 07
  - Offline review by Technical Advisory Committee
- Initial site lease and environmental requests: Oct – Nov 07
- Preliminary Design Review: Feb 08
  - Program review at VT followed by offline TAC review
- Public documents are posted in LWA Memo Series:
  - http://www.ece.vt.edu/swe/lwa/
- Specific top-level documents:
  - [#72, 12/27/06] LWA Program Charter
  - [#56, 9/22/06] LWA Overview
  - [#70, 12/13/06] LWA1+ Scientific Requirements
- SRR documents are being posted as they are vetted.

Technical Advisory Committee

- Don Backer (UC Berkeley/Department of Astronomy)
- Mike Davis (SETI Institute/Allen Telescope Array & Cornell)
- Dick Ferris (Australia Telescope National Facility/CSIRO Electronics Group)
- Peter Napier (NRAO/Expanded VLA Project)
- Jack Welch (UC Berkeley/Allen Telescope Array)

- Two other requests for participation are still out. One is expert in space physics issues.

Fundamental Theorem of Planning

- “The living [plan] is like a cow-path: it is the creation of the cows themselves, who, having created it, follow it or depart from it according to their whims or their needs. From daily use, the path undergoes change. A cow is under no obligation to stay.”
  - E.B. White
- Our underlying goal, then, is to plan better than cows.

Earned Value Management

- As part of the final program plan, we will implement a framework for Earned Value Management (EVM).
- EVM focuses on work accomplished, rather than just money spent, and enables simultaneous tracking of budget and schedule variances.
- The key advantage of using EVM is that you can determine very early in the project whether you are going to have a significant budget variance, and can determine whether rescoping is necessary.
- EVM is easy to learn and easy to implement in a spreadsheet.
- It does require putting significant effort in up front, in order to define the work packages at a reasonable level of granularity (~ 80h).
- Further explanation: LWA Memo #66 (12/25/06)

Backup

LWA Site Acquisition

Greg Taylor (UNM)

September 20, 2007

(LWA: http://lwa.unm.edu)

Virginia Tech

Naval Research Laboratory, Washington, D.C.

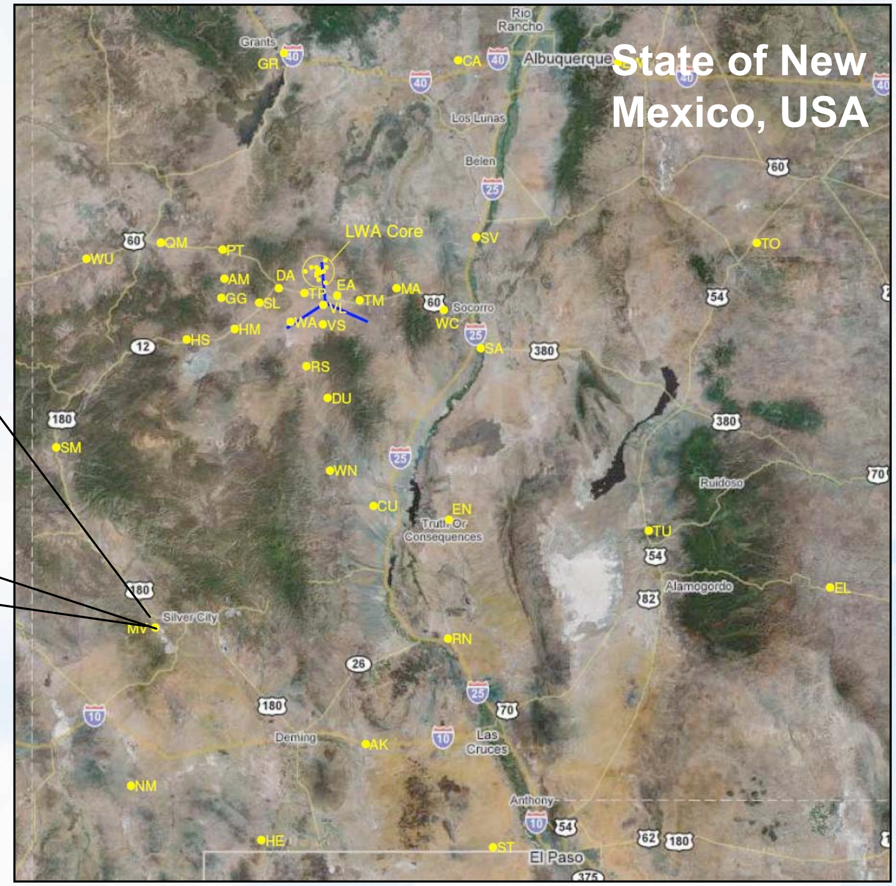
Los Alamos National Laboratory EST. 1943

The University of New Mexico

ARL The University of Texas at Austin

The University of Iowa

The Long Wavelength Array (LWA)



20-80 MHz tuning range (at least)

Baselines up to 400 km for resolution [8,2]'' @ [20,80] MHz

52 "stations" - mJy-class sensitivity

Each station is an array of dipole-like elements in 100 m diameter aperture for FOV = [8,2]°

Stages of Acquisition

Stage 1 - Preliminary Inspection (1 hour)

- Working with planned configuration
- Initial survey for flat land, sparsely covered - owned by State
- Easy access on existing roads
- Access to optical fiber for data com
- Access to commercial power
- Low RFI environment

Stages of Acquisition

Stage 2 - Initial Acceptance (8 hours)

- Short RFI Survey
- Refine configuration studies

Stages of Acquisition

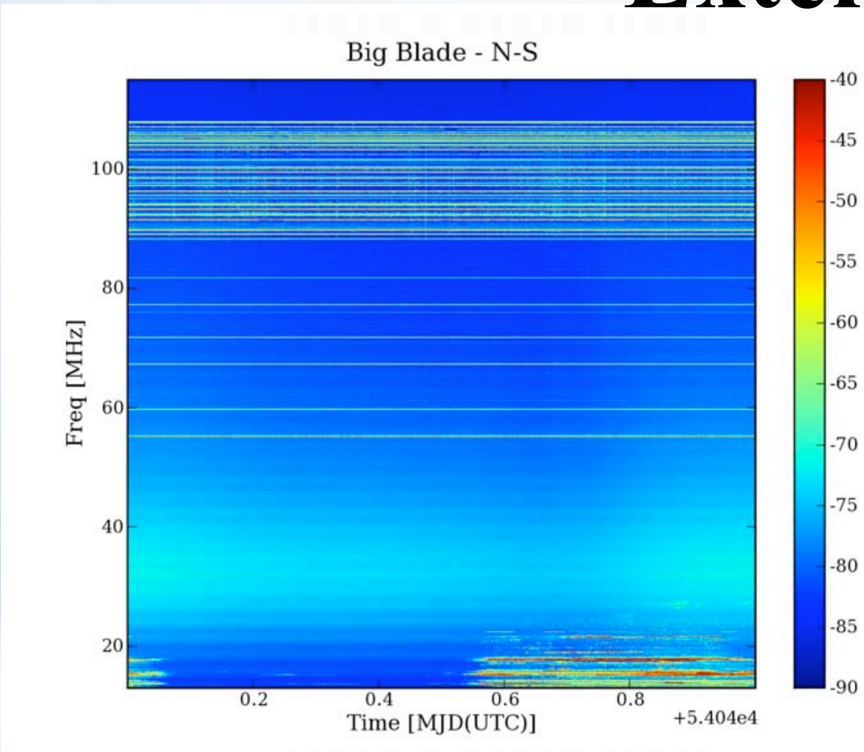
Stage 3 - Site Evaluation (40-60 hours)

