A U.S. Perspective on mm-VLBI

Colin Lonsdale

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Scientific Landscape

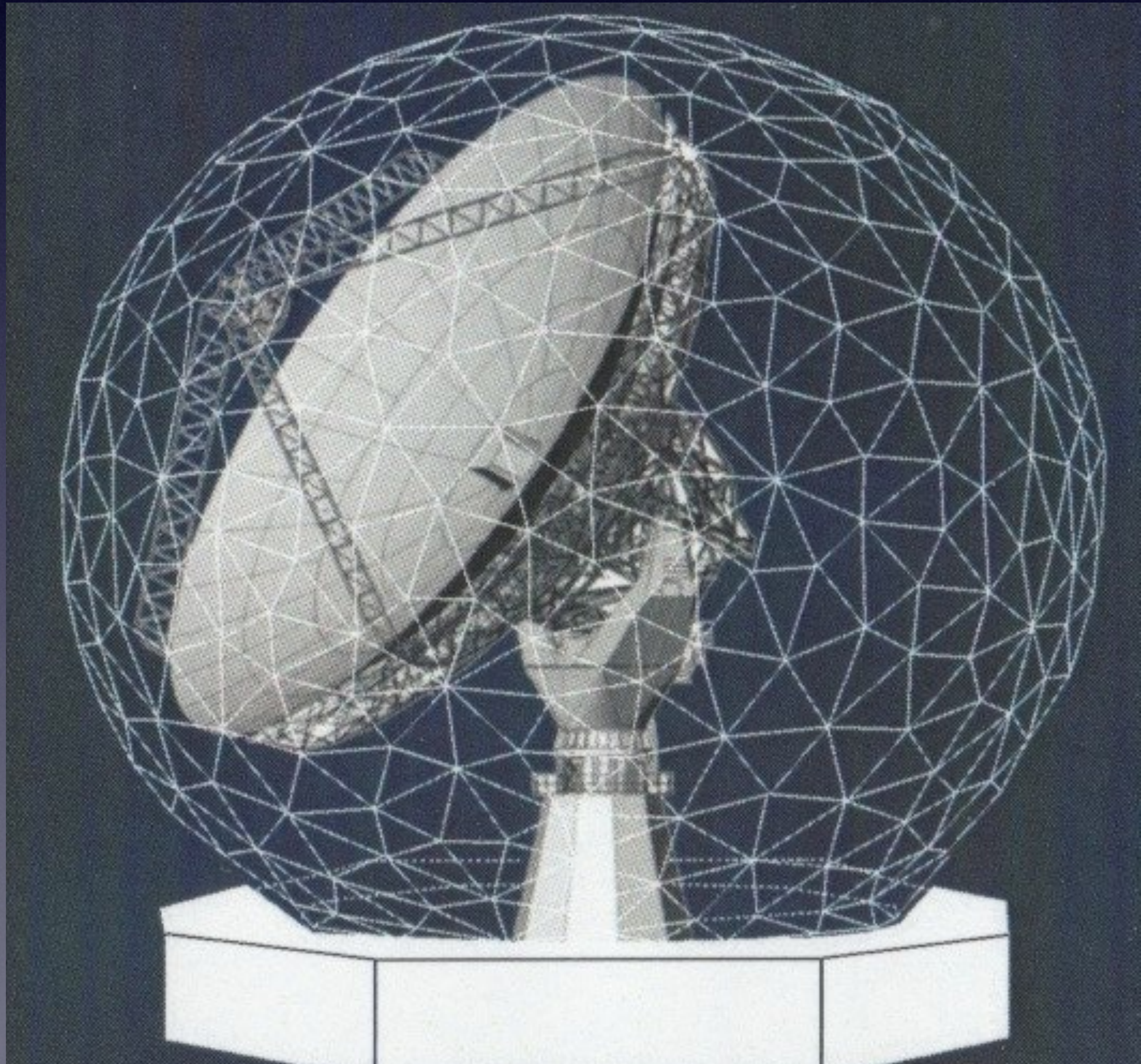
- **mm-VLBI is in infancy, despite excellent results**
  - Sensitivities have been low
  - Target lists have been short
  - Polarimetry is challenging
- **Things are poised to change**
  - Complement angular resolution with other qualities
  - Polarimetry, e.g. of AGN cores with huge RMs
  - Enough sensitivity to find close reference sources
  - Enough sensitivity to make all baselines count
  - Enough uv coverage to transform imaging capabilities
- **Significant scientific growth area**

