A “Mark 6” Recording System for the VLBA Upgrade

Jon Romney
NRAO, Socorro

New Initiatives Workshop
2004 December 13
Original Concept

Implement Mark 5B Initially

Required to operate at 1 Gbps.

Develop Own Upgrade, “Mark 6”

Goals: 4 Gbps by 2009. Rate a subset of EVLA capacity.

Other development efforts not known, had to plan for own development in 2007-08.

Cost estimates.

M&S: $2.6M [primarily disk drives]

Labor: 10+4 work-months
New Concept

Implement Mark 5A Initially
   Mark 5B still not yet available.

Exploit Developments Elsewhere
   Conduant Corporation (developer / vendor for Mark 5) expecting to announce new “Amazon” unit next quarter.
      Enhanced version of current “Big River” unit.
      Based on significantly upgraded “Streamstore” board.
      Record rate capacity ≥ 3.2 Gbps; already 80% of goal for 2009.
      Cost predicted to be “similar to” Mark 5.

Haystack Observatory Mark 5B I/O board.
   Will limit throughput at 2 Gbps (onto 16 disk drives).
NRAO Options for 4 Gbps

Successor to Conduant Amazon Unit
Will very likely be available by 2009, with capacity » 4 Gbps.

Mark 5B I/O Board Possible Bottleneck
Possible that Haystack will develop own “Mark 6”, ≥ 4 Gbps.
But Mark 4 correlator design limits throughput to 2 Gbps.
Quite possible that EVLA correlator will be only system requiring VLBI
data at 4 Gbps.

NRAO could …
Develop own “Mark 6” I/O board.
Collaborate with or contract with Haystack to develop it.
End
The VLBA Spacecraft Navigation
Pilot Project

Jon Romney
NRAO, Socorro

New Initiatives Workshop
2004 December 13
Introduction

NRAO Just Completed ~Year-Long Project
Funded by NASA

Major Components

Feasibility study.
Viability of VLBA spacecraft navigation measurements demonstrated.
Operational reliability yet to be demonstrated.
Variety of details still to be studied.

Implementation studies.
Almost all planned studies completed, with a few exceptions.
Additional work, beyond project goals, completed in many cases.
Motivation: Opportunity to Augment VLBA

New Instrumentation
- Required to support spacecraft navigation functions.
  - Ka-band receivers.
  - Mark 5 recording system, up to 1 Gbps sustained capacity.
  - E-VLBI capability.

Upgraded Operational Infrastructure
- Allowing brief spacecraft navigation observations with minimal impact on astronomy program.

Broader User Base
Navigation Feasibility Study

Collaborative Effort …

with various groups at JPL:
  Navigation / Delta-DOR / Missions.

Test Observations

Standard VLBA phase-referencing technique.
  Imaged by NRAO personnel.
  Total delays delivered to JPL for further analysis.

13 VLBA observations, including both Mars Exploration Rovers, in final week before each landed on Mars.
## Navigation Feasibility Study

### VLBA Spacecraft Navigation Pilot Project

#### Test Observations

<table>
<thead>
<tr>
<th>ObsCode</th>
<th>Start Date &amp; Time [UT]</th>
<th>Duration [h:m]</th>
<th>Stations</th>
<th>Target</th>
<th>Reference</th>
<th>Calibrators</th>
<th>Flux [mJy]</th>
<th>Distance [deg]</th>
<th>Precision [nrad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS020</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>2003/12/19 22:30</td>
<td>3:00</td>
<td>9.5</td>
<td>MER-A</td>
<td>2</td>
<td>1</td>
<td>250</td>
<td>2.2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>MER-B</td>
<td>2</td>
<td>1</td>
<td>250</td>
<td>2.8</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>2004/1/3 22:30</td>
<td>3:00</td>
<td>10</td>
<td>MER-B</td>
<td>5</td>
<td>1</td>
<td>381</td>
<td>3.6</td>
<td>4</td>
</tr>
<tr>
<td>C</td>
<td>2004/1/8 15:09</td>
<td>3:10</td>
<td>10</td>
<td>Stardust</td>
<td>-20</td>
<td>3</td>
<td>200</td>
<td>7.2</td>
<td>4</td>
</tr>
<tr>
<td>D</td>
<td>2004/1/19 22:12</td>
<td>3:15</td>
<td>9.5</td>
<td>MER-B</td>
<td>9</td>
<td>3</td>
<td>700</td>
<td>3.2</td>
<td>2</td>
</tr>
<tr>
<td>E</td>
<td>2004/1/21 22:12</td>
<td>3:15</td>
<td>10</td>
<td>MER-B</td>
<td>9</td>
<td>3</td>
<td>700</td>
<td>2.6</td>
<td>2</td>
</tr>
<tr>
<td>F</td>
<td>2004/1/23 22:12</td>
<td>3:15</td>
<td>9</td>
<td>MER-B</td>
<td>10</td>
<td>3</td>
<td>700</td>
<td>2.5</td>
<td>2</td>
</tr>
<tr>
<td>G</td>
<td>2004/3/24 10:30</td>
<td>6:24</td>
<td>6.5</td>
<td>Stardust</td>
<td>-21</td>
<td>3</td>
<td>200</td>
<td>7.4</td>
<td>7</td>
</tr>
<tr>
<td>H</td>
<td>2004/4/9 19:14</td>
<td>6:43</td>
<td>10</td>
<td>MGS</td>
<td>23</td>
<td>3</td>
<td>266</td>
<td>3.7</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Odyssey</td>
<td>23</td>
<td>3</td>
<td>266</td>
<td>3.7</td>
<td>4</td>
</tr>
<tr>
<td>J</td>
<td>2004/5/20 18:00</td>
<td>8:08</td>
<td>9</td>
<td>MGS</td>
<td>24</td>
<td>3</td>
<td>200</td>
<td>3.6</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Odyssey</td>
<td>24</td>
<td>3</td>
<td>200</td>
<td>3.6</td>
<td>2</td>
</tr>
<tr>
<td>K</td>
<td>2004/6/30 15:00</td>
<td>5:38</td>
<td>10</td>
<td>Cassini</td>
<td>22</td>
<td>4</td>
<td>750</td>
<td>5.4</td>
<td>9</td>
</tr>
<tr>
<td>L</td>
<td>2004/8/23 16:30</td>
<td>4:28</td>
<td>10</td>
<td>Odyssey</td>
<td>9</td>
<td>3</td>
<td>180</td>
<td>2.6</td>
<td>2</td>
</tr>
<tr>
<td>M</td>
<td>2004/9/8 13:00</td>
<td>5:38</td>
<td>9</td>
<td>Cassini</td>
<td>21</td>
<td>4</td>
<td>350</td>
<td>3.1</td>
<td>2</td>
</tr>
</tbody>
</table>
Navigation Feasibility Study

Essential Conclusions

Pilot Project achieved a priori goal, 1 nrad positional accuracy (200 µas).
NRAO spacecraft images within 1-4 nrad of well-determined orbits.
JPL analysis found inclusion of VLBA total delays halved formal error of overall orbit fit.
Accuracy limited primarily by catalog precision and atmosphere.
JPL acknowledged VLBA observations can provide valuable complement to DSN in-house VLBI technique.
Navigation Feasibility Study

“Quasi-Operational” Spacecraft Navigation

One day after formal end of Pilot Project, NRAO received request from Cassini mission for VLBA spacecraft navigation measurements.