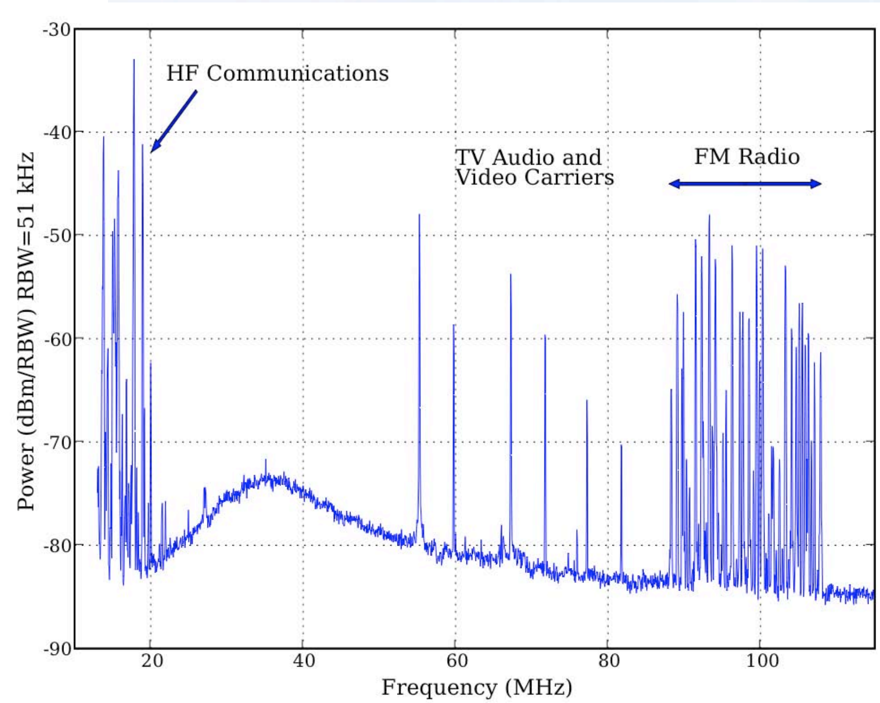
- Discuss LWA with rancher holding primary lease
- More detailed RFI Survey
- Check access to optical fiber for data com
- Check access to commercial power
- Physical surveys
- Archeological inspection
- Biological inspection

Negotiate with State and Federal Agencies

Big Blade and LWDA shelter on July 21, 2006

External RFI





RFI is ALWAYS in the way.

Easy to deal with as long as:

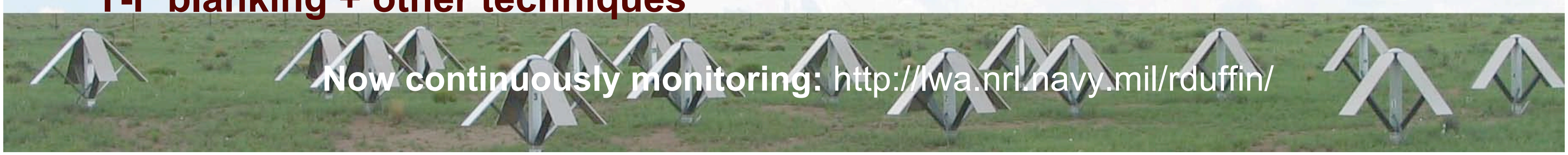
- **Receivers stay linear,**
- **$\Delta t < 1$ ms,**
- **$\Delta \nu < 1$ kHz.**

T-F blanking + other techniques

Concerns:

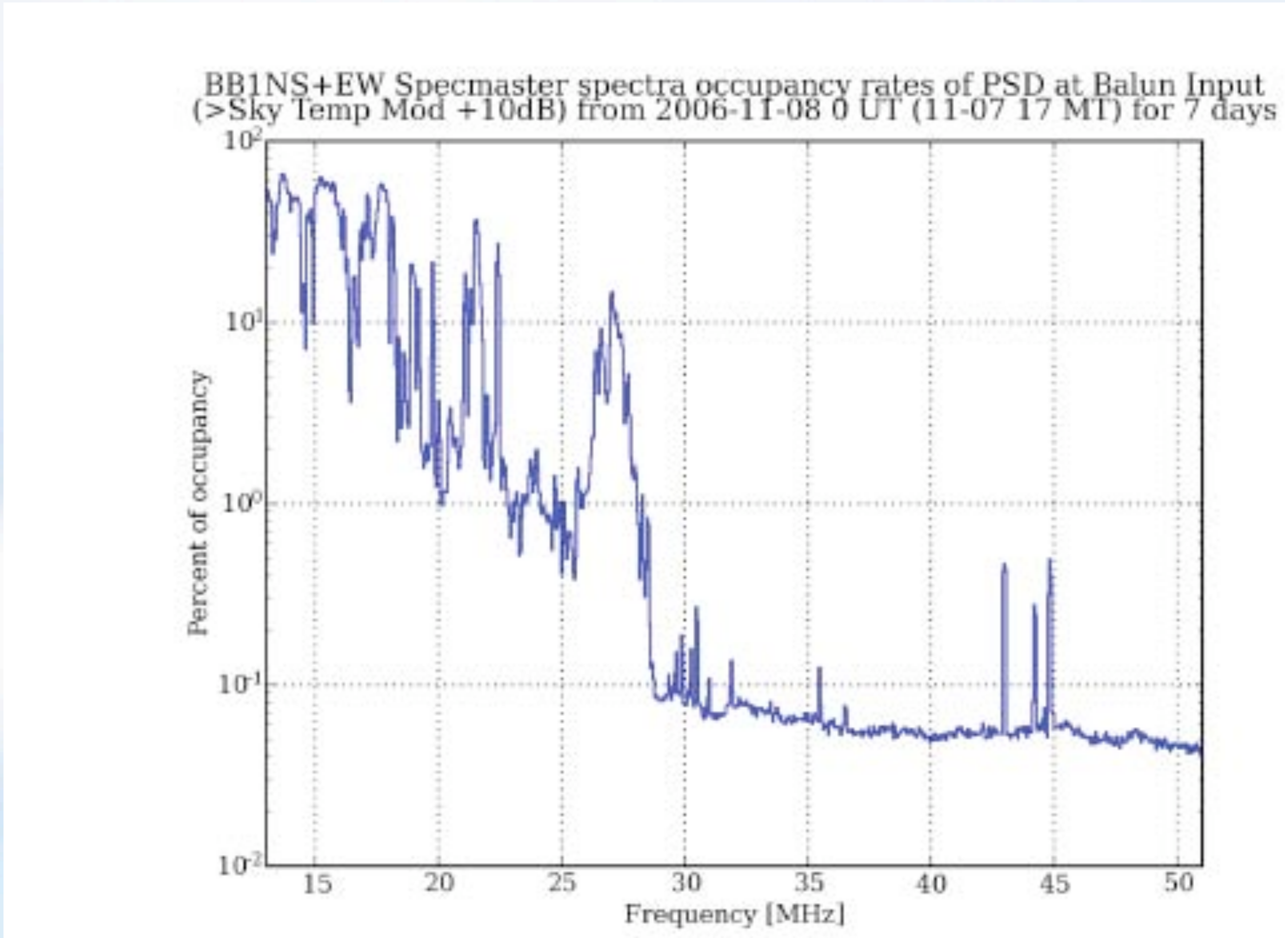
ATSC (digital TV) – could loose portions of 54-72 MHz & 76-88 MHz at some sites (74 MHz is protected)

BPL – no problems observed (yet)



