The Very Large Array: Current Challenges -- Future Capabilities

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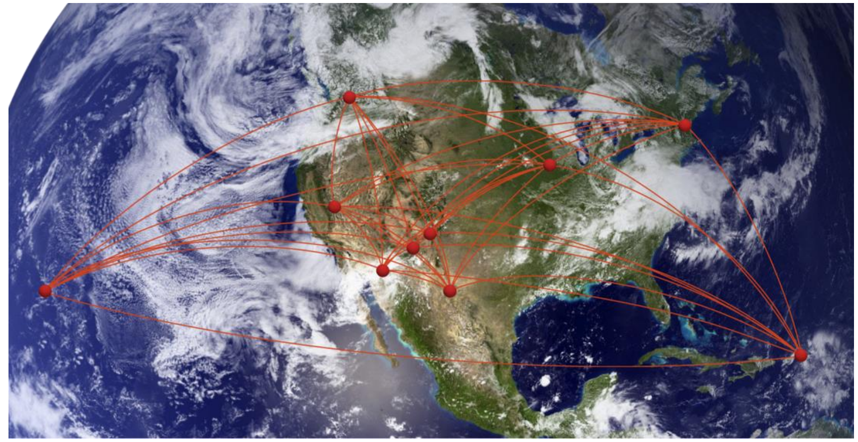
Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

NRAO

NRAO Research Facilities

Jansky Very Large Array

Very Long Baseline Array



Green Bank Telescope

Atacama Large Millimeter/submm Array

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Part I

The Very Large Array, Today

The Very Large Array -- Overview

- The Very Large Array is a 27-element, reconfigurable interferometer array, located in west-central New Mexico, USA. (lat = 34.1, long = 107.6).
- High elevation (2100 m), desert climate (~20 cm yearly precipitation, 76% sunny), means good observing conditions most of the year.
- There are four major configurations, offering a range of over 300 in imaging resolution.
  - e.g. 1.5" to 400" at λ=21cm
- Designed as an imaging array
- Also a good 'light bucket'
- And a decent surveying instrument.
- Recently upgraded.

VLA, looking NW, in D configuration

VLA – A Short History

- Designed early 1970s, construction began1975, completion in 1980.
  - Original design had only four frequency bands (21 cm, 6cm, 2cm, 1.3cm).
  - By today's standards, receivers were very poor, and narrow bandwidth.
- The VLA was absolutely a 'transformational' telescope, overwhelming, by orders of magnitude, all other interferometer arrays.
  - It offered unprecedented sensitivity, frequency coverage, and flexibility.
- From 1980 to 2000, better receivers were installed, and new frequency bands established. But the data transport and correlation technology remained in the 1970s.
- The 'VLA Expansion' (Upgrade) project began in 2001, and was completed in 2012.
  - Expanded VLA's capabilities by one -- three orders of magnitude.
- The 'new' telescope is the 'Jansky Very Large Array' (JVLA).

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Major Capabilities of the Jansky VLA

- **Nine Frequency Bands Spanning 50 MHz – 50 GHz**
  - Eight cryogenic bands, covering 1 – 50 GHz. Utilizes cassegrain subreflector.
  - One uncooled, prime-focus band, covering 50 – 450 MHz.
- **Up to 8 GHz instantaneous bandwidth**
  - Two independent dual-polarization frequency pairs, each of up to 4 GHz BW.
  - All digital design to maximize instrumental stability and repeatability.
- **Full polarization correlator with 8 GHz instantaneous BW**
  - Provides 64 independent 'sub-correlators', and 16384 spectral channels.
  - Many specialized operations modes (burst, pulsar binning, phased arrays …)
- **~5 μJy/beam (1-σ, 1-Hr) continuum sensitivity at most bands.**
- **~2 mJy/beam (1-σ, 1-Hr, 1-km/sec) line sensitivity at most bands.**
- **Resolution Range exceeding factor of 300 at any one band.**
  - e.g. 1.5 to 450 arcseconds at 1400 MHz,
  - 0.045 to 15 arcseconds at 50 GHz.

A Reconfigurable Array

- Maximum flexibility with minimum number of antennas
- Moving 220-ton antennas requires a big transporter, like the one seen on the right, and
- A double railway track as seen below.

Full Frequency Coverage with Outstanding Performance

- There are eight cassegrain focus systems, and one prime focus system.

Band (GHz)	λ (cm)		σ_I (1 Hr) μJy/beam
.05 -- .08	600 -- 375		???
.24 -- .45	125 -- 67	P	100 (?)
1-2	30 -- 15	L	7
2-4	15 – 7.5	S	4
4-8	7.5 – 3.2	C	2.5
8-12	3.2 – 2.5	X	2
12-18	2.5 – 1.7	Ku	2
18-26.5	1.7 – 1.1	K	3
26.5-40	1.1 -- .75	Ka	4
40-50	.75 -- .6	Q	8

25-meter parabaloid reflector

Eight feeds around the cassegrain secondary focus ring.

J-VLA: Everything but the antennas is new …

- Old antennas, old configurations
- New data transmission system
- New receivers
- New electronics
- New correlator
- New software (online, monitor and control, user tools for proposal submission and observation prep, scheduling, data reduction)
- New operations model
- New observing techniques
- New imaging problems (wide fractional bandwidth)

Dynamic scheduling for the VLA

- For the old VLA, Barry Clark made up the schedule a month in advance.
  - Often meant that high frequency observing done in poor weather, and low frequency observing in ideal weather.
- Nowadays, we have full dynamic scheduling. This includes consideration of:
  – Scheduling Block (SB) length (can be arbitrary, from ~0.5hr to many hours; projects comprise multiple SBs, possibly multiple configurations)
  – Scientific priority (provided by TAC)
  – Frequency bands requested
  – Phase stability (from a 300m baseline, 11.7 GHz atmospheric phase interferometer)
  – Wind speed
  – (For the future: measured opacity, weather forecasts)

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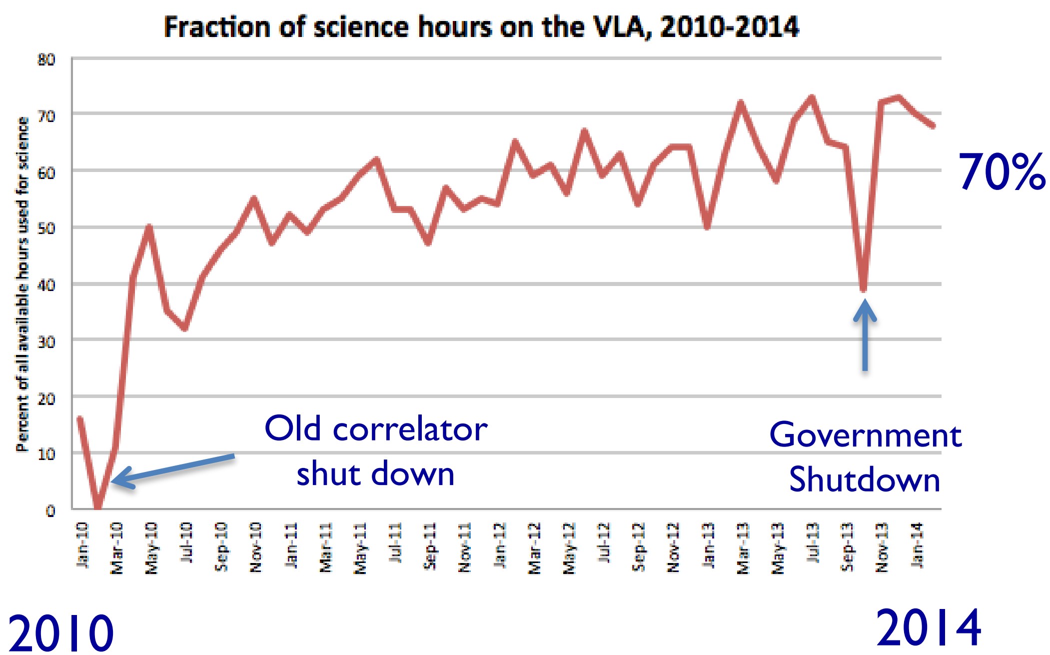
Observing Fraction

- The first three years following installation of the new correlator saw an intensive effort in commissioning.
- Science observing fraction now 70% -- equal to historical average.