New Capabilities

- **Phased ALMA is a game changer**
  - Very large aperture
  - Capable of up to 64 Gbits/sec
  - Excellent geographic location
  - Superb site
- **Large Millimeter Telescope (LMT)**
  - Superb high altitude site in Mexico
  - Will soon be 50 meters, 2.5x area of current 32 m
  - Excellent location within VLBI array
- **Haystack 37-meter**
  - Newly upgraded, important location, link to Europe

37-Meter Rebirth

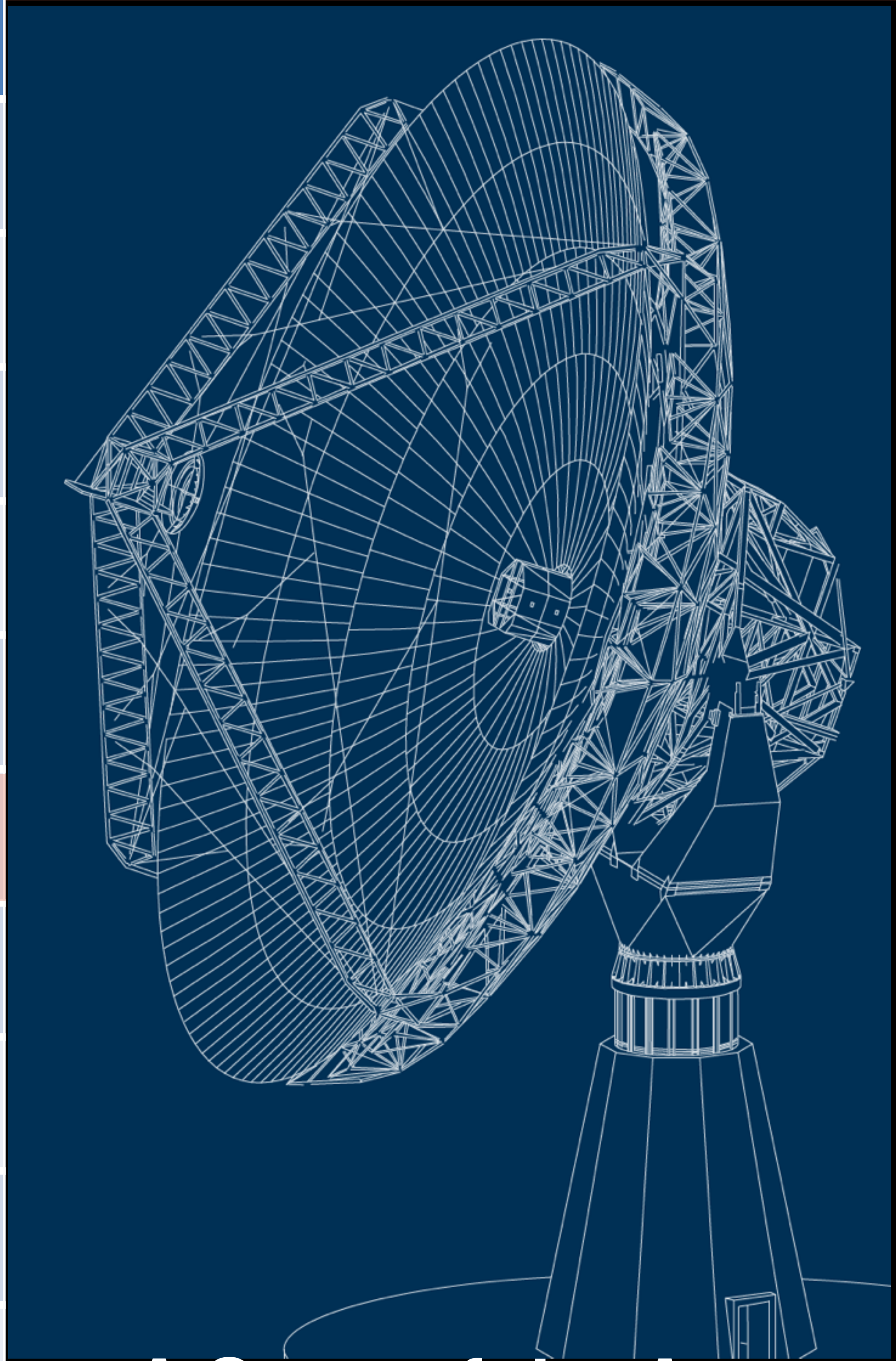
- Fully functional, HUSIR ribbon cutting Feb 2014
- Long term goal: Stable, funded program
- Education, single dish astronomy, VLBI, EHT
- Access to ~35% of the time
    - Mostly night time