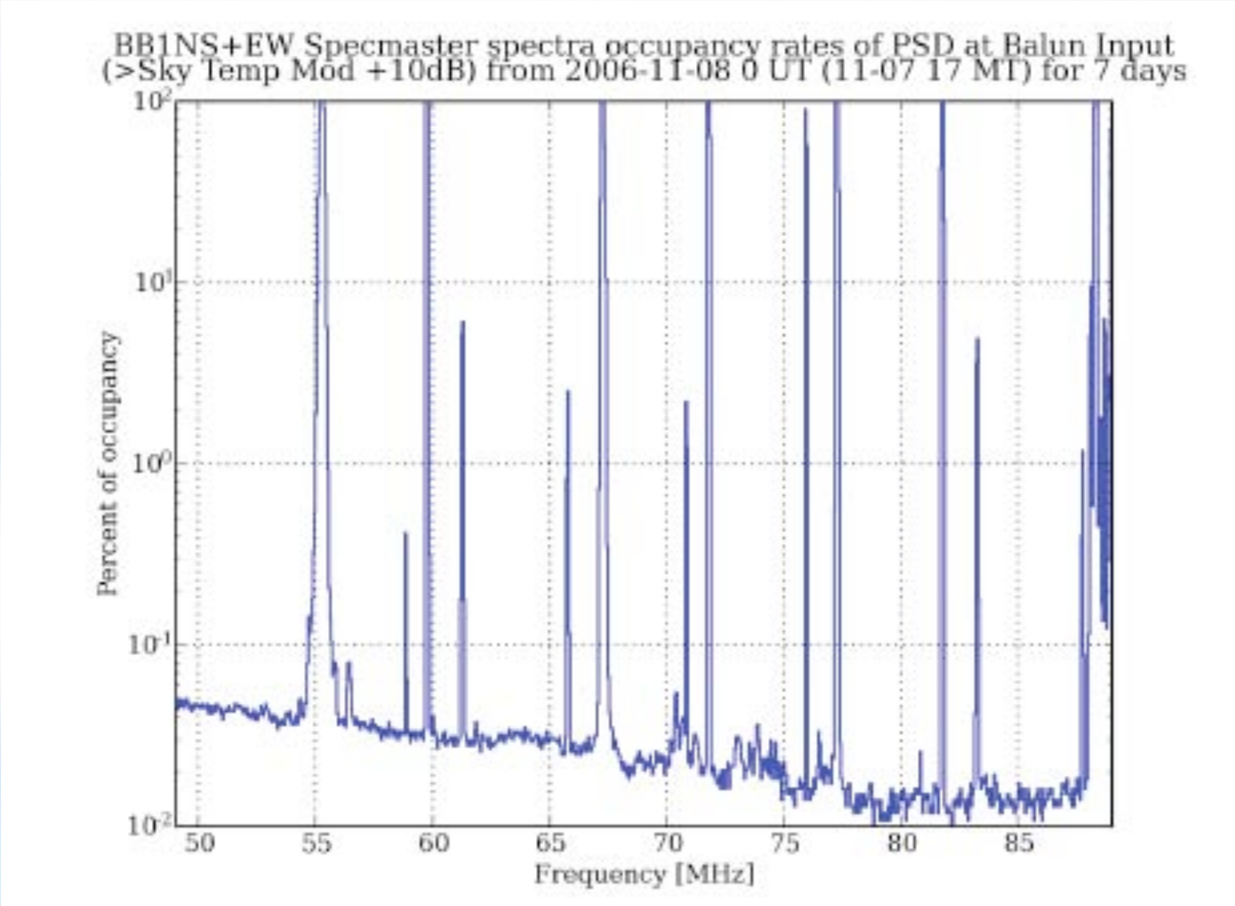
Now continuously monitoring: http://lwa.nrl.navy.mil/rduffin/

