The North American ALMA Science Center

The NAASC will be housed in an addition to the NRAO Edgemont Road building in Charlottesville.
ALMA is a world array
ALMA is being built *where*?

The array is on a 16,500 ft elevation site, called the Array Operations Site (AOS).
Where in Chile is the ALMA Site?

Paranal
La Serena
Santiago
Where does the ALMA operations staff work?

Most staff are to work at the operations support facility ("OSF") at an elevation of ~9000 ft, on a new road connecting the high site with the San Pedro/Tocanao highway.

The OSF has lodging and dining for ~ 100 people.

The OSF is about a 45 minute drive from metropolitan San Pedro.
Joint ALMA Observatory

The Joint ALMA Observatory (JAO) headquarters will be in Santiago, at a suitably neutral location.

The JAO headquarters is currently in rented space in a new office tower in central Los Condes.

Staff will live in Santiago and work at the OSF on the “turno system”.
ALMA Regional Centers

The JAO will have user interfaces known as “ARCs” in each of the three partner regions: North America, Europe, & Japan.

The ARCs will conduct activities needed to receive and process proposals from observers and return data to users, all archive based and organized.

The ARC archives are mirror archives of the central archive in Santiago; they all contain the same data, all the data.
Proposals/Observing Files are sent from ARCs to JAO
Recorded data is sent to the JAO and on to the ARCs

*Tokyo
*Garching
*Coville
*Santiago

ALMA site
Data Flow is LARGE

During full operation, the data flow into the archive is estimated to be \( \sim 100 \) Tbytes per year. \((Total\ flow\ to\ date\ into\ the\ HST\ archive\ is \lesssim 20\ Tbytes)\).

A small dataset might be \( \sim 50\) Gbytes; a large dataset might be \( \sim 1\) Tbyte.

Dataset includes proposal, u-v data, a reference image with pipeline processing history, calibration data, . . .
Beyond the ARCs

- JAO Budget
- NAASC
- NA ARC
- Joint ALMA Observatory
- Chile Operations & Other ARCs
NA ARC

- NAASC Head & Admin. Asst.;
- (6) Astronomers – proposal functions;
- (8) Astronomers – archive functions;
- (10) Engineer/tech – hardware repair;
- (10) Programmers – software maint.;
- $5,000,000 per year – development;
- M&S, travel, capital; overhead.
NAASC Beyond the NA ARC

- Data analysis grants program;
- (12) ALMA Fellows;
- Pre-doctoral & co-op students;
- (+4) Astronomers – archive functions;
- EPO program;
- (3) Systems Admin.;
- Business & library services;
- Office of Chile Affairs.
European ARC ++

Carefully defined core functions will be done at ESO – Garching.

Much, especially “hand-holding”, will be outsourced by ESO to national facilities, for example, Jodrell Bank, Dwingeloo, IRAM, Onsala, . . . , to be paid for by national budgets.
Japanese ARC

The Japanese ARC will almost certainly be part of the National Astronomical Observatory of Japan and located on the NAOJ grounds in Mitaka, a suburb of Tokyo.
Canada

• Obligated to contribute 7% of the North American share of the JAO budget;
• This includes 7% of the NA ARC, but no contribution to NAASC beyond the ARC;
• Could choose to contribute, in part, with personnel, to Chile and to the NA ARC.
• Could reasonably expect to get 7% of the Development work.
Key NAASC Science Tasks For First Science (2007)

- Inform community of science capabilities, observing modes, available resources, via meetings, workshops, webpages; solicit feedback *pre 2006*
- Proposal preparation/user support (proposal call mid-2006) *pre 2006*
- Proposal review/scheduling *starting 2006*
- Testing data reduction scripts/cookbooks *pre 2007*
- Develop calibrator & spectral line databases *pre 2007*
- Post-observation user support: help users with offline data reduction; re-reduce data; submit bugs *starting 2007*
- Help software developers develop/test advanced data processing procedures/tools. *starting 2007*
I WANT YOU for the N.A.A.S.C. ENLIST NOW
Long Wavelength Array - LWA

NRAO New Initiatives Workshop
Socorro, NM
December 13, 2004

South West Consortium - SWC
Namir Kassim, NRL
Tom Gaussiran, UT Austin
Frank Gilfeather, UNM

December 13, 2004
NRAO New Initiatives Workshop
LWA Science

Namir Kassim
Naval Research Laboratory
(http://lwa.nrl.navy.mil/)
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 emission (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

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

The last and most sophisticated LW instrument – closed down nearly a decade ago – WHY?
Why Has LW Astronomy Languished?

– The most important reason: \( \lambda/D \) (angular resolution)

– CLRO TPT
  • D \(~3\) km baselines
  • \(~900"\) resolution at \(30\) MHz
  • \(~1000\) mJy rms with infinite integration – sensitivity 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)

- Limited baselines below 100 MHz to ≤ ~5 km.
- As main-stream radio astronomy went to high resolution and sensitivity with the VLA, LW radio astronomy was left behind.
- Other problems: RFI. 3D imaging – computational tedium that has only recently become manageable.
Technological Breakthrough:
Breaking the ionospheric barrier with the 74 MHz VLA

(a) shock physics of SNRs (a: Cas A - Kassim et al. 1995; b: Crab Nebula – Beitenholz et al. 1996)
(c) emission from relics & clusters (c: Coma - Kassim et al. 2004)
(d,e) radio galaxies (d: Virgo A – Kassim et al. 1993; e: Hydra A - Lane et al. 2004)

