The Next Generation Very Large Array

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The Jansky Very Large Array

VLA began in 1980 with 27 x 25-m antennas

Jansky VLA upgrade by 2011 (includes WIDAR correlator)
A Next Generation VLA (2035 – 2065+)

- Scientific Focus: **Thermal imaging at milli-arcsecond scale resolution**
- Design Goals:
  - 10x effective collecting area of JVLA and ALMA
  - 10x resolution of JVLA and ALMA
  - Frequency range: **1.2 – 116 GHz**
- PI driven / pointed observations model
- Baseline design: **214 x 18-m dishes**, no reconfiguration
- Low technical risk (reasonable step beyond current state-of-the-art)

[https://science.nrao.edu/futures/ngvla](https://science.nrao.edu/futures/ngvla)
ngVLA: comparative sensitivity

Complementary suite from cm to submm, appropriate for the mid-21st century:

- **< 0.3 cm:** ALMA 2030 superb for chemistry, dust, fine structure lines
- **0.3 – 3 cm:** ngVLA superb for terrestrial planet formation, dense gas history, baryon cycling
- **> 3 cm:** SKA superb for pulsars, reionization, HI + continuum surveys
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ngVLA: comparative resolution

- Resolution ~ 10 mas @ 1 cm (300 km)
- Synergy with ALMA submm, future ELTs
- Complement to SKA lower frequency capabilities
ngVLA Science Cases

- 75 Community-led Science Use Cases Submitted for ‘Reqs to Specs’ process (so far)

- ngVLA “consensus vision” developed in June at well-attended Socorro workshop
ngVLA will measure orbital motions of planets and related features on monthly timescales.

Simulated 100 GHz ngVLA observations of a newborn planetary system comprising a Jupiter analogue orbiting at 5 AU from a Solar type star.

http://library.nrao.edu/public/memos/ngvla/NGVLA_19.pdf

Credit: Luca Ricci (Rice Univ.) et al.
ngVLA will detect complex pre-biotic molecules and provide initial chemical conditions in forming solar systems and individual planets, e.g., “chirality”
ngVLA will detect reservoirs of atomic & cold molecular gas over a wide range of redshift.
**ngVLA Costs and Partnerships**

- Target construction baseline budget ~ (2016) $1.5B
- Target operations budget of < (2016) $75M (< 3x current VLA)
  
  Operations, maintenance, computing, archiving, etc.; optimize as part of design

- Partnerships:
  - Possible U.S. Multiagency Interest [including VLBI option]
    - ICRF – DOD / Navy, Air Force
    - Spacecraft tracking/imaging, ‘burst-telemetry’ (mission-critical events) – NASA, DOD
    - Space situational awareness – DOD

  - **Strong International Partnership critical for success:**
    - Canada, Mexico, Japan, Germany, Netherlands, Taiwan

  - Current Industrial Involvement through Community Studies:
    - REhnu Inc., Minex Engineering Corp, LaserLaB, Quantum Design
Canadians are presently:

- **participating** in ngVLA Science and Technical Advisory Councils
- **authoring** ngVLA Science Use Cases
- **organizing** / participating in ngVLA Workshops and AAS Special Sessions
- **pursuing** ngVLA Technical Studies (antennas, correlators, receivers, etc.)

*Future new collaborations will be welcomed!*
ngVLA: the way forward (near-term)

**Goal: NRAO CoDR-level proposal to 2020 Decade Survey**

Compelling science program & defensibly costed design of all major elements

- 2017
  - Sci Case Capture: Mon 10/31/16 - Wed 5/30/17
  - Ref. Design First Draft: Mon 10/31/16 - Fri 4/28/17
  - Community Study Development: Mon 10/31/16 - Tue 8/15/17

- 2018
  - Sci Book First Draft: Thu 6/1/17 - Fri 12/1/17
  - Ref. Design 1.5 Draft: Mon 5/15/17 - Fri 11/24/17
  - Reference Design Second Draft: Mon 11/27/17 - Tue 7/31/18

- 2019
  - Sci Book Second Draft: Mon 12/4/17 - Fri 6/15/18
  - Sci Book Final Draft: Mon 6/18/18 - Fri 12/14/18
  - ngVLA Astro2020 Proposal: Sat 12/15/18 - Mon 7/1/19