- Plot shows the fraction of all time for science, since the new correlator came on-line in March 2010.
- We are now stable at ~70%, the same as in 'historical' VLA times.



The new challenge: Data Processing

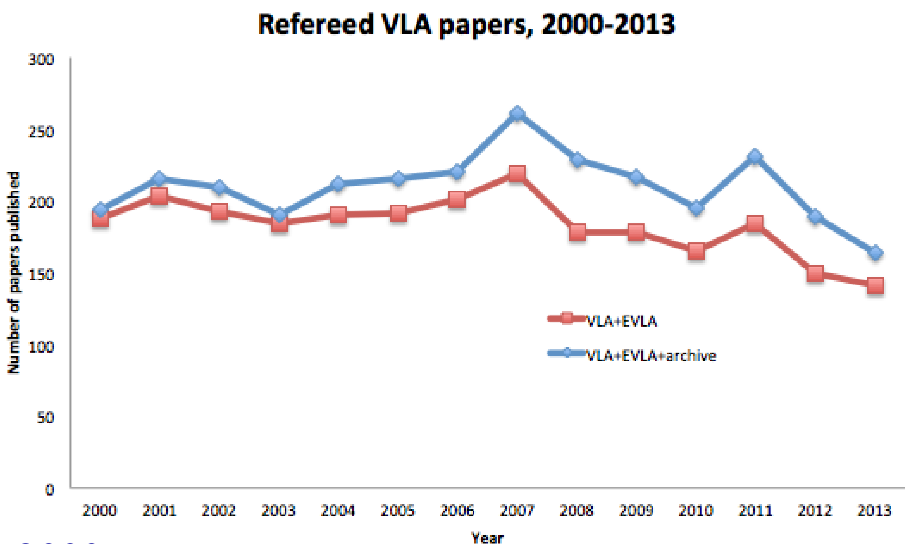
- The increased sensitivity (bandwidth) and spectroscopic flexibility results in a vast increase in dataset size, by up to 3 orders of magnitude
  - Typical VLA dataset ~1GB
  - JVLA datasets ~1 TB
- Data Calibration challenges have risen in proportion
  - Wide bandwidths 'see everything'
  - Effective removal of sporadic RFI is a major challenge
- Imaging challenges with wide bandwidths and wide fields
  - Minor imaging issues, ignored in the past, can no longer be.
  - Imaging issues particularly difficult at low frequency ($\nu < 8$ GHz)
  - Bhatnagar/Rao developing algorithms, but not ready for 'prime time'.

Needed:

- **Better Software for calibration and Imaging, which requires**
- **More human resources**

VLA Publication Rate – Declining!

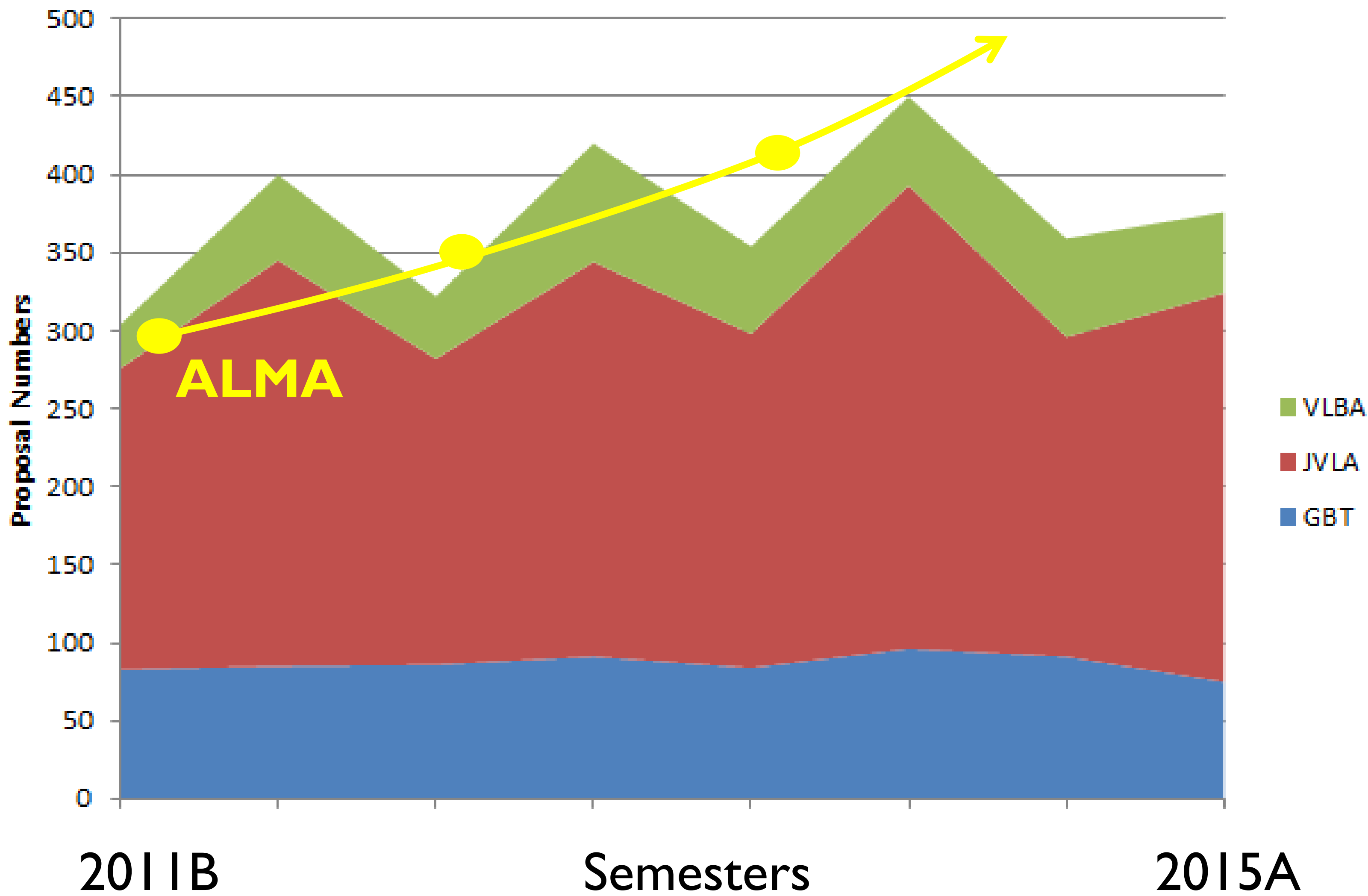
- Contrary to hopes and expectations, the VLA's publication rate has not risen since 2010.
- Instead – a slow decline since 2007
- A major concern …
- Primary causes: (IMHO)
  - Data volumes are enormous.
  - Calibration (esp. RFI flagging) is tough at low frequencies.
  - Wide-band, Wide-field imaging still under development.
- Users are overwhelmed by these (and other) data.
- Methodologies still being developed.



2000 2010

Solution: Easy, efficient, largely automated calibration and imaging software.