Spectrum Occupancy



Duffin & Ray 2007, LWA memo #84

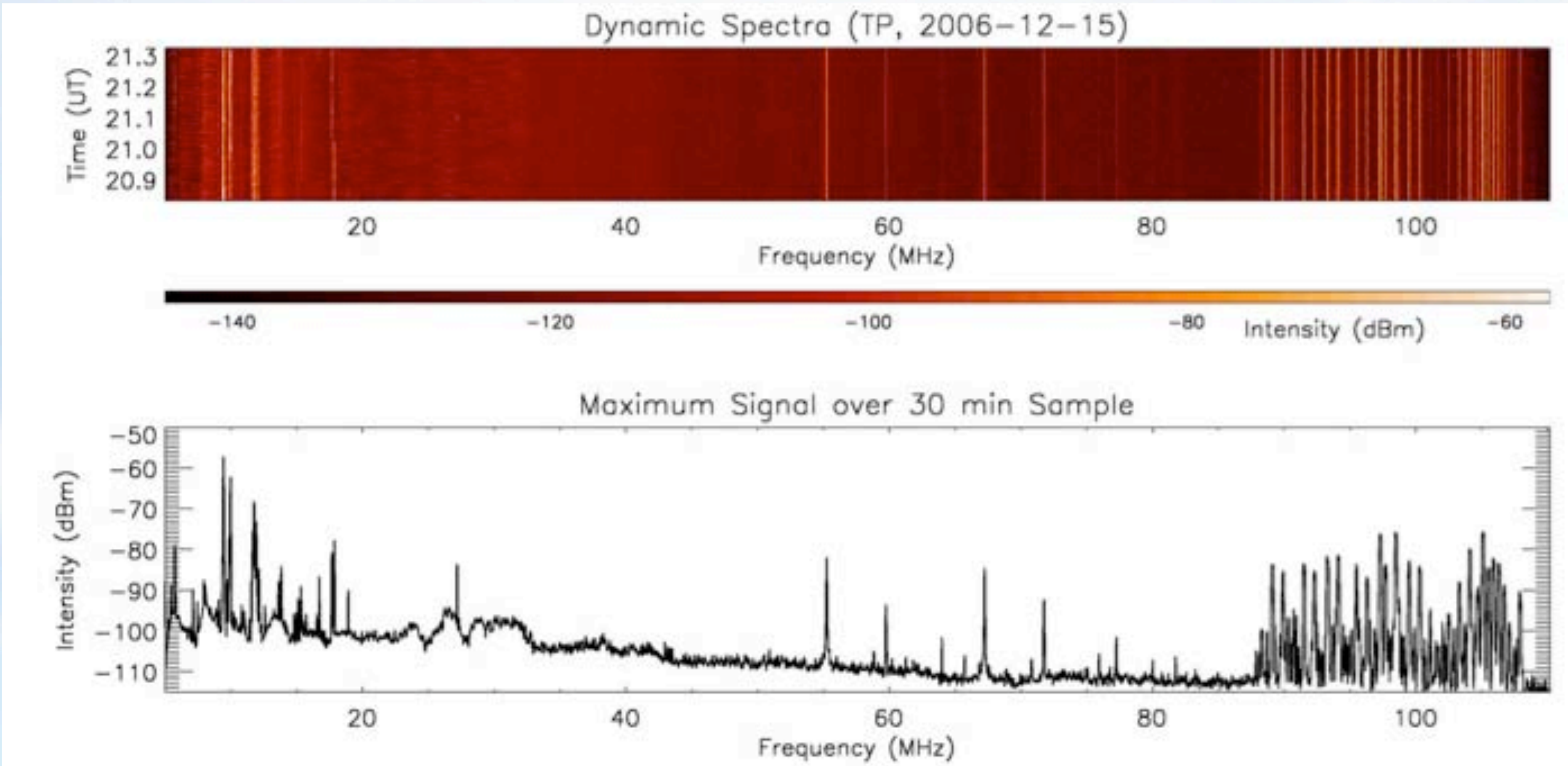
Spectrum Occupancy



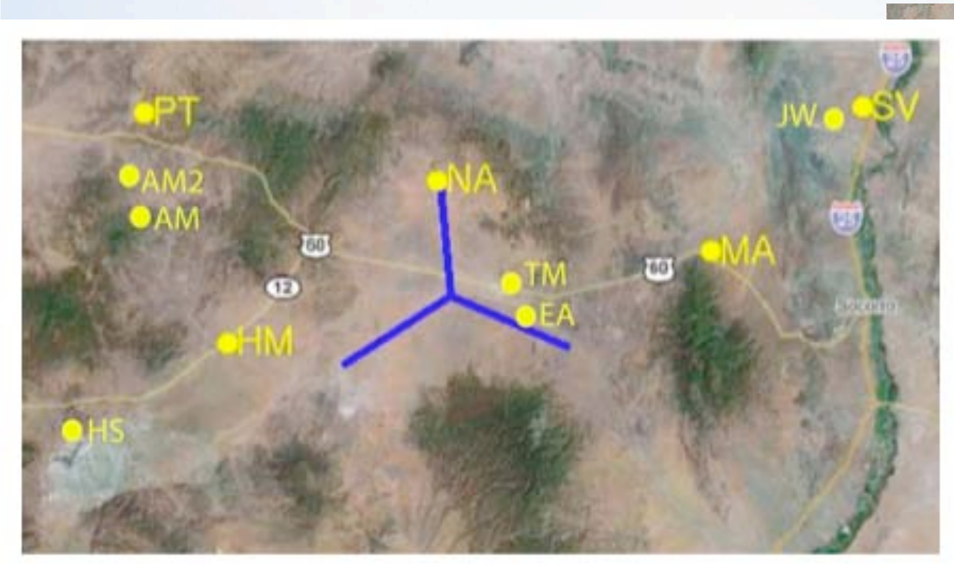
Duffin & Ray 2007, LWA memo #84

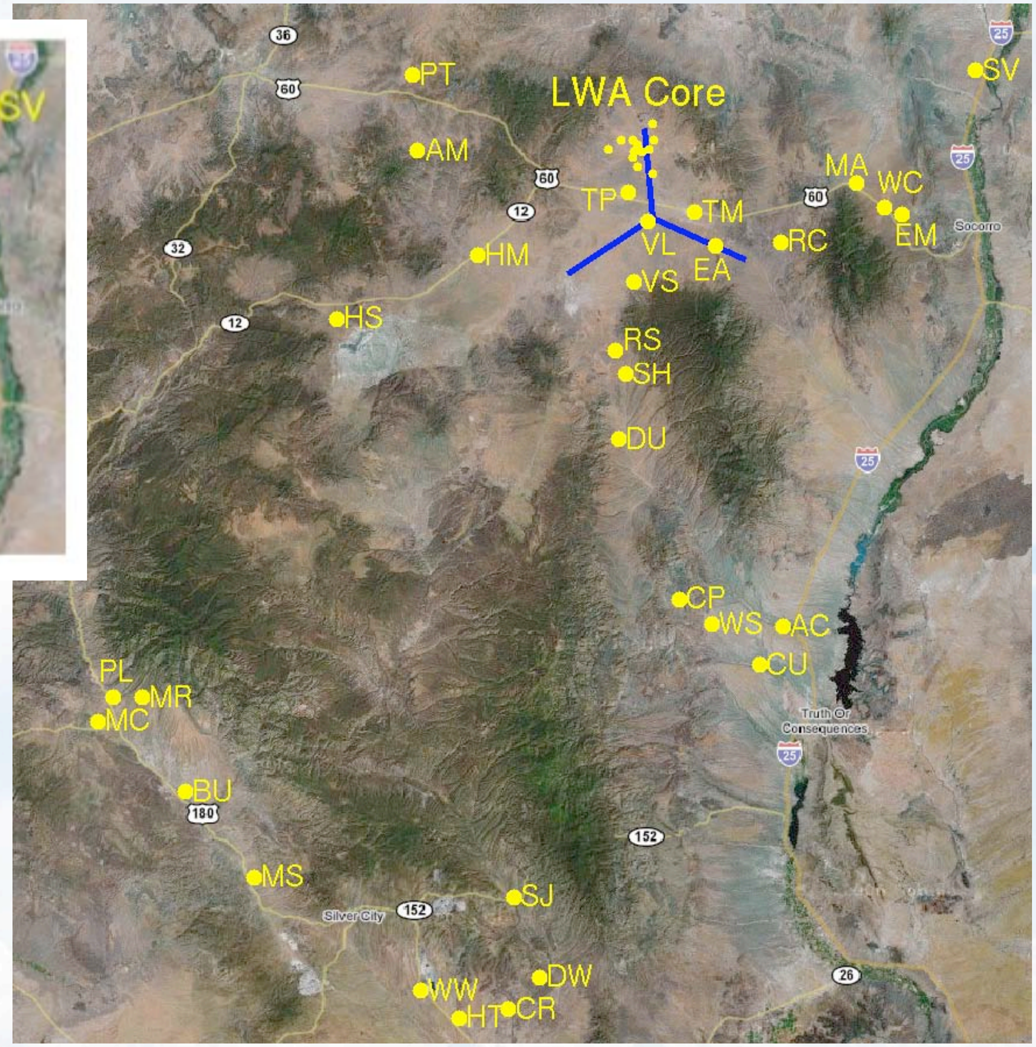
Site Testing at Twin Peaks, December 2006

Results of Radio Interference testing at Twin Peaks site

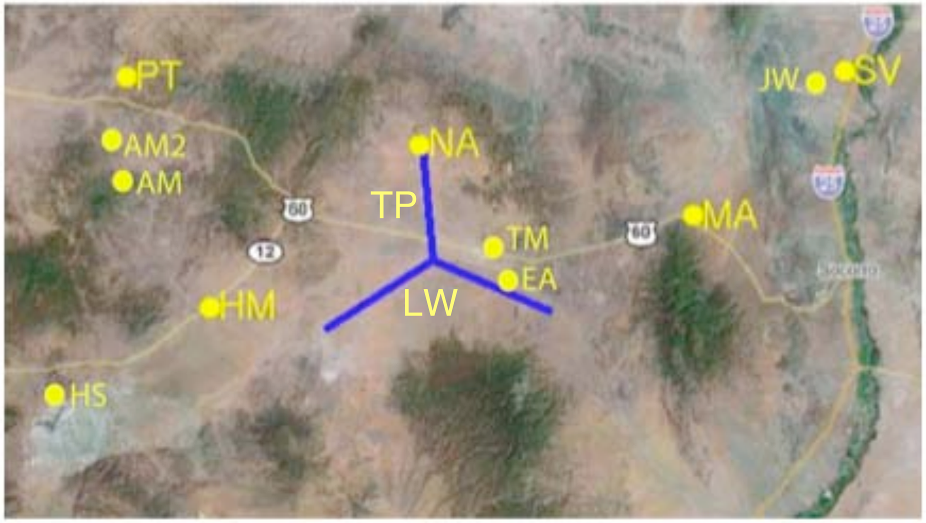


LWIA Site selection





LWA1+ Site selection



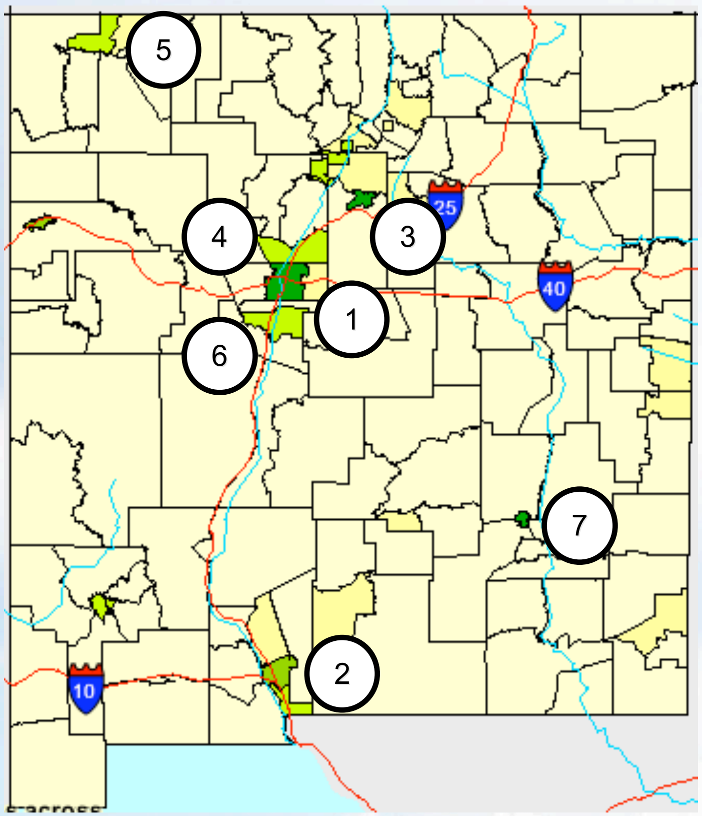
Plan to file a Categorical Exclusion for 4 sites (3 plus one "spare")

Considerations:

- RFI
- Fiber
- Power
- State Land
- Accessibility
- Configuration

Biological and Archeological surveys show that NA, TP, and MA sites are all "clean"