74 MHz VLA validating LWA science case and building new user community.

December 13, 2004
NRAO New Initiatives Workshop
LWA Key Science Drivers

(< 90 MHz)

- **Cosmic Evolution from the Dark Ages to the Present**
  - The High Redshift Universe
    - The first supermassive black holes, HI absorption during the EOR.
  - The Evolution of Large Scale Structure – Dark Matter & Energy.
    - Clusters – radio emission as a discriminator between merging and relaxed systems.
- **Acceleration**
  - In SNRs in normal galaxies at energies up to $10^{15}$ ev.
    - The distribution, spectrum, and origin of Galactic cosmic rays
  - In radio galaxies & clusters at energies up to $10^{18}$ ev.
    - Self-absorption processes, low-$\gamma$ electrons, IC magnetic fields, merger shocks
  - In ultra high energy cosmic rays at energies up to $10^{21}$ ev and beyond.
    - Via CR air-showers – ultimate source unknown.
- **Turbulence in plasmas from the Earth’s Ionosphere to the ISM of Galaxies.**
  - Plasma Astrophysics
    - Propagation, scattering, & absorption in the ISM of the MW & normal galaxies.
  - Ionospheric turbulence, solar & planetary science
    - Ionospheric waves, space weather, Jupiter, Solar bursts.

*LWA science plan & instrument concept recommended in Astronomy Decadal Survey report*
Exploring the High Redshift Universe

Source Samples

Current Sky Coverage

VLA Low-Frequency Sky Survey
http://lwa.nrl.navy.mil/VLSS

20 cm follow-ups of VLSS HZRG candidates - being pursued at Keck Djorgovski.

“USS” VLSS Sources: What are they?
- High Redshift Radio Galaxies?
- Fossil Radio Galaxies & Cluster Halos
- Pulsars?
- Something else??
Clusters & Relics:
Tracing the evolution of large scale structure as a function of redshift

LWA will increase the radio cluster Pop. by 1-2 orders of magnitude

Kassim et al. 2001
Buoyant Bubbles of Relativistic Electrons?

Perseus A at 74 MHz
Steep spectrum radio emission coincident with Chandra X-ray bubble
X-ray bubbles coincident with jets of 3C84 radio galaxy

Key issues include:
• Pressure balance between radio & X-ray gas.
• Bubbles as means of solving cooling flow crisis, transporting magnetic fields.
• Influence of AGN on cluster environment.
Physical Processes in Radio Sources

- Radio Galaxies
  - Low energy electrons
  - Self-absorption processes
  - Evolution & Death

74 MHz VLA + PT link

- Normal Galaxies
  - Ionized gas via absorption
  - Magnetic fields in interactions
  - Cosmic ray propagation (halos)

330 MHz VLA

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

Carilli et al. 1991

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Low $\gamma$ electrons: where the energy is.

- Ignorance of low $\gamma$ spectrum: we do not have a good estimate of the energy and pressure of the plasmas we study.
  - Deviations from power laws? Low energy cutoffs? Unknown.
- Situation even worse for IC emission.
  - Rely on electrons with Lorentz Factors $1000 < \gamma < 50$

![Graph showing flux density vs. frequency](image1)

**Extrapolated Sync.**

(0.2 to 5 keV)

**Observed Radio**

(5 to 8 GHz)

Harris 2004
Shock Acceleration & Thermal Absorption

VLA “A configuration” (35 km)  VLA + Pie Town outrigger (73 km)

Thermal Cocoon (74/330 MHz radio)

Neutron Star (Chandra X-rays)
Thermal Absorption

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

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

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

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

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

Brogan et al. 2004

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Full SNR census
(& distances to many of them)

330 MHz VLA currently tripling census of known SNRs between $l = 5$ to 20.

(Brogan, Gaensler et al.)

2 Color Image:
Red: MSX at 8 $\mu$m
Blue: VLA 330 MHz
The greatest discoveries in astrophysics have coupled key technical innovations with new spectral windows.

Astrophysical discovery space – what is left?
- New wavelengths – $< 100$ MHz last, poorly explored region.
- Resolution & sensitivity – orders of magnitude to be gained.
- Volume of space sampled – rare objects.
- New observing paradigms: multi-beaming

\[ \text{Natural strength of electronic LW arrays.} \]

\[ \text{The LWA efficiently exploits the last remaining areas of discovery space for astrophysics.} \]
Opening a new window on the EM Spectrum

Tremendous improvement in imaging power brings the potential for exciting discovery science.
Potential for New Discoveries:
Extra-solar Coherent Emission

- Below 40 MHz, Jupiter is the brightest object in the solar system.
  - Coherent cyclotron emission from interaction of Jupiter’s magnetosphere with solar wind.
- The LWA has good chance of detecting emission from extra-solar “Jupiters”.
  - Would provide independent verification of planetary systems using new technique.
  - Would confirm presence of magnetic field – pre-requisite for life as cosmic ray shield.

![Diagram of Jupiter's magnetosphere and solar wind interaction](image-url)

**Frequency (MHz)**

<table>
<thead>
<tr>
<th>1</th>
<th>10</th>
<th>10^2</th>
<th>10^3</th>
<th>10^4</th>
<th>10^5</th>
<th>10^6</th>
<th>10^7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jy</td>
<td>Jy</td>
<td>Jy</td>
<td>Jy</td>
<td>Jy</td>
<td>Jy</td>
<td>Jy</td>
<td>Jy</td>
</tr>
</tbody>
</table>

Interaction of Jupiter’s magnetosphere with the Solar Wind.