Goal: help measure mass of Saturnian satellite Iapetus.
  Huygens probe will pass close to Iapetus en route to Titan.

Target of Opportunity observation organized; 5 runs of 1 or 3 hours over 7 days; same reference calibrators used.

Analysis in process at JPL.
Implementation Studies

Navigation Implementation Study
Scheduling/correlator software upgrades.
New AIPS tasks.

Mark 5 Implementation Study
Station/correlator control software upgrades to support Mark 5A.
Partial design of Playback Interface hardware replacement, for eventual upgrade to Mark 5B.

VLBA Ka-Band System Design Study
Receiver similar to EVLA design; feed similar to GBT.
X/Ka-band dual-frequency dichroic system option.
Current Project Status

Pilot Project Completed

Final report submitted 2004/12/1
Wrap-up meeting held at JPL 2004/12/10

Follow-on Project(s) Under Discussion

Continued technical studies.
   Establish reliability of VLBA spacecraft navigation observations.
   Develop approach to integration into VLBA and JPL operations.
Implementation of new equipment and catalog.
   Mark 5 recording system.
   Ka-band receivers.
   Ka-band calibrator catalog.
Thanks to these NRAO Personnel

Project Manager
Jon Romney

Navigation Feasibility & Implementation Studies
John Benson
Vivek Dhawan
Ed Fomalont
Craig Walker
Bob Zavala

Mark 5 Implementation Study
Walter Brisken
Barry Clark
Juan Cordova
Mike Revnell
Bruce Rowen

Ka-Band Implementation Study
Bob Hayward
Ylva Pihlstroem
Marian Pospieszalski
Sivasankaran Srikanth
Jon Thunborg
John Webber
End
New Initiatives in Cosmic Microwave Background Studies

Steven T. Myers

National Radio Astronomy Observatory

Socorro, NM
Where we are
WMAP Satellite

ACBAR
WMAP: 5-band images of the sky

- HEALpix maps:
  - K: 23GHz
  - Ka: 33GHz
  - Q: 41GHz
  - W: 94GHz
  - V: 61GHz

CBI 2000+2001, WMAP, ACBAR, BIMA

Secondary CMB

SZE Secondary

$\ell$
Polarization: WMAP & DASI

Carlstrom et al. 2003 astro-ph/0308478

Leitch et al. 2004 astro-ph/0409357
New: CBI Polarization Power Spectra

7-band fits ($\Delta l = 150$)
10-band fits ($\Delta l = 100$)

CBI Spectra for Polarization TT

CBI Spectra for Polarization EE

CBI Spectra for Polarization BB

CBI Spectra for Polarization TE
New: CBI, DASI, Capmap EE

![Graph showing CBI, DASI, and Capmap data compared to WMAP LCDM PL.](image)
Forefronts - CBI & DASI Fields

galactic projection – image WMAP “synchrotron” (Bennett et al. 2003)
Anomalous Microwave Emission

- Spinning dust or very hot HII? seen in NCP region
SZE Sample from 60 OVRO/BIMA imaged clusters, 0.07 < \( z < 1.03 \)
Summary

- CMB temperature power spectrum measured
- CMB polarization power spectrum measured
- SZE secondary possibly detected
- SZE imaging “routine”
- Foregrounds (other than point sources) not yet limiting
Where we need to go
Planck Projections

Planck “error boxes”

Note: polarization peaks out of phase w.r.t. intensity peaks

B-modes from Inflation: Beyond Einstein mission key mission goal.

B-modes from Lensing: dominant signal.

Hu & Dodelson ARAA 2002
Intermediate $l$ goals

- The goal: EE and BB (lensing)

Gravity-wave B-modes: for T/S ratio of 0.001

B-modes from Lensing: reachable from ground.
Forefront Projections

- Will BB (lensing) be foreground limited?
Point Source Foregrounds

- High-frequency population unknown at mJy levels
  - Toffolatti et al. 2004 (astro-ph/0410605) in dispute:
Diffuse Foregrounds

- Spinning dust (Draine, Lazarian, et al.) – not confirmed
Secondary Anisotropies

Primary Anisotropies

recombination
z~1000

reionization
z~10

Planck rel.

\(\Lambda\)-domination
z~1

Doppler

SZ

ISW

Lensing

Courtesy Wayne Hu – http://background.uchicago.edu
Gravitational Secondaries: Lensing

- due to CMB passing through potential fluctuations
  - spatial (lensing) & temporal (ISW, Rees-Sciama)
- dominant effect: CMB lensing by large-scale structure
  - distorts the background temperature and polarization
  - converts E $\rightarrow$ B polarization
  - can reconstruct from T, E, B on arcminute scales
  - can probe clusters

Courtesy Wayne Hu – http://background.uchicago.edu
Scattering Secondaries

- Due to variations in density, velocity, ionization:

At high $l$: SZ dominant, must disentangle others

Courtesy Wayne Hu – http://background.uchicago.edu
e.g. SZE Secondary Anisotropies

- Spectral distortion of CMB
- Dominated by massive halos (galaxy clusters)
- Low-z clusters: ~ 20’-30’
- z=1: ~1’ \rightarrow\text{expected dominant signal in CMB on small angular scales}
- Amplitude highly sensitive to $\sigma_8$

A. Cooray (astro-ph/0203048)

Goals & Requirements

• Primary anisotropies: non-Gaussianity
  – sensitive wide-field images
• Primary anisotropies: BB polarization
  – degree scales: all-sky, satellites; but lensing foreground
• Secondary anisotropies: SZE & EE/BB lensing
  – moderate sized fields, can be done from ground, multi-band
• other secondaries very difficult (but possible)
  – need spectral information and cross-correlation with templates
• foregrounds: will likely limit the sensitivity of observations
  – need multi-wavelength surveys for correction or templates
  – knowledge of mJy source populations at 30-100 GHz
  – not glamorous but necessary!
Future CMB Instruments
Current & Future “CMB” Experiments