Upgrade Properties

- ~75 µm rms surface accuracy (~210 µm previously)
- Aperture efficiency ~47% @100 GHz (<10% previously)
- Useful aperture efficiency to 230 GHz (>20%)
- Order of magnitude improvement in servos
- Blind pointing 3.6″ rms (~6″ previously)
- Rapid switching (<1 hr) between radar and astronomy modes

Antenna	Diam.	Beam (@3mm)	Surface rms	*D/rms*
GBT	*100m*	*9″*	*300μm*	*3.3 × 10*
Effelsberg	*100m*	*11″*	*550μm*	*1.8 × 10*
LMT	*50m*	*15″*	*75μm*	*6.7 × 10*
Nobeyama	*45m*	*17″*	*100μm*	*4.5 × 10*
Yebes	*40m*	*19″*	*150μm*	*2.7 × 10*
Haystack	*37m*	*21″*	*75μm*	*4.9 × 10*
IRAM	*30m*	*29″*	*55μm*	*5.5 × 10*
Mopra	*22m*	*38″*	*200μm*	*1.1 × 10*
KVN Yonsei	*21m*	*37″*	*150μm*	*1.4 × 10*
Onsala	*20m*	*44″*	*130μm*	*1.5 × 10*
Metsahövi	*13.7m*	*57″*	*100μm*	*1.4 × 10*



A State of the Art, World-Class Antenna

Current Instrumentation Status

- **1.3cm (20-25 GHz) receiver (K-band)**
  - T_{sys}~120K, dual pol, operational
- **7mm (36-49 GHz) receiver (Q-band)**
  - T_{sys}~120-200K, dual pol (only 1 operational at present)

Proposal pending
for major instrumentation upgrades

  - Generates 500 MHz passband within 17 GHz IF
  - Designed for 6 channels, one currently operational
- **Acqiris digital spectrometer**
  - 16384 channels across 500 MHz (0.16 km.s @ 90GHz)
  - Temporary

37-meter Use Cases

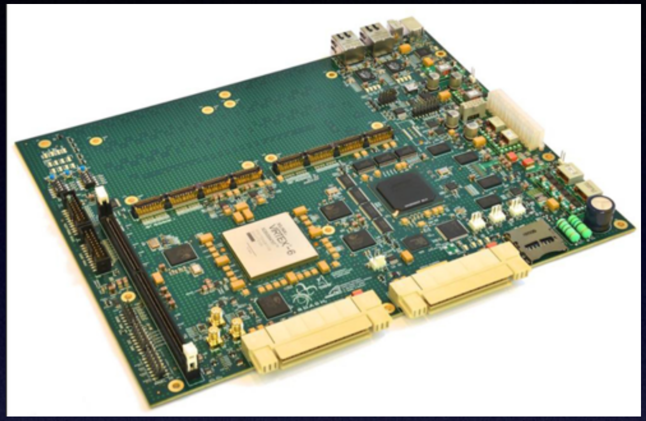
- **Single dish spectroscopy**
  - Line surveys (star forming regions, evolved stars, …)
  - Time domain studies (masers)
- **Single dish continuum**
  - Monitoring (quasars, flare stars)
  - Target of opportunity (transient followup, solar system events)
- **Participation in VLBI networks**
  - VLBA, EHT, GMVA, …
- **Education and outreach**

Technology Landscape

- **Rapid increase in bandwidth**
  - Very potent scientifically (sensitivity, $\Delta\nu/\nu$, RM, …)
  - EHT driving toward 64 Gbit/sec
  - What is possible at 3mm sites, VLBA?
  - Need plans to handle data volume, correlation
- **Back end costs will continue to fall**
  - R2DBE, DBBC3, Mk6 today … faster and cheaper tomorrow
  - Will $250k masers still be the gold standard in 5 yrs?