- Decametric
- ~40 MHz
- Synchrotron
- Thermal

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LWA Technical

Thomas L. Gaussiran II
Applied Research Laboratories
The University of Texas at Austin

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The Long Wavelength Array

- Consist of 52 stations
- Diameter of ~400 km
- Station provide good u,v coverage
- Cover 25 - 85 MHz
- Direct sample receivers
- 1-8 independent beams
- 32 MHz bandwidth
- Composed of dipole antennas
- Electronically steered
- Angular resolution
  - 5 arcseconds at 25 MHz
  - 1.4 arcseconds at 75 MHz
- Point source sensitivity (1 hr integration, 4 MHz IF)
  - 1.1 mJy at 30 MHz
  - 0.7 mJy at 75 MHz
- Dynamic range > $10^4$
- Full Stokes polarization
- Time resolution 1 ms
- Implementation Plan
  - CY04 Phase 0 - Existing VLA
  - 04-06 Phase 1 - LWDA
  - 06-08 Phase 2 - Intermediate
  - 08-10 Phase 3 - LWA Core
  - 08-10 Phase 4 - High Resolution
Station Level description

- Station composed of 256 dipole antennas
- Station diameter ~100 m
- Act as a single “dish”
- Sufficient collecting area to allow for self-calibration
- Multiple beams formed at the station level and transmitted back to central processor facility
Antenna Schematic

Single dipole antenna

Filter before LNA for suppression of intermod’s.

LPF allows receiver ADC to be upgraded later w/out changing balun.

HX62A 180° Hybrid

$\text{SLL} \approx 0.5 \text{ dB}$

$f_{\text{3 dB}} = 80 \text{ MHz}$

$\geq 40 \text{ dB down at 88 MHz}$

$L_{\text{int}} \leq 1 \text{ dB}$

BALUN

GALI-52

$G = 23 \text{ dB}$

$IIP2 = 19 \text{ dBm}$

$IIP3 = 9 \text{ dBm}$

RG-6 coax

$f_{\text{3 dB}} = 60 \text{ MHz and 80 MHz}$

roll-off = 40 dB / 10 MHz

RECEIVER

ADC amp.

$f_s = 98 \text{ Msp}$

Sample rate to avoid aliasing of FM band w/ “cheap” filter

December 13, 2004

NRAO New Initiatives Workshop
Dipole Antenna

- Dual polarization
- “Blade” design
- Electronics housed in mast or at hut
- Blades are ~1 m
- Solid aluminum construction
- No ground plane
Balun/LNA

- 180 degree hybrid
- Low pass/band pass filters
  - Prevent intermodulation
  - 40 dB suppression from 80-88 MHz
- Provides 1st stage of gain
- IP2/IP3 metrics are critical
  - IIP2 = 19 dB
  - IIP3 = 9 dB
- Current design to be tested at VLA and Green Bank sites
LWA Direct Sample Receiver

- **Components**
  - Bandpass filter
  - Gain Control Amp
  - 10 bit ADC
  - FPGA
- **FPGA function**
  - Integer sample delay
  - Fractional sample delay
  - Sub-band filter
  - Linear to circular
  - Clock disciplining
- **LWDA RX operates in the 2nd Nyquist zone**

- LVDS output
- **Sampling Rate**
  - LWDA ~ 98 Msps
  - LWA ~ 200 Msps
- Draws < 5 W
- 270 Mbps downstream
- 5 Mbps upstream
Beamformer

- Adds input from 8 different antennas
- Controls/provides voltage to each of the receiver
- Responsible for clock distribution/alignment
- Can be connected to other beamformers
Software

• Command and Control software
  – Leverage the C&C designed for the EVLA
  – Implement based on the design laid out by NRAO

• Data reduction and Imaging software
  – Leverage the current 74 MHz reduction software
  – Develop specific imaging capabilities

• Computing – UNM High Performance Computing Center and LANL

• Science Center
  – Socorro near AOC
  – UNM utilizing LambdaRail network
  – Access via academic networks
Organizing the LWA Team

Frank Gilfeather
University of New Mexico

December 13, 2004     NRAO New Initiatives Workshop
SWC Core Institutions

• University of New Mexico – science, computing and infrastructure support

• University of Texas – ARL – engineering and ionospheric studies

• Los Alamos National Laboratory – science and computing

• Naval Research Laboratory – science and engineering
The Long Wavelength Array

- Re-vitalize university-based radio astronomy – add faculty and students
- Build in US South West – leverage EVLA and related project development
- Use existing infrastructure – power, fiber-optic networks
- Reasonable RFI environment at low frequencies – proven environment
- Synergy with Very Large Array and EVLA – joint activities
- Large, nearby population of astronomers, earth & space scientists, engineers – good for NM and region
- Initiate and expand educational programs - cooperation with NRAO
Basic Premises

- Multi-disciplinary instrument – develop unique applications
- Multi-user instrument – open to the broad community
- Radio astronomy - using technology to make a software telescope
- Phased development plan – doing science as LWA develops
- Engage cooperation of individuals at many institutions – broad buy-in
- Develop a special cooperative relationship with EVLA/NRAO – as NM instruments
Many Steps to LWA