- CMB Polarization:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>FWHM [°]</th>
<th>ν [GHz]</th>
<th>N</th>
<th>Type</th>
<th>Pol. Modulation</th>
<th>Site</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>In progress</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CBI</td>
<td>0.75</td>
<td>30</td>
<td>13</td>
<td>HEMT</td>
<td>Multiplying interf.</td>
<td>Chile</td>
<td>Readhead2004, Padin2002</td>
</tr>
<tr>
<td>CAPMAP</td>
<td>0.06-0.14</td>
<td>40,90</td>
<td>4,12</td>
<td>MMIC-LNA</td>
<td>Phase Switched LO</td>
<td>NJ</td>
<td>Barkats2004</td>
</tr>
<tr>
<td>Maxipol</td>
<td>0.17</td>
<td>140,420</td>
<td>12.4</td>
<td>Bolometer</td>
<td>1-2-wave plate</td>
<td>Balloon</td>
<td>Johnson2003</td>
</tr>
<tr>
<td>B2K</td>
<td>0.11-0.16</td>
<td>145,245,345</td>
<td>(4,2,2)×2</td>
<td>Bolometer</td>
<td>Spatial</td>
<td>Balloon</td>
<td>Monroy2003</td>
</tr>
<tr>
<td>WMAP</td>
<td>0.21-0.82</td>
<td>22,30,40,60,90</td>
<td>(1,1,2,2,4)×2</td>
<td>HEMT</td>
<td>Scan</td>
<td>L2</td>
<td>Kogut2003</td>
</tr>
<tr>
<td>In development</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KUPID</td>
<td>0.2</td>
<td>12-18</td>
<td>1</td>
<td>HEMT</td>
<td>RF Phase Switch</td>
<td>NJ</td>
<td>Gundersen2003</td>
</tr>
<tr>
<td>QUaD</td>
<td>0.07</td>
<td>100,150</td>
<td>(12,19)×2</td>
<td>PSB</td>
<td>1-2-wave plate</td>
<td>SP</td>
<td>Bowden2004, Church2003</td>
</tr>
<tr>
<td>BICEP</td>
<td>1.07</td>
<td>100,150</td>
<td>(16,32)×2</td>
<td>PSB</td>
<td>Faraday Switch</td>
<td>SP</td>
<td>Keating2003</td>
</tr>
<tr>
<td>Planck</td>
<td>0.23-0.55</td>
<td>30,41,70</td>
<td>(2,3,6)×2</td>
<td>MMIC-LNA</td>
<td>Scan</td>
<td>L2</td>
<td>Lawrence2003</td>
</tr>
<tr>
<td>MBI</td>
<td>0.08-0.15</td>
<td>100,143,217,353</td>
<td>(4,4,4)×2</td>
<td>PSB</td>
<td></td>
<td></td>
<td>Lemaire2003</td>
</tr>
<tr>
<td>SPORT</td>
<td>1.4</td>
<td>90,180,270</td>
<td>1.1,2</td>
<td>Bolometer</td>
<td>Adding Interf.</td>
<td></td>
<td>Tucker2003</td>
</tr>
<tr>
<td>AMiBA</td>
<td>7</td>
<td>22,32,90</td>
<td>19</td>
<td>HEMT</td>
<td>RF Phase Switch</td>
<td>Space St.</td>
<td>Carretti2002</td>
</tr>
<tr>
<td>CLOVER</td>
<td>0.25</td>
<td>90,150,220</td>
<td>(256,256,256)×2</td>
<td>MMIC-LNA</td>
<td>Multiplying Interf.</td>
<td>Hawaii</td>
<td>Lo2000</td>
</tr>
<tr>
<td>QUIET</td>
<td></td>
<td></td>
<td></td>
<td>PSB</td>
<td>Scan</td>
<td>Dome C</td>
<td>Taylor2004</td>
</tr>
<tr>
<td>Large scale</td>
<td>0.15-0.35</td>
<td>90,40</td>
<td>794,91</td>
<td>MMIC Pol.</td>
<td>RF Phase Switched</td>
<td>Chile</td>
<td>Gaier2003</td>
</tr>
<tr>
<td>Small</td>
<td>0.06-0.14</td>
<td>90 or 40</td>
<td>397 or 91</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- PSB based instruments (Planck HFI, QUad, BICEP, etc.)
- MMIC based instruments (Planck LFI, QUIET, etc.)
Current & Future “CMB” Experiments

- SZA [8x3.5m], SPT [8m] (Carlstom) – cluster counts
- ACT [6m] (Penn/Princeton) – CMB, cluster counts
- BLAST [1.9m] (Penn/Toronto/UBC) – sub-mm counts
- APEX [12m] (MPI) – dusty galaxies
- Atacama 25-meter (Cornell/Caltech) – FIR/sub-mm
MMIC Array Technology

- Allows fabrication of large-format heterodyne arrays:

Array element: Complete 100 GHz Polarimeter receiver in a Plug-in Module

- Input Waveguide From OMT
- Detector Diodes
- 180 deg Coupler
- Amplifier
- Bandpass Filter
- Phase Switch
- JEDEC STD Plug-in Module
QUIET

- JPL (Todd Gaier)
- test on CBI platform as 100-element horn array
- aim for 1000-element array on 6-8m telescope
- cross-correlation for polarization
NRAO & CMB
What is NRAO doing for CMB?

- HEMT development & fabrication (Pospieszalski)
- CBI science & analysis (Myers, Mason)
- GBT Ka-band follow-up of foregrounds (Mason, CIT)
- GBT Penn Array (Mason, UPenn)
- foregrounds with VLA & GBT (various)
CBI Upgrade: New NRAO HEMTs

Ka-band Receiver

Noise Temperature (K) vs. Frequency (GHz)

- Frequency ranges from 26 GHz to 40 GHz.
- Noise temperature varies from approximately 5 K to 20 K.

The graph shows the noise temperature of a Ka-band receiver as a function of frequency.
Penn Array Receiver

- 86 to 94 GHz bandpass initially
- 8 by 8 array of TES bolometric detectors
- beam: 8” fwhm
- A fully sampled (0.5fλ) focal plane
- Background limited detectors
### GBT: PennArray In 1 hour

<table>
<thead>
<tr>
<th>Observing mode</th>
<th>Sky coverage</th>
<th>Sensitivity (1σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point source (switching)</td>
<td>32'' × 32''</td>
<td>2.5 µJy</td>
</tr>
<tr>
<td>Slow scanning</td>
<td>5' × 5'</td>
<td>25 µJy</td>
</tr>
<tr>
<td>Fast scanning</td>
<td>1° × 1°</td>
<td>290 µJy</td>
</tr>
</tbody>
</table>

- Photometric redshifts for known sources
- Observations of the galactic center
- Measuring the albedo of known Trans-Neptunian objects
- High resolution maps of the Sunyaev-Zel'dovich effect
- Understanding the physics of star and planet formation
- Studies of centimeter-sized dust grains in the Solar system
- Large area surveys: bright point sources, galactic plane etc
The SZE with Penn Array

With Nobeyama 45m
80" resolution @21GHz
0.5 mJy/beam
34 hour integration

With the GBT
8" resolution @90GHz
0.05 mJy/beam
15 minute integration
Z~0.08 → 8"=8 kpc!