Number of Proposals/Semester Rising



A Worrisome Mix:
Instrument Support + Flat Budgets + Rising Expectations

- Greatly Increased Data Product Flow
- Critical Need for Better Calibration Methodologies
  - RFI-rich environment
- Critical Need for More Robust Imaging Algorithms
  - Wide-field, wide-band (low frequencies) especially hard
- Declining Support Budget
- Numerous retires (and departures)
  - No corresponding hiring program for sharp young people
- Increasing Ambitions

Part II
Ongoing Developments

Commissioning of new capabilities continues…

- The pace of commissioning has slowed considerably – a good thing.
- All `standard' correlator modes now very stable and reliable.
- Development continues on:
  - On-the-fly interferometric mosaicing for large surveys
  - Fast correlator dumps for solar flares, fast radio bursts
    - Current standard maximum is 50 ms for full array.
    - Maximum now is 5 ms, for one SPW, all antennas.
  - Pulsar binning modes
  - Higher spectral resolution (recirculation factors > 64)
  - > 3 simultaneous subarrays

Fast Dumps – the Search for FRBs

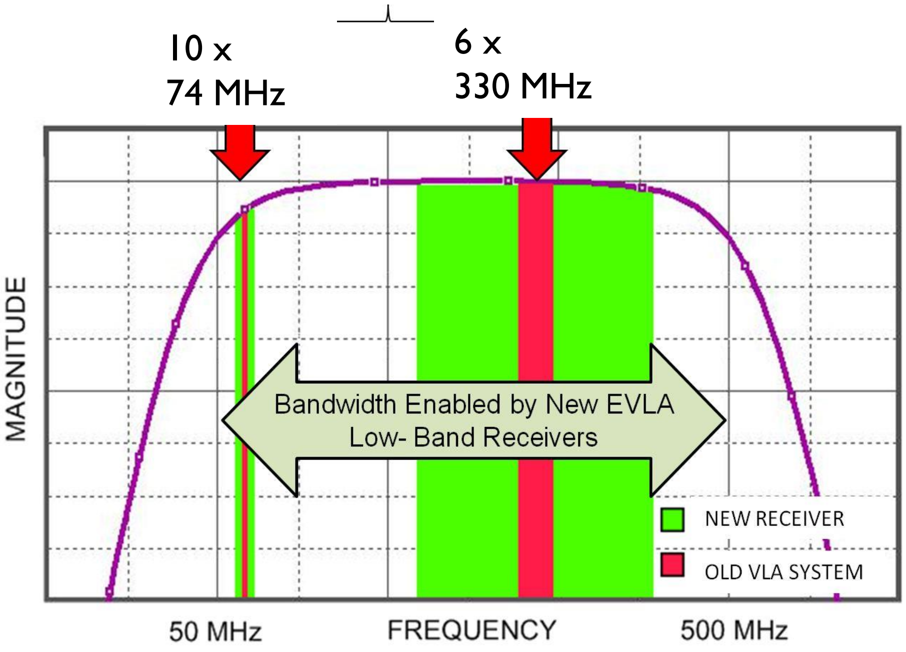
- The recent excitement over FRBs spurred considerable development of the correlator fast dump capabilities.
- Law, Bower, Burke-Spolaor et al. have utilized nearly 200 hours of VLA time trying to catch – and localize – an FRB.
  - Dump Time = 5 ms. BW = 256 MHz, 256 spectral channels, 2 pol.
  - All VLA configurations, at 1.45 GHz (L-band).
  - Sensitivity is 12 mJy (1-sigma).
  - Visibilities were de-dispersed over a range of DM (119 values to 3000 pc/cm^3). Images for each integration made for each DM.
  - Original expectation was 50% probability of detection in 50 hours.
  - Found … nothing.
  - From this, they exclude the published event rate with 90% confidence.
- New Approach: Develop a commensal system, to use real-time VLA data stream, all the time.

The New LowBand System

- Unlike the Cassegrain bands, the low-frequency system can be operating `24-7'.
- Low frequency sensitivity largely independent of subreflector position.
- Naval Research Lab has funded installation of new wide-band low frequency receivers on the VLA.

A Major Increase in Bandwidth

- The new VLA electronics were incompatible with the old 'P-band' system.
- NRL acquired funds to re-engineer and build a new wideband system.
- The new system provides both better Tsys, and a very large increase in bandwidth.
- However, we still require two feeds for the two 'traditional' bands.
- Receiver design permits two more feeds (such as near 200 MHz).
- The 'Erickson Dipole' 74 MHz feed system no longer used.
- A new wideband 4-band feed system is being tested.



RFI Spectrum – Not bad …

- There will be no surprise to learn that the 230 – 486 MHz range contains RFI. But it is not too bad.
- About 2/3 of the spectrum is useable.
- Two example spectra are shown.

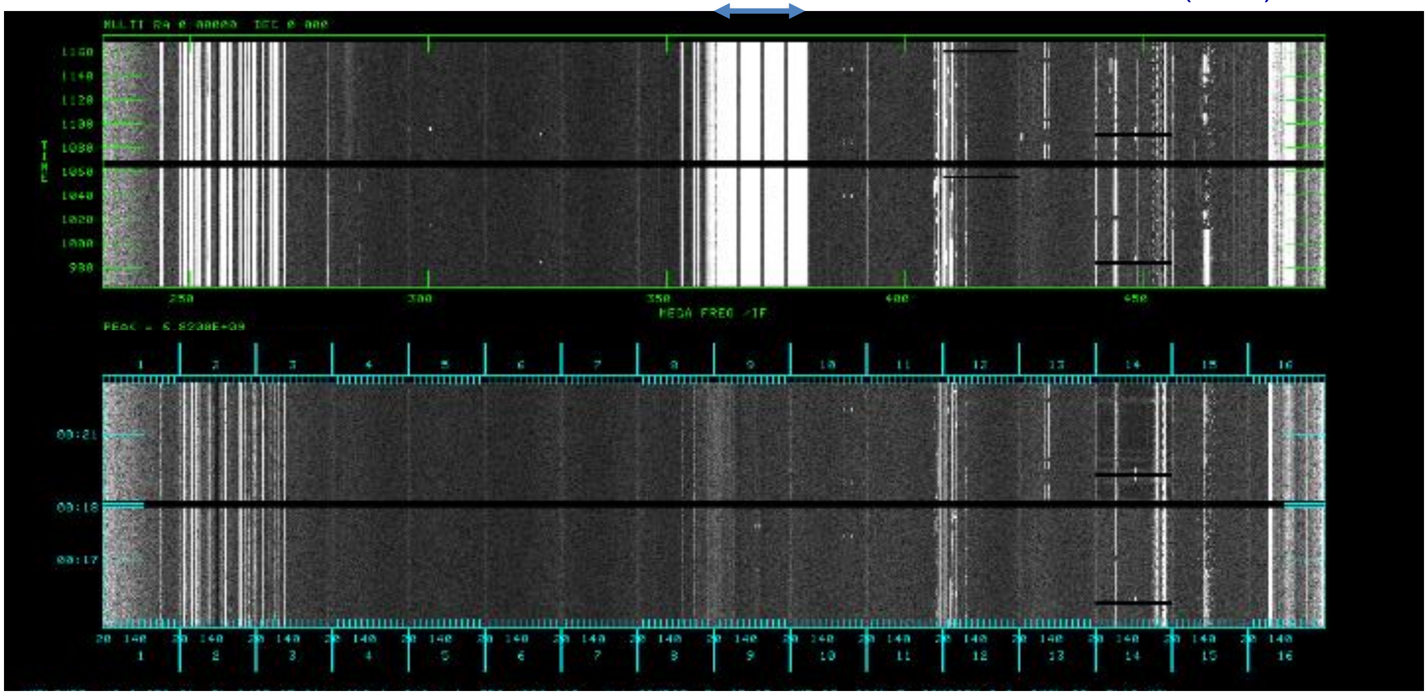
MUOS

MUOS: Mobile User Objective System.

4 geosynchronous satellites. (USN)