- 1984 - Perley, R. A. & Erickson, W. C. (VLA Scientific Memorandum 146 (Socorro: NRAO) p. 1-65) - A proposal for a large, low frequency array located at the VLA site
- 1990 – Kassim, Perley and Erickson (1990, BAAS 22: 802) – Report of first observations with initial 74 MHz system
- 1993 – Kassim et al. (A.J. 106: 2281) – 8-element VLA
- 1998 – Full 74 MHz system becomes VLA facility instrument
- 1998 – Kassim and Erickson (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 South-West Consortium
- 2004 – Wavelengths on Human Scales – September 8, 2004

74 MHz VLA System and Beyond
## LWA Timescale

<table>
<thead>
<tr>
<th>Year</th>
<th>Phase</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>Phase 0</td>
<td>Existing 74 MHz VLA System</td>
</tr>
<tr>
<td>2004–2006</td>
<td>Phase 1</td>
<td>Long Wavelength Demonstrator Array (LWDA)</td>
</tr>
<tr>
<td>2006–2008</td>
<td>Phase 2</td>
<td>8-9 (6-7+2) Station Intermediate Array (LWIA)</td>
</tr>
<tr>
<td>2008–2010</td>
<td>Phase 3</td>
<td>Complete LWA Core Array</td>
</tr>
<tr>
<td>2008–2010</td>
<td>Phase 4</td>
<td>High Resolution LWA</td>
</tr>
</tbody>
</table>
What we need to realize LWA

• Strengthen the constituency for the LWA – a university/national lab led, world-class observatory
• Strengthen internal organization – workshops, personnel
• Obtain significant R&D funding through diverse agencies
• Build-out through a phased development strategy
• Continue to overcome technical challenges - calibration
• Build synergy with other projects – FASR, MRA, etc.
• Firm a symbiotic relationship with NRAO
Obvious questions

• Can we overcome engineering (software) challenges?
• Is our organizational structure sound and strong enough?
• Is there funding to do all the valuable projects in the national queue?
• How do we coordinate with other developing projects e.g. FASR?
• Is NRAO able to accommodate our effort – even if we work to accommodate their needs?
• Is the proposed timeline sensible?
A new ‘species’ on the Plains
Thanks
Why should NRAO care about SWC/LWA?

- First and foremost for the science.
- LWA opens up new parameter space for our user community.
- Great potential exists for new astronomical discoveries.
- Other scientific areas also benefit.
To Contribute and work with SWC on issues of common interest.

• Wide Field Imaging
• High Speed Computing
• Data Transport on optical fibers
• EPO
• Access to public land
To help revitalize the University Radio Astronomy Community.

- LWA brings UNM, University of Texas and Groups at several other universities into the project as major players.
To Involve Other National Labs

• NRL and LANL are major partners with extensive resources.
• They bring their own talents and energy to our general goal of stimulating radio astronomy and other related science.
To add new funding sources.

• NRAO is a NSF contractor and thus has primarily the NSF as its funding source.
• Universities and other National Labs have other sources of funding.
• At least for now the NSF funding pot looks severely limited.
• By working with the SWC we can find new ways to bring funding into projects we support.
Conclusion

The LWA project offers NRAO and new way to make use of it role as the National Radio Astronomy Observatory to do important new research. However, it also offers a new model for how we can extend our ability to facilitate radio astronomy for our community and to increase the vitality of our field.
But what is going on in A2125 to enhance the radio fraction?

Are the excess radio emitters due to a merger?

Is the excess AGN or star-formation driven?

To help find the answer, we have obtained deeper VLA 20cm imaging, deeper, multiband optical imaging, much more spectroscopy, and a deep CHANDRA integration (80ksec).
New A2125 Dataset

- Deeper, higher resolution 20cm VLA imaging.
- 223 spectroscopically confirmed members
- 90 radio detected members
- 3 fields imaged with HST
- 80ksec CHANDRA imaging
Velocity Field

Best fit to spatial and velocity information suggests 3 subclumps:

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean V</th>
<th>dispersion (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>141</td>
<td>73677</td>
<td>639</td>
</tr>
<tr>
<td>Sub#1</td>
<td>53</td>
<td>75946</td>
<td>709</td>
</tr>
<tr>
<td>Sub#2</td>
<td>29</td>
<td>71877</td>
<td>481</td>
</tr>
</tbody>
</table>
Summary

• A2125 appears to be in the middle of a major collision/merger which is accompanied by an unusual amount of star-formation activity for such a rich massive system.

• The core appears to be a collision between massive cores of the two principal components of the system.

• Most of the excess radio emission is probably associated with star-formation, often hidden by significant dust obscuration.

• These results, combined with those for other clusters suggest much of the star-formation must have been induced by the collision/merger process.
The Frequency Agile Solar Array

T. S. Bastian (NRAO)
- Background
- FASR Overview
- FASR science
- Status and plans
In an exercise similar to the AASC decadal review the **NRC Solar and Space Physics Survey Committee** considered priorities for solar, heliospheric, magnetospheric, and ionospheric physics.
$400M (large)
Solar Probe
Solar Probe will make the first in-situ measurements inside 0.3 AU, the innermost region of the heliosphere and the birthplace of the heliosphere itself.

$250-400M (moderate)
Magnetospheric Multiscale Mission (MMS)
The 4 MMS spacecraft will study the fundamental physical processes that transport, accelerate, and energize plasma in the boundary layers of Earth’s magnetosphere.

<$250M (small)
Frequency Agile Solar Radiotelescope (FASR)
A multi-frequency (~0.1 - 30 GHz) imaging array composed of ~100 antennas for imaging the Sun with high spectral, spatial, and temporal resolution.
The essential idea

FASR is a solar-dedicated radio telescope designed to perform dynamic broadband imaging spectroscopy.