⇒ 8 μJy in 10 hours
5'×5' map
SNR ~5 in core of nearby cluster
GBT 1-cm Receiver

• Frequency range 26-40 GHz
• MAP-style balanced radiometers (1/f rejection)
• Two-horn, dual polarization, 0.25 mJy in 1 sec
• Caltech backend ➔ fast switching (also 3mm Rx)
What could NRAO do in CMB?

- MMIC development & fabrication
- contribute to CBI operations
- GBT foreground surveys (C,X,Ku)
- GBT Mega-pixel Array (bolometer or heterodyne)
- ALMA 30 GHz
- EVLA E-configuration
- join a big CMB project (ground and/or space)
- sky surveys (EVLA, GBT, ALMA) for foregrounds
ALMA Cosmology

- Sub-mm galaxies identification and followup
- High-resolution CMB & SZE at 30 GHz
The Cosmic Background Imager

- 13 90-cm Cassegrain antennas
  - 78 baselines
- 6-meter platform
  - Baselines 1m – 5.51m
- 10 1 GHz channels 26-36 GHz
  - HEMT amplifiers (NRAO)
  - Cryogenic 6K, Tsys 20 K
- Single polarization (R or L)
  - Polarizers from U. Chicago
- Analog correlators
  - 780 complex correlators
- Field-of-view 44 arcmin
  - Image noise 4 mJy/bm 900s
- Resolution 4.5 – 10 arcmin
- Rotatable platform
CBI Status & Future

- It is working well!
- Significant gains projected through 2006
- Currently unfunded (in debt)
- NSF proposal submitted Nov04, but funding gap
- Shutdown in Jan 2005 (need ~200K$)
- Already NRAO involvement (Myers, Mason, Pospiesalski)
CBI Projections

- Run through 2006: EE 2.7× & BB 3.5× improvement
New Initiatives
New Initiatives in CMB: Small

- **GBT: Continuum receivers**
  - Upgrade C, X, Ku (& possibly K) to balanced design
  - Enables sensitive continuum mapping (CMB foregrounds)
- **EVLA E-configuration & ALMA 30 GHz**
  - Increases surface brightness sensitivity
  - complementary (EVLA@15 GHz = ALMA@30 GHz)
  - Enables SZE and diffuse foreground studies
- **CBI support**
  - modest investment to keep Chile operations running
  - Caltech looking for partners (at 200K$ level)
  - CBI partner automatically part of QUIET
  - NSF funding future (CBI & QUIET) uncertain, but our support could make a large difference
New Initiatives in CMB: Large

• GBT: Mega-pixel array
  – build on experience from PennArray
  – large bolometer camera
  – or large heterodyne focal-plane array
  – Enables deep 3mm imaging or spectroscopy
  – bolometer: best mapping performance, highest sensitivity
  – heterodyne: allows spectroscopy, imaging more difficult
  – do we just buy the camera, or invest in development ourselves?

• New technology investment
  – build (or buy up!) major lab for MMIC or bolometer development
  – bolometers: several existing big groups (NIST,Goddard,UCB,JPL)
  – MMIC: JPL (currently unfunded)
  – or something different…
New Initiatives in CMB: Interferometry

- CBI, DASI, & VSA have demonstrated the utility of interferometry for CMB (particularly for polarization)
- sensitivity limited by number of elements
  - would need 100’s of elements
  - could combine FPA and interferometer for multi-beaming
- would require massive wide-band correlators
  - development of inexpensive large-scale correlators
  - of interest to other next generation big arrays (e.g. SKA)
- would be competing against bolometer & MMIC arrays
  - but interferometer polarization systematics much cleaner!
- risky & expensive, but worth exploring…
New Initiatives in CMB: Other

- Beyond our current portfolio (ALMA, EVLA, GBT)
  - complementary telescopes, e.g. Atacama 25-m
  - space missions
  - instruments on other telescopes, e.g. SCUBA-2

- Partnership
  - what do we bring to the table (other than $$)?
  - what do we get (other than observing time)?
New Initiatives in CMB: Sky Surveys

• Needed for CMB foreground templates
  – high-frequency source population & polarization unknown!

• EVLA
  – NVSS & FIRST insufficient
  – C or X band survey at mJy level (plus deeper S & L surveys)
  – OTF scanning (need to cover $>10^4$ sq. degrees)
  – wide-band continuum mapping (algorithm development necessary)
  – start early in EVLA lifetime (don’t wait!)
  – enables other projects (e.g. gravitational lens surveys)
  – E-configuration diffuse polarized emission survey also possible

• GBT
  – 3mm Penn Array survey
  – mega-pixel camera surveys if instrumented
Conclusions

• Few easy or clear answers
• “Sure” “crazy-not-to” winners
  – EVLA sky surveys! start in 2009 (or before)
  – better GBT continuum receivers (C-K bands)
    • make sure enough funds & manpower available!
• “Sure” “find someway to do it” winners
  – GBT mega-pixel camera (3mm bolometer array)
  – EVLA E-configuration
  – ALMA 30 GHz
• Riskier
  – major investment in bolometer or MMIC technology development
  – develop technology for large-scale CMB interferometry!
  – completely new telescopes (e.g. Atacama 25-m)
History of IGM

• bench-mark in cosmic structure formation indicating the first luminous structures
The Gunn Peterson Effect

Fast reionization at $z=6.3$
$\Rightarrow$ opaque at $\lambda_{\text{obs}} < 0.9 \mu m$
$f(\text{HI}) > 0.001$ at $z = 6.3$

Fan et al 2003
Z_{host}(CO) = 6.419; Z_{gp} = 6.32 \Rightarrow \text{photons leaking 6.32<z<6.419}

‘time bounded’ Stromgren sphere: R = 4.7 \text{ Mpc} \Rightarrow

- t_{qso}= 1e5 R^3 f(\text{HI})= 1e7\text{yrs} \text{ for } f(\text{HI}) = 1 \text{ or}
- f(\text{HI}) > 0.1 \text{ at } z>6.2 \text{ for } t_{qso} = t_{\text{fid}} > 1e6 \text{ yrs}
Loeb & Rybicki 2000
Complex reionization $z=6.3$ to 17?

- GP $\Rightarrow$ fairly fast at $z=6.2$

- CSS $\Rightarrow$ very fast at $z=6.2$?

- WMAP $\Rightarrow$ complex to $z=17$?