1 Km baseline

35 Km baseline



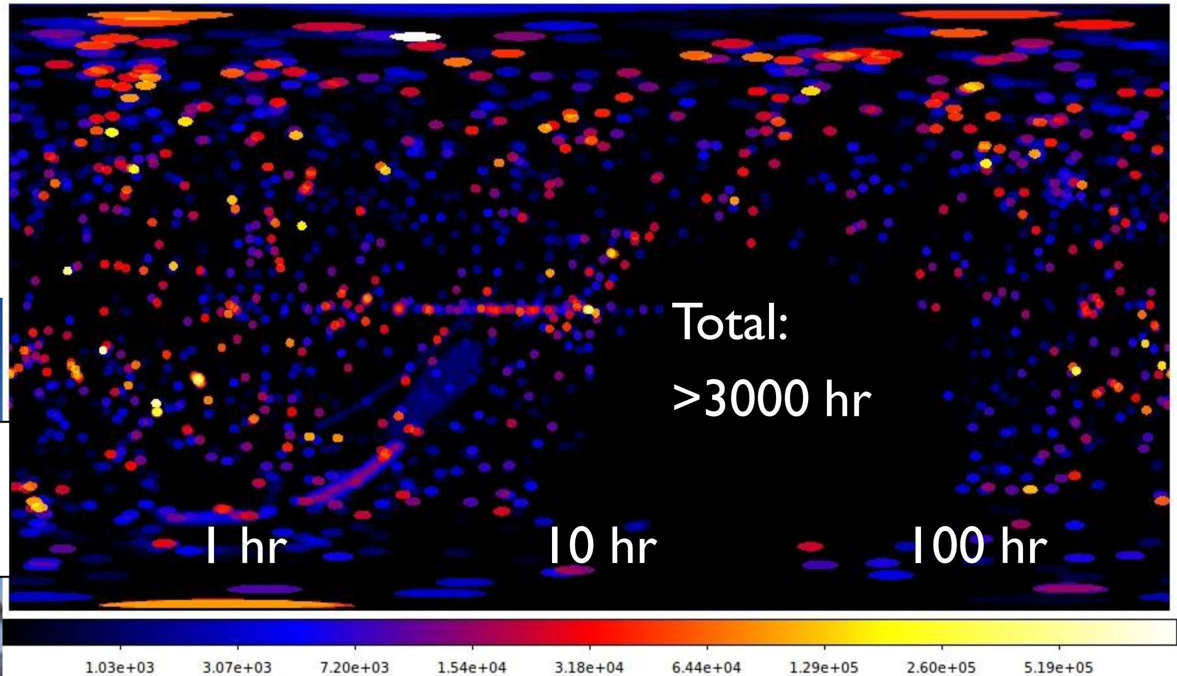
232 MHz

350 MHz

488 MHz

VLITE: Overview

- VLITE is a new commensal backend on the NRAO VLA
- It uses dedicated samplers, fiber transmission, and a dedicated backend software correlator to tap into the low band receivers on 10 VLA antennas
- VLITE samples a bandwidth of 64 MHz, centered on 352 MHz and provides a temporal resolution of 2s and spectral resolution of 100 kHz
- VLITE will operate on all PI-driven observations at 1 GHz and above and is expected to produce several thousand hours of commensal P band data per year of operation
  - VLITE is a $1M prototype of a full BW, all-antenna system: LOBO

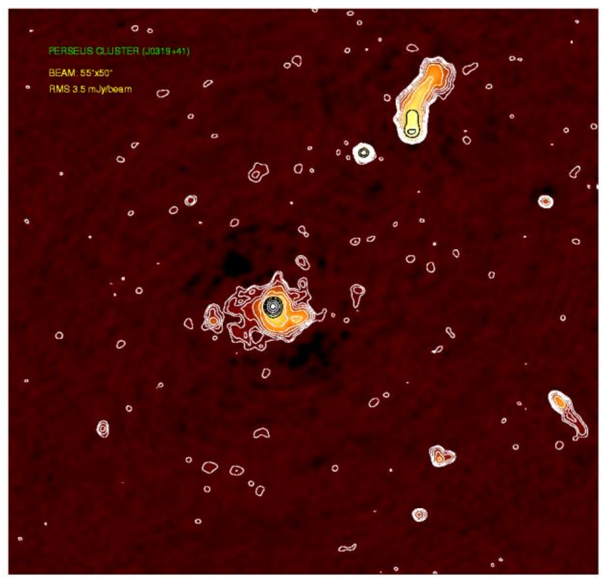


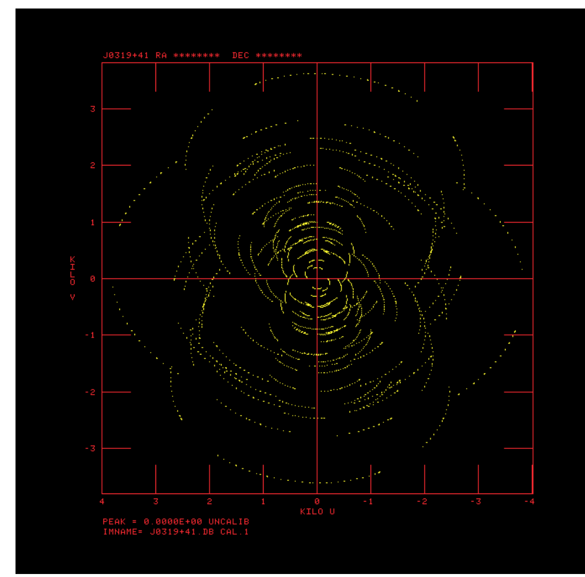
Right: One year of VLA pointings (>3000 hr) shown for the 330 MHz primary beam. This would cover 25% of the VLA sky.

VLITE: Scientific Drivers

- **Ionosphere:** high resolution remote sensing of the Earth's ionosphere to study coupling mechanisms of fine, medium and large scale ionospheric dynamics
- **Slow transients:** searches of large (2.5°) FoV for transients on time scales of 2s to 1 hour in real-time plus off-line searches for longer term transients
- **Astrophysics:** off-line process will provide sensitive simultaneous imaging for spectral studies, source size, extended emission properties etc. for nearly all PI-driven science programs

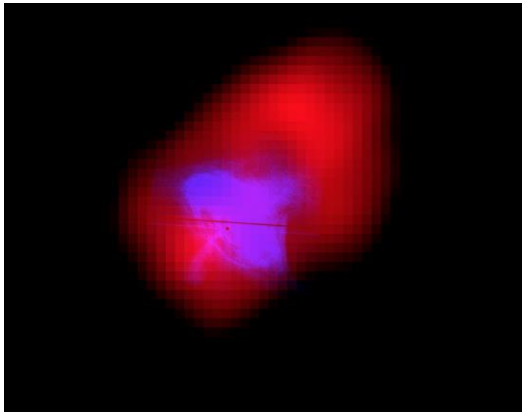
- VLITE P-band image of Perseus A (3C84 and 3C83.1) made from a PI-driven observation at C-band.
- 3C84 was the calibrator for the PI program.
- Data taken on two days – only 35 minutes integration.





VLITE: Current Status

- VLITE has undergone rapid deployment:
  - System Requirements Review November 2013
  - Preliminary Design Review December 2013
  - Critical Design Review April 2014
  - NRL Acceptance Dec 1, 2014
- First system deployed on the VLA in June 2014
- First light fringes: July 17, 2014
- Single target field image: July 29, 2014 (5 antennas)
- Multi-target field image: August 8, 2014 (5 antennas)
- Full 10 antennas outfitted on the VLA September 1, 2014
- Scientific and Technical Commissioning June – November 2014
- Project Completion Dec 2014
- Full operations now enabled
- For more information on VLITE contact:
  - Namir Kassim (VLITE PI and transient pipeline)
  - Tracy Clarke (VLITE Commissioning and astrophysics pipeline)
  - Joseph Helmboldt (Ionospheric science)



VLITE image (red) of Crab nebula with *Chandra* in blue.

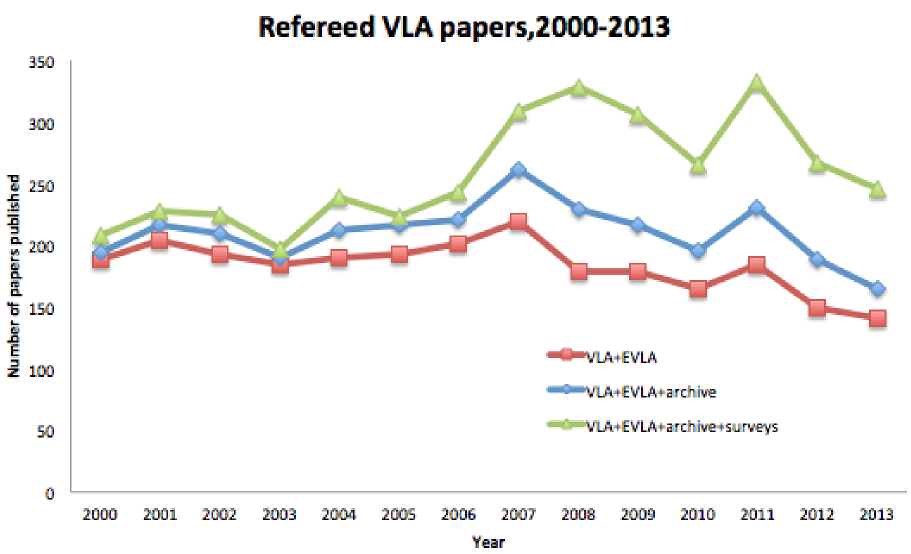
The Advantage of Leveraged Projects

- The VLITE/LOBO, LowBand Receivers, and potential 'FRB' commensal system illustrate the value of leveraged projects.
- Infusions of relatively small resources into the NRAO/VLA infrastructure can leverage big results.
- NRAO is open to a wide range of shared projects of this type.
- Examples:
  - Completion of 4-band system: ~ $80K plus labor.
  - Full outfitting of LOBO: ~ $5M.