New Mexico Population Density



Most Populous Areas in New Mexico

1	Albuquerque
2	Las Cruces
3	Santa Fe
4	Bernalillo
5	Farmington
6	Los Lunas
7	Roswell

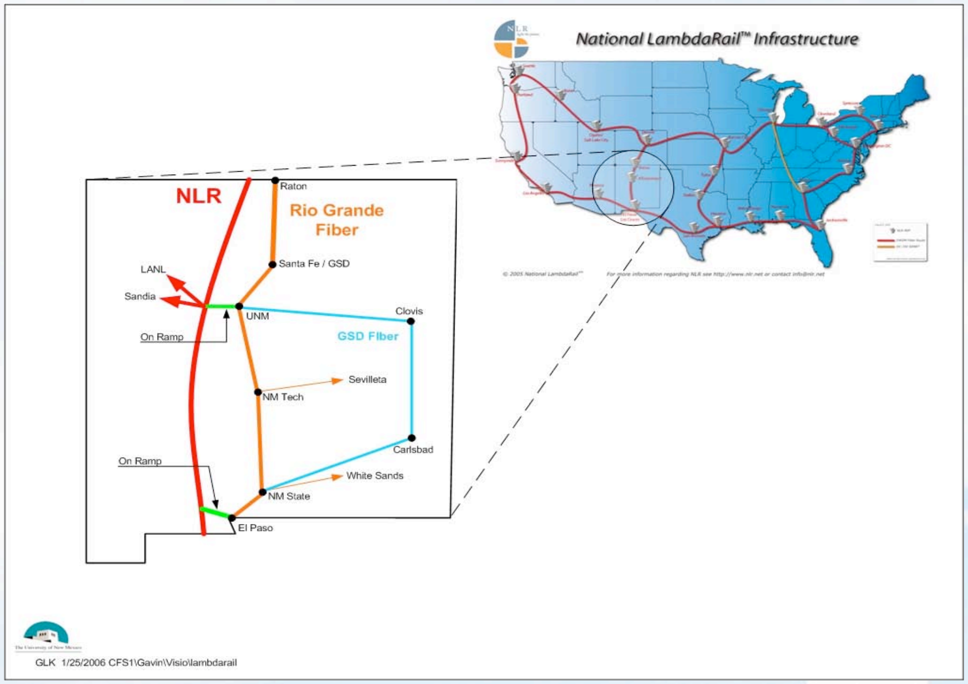
2000 Census
"County Subdivision"
Population Density

Why should the State and Universities work together?

- University networks can support state mandated programs (and vice versa)
  - Tele-health
  - Public safety
  - Distance Education—IDEAL
  - New Mexico Computing Application Center
  - Rural Library access
  - Digital Media
  - Lambda Rail

University Efforts, continued

- State Networking
  - Links to other research universities
  - Los Alamos Lab
  - Branches
  - Economic Development
  - Education and Distance Education
  - NM Computing Application Centers colleges.
  - Santa Fe Institute, NCGR, etc.?

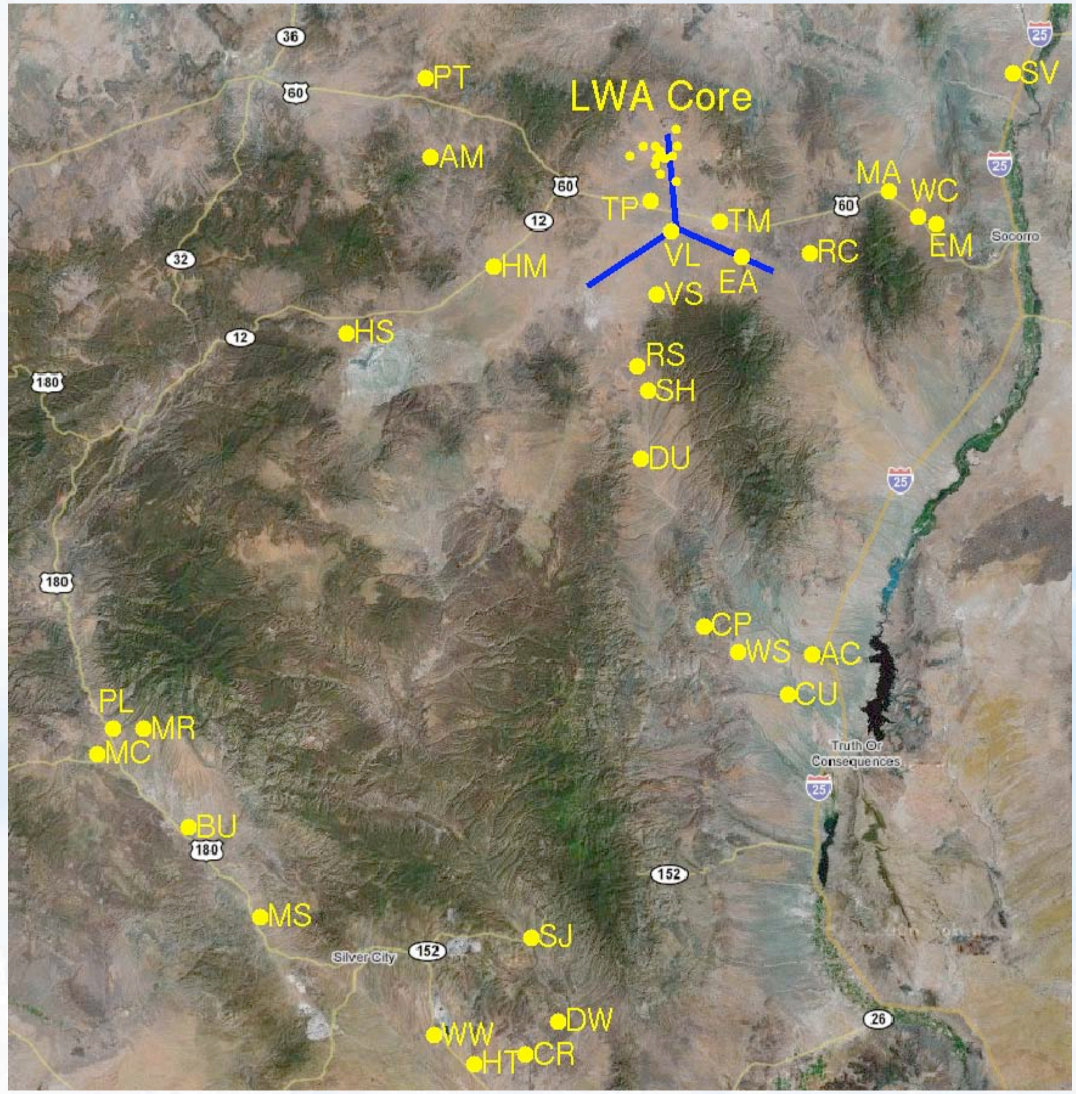


LWIA Site selection - Sites Visited to date

Plan to file a Environmental Assessment for 11+ sites (5 already developed)