See also Cosmic Stromgren Surfaces (Mesinger & Haiman 04), but cf. Ly $\gamma$, Oh & Furlanetto 05
HI 21cm Tomography of IGM at 100 – 200 MHz
Zaldarriaga + 2003

- $\Delta T_B(2') = 10 \text{ s} \text{ mK}$
- SKA rms (100hr) = 4mK
- LOFAR rms (1000hr) = 80mK
VLA-VHF: 180 – 200 MHz
prime focus dipole (CfA/NRAO)

- Leverage: existing telescopes, IF, correlator, operations
- $110K D+D/construction (CfA)
- Labor (CfA/NRAO)

Table 1. Personnel & Responsibilities

<table>
<thead>
<tr>
<th>Personnel</th>
<th>Inst.</th>
<th>Background(*)</th>
<th>Responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>L. Greenhill</td>
<td>SAO</td>
<td>sei</td>
<td>Project scientist and manager; data analysis</td>
</tr>
<tr>
<td>R. Blundell</td>
<td>SAO</td>
<td>sei/eng</td>
<td>Lead for SAO receiver lab activities</td>
</tr>
<tr>
<td>E. Tong</td>
<td>SAO</td>
<td>eng</td>
<td>Antennas and electronics design</td>
</tr>
<tr>
<td>R. Kimberk</td>
<td>SAO</td>
<td>eng</td>
<td>Construction and lab testing; deployment</td>
</tr>
<tr>
<td>S. Leiker</td>
<td>SAO</td>
<td>eng</td>
<td>Construction and lab testing; deployment</td>
</tr>
<tr>
<td>C. Carilli</td>
<td>NRAO</td>
<td>sei</td>
<td>Prototype testing; commissioning calibration and measurement; data analysis</td>
</tr>
<tr>
<td>R. Perley</td>
<td>NRAO</td>
<td>sei/eng</td>
<td>Prototype testing; commissioning calibration and measurement; data analysis</td>
</tr>
<tr>
<td>A. Loch</td>
<td>Harvard</td>
<td>sei</td>
<td>Theory and modelling</td>
</tr>
<tr>
<td>M. Zaldarriaga</td>
<td>Harvard</td>
<td>sei</td>
<td>Theory and modelling</td>
</tr>
<tr>
<td>S. Furlanetto</td>
<td>CalTech</td>
<td>sei</td>
<td>Theory and modelling</td>
</tr>
</tbody>
</table>
Main Experiment: Cosmic Stromgren spheres around \( z=6 \) to 6.5 SDSS QSOs (Wyithe & Loeb 2004)

- VLA spectral/spatial resolution well matched to expected signal: 7’, 1000 km/s
- Set first hard limits on \( f(\text{HI}) \) at end of cosmic reionization (\( f(\text{HI}) < 0.3 \))
- Easily rule-out cold IGM (\( T_s < T_{\text{cmb}} \)): signal = 360 mK

\[ 20 \text{ f(\text{HI}) mK} \]

\[ 0.50^{+/-0.12} \text{ mJy} \]
System/Site characteristics

First sidelobe = 15db

Table 1. VLA Low Frequency Systems

<table>
<thead>
<tr>
<th>Band [MHz]</th>
<th>Passband [MHz]</th>
<th>$A_n$</th>
<th>$T_{rt}$ [K]</th>
<th>$T_{sky}$ [K]</th>
<th>$D/\lambda$</th>
<th>RMS(10min) [mJy]</th>
<th>$\Delta/\lambda$</th>
<th>Focus loss</th>
<th>FoV$^\dagger$ [°]</th>
<th>(FoV/sealed rms)$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>74</td>
<td>73-74.5</td>
<td>0.15</td>
<td>$\ldots$</td>
<td>$10^2$</td>
<td>6</td>
<td>150</td>
<td>0.10</td>
<td>0.01</td>
<td>9.3</td>
<td>0.004</td>
</tr>
<tr>
<td>VHF</td>
<td>178-202</td>
<td>0.50</td>
<td>60$^*$</td>
<td>100</td>
<td>16</td>
<td>2</td>
<td>0.27</td>
<td>0.08</td>
<td>3.5</td>
<td>0.43</td>
</tr>
<tr>
<td>320</td>
<td>305-337</td>
<td>0.40</td>
<td>100$^*$</td>
<td>25</td>
<td>27</td>
<td>1.4</td>
<td>0.43</td>
<td>0.24</td>
<td>2.1</td>
<td>0.11</td>
</tr>
<tr>
<td>1400</td>
<td>1240-1700</td>
<td>0.55</td>
<td>30</td>
<td>3</td>
<td>125</td>
<td>0.06</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
<td>0.5</td>
<td>0.25</td>
</tr>
</tbody>
</table>
0.5db loss (12\%) at 327 due VHF
Challenges and ‘mitigation’: VLA-VHF CSS

- Ionospheric phase errors – Freq^-2; 4deg FoV; 1km B_max
- Sky temp = 100 (ν/200 MHz)^-2.6 K
- Confusion (in-beam) – spectral measurement (eg. Morales & Hewitt 2004); mJy point source removal w. A array; precise position and redshift
- Wide field problems – polarization, sidelobes, bandpass – all chromatic?
- RFI – “interferometric excision” (but D array); consistently ‘clean’ times in monitor plots (but very insensitive measure)?
- Effect on P/L?
Timeline:  Funding proposal accepted SAO Aug04

- Observing proposal NRAO Sept 04
- P/VHF feed tests  SAO Dec 04
- M+T doc. for NRAO Dec04
- Construct 10:1 scale model  SAO Dec 04
- Construct/deliver prototype  SAO Jan05
- Single dish tests: RFI, impact L/P, T_sys, beam, eff… VLA  Jan-Feb 05
- Interferometric tests 4 ants Mar-Apr 05
- Final design choice (fixed/deployable) Apr 05
- Full const/installation May – Aug 05
- First exp (150hr) D array Q4 05
- Large proposal: D array, Q1 07
Probing Cosmic Reionization with the VLA

• High freq: Study physics of the first luminous sources – mol gas + star form/AGN

• VHF: study process of reionization via CSS → set first hard constraints on f(HI) (<0.3) during the EoR

• Legacy: free new Rx band, potentially ‘band of choice’ at low frequencies
The Square Kilometre Array

- What?
- Why?
- How?
- Where?
- When?
- Who?
- How Much?
- Issues and problems
Official SKA design goals

• Aeff/Tsys: $2 \times 10^4$ m$^2$/K
  ($T_{\text{sys}} = 0.2$Jy) ($T_{\text{sys/VLA}} = 16$Jy)
• $\sigma = 50$ nanoJy rms - 1 hour
• Angular resolution: 0.1 arcsec or better @ 1.4 GHz
• Frequency range 300 MHz - 30 GHz
• Imaging Field of View: 1 square deg. @ 1.4 GHz
• Number of instantaneous pencil beams: 100
• Number of pixels: $10^8$
• Surface brightness: 1K @ 0.1 arcsec (continuum)
• Instantaneous bandwidth: 0.5 + $f/5$ GHz
• Minimum number of spectral channels: $10^4$
• Number of widely spaced, simultaneous frequency bands: 2
• Polarisation purity: -40 dB
• Dynamic range: $10^{6-7}$
Radio Telescope Sensitivity