It will do so with **time** resolution, **frequency** resolution, and **angular** resolution commensurate with physical phenomena of interest.

It will be entirely unique.
Distinctive character of solar observations

- Sensitivity is not a driver ($10^4 - 10^{10}$ Jy: $T_{\text{sys}}$ is source-dominated)
- Angular resolution requirements are bounded (~20"/GHz)
- Snapshot imaging is often more important than earth-rotation synthesis
- Observations over wide band needed, ~ “continuous” in frequency
  
  NB: Most observations are outside protected frequency bands.
- Spectral resolution science requirements are modest (RFI driven)
- Time resolution science requirements frequency dependent

- Interpretation usually involves multi-wavelength analysis
- Users may not have a good understanding of instrumentation
- Time variable sources

  Poor match to pre-scheduled operations model
  Observational continuity is highly desirable
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from Benz 2004
Distinctive character of solar observations

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  Poor match to pre-scheduled operations model

Observational continuity is highly desirable
System Overview

- FASR will perform Fourier synthesis imaging
- It will be composed of sub-arrays of antennas, e.g.,

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Antenna Type</th>
<th>Number of Antennas</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-300 MHz</td>
<td>fixed LPDA or similar</td>
<td>~60 antennas</td>
</tr>
<tr>
<td>0.3-3 GHz</td>
<td>steerable 6 m para</td>
<td>~80 antennas</td>
</tr>
<tr>
<td>3-24 GHz</td>
<td>steerable 2m para</td>
<td>~100 antennas</td>
</tr>
</tbody>
</table>

- No cryogenics required
- Simple, robust electronics in the field
- Broadband data transmission on optical fiber links
- Use of interim archive for ~10 Tbytes/day
- Pipeline calibration, imaging, and deconvolution
Nobeyama Radioheliograph

I. Gary
<table>
<thead>
<tr>
<th>Specifications</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range</td>
<td>30 MHz - 30 GHz</td>
</tr>
<tr>
<td>Frequency resolution</td>
<td>1%, 30 - 300 MHz 0.1%, 0.3 – 3 GHz 1%, 3 – 18 GHz</td>
</tr>
<tr>
<td>Time resolution</td>
<td>100 ms, 30 – 300 MHz 10 ms, 0.3 – 3 GHz 100 ms, 3 – 18 GHz</td>
</tr>
<tr>
<td>Number antennas</td>
<td>~100 (4950 baselines) ~80 (3160) ~60 (1770)</td>
</tr>
<tr>
<td>Size antennas</td>
<td>LPDA, 6 m, 2 m</td>
</tr>
<tr>
<td>Polarization</td>
<td>Stokes IV(QU)</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>$20/n$ arcsec</td>
</tr>
<tr>
<td>Footprint</td>
<td>~6 km</td>
</tr>
<tr>
<td>Field of View</td>
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High Frequency Array Straw Man Block Diagram

- 2-meter Parabolic Antenna
- 2-24 GHz
- Analog Fiber Optic Link
- X2 polarizations

2-GHz Band

- Analog IF Processor
- Local Oscillator Reference

- Selected 1 GHz Band
- Digital Fiber Optic Link, 12 Gbit/sec per antenna per 1 GHz channel
- Signals from other antennas

- A/D
- Correlator
- Central Oscillator Reference
- Data Analysis Computer

- Analog Fiber Optic Link

Expansion by adding 1 GHz bandwidth IF processors and digital fiber optic links
FASR Key Science

- **Nature & Evolution of Coronal Magnetic Fields**
  - Measurement of coronal magnetic fields
  - Temporal & spatial evolution of fields
  - Role of electric currents in corona
  - Coronal seismology

- **Flares**
  - Energy release
  - Plasma heating
  - Electron acceleration and transport
  - Origin of SEPs

- **Drivers of Space Weather**
  - Birth & acceleration of CMEs
  - Prominence eruptions
  - Origin of SEPs
  - Fast solar wind streams
FASR Science (cont)

- The “thermal” solar atmosphere
  - Coronal heating - nanoflares
  - Thermodynamic structure & dynamics
  - Formation & structure of filaments

- Solar Wind
  - Birth in network
  - Coronal holes
  - Fast/slow wind streams
  - Turbulence and waves

- Synoptic studies
  - Radiative inputs to upper atmosphere
  - Global magnetic field/dynamo
  - Flare statistics
FASR will perform broadband imaging spectroscopy of the Sun

Imaging spectroscopy provides access to a number of unique diagnostics that have been unavailable to date:
- Measurement of coronal magnetic fields
- Magnetic energy release
- Electron distribution function and its evolution
- Origin and propagation of MHD shocks/waves

Imaging spectroscopy provides an integrated picture of solar phenomena from the chromosphere into the corona.

With STEREO/SWAVES and possibly, SIRA, FASR will provide an integrated picture of radio phenomena from the Sun to Earth.

FASR will be well-positioned to make new discoveries!
FASR Planning and Construction Phases

1. Implement a design and development plan (DDP), via a proposal to NSF/ATM under the leadership of the NRAO, that will result in a proposal to design, build and operate FASR.