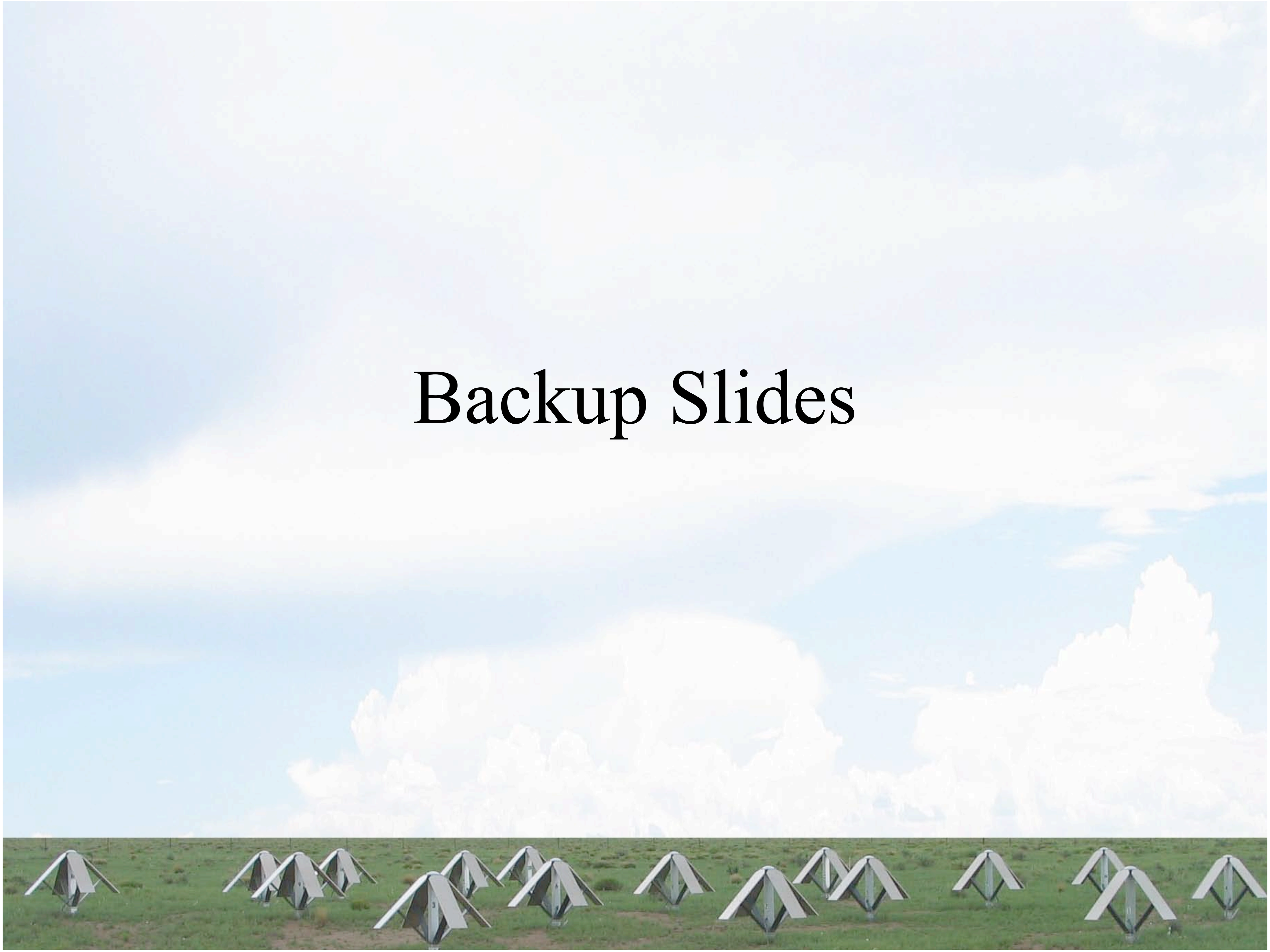
Considerations:

- RFI
- Fiber
- Power
- State Land
- Accessibility
- Configuration

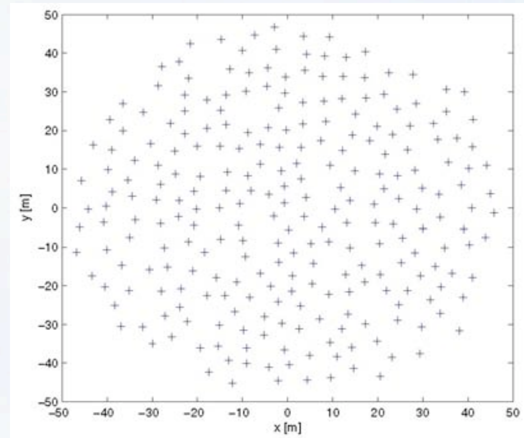


SUMMARY

- Land acquisition on target
- Fiber still very much a concern
- Power still very much a concern


Backup Slides

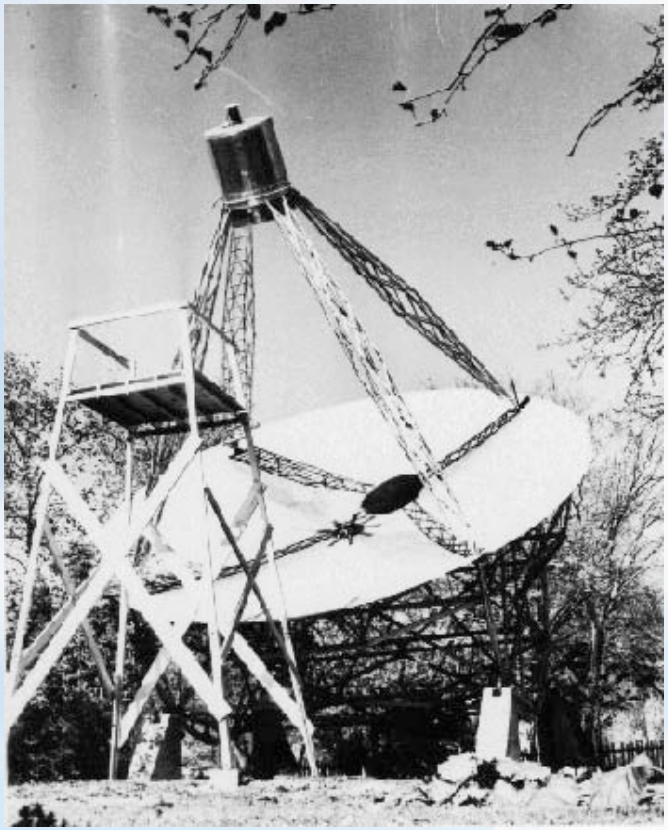
Sparse Pseudorandom Station Geometry

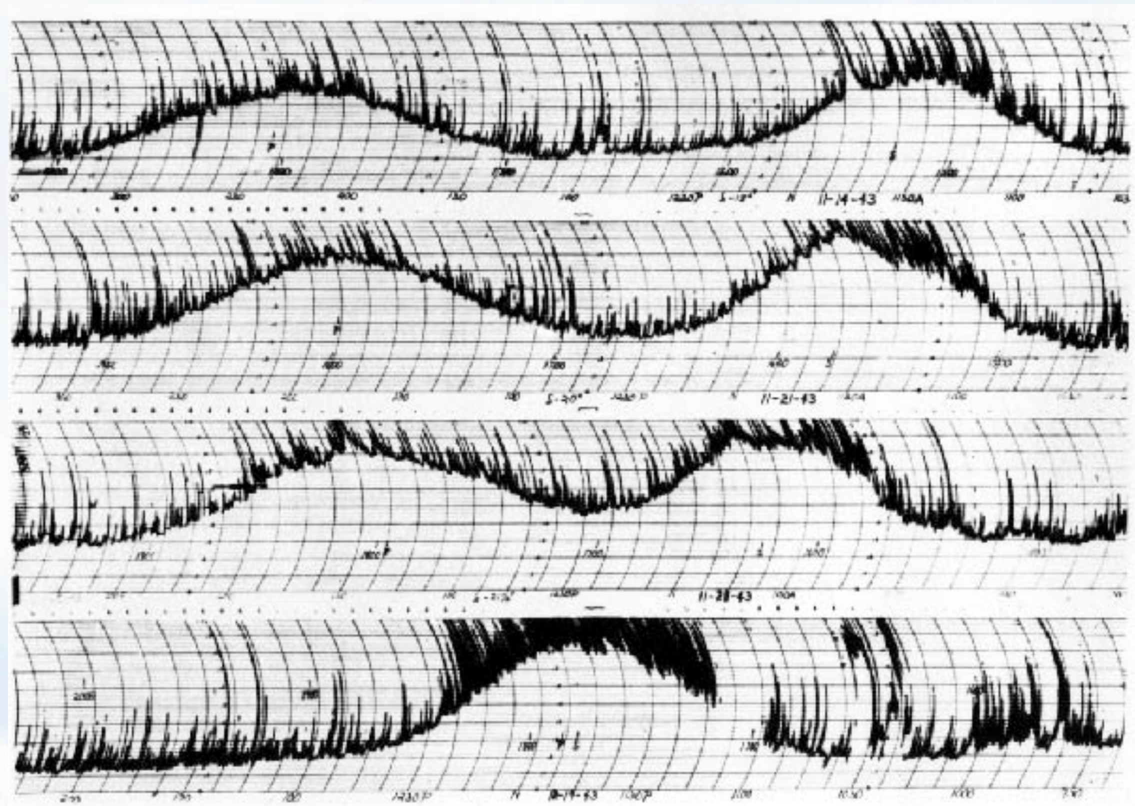


- Every element digitized to allow unconstrained pointing of beams
- Cost ∝ N_a, so prefer to minimize N_a
- Using 256 stands results in spacings 3 x Nyquist at 80 MHz
- Therefore, array has to be pseudorandom to mitigate against aliasing

- Have to depend on elements & front end noise temp. for broadbanding
- Alternative scheme using large numbers of closely-spaced electrically-short elements (broadbanded using mutual coupling) also being considered.