Jansky
Reber
Cam b. Int.
2C
3C
Caltech
5C1
5C2
WSRT
VLA
VLA
WSRT
(EVLA)
(SKA)

Sensitivity - $10^{10}$
Cost – $10^5$
Cost $\alpha$ Sensitivity$^{1/2}$


Minimum Detected Flux Density

Year
Confusion may be a problem

Angular Resolution Required to Avoid Confusion

Array Dimensions Needed to Avoid Confusion

Natural confusion
VLA: 42 hours
MERLIN 18 x 24 hours
Key Science Goals
http://www.aoc.nrao.edu/~ccarilli/DHAPS.shtml

• The Cradle of Life
• Probing the Dark Ages
• Origin and evolution of cosmic magnetism
• Strong field tests of gravity (pulsars & black holes)
• Evolution of galaxies and large scale structure
• Exploration of the unknown
Astronomy is an observational science. We cannot do experiments. We can only observe, and we should not be afraid discovering something new. Today’s hot new issues (fads) are tomorrow’s old issues.

The excitement of the SKA will be not in the old questions it will answer but in the new questions it will raise.
Radio Astronomy Discoveries

- Cosmic radio noise
- Non thermal radiation
- Solar radio bursts
- Jupiter radio bursts
- Rotation of Mercury
- Internal heat source in giant planets
- Giant molecular clouds
- Cosmic masers
- Extrasolar planetary systems
- Radio Galaxies (black holes)
- Cosmic evolution
- Quasars
- Relativistic jets
- Pulsars (neutron stars)
- Gravitation lensing
- Gravitational radiation
- Cosmic Microwave Background
Why radio?

• The sky is nearly empty, so we can use unfilled apertures.
• Long coherent integration times are possible
• We can build amplifiers and split the signal without loss
• High resolution diffraction limited imaging is possible with post processing so that adaptive optics at radio frequencies involves no precision moving parts
• But, large radio telescopes are needed! Even moderate sized radio telescopes are uninteresting.
How to build the SKA

• *Brute force* – Replace all EVLA antennas (27 VLA + 8 NMA + 10 VLBA) with 45 GBTs. Use EVLA infrastructure - fiber, correlator, receivers, computers, software: *Cost about $ 5 x 10^9*

• *Be Clever!*
Square Km Array

Europe

USA

Canada

Australia

China

India
Europe
SKADS (€ 32 M)
1 x 500 m² array at WSRT
3 x 100 m²
Upgrade of Bologna Cross
Canada
LAR
200 m prototype

Large Adaptive Reflector
SKAMP

HIFAR

Australia
MNRF

MWA (son of LOFAR) with Haystack 80-300 MHz
China

Brief Introduction on Shangjiachong Karst Depression in Puding County, Guizhou Province, China

FAST
Five hundred meter Aperture Spherical Telescope
U.S. Consortium Concept
ATA type Synthesis Array

Large N/Small D

Why parabolic dishes?
- experience
- sky coverage
- frequency coverage

Why large N?
- collecting area
- dynamic range
- baseline diversity
- snapshot mode
- self-calibration
- RFI excision

Why small D?
- field-of-view
- minimizes cost?

4400 x 12 m dishes
Where will the SKA be built?

- RFI environment (low population density)
- Troposphere stability (high dry desert site)
- Southern hemisphere – Galactic Center
- Political issues – who has the money. He who has the gold rules!
- 6 preliminary proposals submitted
  - U.S, Australia, South Africa, China, Argentina, (Brazil)
- Siting RFP issued September, 2004
- Site proposals due December 31, 2005
- 2006 Site selection or down-selection
Distribution of RFI
Northern Cape Province, South Africa
Argentine Site
- Infrastructure
- Roads
- Fiber
- Schools
- Medical facilities
- Scientists/Engineers
- Federal Labs, Nat. Obs
- VLA
  - Long term site data
  - Good phase stability
  - RFI?
  - Political situation?
US – Large-N/Small-D

2320 x 12m antennas within 35 km core

84 stations 35-350 km
76 stations 350-3500 km

Inexpensive, hydroformed dishes
US SKA Configuration

Centrally condensed
Scale free array
2320 antenna inside 35 km
84 stations: 35 to 350 km
76 stations: 350 to 3500 km

Resolution 0.01 arcsec @ 21 cm

Scale free configuration adopted to accommodate a wide range of scientific goals, but this is controversial.
When

- **1994** IAU/URSI Large radio telescope WG formed
- **1998** Green Bank Workshop
- **1999** Formation of U.S. SKA Consortium
- **2000** MOU signed by six groups, ISSC formed
- **2002** Seven design concepts (white papers) received by ISSC
- **2004 Sept:** Siting RFP
- **2005 Dec 31:** Site proposals due
- **2006** Site selection or down-selection
- **2008** Facility definition, plan pathfinder/prototype/demonstrator
- **2009** Start pathfinder construction (5-10% SKA)
- **2011** Propose SKA construction
- **2012** Start construction
- **2015** First Science
- **2020** Full operation
International SKA Steering Committee (ISSC)
22 members representing 12 countries
Chair: Phil Diamond (MERLIN)

– 6 European (UK, Germany, Netherlands, UK, Italy, +1)
– 6 United States (Tarter, Welch, Terzian, Kellermann, Preston, Cordes, +1)
– 2 Canada
– 2 Australia
– 2 Asia (China, India)
– 1 (South Africa)
– 1 At-large member (Ekers)
<table>
<thead>
<tr>
<th>Engineering Working Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chair: Peter Hall (Australia)</td>
</tr>
<tr>
<td>Antennas</td>
</tr>
<tr>
<td>Software &amp; Computing – Tim Cornwell</td>
</tr>
<tr>
<td>Signal Transmission</td>
</tr>
<tr>
<td>RF Systems</td>
</tr>
<tr>
<td>Signal processing – Larry D’Addario</td>
</tr>
<tr>
<td>Interference mitigation</td>
</tr>
<tr>
<td>Systems Engineering – Dick Thompson</td>
</tr>
<tr>
<td>Industrial liaison</td>
</tr>
</tbody>
</table>
International Project Office
Director: Richard Schilizzi
Project Engineer: Peter Hall

• 2004 Budget: $185 K for Project Director
  – 1/3 from U.S.
    • 50 K from NSF grant to U.S. Consortium
    • 12 K from member dues to Consortium

• 2005 Budget: $707K Euro = $947K
  – Project Director
  – Project Engineer (currently supported by Australia)
  – RFI testing (currently supported by ASTRON)
  – 1/3 from U.S. or $315K
    • $150K available from NSF grant and consortium funds
US SKA Consortium*