The Proposed VLA Sky Survey (VLASS)

- Surveys have always been a major part of astronomy.
- The VLA has been successfully used for many surveys, the best known of which are NVSS and FIRST.
- These papers have been cited 3550 times, by 9086 unique authors.
- With this popularity, and with the new capabilities offered by the Jansky VLA, what new survey(s) should be done? And when?

- NRAO has offered the community up to 10000 hours for a new survey.
- The Community must decide itself what the survey will be.
- Long process, involving many 'white papers', panels and telecons.



The VLA Sky Survey: why now?

- Science:
  - The cosmic view:
    - Radio galaxy surveys need wide areas at substantial depth
    - Arc-second or better resolution for identification
    - Other multi-wavelength surveys, co-observing opportunities
  - The dynamic view:
    - Synoptic surveys need time baseline (3+ years), OTF $\Rightarrow$ rapid sky coverage
    - Characterize the "null" (static+variable) sky
      - Lay groundwork for LIGO & LSST era
  - Prepare for the future – science proving ground for SKA
- Strategy: Astro2020:
  - Starts ~2019, need strong case for continued support of radio astronomy by the entire US astronomy community ~2018 $\Rightarrow$
  - start survey ~2015 to minimize impact on PI science and maximize transient science

VLASS Status (1)

- The final version – following NRAO staff scientific/technical review -- is completed, and available on the NRAO wiki site **(https://safe.nrao.edu/wiki/bin/view/JVLA/VLASS)**
- Proposes a three-tiered, S-band (2 – 4 GHz) high-resolution survey with all-sky, wide-area, and deep-field components.
  - **All-Sky:** 33885 sq. deg., 1860 hours, 100 μJy/b, B, BnA Config. 2”
  - **Wide:** 10000 2824 50 B 2”
  - **Galactic** 3160 840 50 A & B 0.75”
  - **Deep** (3 flds)10 sq.deg 3391 1.5 A Config 0.65”
- The total of ~9000 hours is a lot of time, to be taken from the most heavily used configurations for PI-driven science.
- There would also be a significant load on VLA Support Staff (estimated currently as 3 FTE).

VLASS Status (2)

- Currently in a 'community comment' period. Your opinion is solicited.
  - Feb 15: Close of community comment period.
  - March 4 – 6: VLASS external Community Review, in Socorro.
- The final Go/No Go decision is up to the Director.
- Observing won't start until at least Spring 2016.

Part III

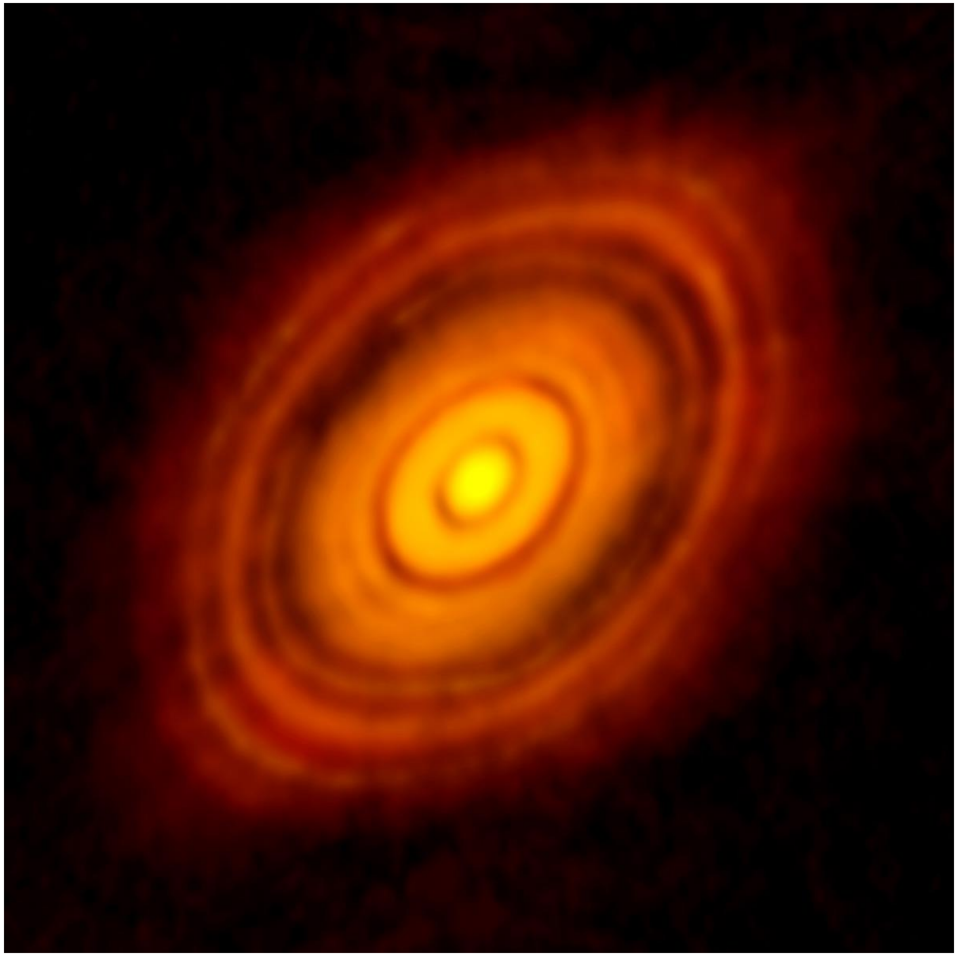
The Very Large Array of the Future

Should We Plan for a New/Better Facility?

- Considering:
  - The amazing suite of instruments we have now (J-VLA, GBT, VLBA, ALMA), and
  - That we are still learning to use these effecitively
  - Support for these facilities is not rising as it should …
- Perhaps the NRAO plan for 2020 – 2030 should be one of 'consolidation'.
- Response: Absolutely Not!
  - Science evolves
  - New instruments (esp. ALMA) opening new paths.
- We Must Plan for new instruments.
- NRAO considering a suite of new initiatives.

New Directions – driven by ALMA

- Recent HL Tau image from ALMA shows the transformational power of this telescope.
- Increasing focus on high frequency 'thermal' science.
- Resolution 35 mas. λ =1 mm
- To penetrate the dust in these systems, lower frequency at similar resolution needed.
- At cm wavelengths, baselines up to ~300 km needed.
- Would do wonders for 'non-thermal science as well1



The VLA – Where To From Here?

- The EVLA Project expanded all basic capabilities of the VLA by order(s) of magnitude – except for resolution.
- A Phase II proposal (for $120M) was submitted in 2004.
  - Key component: 10 x 25-meter antennas, out to 300 km baselines.
  - Key capability: 10 – 100 mK brightness temperature sensitivity at milliarcsecond resolution.
  - Strong ties to (and leverage from) ALMA, and the expected major rise in high frequency 'thermal science'.
- This proposal was not successful.
- My opinion for failure: Proposal timing was wrong, proposal science justification insufficient, insufficient effort to 'sell' it to the community, and the proposal was too modest.
- Now, 10 years later, is the time better to 'Go Big'?

How Big? How Bold? What are the Limits?

- A 'Next Generation' Very Large Array could be imagined as:
  - 1 – 100 GHz (more likely, 50 GHz maximum)
  - Collecting Area 3 – 10 X the VLA
  - Maximum Baselines 3 – 10 X the VLA (100 – 400 km.)
  - Antenna diameter: 12 – 25 m
    - Venerable VLA antennas need not be retained
  - Location: Central NM, USA
    - To take advantage of good site, and existing infrastructure.
  - Cost: TBD, but 'not small'.
- **An Outstanding Science Case is Critical!**
  - The Director has called for 'Killer Aps'.