Radio Frequency Interference





Grote Reber’s telescope and Radio Frequency Interference in 1938

Framework for Collaborative Ventures

Greg Taylor (UNM)

September 20, 2007

(LWA: http://lwa.unm.edu)

UNM Involvement

- Project Office (McIver, Rickard, Janes, Lujan, Sanchez)
- Physics and Astronomy
  - Greg Taylor (LWA Sci. Director); Ylva Pihlstrom (RFI Coord); Trish Henning
  - Adjunct Professors John Dickel (Site Eval) and Lanie Dickel (Web)
  - Postdocs - Gianfranco Gentile, Masaya Kuniyoshi
  - Students - Frank Schinzel, Steve Tremblay, Stefanie Moats, Bobby Edmonds
- ECE
  - Christopher Watts (Ionospheric Scientist)
- Civil Engineering
  - Walter Gerstle
  - Students - Eduardo Gonzalez
- Biology (Jerry Dragoo)
- Contract Archeology (Alex Kurota)
- ITS (Cris Landgraf, Louella Phillips, Gary Bauerschmidt)
- High Performance Computing (Tim Thomas)

LWA Involvement

- Current LWA membership:
  - UNM, UT/ARL, NRL, LANL : Southwest Consortium
  - Iowa, Virginia Tech
  - Adding partners to LWA takes ~ 1 year
- Use subcontracts
  - Straightforward financial arrangement
  - requires incorporation within annual proposal
- Use Joint Proposals
  - Outside existing ONR proposals
  - Normal scientific collaborations - already established with VLA (see VLA 74 MHz publications from NRL/UNM/etc)

Correlator

- Hardware Correlator
  - iBOB/BEE2 by Dan Wertheimer (UCB/SETI)
- Software Correlator (DiFX by Deller)
  - Development ongoing at NRAO/Swinburn
  - USNO/NRL/NRAO Meeting planned Sept. 25 in DC
  - NRAO/UNM Meeting planned Sept 28 in Socorro

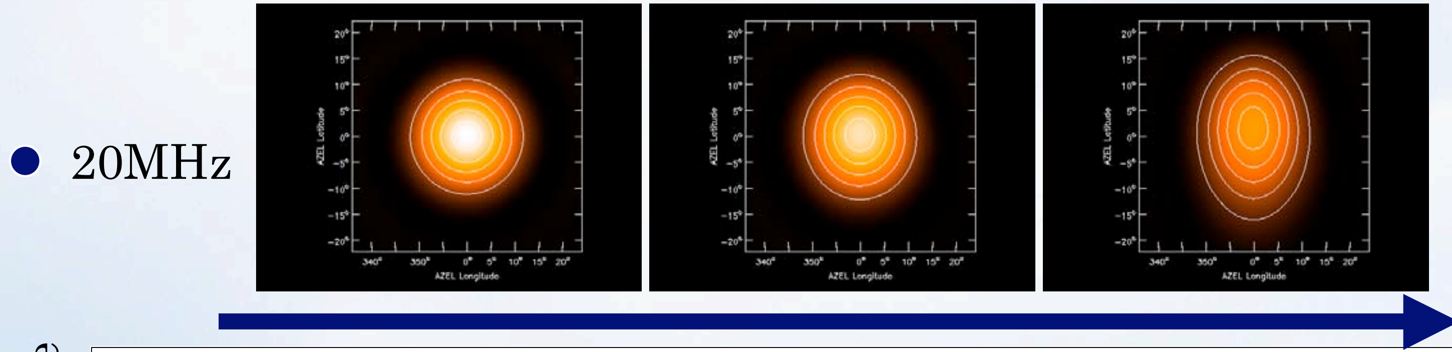
Data Communications

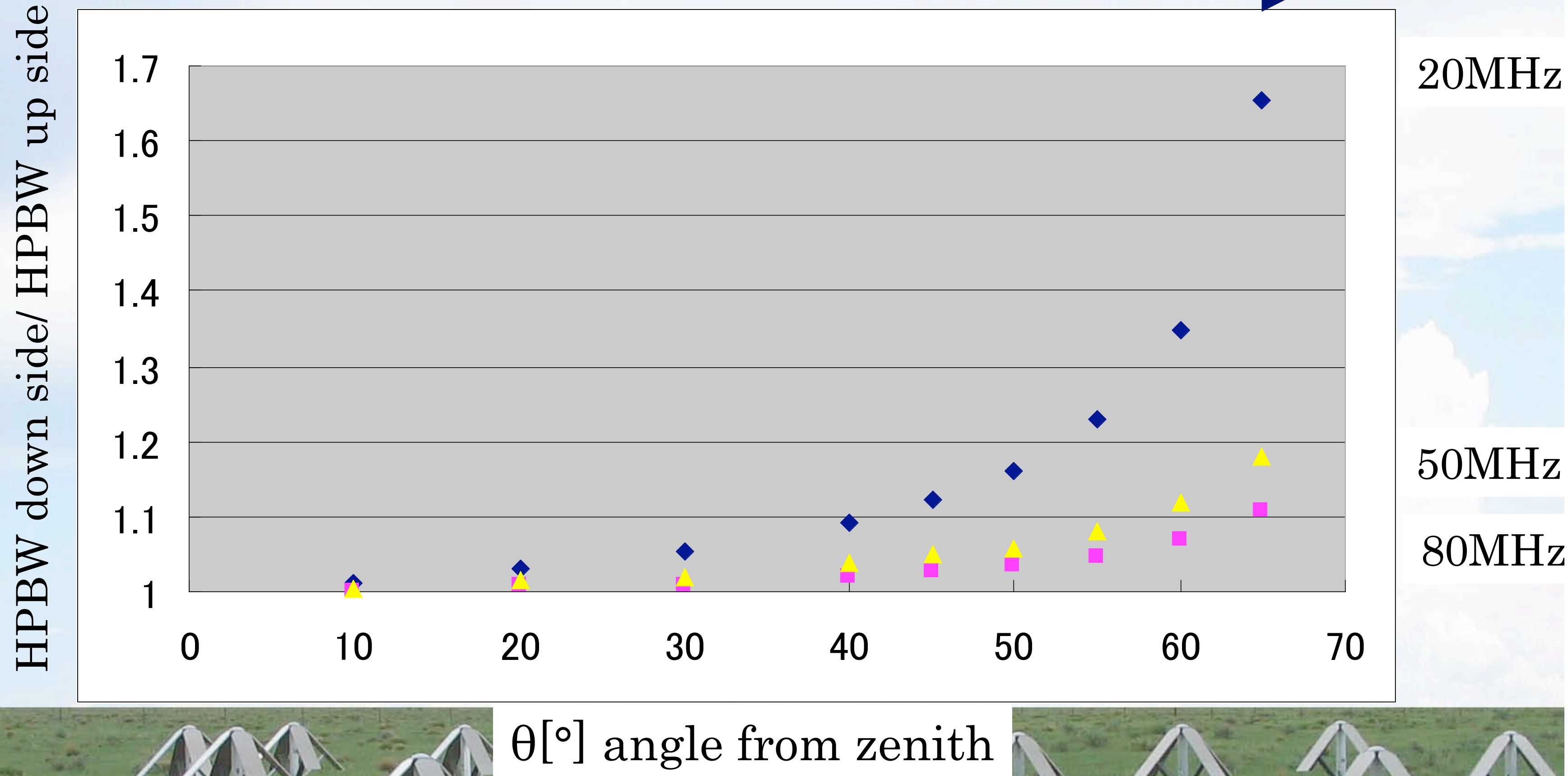
- NRAO designed Fiber communications board by Steve Durand
  - Hire NMT engineering student to build prototype for LWA1