Chair: Yervant Terzian (Cornell)
Vice Chair: Jack Welch (UCB)

Caltech/JPL
Cornell/NAIC
Harvard/Smithsonian CfA
MIT/Haystack
NRAO (KIK, RCW)
NRL
SETI Institute

Virginia Tech
University of Minnesota
University of New Mexico
UC Berkeley
University of Illinois
University of Wisconsin

*Each institution pays $3 K per year in dues for EPO, travel, IPO
## US SKA Prototype Activities

<table>
<thead>
<tr>
<th>Allen Telescope Array (SETI)</th>
<th>DSN Array</th>
<th>EVLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>310 6m dishes</td>
<td>3 x 3600 x 12m dishes</td>
<td>45 x 25m antennas</td>
</tr>
<tr>
<td>$f = 0.5$-11GHz</td>
<td>$f = 8/32$GHz</td>
<td>$f = 1$-50 (90) GHz</td>
</tr>
<tr>
<td><strong>2003</strong>: First antenna</td>
<td><strong>2003</strong> 6m prototype</td>
<td><strong>2001</strong> Start Upgrade</td>
</tr>
<tr>
<td><strong>2004</strong>: 3-elements?</td>
<td><strong>2005</strong> 2x6m interferometry + 1 x 12 m</td>
<td><strong>2006</strong> Start NMA construction</td>
</tr>
<tr>
<td><strong>2005</strong>: 32-elements?</td>
<td><strong>2008</strong> 6 x12m x 3 sites</td>
<td><strong>2012</strong> EVLA I Operation</td>
</tr>
<tr>
<td><strong>2006 or 7</strong>: 200 elements</td>
<td><strong>2013</strong> 400x12mx3 sites =1200</td>
<td><strong>2012</strong> EVLAII Operation</td>
</tr>
<tr>
<td><strong>Goal</strong>: 351 elements</td>
<td><strong>Expensive?</strong></td>
<td>Symmetric Antennas</td>
</tr>
</tbody>
</table>

**Symmetric Antennas**

45 x 25m antennas

$V_LAW+NMA+VLBA$

**Long Wavelength Array**
U.S. SKA Technology Development Program

- U.S. development program is currently supported via a 3 year $1.5M grant to Cornell – June 2002 to June 2005
- U.S. Technology Development Program $ 32 M proposed to NSF over 5 years. Managed by NAIC.
  - Antennas, Feeds, Optics, Receivers – Weinreb, JPL
  - Digital signal transport and processing – Cappallo, Hsk
  - System analysis and design – Jones, JPL
  - Operations and costing – Goldsmith, NAIC
  - ATA test facility – Bock? UCB
  - Site Proposal Preparation (due end of 2005) - UNM?
  - EPO – Tarter, SETI
  - International Project Office, exchange rate problem, NSF problem

- TDP competing with FASR, LWA, LSST, and TMT
- TDP funding not likely to receive full 32M; gap is likely
- Time scale (2005-2009) of TDP is a problem
  - 2008 Concept selection
  - 2006 Site selection

- TDP Review was held at the NSF on October 26
  - Unclear goals of TDP – does not lead to construction
  - Unclear management, what right has the ISSC to decide anything?
  - Cost and value of prototype hydroformed dish
Other SKA development programs

**Australia**
Major National Research Funding Program
HIFAR (AUD 100M)
MWA (AUD 50)
Site proposal (WA)

**Europe (SKADS)**
Square Km Array Design Studies
€ 32M (€ 14/10M EC),
34 Institutions in 13 “European” Countries - 5 year program
Netherlands, UK, Paris, Bologna, MPIfR, Spain, Russia, Canada, South Africa, Poland, Sweden, Australia

South Africa, Australia & Argentina have major funding for site proposal

Canada – LAR
NRAO and the SKA

- NRAO staff are heavily involved in the international SKA program. ISSC, EWG, SWG
- NRAO organized the first meeting of U.S. scientists interested in the SKA
- NRAO is a member of the U.S. SKA Consortium
- The U.S. LNSD White paper was prepared at NRAO
- NRAO has tried to keep a low profile in the organization of U.S. SKA activities. NRAO is not part of NSF TDP proposal
  - Zero sum game for NRAO
  - The planning and design of new facilities is part of our job. Most of the areas where we plan to contribute are spin-offs from EVLA development
    - Wide field high dynamic range imaging, data management, and archiving
    - Long distance data transmission
    - Site proposal – NMA sites
    - Building the scientific case
## How much will it cost?

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>4400 x 12 m antennas</td>
<td>$660 M</td>
</tr>
<tr>
<td>Receivers</td>
<td>170</td>
</tr>
<tr>
<td>Data transmission</td>
<td>40</td>
</tr>
<tr>
<td>Civil costs (central site)</td>
<td>65</td>
</tr>
<tr>
<td>Civil costs (outer configuration)</td>
<td>135</td>
</tr>
<tr>
<td>Signal processing</td>
<td>80</td>
</tr>
<tr>
<td>Computing hardware</td>
<td>80 (500?)</td>
</tr>
<tr>
<td>Software development (660 man years)</td>
<td>50</td>
</tr>
<tr>
<td>Non-recurring engineering</td>
<td>60</td>
</tr>
<tr>
<td>Contingency (20%)</td>
<td>270</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$1,610 M</strong></td>
</tr>
</tbody>
</table>
## How much will it cost to operate

<table>
<thead>
<tr>
<th>Department</th>
<th>FTE’s</th>
<th>Annual Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operations Staff</td>
<td>36 FTE’s</td>
<td>$ 1.8 M/year</td>
</tr>
<tr>
<td>Scientific Staff</td>
<td>30</td>
<td>3.0</td>
</tr>
<tr>
<td>Computing Hardware Support</td>
<td>10</td>
<td>0.9</td>
</tr>
<tr>
<td>Computing systems plus M/C</td>
<td>40</td>
<td>4.0</td>
</tr>
<tr>
<td>Data management</td>
<td>10</td>
<td>1.2</td>
</tr>
<tr>
<td>Central engineering</td>
<td>150</td>
<td>12.0</td>
</tr>
<tr>
<td>Distributed engineering</td>
<td>240</td>
<td>19.2</td>
</tr>
<tr>
<td>Administration</td>
<td>50</td>
<td>4.0</td>
</tr>
<tr>
<td>Fiber rental</td>
<td></td>
<td>10+??</td>
</tr>
<tr>
<td>M&amp;S</td>
<td></td>
<td>15.4</td>
</tr>
<tr>
<td>Upgrades (3% construction)</td>
<td></td>
<td>50.0</td>
</tr>
<tr>
<td>User support (3% construction)</td>
<td></td>
<td>50.0</td>
</tr>
<tr>
<td><strong>Total annual operating cost</strong></td>
<td></td>
<td><strong>$ 171.5</strong></td>
</tr>
</tbody>
</table>
Who is going to Pay for it?