2. Transition the FASR project to a new center, institute, or observatory under management of AUI. This new organization would be responsible for implementing the proposal to design, build and operate FASR.
DDP Task Areas

1. Technical design of the instrument
2. Software and data management planning
3. Science and operations planning
4. Site evaluation and selection
5. Project implementation planning
6. Education and public outreach
Institutional Partners

- National Radio Astronomy Observatory
- University of Michigan
- University of California, Berkeley
- New Jersey Institute of Technology
- University of Maryland
- Caltech & JPL
- University of New Mexico
- Naval Research Lab
- Paris Observatory
Technical systems


Antennas/optics: UCB, NRAO
Front ends: NRAO
RF/IF conversion: NRAO
LO and timing: JPL, NRAO
Phase switching and fringe rotation: NRAO, JPL
Analog signal distribution: NRAO
Analog to digital: U. Mich with input from NRAO, Paris Obs., NJIT
Correlator: U. Mich. with input from NRAO
High Frequency Array (FASR A)
Straw Man Block Diagram

2m parabolic antenna
2-24 GHz
Analog fiber optic link
x2 polarizations

Analog IF Processor
Local Oscillator Reference
Expansion by adding 1 GHz bandwidth IF processors and digital fiber optic links

Selected 1 GHz band
A/D
Digital fiber optic link
12 Gbit/sec per antenna per 1 GHz data channel

Signals from other antennas
Correlator
Central Oscillator Reference

Data Analysis Computer

UC Berkeley
Univ. Michigan
NRAO
Schematic Schedule

2005  FASR DDP proposal (NRAO)
2006  FASR proposal for construction and operation (AUI)
2007  Construction begins
2009  First FASR science
2011  Project completed
Focal Plane Arrays for the VLA?

Walter Brisken (NRAO)

and collaborators:

Christophe Craeye (UCL, Belgium)
Peter Napier, Rick Perley (NRAO)
Bruce Veidt (DRAO)

New Initiatives, Socorro, NM Dec 13, 2004
Extending frequency coverage downwards...

- Currently has 74 and 330 MHz dipoles
- Goal: complete the frequency coverage down to 240 MHz
  - Top of LOFAR / LWA band
- Originally part of EVLA phase II plan
  - 2 or 3 horn antennas at prime focus spanning the 240 to 1000 MHz band
  - Dropped because of complexity, cost
No room at secondary focus

- Feeds need to be $9\lambda$ wide to illuminate the subreflector efficiently
- 1.2 GHz is the lowest possible freq. here

2-4 GHz feed slot

Space for 1.2-2 GHz feed

EVLA feed cone
Prime focus is inaccessible

- Could rotate subreflector out of way
  - Allows space for several horn feeds
  - Expensive
  - Structural change
- Out of focus feed / off axis feed
  - Too inefficient
- Phased array feed
  - Add 0.3 m travel to subreflector
  - Deploy array feed in front
Phased Array Advantages

- Potentially low cost
- Minimal antenna changes required
  - Add additional travel to subreflector
- Performance
  - Phased beam can be highly optimized
- Multi-beam possibility
Vivaldi Arrays

UMass Antenna Lab designed, fabricated and tested the above 8x9x2 array. Support was from ASTRON. Picture courtesy Dan Schaubert.

Vivaldi elements and array designed and built by Ed Reid at DRAO.
Finite Vivaldi Array Properties

• Elements are tightly coupled
  – Each element has a different beam pattern
    • Edge elements are the most exceptional
    – Element patterns are freq. dependent
    – Coupling exploited to increase bandwidth

• Bandwidth ratios of 5:1 are possible

• Shortest useful wavelength is about 2 element spacings
Goals of a detailed study for the VLA

- Synthesize wide-band feed with vivaldi array
- Use realistic Vivaldi beam patterns
- Use a realistic VLA antenna model
- Incorporate physical optics
- Determine array suitability based on
  - $G/T_{\text{sys}}$
  - phasing bandwidth
  - phased beam shapes
Vivaldi Array Model

• 180 elements: 9x10 array for each linear polarization

• Element size
  – 18 cm wide (1/2\(\lambda\) at 833 MHz)
  – 29.5 cm deep

• Operating range: <250 – 800 MHz

• Array centered at antenna prime focus
Vivaldi Array Geometry

9x10x2 Vivaldi Array

Size of array compared to VLA subreflector
Vivaldi Element Patterns

- Computed by Christophe Craeye (UCL)
- Method of Moments (MoM) used
- Each element pattern computed assuming all others are terminated
- Assumes infinite ground plane
  - Restriction can be lifted in future
- Computed for 25 elements – the others follow from symmetry
- Ohmic losses ignored
Element Geometry

MoM Current Segment

Slot line

Delta Gap (Feed Point)

Cavity

(Modified figure of C. Craeye. Gridding done by X. Dardenne)
500 MHz Element Patterns
Antenna Model

- Shaped 25 m diameter primary
- 4 struts
- Subreflector
- Ticra's Grasp8 software used

Approximations
  - Feed cone is symmetric
  - No scattering off of focal plane
311 MHz Antenna Patterns

Contours every 1.5 dB

Degrees on sky
Optimize beam pattern

- Assign a complex weight to each element.
- Express $G$ and $T_{sys}$ as functions of these weights
- Solve for weights giving maximal $G/T_{sys}$
- Sum beam patterns with these weights
Weights I: Total Power

Power Pattern

\[
\frac{dP}{d\Omega}(\theta, \phi) = \frac{1}{2\eta} \left| \vec{E}_a(\theta, \phi) \right|^2
\]

Total Power

\[
P_{\text{tot}} = \int d\Omega \frac{dP}{d\Omega}(\theta, \phi)
\]

\[
= \vec{w}^H \cdot P \cdot \vec{w}
\]