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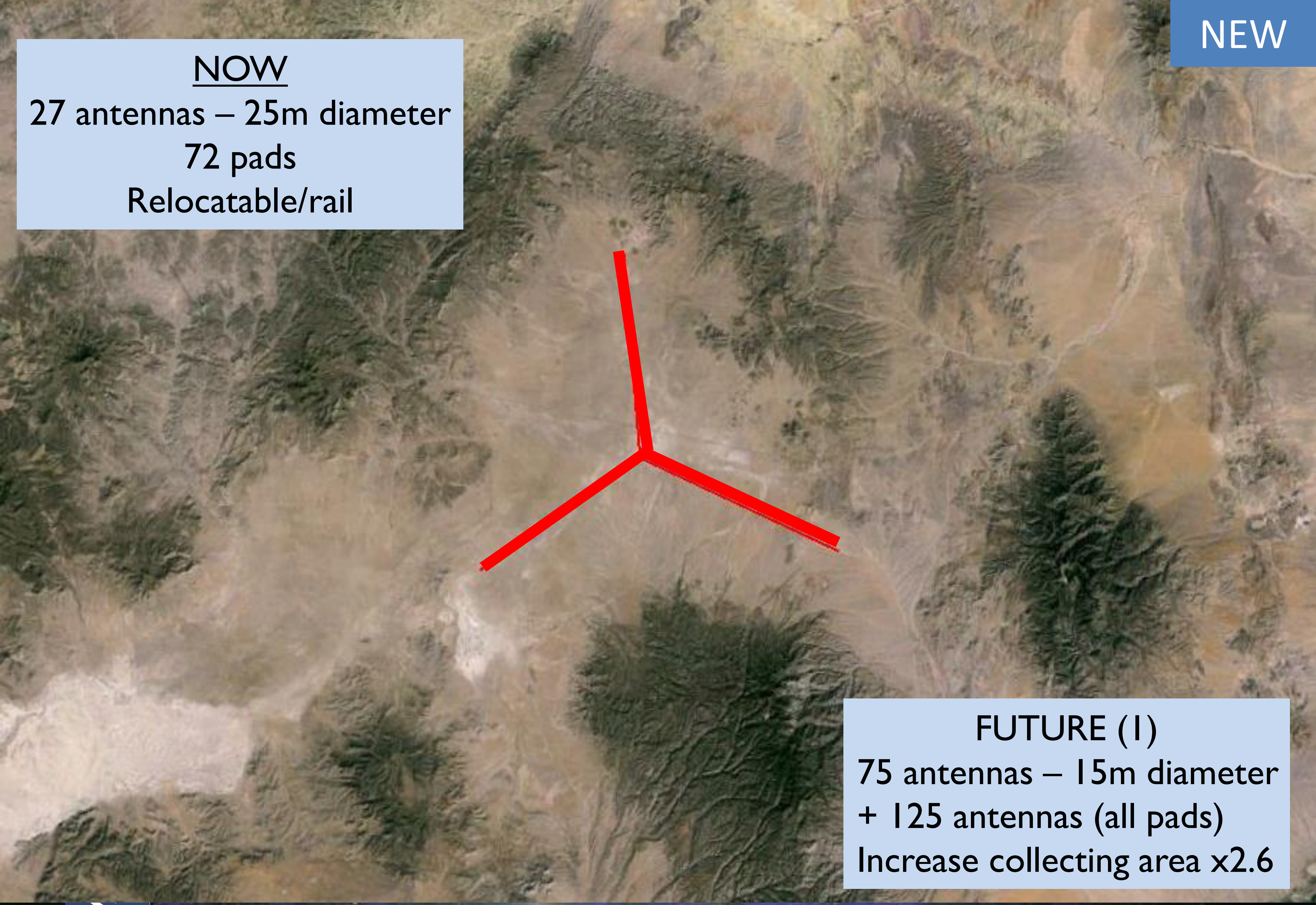


NOW

27 antennas – 25m diameter

72 pads

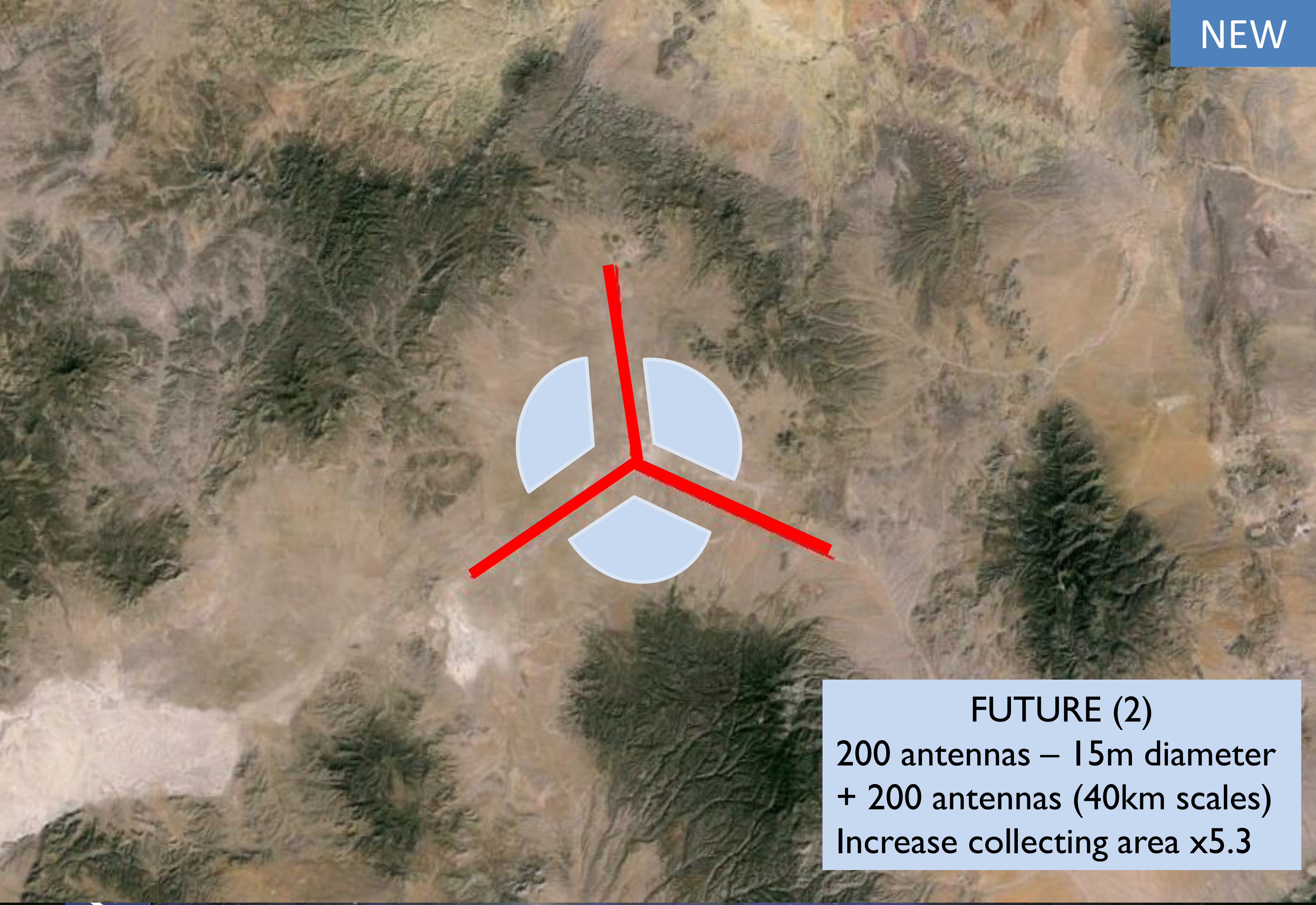
Relocatable/rail

FUTURE (1)

75 antennas – 15m diameter

+ 125 antennas (all pads)