• Default plan
  – U.S. 1/3
  – Europe 1/3
  – RoW (Canada, Australia, Asia, Africa) 1/3

• Problems with this plan
  – U.S. funding must wait until EVLA, LSST, ATSC, and TMT (aka GSMT)
  – NSF not interested in divesting control/power
  – European priority with OWL
  – Canada: may depend on choice of concept
  – Australia, South Africa may depend on site
Technical challenges for the SKA

• Constructing a cost effective SKA
  – Antenna elements
  – Low cost high reliability radiometers
  – High data rate signal transfer (100 x EVLA
  – Correlator
  – Wide field high dynamic range imaging
  – RFI mitigation
  – Data management and archiving
• Confusion levels - natural confusion
• Reliable and cost effective operations
Logistical, administrative, cultural, financial challenges

Funding an international project?
- SKA was international from the start
- Different funding/management cultures in each country

• Who is responsible for
  - Setting policy?
  - Fiscal accountability?
  - Program management?
  - Banking Issue

• Should there be
  - Strong central management – e.g., NRAO/AUI, ESO
  - Weak central management with power shared among partners – e.g., ALMA

• Intellectual Property Rights/ITAR/visas

• Continued broad participation after site and concept selection.

• Rationalization of construction schedule with U.S. TDP and European SKADS technology development schedules, and with expected funding profile.

• Competition from national ambitions (SKA demonstrators/prototypes)
  - US (ATA, EVLA, LWA, FASR)
  - Australia (HIFAR, MWA)
  - China (FAST)
  - Canada (LAR)
  - Europe (e-MERLIN, LOFAR)

• The SKA has been a catalyst for a wide range of technical investigations with applications to radio astronomy and space craft tracking.
Some SKA scenarios

- Build on EVLA = VLA/NMA/VLBA by increasing collecting area and using existing infrastructure, e.g., roads, power, fiber, skilled scientists and engineers currently in New Mexico.
  - This approach is probably decades away
- Build a low frequency ($\nu < 1$ GHz) array on a radio quiet site in Western Australia which complements the EVLA
  - Who will pay for it?
    - U.S. (NSF) should contribute as we need a facility for $\nu < 1$ GHz
    - RoW has been using VLA, Green Bank, Arecibo for free
      - Time for the RoW to provide their share
      - Will we have an open skies policy in the ALMA era
- NSF to negotiate with NASA for time on DSN array with NSF supported instrumentation for radio astronomy
Whither NRAO?

- Continue to muddle along with the crowd, write reports, go to meetings in exotic places.
- Assert leadership
- Forget it for the present. We have too many other things to do.
Resources for further study

Science Case:
http://www.aoc.nrao.edu/~ccarilli/DHAPS.shtml

International SKA:
http://www.skatelescope.org/

U.S. SKA
LNSD
U.S. Site Proposal
Current SKA Management Structure

ISSC
Chair: Tarter (USA)
Vice Chair: Butcher (Neth)

International Science Advisory committee
Chair: Carilli (USA)

International SKA Project Director
Richard Schilizzi

Site Evaluation and Selection
Chair: Terzian

Long term planning committee
Butcher, Kellermann
Schilizzi, Preston

Simulations Group

Engineering Management Team
Chair: Hall (Australia)

Industrial Relations Group

Outreach
Chair: Wilkinson (UK)
U.S. SKA Plan

- Complete ATA
- Continue DSN Prototype
- Develop new technologies with NSF funds
- Build LOFAR in U.S. South West (NM)
- Complete EVLA
- Grow SKA in the US Southwest using new antenna technology
SKA Goal – 40 x improvement in sensitivity over EVLA

• First epoch of star formation and galaxy formation at $z = 1$
  – Molecules at $z >> 1$
• NanoJy continuum surveys
  – 25 nJy rms in 1 hour
  – Normal Galaxies at $z = 1$
• Spiral galaxies HI at $z = 1$
  – CO at $z = 5$
• Transient radio sources
  – Giant pulses, flares
  – ISS – high resolution observations of pulsars, GRBs
• Radio galaxies, quasars, BH and relativistic beam physics
  – Acceleration near MBHs
• Magnetic fields
  – Jets, galaxies, clusters, Faraday rotation
• Cosmic (H$_2$O) masers
  – Geometric distance beyond the local flow
• Stars of all types - thermal
• Solar System
  – Asteroids, TNOs, radar
• Census of MilkyWay Pulsars
• SETI
New Mexico fiber installation
U.S. Proposal
North American Array
Most of collecting area is in New Mexico
About half the collecting area near VLA site

• Large, high, dry, site (VLA) is ideal
• Extensive infrastructure already in place in NM
  – Land, roads, fiber, personnel, universities, federal labs, national observatories
• Existing long term site studies for VLA/NMA/LOFAR – excellent sites
• Co-location with VLA+NMA+VLBA allows phased development
• Long term rfi situation unclear
LOFAR
The Low Frequency Array
Haystack, Astron, NRL, SWC*

Frequency: 10-240 MHz
Size: 400 km. 100 patches
Resolution: 2-20 arcsec
Elements: 2 x 13,000 dipoles
Sky coverage: Multiple beams
Location:
  SW United States (NM)
  Western Australia
  Netherlands

Time Table
  PDR June 2003
  Site Selection late 2003
  Initial Operations 2006
  Full Operations 2008

*UNM, LASL, U Tex, NMS, NM Tech
By products of SKA Development

• In other countries, e.g., Australia and Canada, there are major industrial components.

• In the U.S. an NSF grant to the SKA Consortium has revitalized university research in radio astronomy instrumentation.
SKA Cost Breakdown by Subsystem vs Antenna Diameter

A_{eff}/T_{sys} = 20,000, A_{eff}=360,000, T_{sys}=18K, BW=4GHz, 15K Cryogenics
Antenna Cost = 0.1D^{2.7} K$, 2001 Electronics Cost = $54K per Element
SKA History

- First Discussions: 1991
- 1994 URSI---IAU Large Radio Telescope WG formed
- 1997 S&T Workshop, Leiden, Netherlands
- 1998 S&T Workshop, Calgary, Alberta, Canada
- 1998 S&T Workshop, Green Bank, WV
- 1999 S&T Workshops, Leiden & Dwingeloo, Netherlands
- 2000 S&T Workshop, Manchester, UK
- 2000 ISSC formed, MOU signed at IAU GA
- 2001 S&T Workshop, Berkeley, CA, USA
- 2002 S&T Workshops, Bologna, Italy, Groningen, Netherlands
- 2003 S&T Workshop, Geraldton, WA, Australia, July, 28-31
A Foot Print of Time

A lasting impression....
DDP116 at the Green Bank Interferometer
It is said to be BGC’s footprint