Elements of Power Hermitian matrix

\[
P_{ij} = \frac{1}{2\eta} \int d\Omega \vec{E}_{a,i}^* \cdot \vec{E}_{a,j}
\]
Weights II: Forward gain

X-polarized forward gain

\[ G_X \equiv 4\pi \frac{\frac{dX}{d\Omega}(0, 0)}{P_{tot}} = \frac{2\pi}{\eta} \left| \frac{\vec{E}_a(0, 0) \cdot \mathbf{e}_X}{P_{tot}} \right|^2 \]

X-polarized power pattern

\[ \frac{dX}{d\Omega}(0, 0) = \frac{1}{2\eta} \left| \vec{E}_a(0, 0) \cdot \mathbf{e}_X \right|^2 \]

\[ G_X(\vec{w}) = \frac{\vec{w}^H \cdot \mathbf{G}_X \cdot \vec{w}}{\vec{w}^H \cdot \mathbf{P} \cdot \vec{w}} \]

Elements of X-polarized gain Matrix

\[ G_{X_{ij}} = \frac{2\pi}{\eta} \left( \vec{E}_{a,i}(0, 0) \cdot \mathbf{e}_X \right)^* \left( \vec{E}_{a,j}(0, 0) \cdot \mathbf{e}_X \right) \]
Weights III: System Temperature

System temperature

$$T = \frac{\int d\Omega \left( T_{\text{rad}}(\theta, \phi) + T_{\text{rec}} \right) P(\theta, \phi)}{P_{\text{tot}}}$$

Expressed as function of weights

$$T(\vec{w}) = \frac{\vec{w}^H \cdot \mathbf{T} \cdot \vec{w}}{\vec{w}^H \cdot \mathbf{P} \cdot \vec{w}}$$

Elements of Temperature matrix

$$T_{ij} = \frac{1}{2\eta} \int d\Omega \left( T_{\text{rad}}(\theta, \phi) + T_{\text{rec}} \right) \times \vec{E}^*_{a,i}(\theta, \phi) \cdot \vec{E}_{a,j}(\theta, \phi)$$
Optimization of G/T_{sys}

Maximize ratio of gain to T_{sys}

\[ R(\vec{w}) \equiv \frac{G_{X}(\vec{w})}{T(\vec{w})} = \frac{\vec{w}^H \cdot G_{X} \cdot \vec{w}}{\vec{w}^H \cdot T \cdot \vec{w}} \]

Employ Cholesky Decomposition

\[ T = L \cdot L^H \]

\[ \vec{w} = L^{H^{-1}} \cdot \vec{z} \]

\[ \vec{w}^H = \vec{z}^H \cdot L^{-1} \]

\[ G_{X} = L \cdot M \cdot L^H \]

Solve for z using eigenvector techniques

\[ R(\vec{z}) = \frac{\vec{z}^H \cdot M \cdot \vec{z}}{\vec{z}^H \cdot \vec{z}} \]
500 MHz Results (1)
Phased-array and antenna patterns

Optimized phased-array pattern

Contours every 1.5 dB

Degrees on sky

Optimized antenna beam
500 MHz Results (2)

Spillover cancellation

Blue: central element only, $T_{sys}=73.0\text{K}$
Red: all elements, optimized, $T_{sys}=39.8\text{K}$

Sky-directed spillover
Ground-directed spillover
500 MHz Results (3)
Element weights
760 MHz Results (1)
Phased-array and antenna patterns

Optimized phased-array pattern

Contours every 1.5 dB

Degrees on sky

Optimized antenna beam
760 MHz Results (2)
Spillover cancellation

Blue: central element only  $T_{sys}=71.8\,\text{K}$
Red: all elements, optimized $T_{sys}=29.1\,\text{K}$

Sky-directed spillover
Ground-directed spillover
Secondary diffraction
Array sidelobe
Strut diffraction

Azimuth-averaged gain [dBi]
Boresight angle [deg]
760 MHz Results (3)
Element weights
X-pol offset phasing

500 MHz

760 MHz
Performance

Focal plane array sensitivity (x 80%)

UHF Band

EVLA sensitivity goal

Focal plane array sensitivity (x 80%)
Conclusions

- Great performance is possible!
- Useful tunable bandwidth $> 2.5:1$
- Useful cophased BW $> 1.25:1$ (20%)
Future Directions

- Use finite ground plane
- Use more realistic elements
  - Add dielectric
  - Simulate new balun
- Optimize over a finite bandwidth
  - Mathematics becomes tricky and figure of merit is less well defined
- Receiver noise should be investigated
  - Is noise correlated?
  - Ohmic loss
The End
500 MHz Results (3)
Element weights

Voltage weights

Current weights
760 MHz Results (3)

Element weights

Voltage weights

Current weights
TODO

- Efficiency as func of number of phased elements
- Broad band optimization
- Delays, not phases
VLBA Upgrade

A Response to the VLBI Future Report

R. Craig Walker
Socorro NM

(Yes, we need a better name)
VLBI FUTURE REPORT

- “Mapping the Future of VLBI Science in the U.S.”
  - Prepared by committee of 9 convened by the directors of NRAO and MIT Haystack Observatory
    - Led by Greg Taylor and Colin Lonsdale
  - Result of a year-long activity consulting many in the U.S. VLBI community and the broader scientific community
  - Submitted to NSF
- Reviewed scientific highlights of VLBI and VLBA
- Projected future science prospects
- Presented a technical roadmap
VLBI FUTURE REPORT