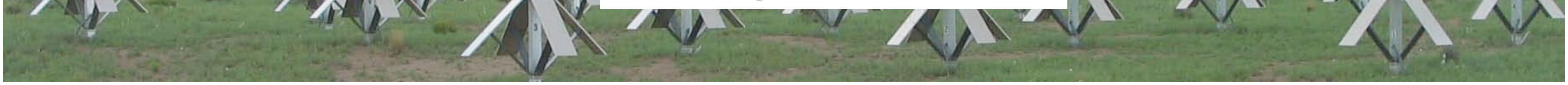
Software

- Masaya Kuniyoshi (UNM) working with Sanjay Bhatnagar and Kumar Golap (NRAO) on Simulating the LWA data (including primary beam effects)
- Gianfranco Gentile (UNM) working with Kumar Golap on wide field imaging
- NRL efforts with Bill Cotton

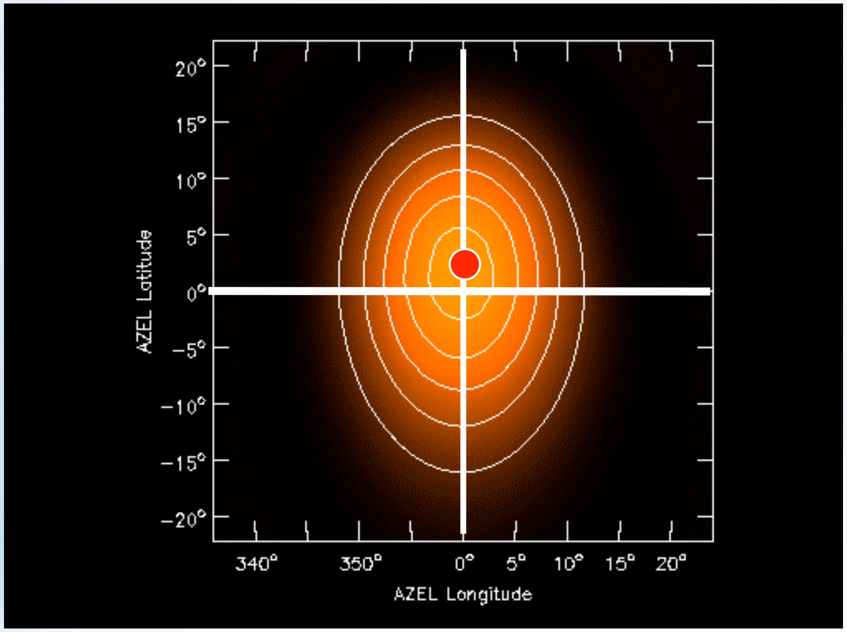
Asymmetric rate of a LWA station beam

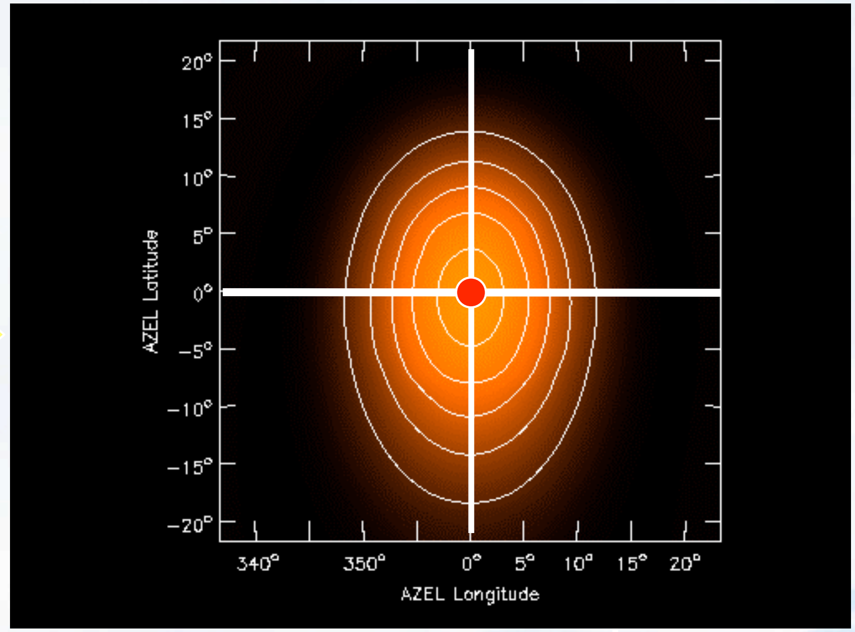






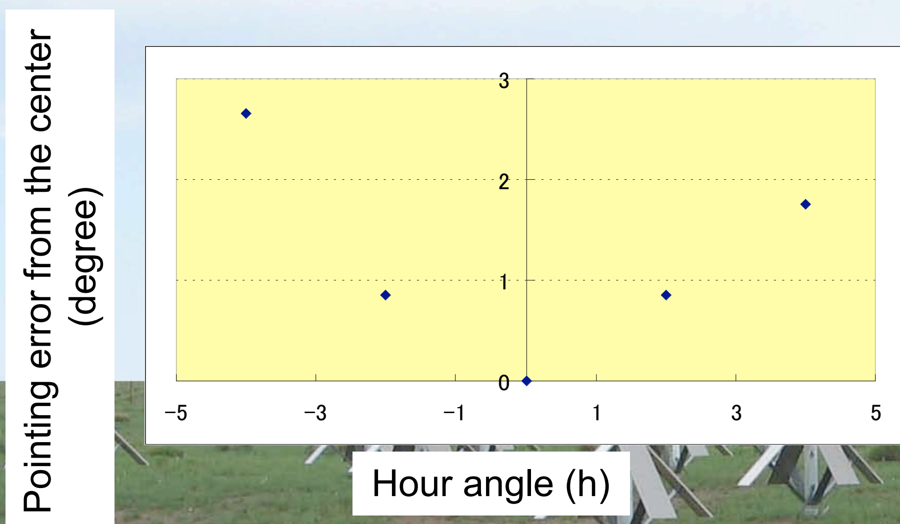
Pointing error (H=+4h, Frequency 20MHz)





$\sqrt{BBP}$ causes pointing error (2.7 degrees).

Correction by adding $\exp(i\alpha)$



$$E_k(\theta,\phi) = \sum_{j=1}^{256} \Delta\nu \exp(is_j\nu_k + i\alpha_{kj}) \frac{\sin(s_j \frac{\Delta\nu}{2})}{(s_j \frac{\Delta\nu}{2})} \cdot \sqrt{BBP(\theta,\phi)}$$

Ionosphere & Space Weather

- COSMIC/VLA campaign completed observations 9/17
- HAARP
  - Joint experiments in planning stage
- Hanscom Space Weather Group
  - Technical collaboration meeting in November

Supplements

- DOE possibilities being explored
- NSF support possible as a University Radio Observatory
- NSF support for an archiving facility at the High Performance Computing center
- NASA support as a demonstrator for astronomy on the moon
- LANL Signature Facility Proposal
  - Software collaborations
  - Increase capability of Transient Buffers

Low Frequency Roadmap

- Coordination with other US instruments (MWA, PAPER, ETA) as a low-frequency ‘pathfinder’
- Committee being formed (chaired by Tony Beasley) to write a position paper for the upcoming Decadal Review
- Potential collaboration with NRAO on a high frequency demonstrator

SUMMARY

- Willing to collaborate
  - Engage experts across the communities
  - Avoid the “marching army” problem
  - Increase efficiency
  - Be careful about putting items on the critical path outside of formal project controls