Increase collecting area x2.6



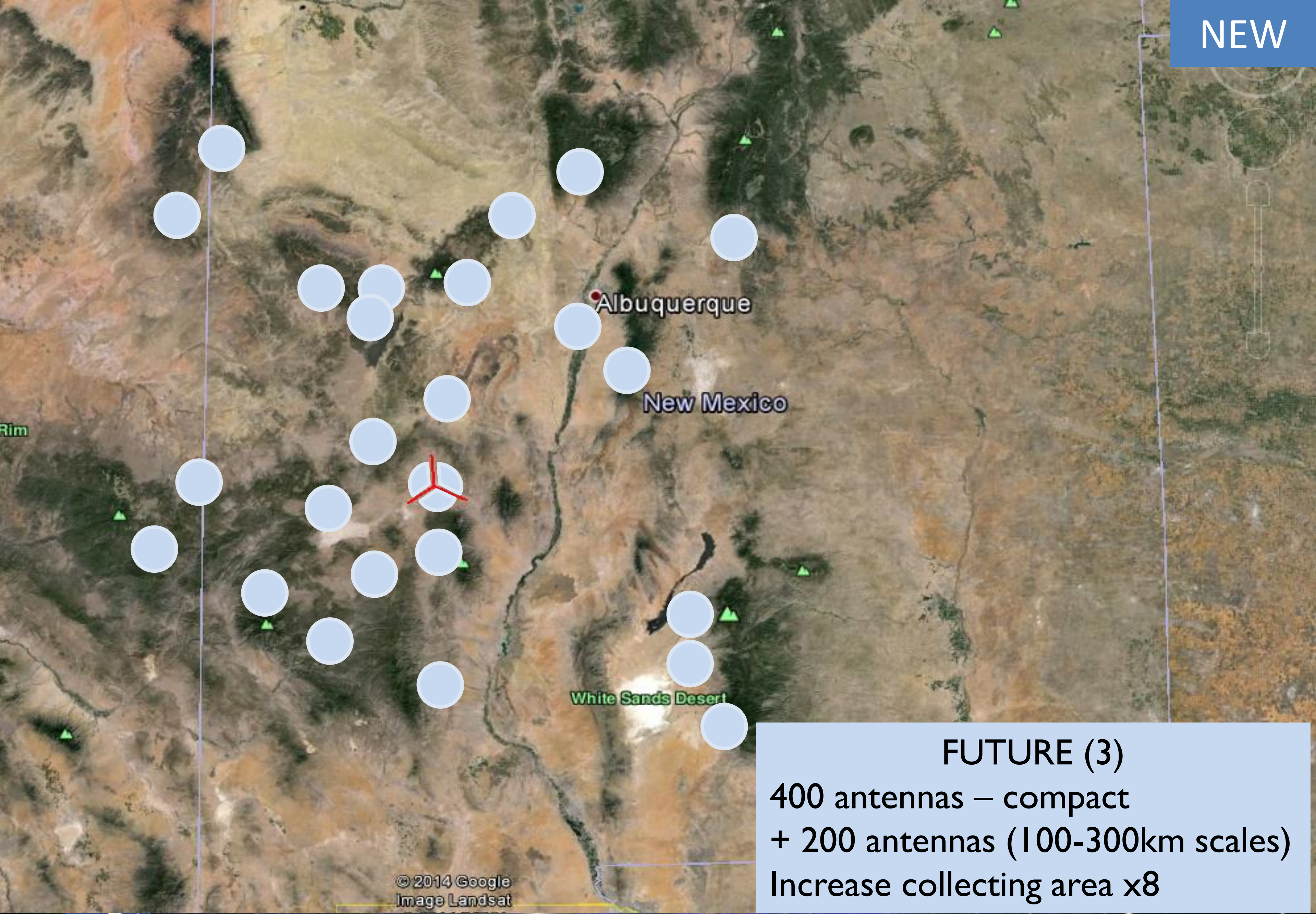
NEW

FUTURE (2)

200 antennas – 15m diameter

+ 200 antennas (40km scales)

Increase collecting area x5.3



NEW

FUTURE (3)

400 antennas – compact

+ 200 antennas (100-300km scales)