RECOMMENDATIONS

- Hardware investment
  - Implement Mark 5 disk based recording on the VLBA, with priority
  - Equip Arecibo and the Green Bank Telescope with state of the art VLBI equipment, and increase participation of these facilities with the VLBA and global VLBI
  - Perform inexpensive upgrades to exploit the full 22-86 GHz performance potential of the VLBA antennas.
  - Investigate connections with the Expanded VLA (ELVA) and future facilities to enhance VLBI capabilities.
  - Support the development of sensitive VLBI at millimeter wavelengths using new and planned telescopes such as SMA, CARMA, LMT, and ALMA.
VLBI FUTURE REPORT
RECOMMENDATIONS

● **Software investments:**
  – Dedicate new resources at the 3 to 5 person level, for the purpose of overhauling user software support for the VLBA, and for global VLBI
  – Coordinate these activities with foreign partners, and the US university community

● **Astronomical community investments:**
  – Provide a funding mechanism for the improved support of graduate students at US universities to work on VLBI related research. Multiple possible avenues are identified and should be explored
  – Investigate the provision of funds for financial support attached to time granted to US observers on VLBI networks.
VLBA UPGRADE WBS

- An effort to cost the enhancements requested by the VLBI FUTURE report
  - Consolidates many existing and planned projects
- Major items:
  - Project management
  - VLBA Software
  - Bandwidth expansion (dominates cost – goes >>1 Gbps)
  - eVLBI Test Plan
  - High Frequency Improvements
  - Front End Systems (33 GHz and 4-8 GHz systems)
  - Education and Public Outreach (mainly student funding)
- 5 yr (3 yr for lower cost items, 2 yr for rest)
- Total cost roughly $30M
- Note: Does not reach final goal of full EVLA integration
VLBA SOFTWARE

- Scheduling
  - New hardware, GUI, Info to PP, WIDAR correlator

- Real time systems
  - Mark5B (1Gbps). Later wider bandwidth support

- Post processing
  - VLBI in aips++ (fringe fitting, Tsys/gain, pulse cal, autocorrelation corrections, ionosphere corrections, spectral shifting, geodesy/astrometry, correlator model awareness, model fitting, pipeline)

- Archives
  - Disk space and access tools
BANDWIDTH EXPANSION

• Recording system upgrade to Mark5
• Electronics upgrade to EVLA style
  – Basically everything between receivers and recorders
  – Allows 4 GHz or more bandwidth
• Transition to WIDAR correlator
  – Needed for > 256 Mhz
• “Mark6” Wider band upgrade from Mark5
  – Needed for > 1 (2) Gbps
eVLBI Test Plan

- Real time or near real time data transmission
  - Much research going on elsewhere
- Last mile costs
  - Connect VLBA and GBT to fibers
- eVLBI capability on the VLBA
  - Determine the costs of fiber access for real time operation
  - Develop the eVLBI capability
- Does not include transition to eVLBI
  - Don't know the fiber access cost
    - Could be extremely expensive (> NRAO budget)
    - Could be free on research networks
HIGH FREQUENCY IMPROVEMENTS

- Enhance VLBA high frequency performance
  - Subreflector and primary surface improvements
  - WVR testing and development efforts
  - Test and implement frequency band switching
  - Pointing improvements using 500 MHz
  - Research on pointing improvements
- VLBI backends for CARMA, ALMA, SMT, SMA ...
RECEIVERS

- Ka Band (26-40 GHz)
  - Needed for spacecraft navigation
  - Very good for high resolution astronomy
- C band (4-8 GHz)
  - Prime phase referencing range
  - Need bandwidth if go above 1 GHz
  - Several interesting spectral lines near 6 GHz
- Upgrade 22 and 43 GHz low noise amplifiers
- Finish 3mm receivers
- Hardware upgrades for 3mm receivers
EPO

- Student award program
  - Modeled on Green Bank program

- Public outreach:
  - Displays (including at each site)
  - Web
  - Passport program
  - Informational and promotional brochures handouts and CDs
### BUDGET SUMMARY

#### VLBA Cost Summary for (M&S, Labor, Travel, FTE Overhead, Contingency)

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FUNDING PROSPECTS

- Mark5: Top priority for current funding
  - Operations funding, reduced tape maintenance, lowering staff. Doing everything possible to fund the switch
  - NASA and ESA/JIVE gave 6 Mark5 units for Huygens observations

- Possible NASA funding for spacecraft navigation:
  - Mark5 units and disks
  - Ka band receivers and X/Ka dichroic
  - eVLBI development

- 3mm: Past and possible future MPI contribution

- EVLA2: Some integration of NMA with VLBA included
  - Inputs to WIDAR correlator for VLBI
  - Conversion of LA and PT to EVLA electronics

- Rest: Some from operations, but new money needed for most
INTERMEDIATE BANDWIDTH OPTION

- Bandwidth break points:
  - 256 MHz  Maximum for current samplers and correlator
  - 1 GHz   Maximum for current LO/IF. Requires WIDAR
  - 4 GHz   Maximum for shared WIDAR correlator stations
  - 16 GHz  Full EVLA bandwidth. Requires WIDAR upgrade

- Upgrade plan “does it right” with EVLA LO/IF

- Could handle 1 GHz with with a “digital BBC”
  - Models being developed at Noto, Berkeley ...
  - EVLA station board might serve

- Should we consider a 1 GHz plan
  - Much cheaper, but no expansion beyond 1 GHz
PROJECT MANAGEMENT

- Two half time people for 5 years
- Some M&S support
- Advisory committee support