VLBI Backend Systems

- **Roach 2 digital backend (R2DBE), 16 Gbps**
  - Interface to high speed samplers
  - Virtex 6 FPGA filters and formats data
  - Commercially available



- **Mk6 - operational 16 Gbit/sec recording system**
  - All COTS hardware, available to order from Conduant Corp.
  - Open software system for recording and playback
  - ~2 dozen systems already in use

- **Systems will track Moore's law**
  - Rapidly getting cheaper, more capable
  - Future technical "break points"

Correlation

- **Wider bandwidths increase correlation load**
  - 1 to 2 Gbit/sec for <15 telescopes today at 3mm
  - 64 Gbit/sec for ~20 telescopes is 2 orders of magnitude
  - Requirement likely to face us within a few years
- **Scaling up clusters and using DifX problematic**
  - Optimizing for latest computing architectures is hard
  - Code base is challenging to maintain/augment
- **Sound computer science based approach needed**
  - Well chosen abstraction layers
  - Modular re-use and sharing across radio science applications
  - Clean interfaces, sharing of development burden

A New Situation

- **Big jumps in sensitivity coming**
  - Large new apertures - ALMA, LMT, Haystack
  - Significant boost in spectral line sensitivity
  - Expanding bandwidths - additional boost for continuum
- **Wider sky access**
  - LMT and ALMA, with VLBA, yield good low-dec capability
  - Subsets of the array suited for different parts of sky
- **Technology development needed**
  - Exploiting full antenna capability currently too expensive
  - Must drive down cost, drive up data capacity
  - Big scientific payoff

mm-VLBI Vision

- **Increasing demand, driven by scientific capability**
- **Ongoing hardware and software development**
- **A truly global effort engaging all regions**
- **Build on GMVA foundation**
  - 7mm and 3mm initially, 1.3mm later
  - Add data handling, organizational capacity from US (NRAO)
  - Combine, coordinate technology efforts (Haystack)
- **Broaden scientific conversation**
  - Increasing technical reach reduces scientific isolation of mmVLBI
  - For example, topics driving NG VLA discussions …

Next Generation VLA

- **Workshop at recent AAS meeting in Seattle**
- **93 registrants, mostly US, many others**
- **Context is preparation for Astro 2020**
  - US is not currently a partner in SKA
  - “Next big thing” in US radio astronomy?
  - Complement SKA, don’t ignore it
  - Concentrate on high frequencies (SKA-high in some sense)
- **Workshop focused strongly on NG VLA science**
  - Broad science case
  - Covered all angular resolutions and frequencies

Frequency Coverage

Spec: 5-100 GHz
Goal: 1-118 GHz

Notes: The choice of upper frequency limit has strong impact on required surface accuracy and pointing. Choice of lower frequency has strong impact on optics design. Also, outfitting of array need not be homogeneous. Inner array (<36km) could be outfitted to 100+ GHz, outer array to 50 GHz (perhaps with some stations at 100+ GHz). Will be driven by key science.

Maximum Baseline Length

This gives the resolution in a naturally weighted image (other weightings give better resolution at decreased sensitivity). Current VLA gives 3″ at 1 GHz.

Spec: resolution ~ 0.6″ at 1GHz, 12 mas at 50GHz (180km max. baseline, 5xVLA)
Goal: resolution ~ 0.3″ at 1GHz, 6 mas at 50GHz (360km max. baseline, 10xVLA)

Notes: Impact on length of fiber runs, and surface brightness sensitivity (for a given antenna location density profile). This is for a "New Mexico" Array. A "Northern Hemisphere" Array with VLBI capability is also possible, and this array would be a key part of a new Ultra-High Sensitivity Array when combined with the new generation of large antennas being constructed by our international partners.

Workshop Outcomes

- **Strong interest in 100 GHz**
- **Strong interest in VLBI angular scales**
- **Not necessarily both at once**
- **Significant overlap with mm-VLBI science topics**
  - e.g. Among posters at this meeting:
    - *Extragalactic masers*
    - *Non thermal emission from young stars*
    - *Reference frame ties with VLBI and GAIA*
    - *Lensed structures*
    - *Fundamental constants*
  - Many calls to expand VLBA and link it in
  - Recommended minimum 20% of area on VLBI scales

WG Report
Time domain, fundamental physics, cosmology

Technical Requirements

Technical Requirement	Science Case
Long Baselines	Megamasers, astrometry, resolved galactic transients
Compact Configuration	Plasma physics, intensity mapping, GC pulsars, megamasers, fundamental constants
Wide Field of View/Survey Speed	Intensity mapping, EM GW sources
High Frequencies (> 50 GHz)	Fundamental constants, intensity mapping, plasma physics
High Time Resolution (imaging, beamforming)	GC Pulsars
Real time processing	Transients

Summary

- **Significant scientific interest in the US community**
  - Global interest will grow with capability - also in US
- **Major capabilities coming in addition to ALMA**
  - LMT, Haystack
  - Rapid improvements in instrumentation
  - Combination will be transformational
- **Wish to work closely with international partners**
  - Take millimeter VLBI to the next level
- **GMVA as nucleus, with strong US participation**
  - Exploit complementarities, expand capacity