Increase collecting area x8

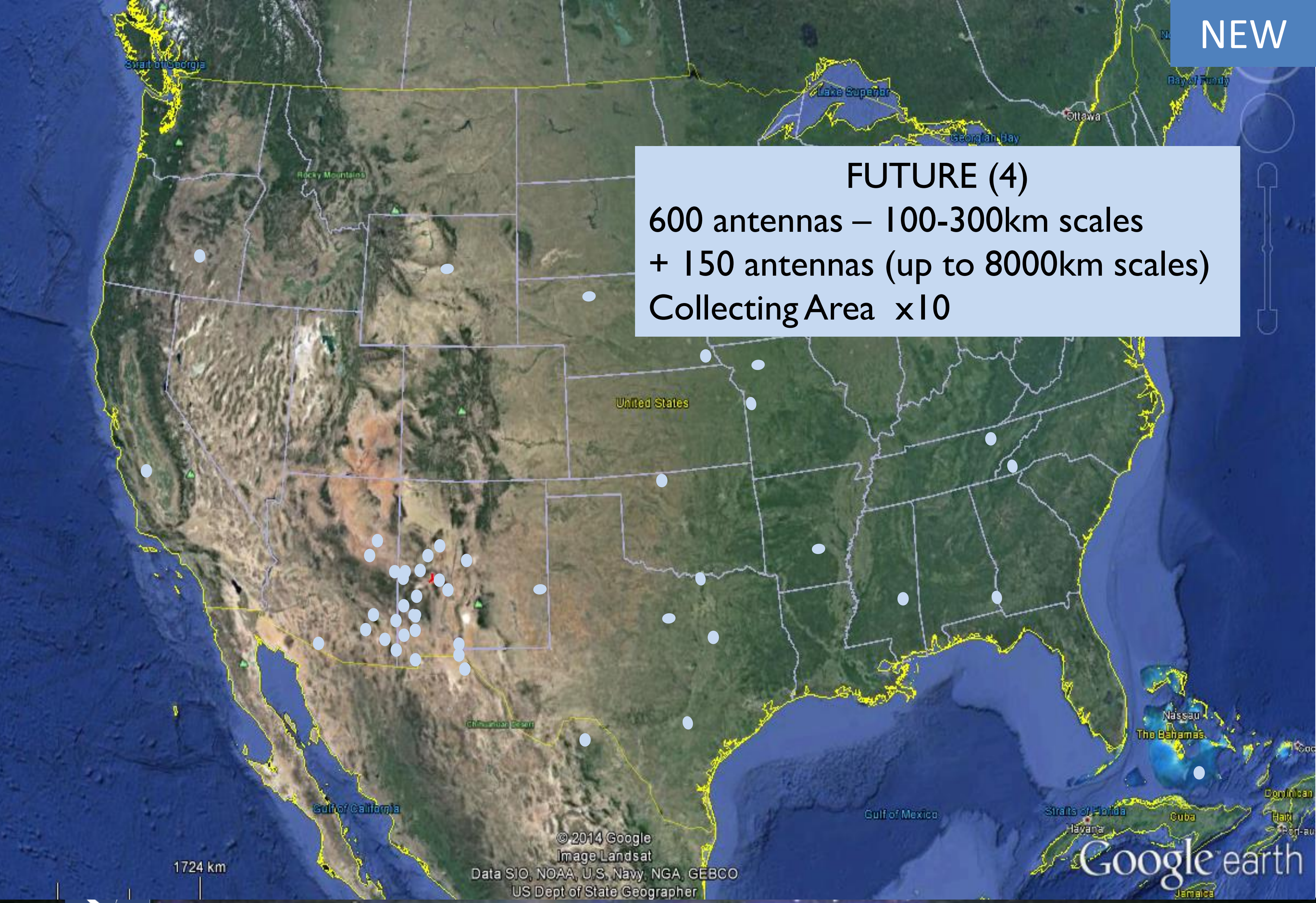
NEW

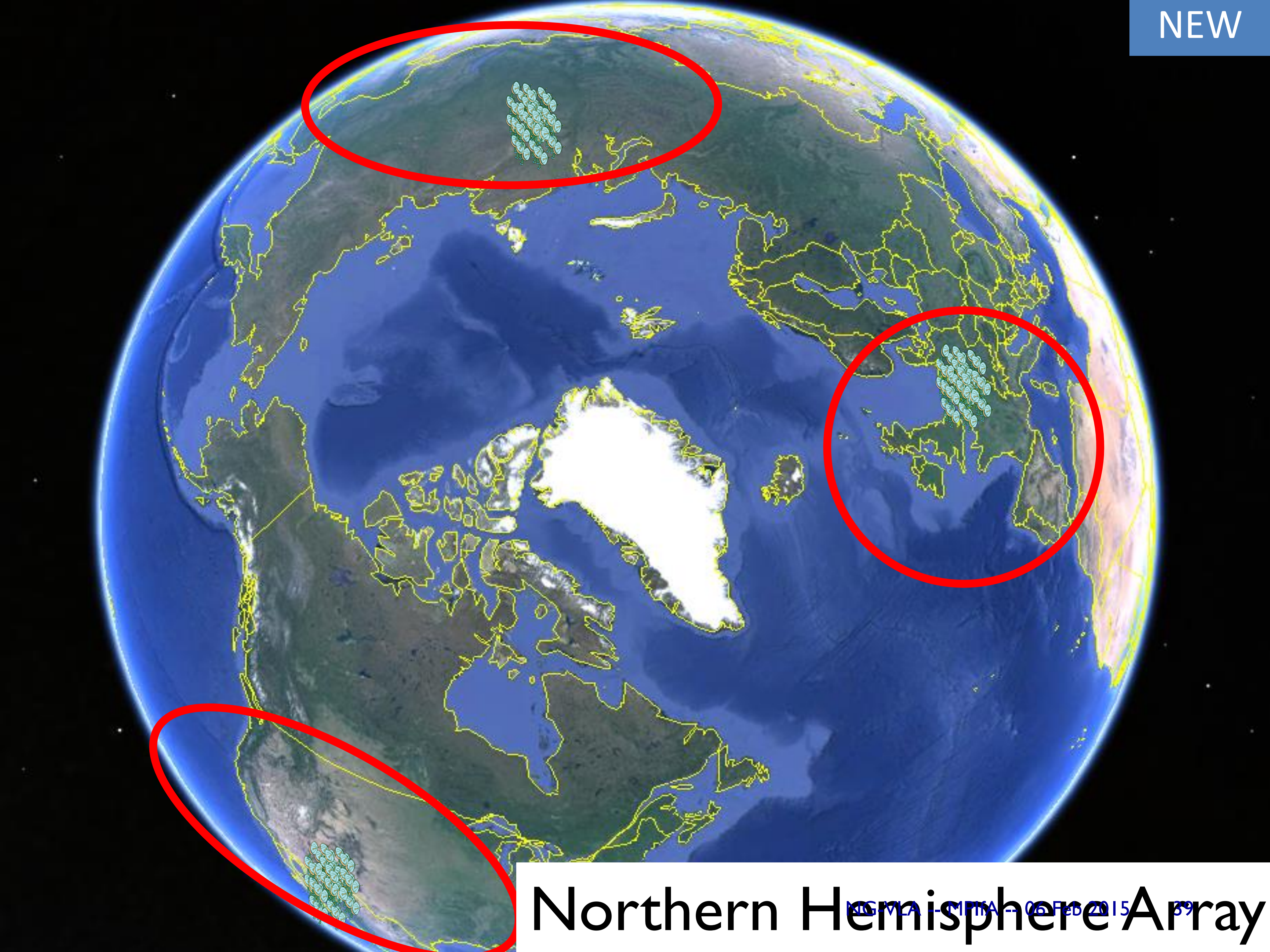
FUTURE (4)

600 antennas – 100-300km scales

+ 150 antennas (up to 8000km scales)

Collecting Area x10




NEW
Northern Hemisphere Array

Generating a Science Case, Engaging the Community

- Enthusiastic 'Buy-In' for this concept by the astronomy community (not just radio) is essential.
- A compelling science case is critical.
- To start this process, the NRAO sponsored a one-day 'US Radio Futures: Building from ALMA and the VLA' workshop on Sunday, 04 January, 2015
- Meeting was well attended – 150+ -- filled the room.
- Presentations by speakers covering full range of radio astronomy science.
- All presentations now available at

https://science.nrao.edu/science/meetings/2015/aas225/next-gen-vla/program

Science Working Groups

- Four science working groups were defined, and chairs (external and internal) nominated:
  - 1) **The Cradle of Life:** (proto-)planetary systems and formation, cloud cores to stars; astrochemisty/biology; Solar System, SETI
    - Chairs: Andrea Isella, Arielle Moullet, Chat Hull
  - 2**) Galaxy Ecosystems (baryon cycle):** Galactic structure, interstellar medium and star formation' star formation laws, nearby galaxies; outflows and inflows; supermassive black holes.
    - Chairs: Eric Murphy, Adam Leroy
  - 3) **Galaxy Assembly through Cosmic Time (high z universe):** cool gas and dust; dynamics; AGN/SMBHs
    - Chairs: Caitlin Casey, Mark Lacy, Jackie Hodge
  - 4**) Time domain, Cosmology, Physics:** Transient sky; synoptic surveys; AGN physics; high energy phenomena; stellar phenomena; pulsars.
    - Chairs: Geoff Bower, Paul Demorest

US Radio Astronomy Futures

Tony Beasley

The National Radio Astronomy Observatory enables forefront research into the Universe at radio wavelengths.

In partnership with the scientific community, we:

- provide world leading telescopes, instrumentation and expertise,
- train the next generation of scientists and engineers, and
- promote astronomy to foster a more scientifically literate society.

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- Inputs: SCIENCE; Partners; Community Health; Politics; Epoch/Landscape (e.g. SKA)
- Outputs: Instruments/facility concepts/projects

- Some options for the next decade:

Space:	**DARE, Far-infrared Interferometer**
Low-frequency:	**SKA-L, HERA, GW Observatory**
Mid-frequency:	**SKA-Mid/High, Fast Transients, VLA+**
High-frequency:	**ALMA upgrade/expansion (2030s)**

Possible Next Steps

- Needed: science case; partnering plans; design/development (technology development, prototyping); organizational development; political support; community health & involvement

- Setting up working groups to explore options: expect 2018-2020 development of proposal for ASTRO2020 (pencil-ready or shovel-ready? 10% development cost?)

- Organizationally: need to align our scientific & development interests with this future – including some tough decisions.

- This meeting …. SCIENCE. Exploring all options.
- Later this year – Kavli Meeting – US Radio Astronomy Futures
- Thank all of you for participating…

Operations Costs, Technical Challenges

- Operations Costs are key.
  - 70% of the VLA's power bill goes to the eight cryogenic systems.
  - > $1M/year.
- Wideband feed development (e.g. Sandy Weinreb) looks promising.
  - Efficient 7:1 BWR feeds look possible.
  - Two system would cover 1 – 50 GHz.
- The Director has suggested as a goal:
  - Operations costs no higher than we are spending now.
  - One Maintenance Visit per antenna, per year.
- Even better – total standalone operation – no external power.
- Needed: Technical Development!

Technical Challenges (as seen by Sandy Weinreb)

- Sandy Weinreb (JPL/Caltech) has listed the key technical challenges that need R&D.
- Goals are verified cost and performance by 2019
  Listed in order of difficulty as perceived by him in 2014

- **Data Transmission** – 100 km with 90 GHz bandwidth
- **Feed -** Good efficiency and 10:1 frequency range
- **LNA** – Very low noise from 10 to 100 GHz
- **Correlator** – Cost and power consumption >500 times the size of the JVLA correlator.
- **Reflector** – Cost vs diameter. Who builds it where out of what
- **Cryocoolers** – Any new technology or use proven coolers

- **Estimated Development Cost:** $5/yr until 2019.

A Summary

- Thanks to the Expanded Very Large Array project, the JVLA remains the 'gold standard' in cm-wavelength radio synthesis imaging telescopes
- It has unrivalled sensitivity, frequency coverage, resolution flexibility.
- But … adapting to the new processing challenges is challenging, and appropriate support for the JVLA (and other telescopes) is increasingly difficult to secure.
- The NRAO is considering a bigger, brighter VLA of the future.
  - The natural growth path is in high frequencies, and higher resolution.
  - A well developed plan must be in place by 2019.
  - A widely accepted, enthusiastically supported science plan is a necessary beginning.