- Other key dates:
  - US Radio Futures Conference #3: Community Study Final Reports Due
  - Release 2nd Draft of Sci Book
  - Pre-Proposal Review #1
  - Submit NOI
  - Submit SWPs
  - Pre-Proposal Review #2
  - Submit RFIR1
  - Submit RFIR2

- Key events:
  - VLA Special Session at Washington AAS (Jan. 2018)
  - Science meeting in Boulder, CO (June 2018)
ngVLA: the way forward (long-term)

MREFC = “Major Research Equipment and Facilities Construction”
ngVLA Summary

• The Next Generation Very Large Array is a burgeoning effort in the U.S. and abroad for a new instrument with 10x better sensitivity / resolution than JVLA

• The project has a lot of momentum, with wide community engagement and science and technical development studies underway

• The U.S. community is organizing to make a strong push for the ngVLA in the upcoming Astro2020 Decadal Survey process

• International partners are welcome and Canada can bring a lot of scientific and technical expertise to the table
ngVLA-Canada

- Engage, inform, and coordinate Canadian community about ngVLA, as the project moves toward Astro2020 submission (and LRP2020)

- Keep up to date on ongoing Science Case developments and Technical Study progress, discuss roles

- To join, contact James Di Francesco (james.difrancesco@nrc-cnrc.gc.ca)
Thanks to:
Andrea Isella (Rice)
Mark McKinnon (NRAO)
Eric Murphy (NRAO)
Rob Selina (NRAO)
Melissa Soriano (JPL)

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Current ngVLA Reference Design Specifications  
(ngVLA Memo #17)

- 214 18m offset Gregorian (feed-low) antennas  
  - Supported by internal costing exercise
- Fixed antenna locations across NM, TX, MX  
  - ~1000 km baselines being explored
- 1.2 – 50.5 GHz; 70 – 116 GHz  
  - Single-pixel feeds
  - 6 feeds / 2 dewar package
- Short-spacing/total power array under consideration

- Continuum Sensitivity: ~0.1 uJy/bm @ 1 cm, 10 mas, 10 hr => $T_B \sim 1$ K
- Line sensitivity: ~20 uJy @ 1 cm/bm, 10 km/s, 1” => $T_B \sim 25$ mK

| Band # | Dewar | $f_L$ GHz | $f_M$ GHz | $f_H$ GHz | $f_H : f_L$ | BW GHz |
|--------|-------|-----------|-----------|-----------|-------------|--------|
| 1      | A     | 1.2       | 2.55      | 3.9       | 3.25        | 2.7    |
| 2      | A     | 3.9       | 8.25      | 12.6      | 3.23        | 8.7    |
| 3      | B     | 12.6      | 16.8      | 21.0      | 1.67        | 8.4    |
| 4      | B     | 21.0      | 28.0      | 35.0      | 1.67        | 14.0   |
| 5      | B     | 30.5      | 40.5      | 50.5      | 1.66        | 20.0   |
| 6      | B     | 70.0      | 93.0      | 116       | 1.66        | 46.0   |
ngVLA Operating Modes / Functional Capabilities

- Spectral Line & Continuum Modes
- Time Domain Capabilities
- VLBI Capabilities
- Phased Array Capability
- Total Power Measurements
- Sub-Array Capabilities
- Solar Observation Capabilities

- Goal to maximize flexibility of both modes. Both equally represented.
- Time domain search capabilities on msec scales.
- Combine with other antennas out to continental scale baselines.
- Operate as both an interferometer and phased array.
- Need a solution to recover total flux.
- Flexible sub-array capability.
- Analog dynamic range for bright sources.
Key Open Questions – Specification Decisions

• Recovering Large Scale Structure
  ➢ Is a 30m minimum spacing good enough?
  ➢ Large single dish w/ FPA (e.g., 45m x 20 beams – D. Frayer, ngVLA memo 14)?
  ➢ Short-spacing array of small dishes + TP mode (e.g., 6m – Murphy/Condon+, Sci. Case NGA-3)?

• Distribution of collecting area – sensitivity over a range of angular scales needed.

• Maximum baseline in the reference design.
  • 300 – 500 km. Up to 1000 km?
  • How far should we go with connected elements?
ngVLA Science Options

• Commensal Low Frequency Science (Taylor)
  • Leverage ngVLA infrastructure (land/fiber/power) for commensal LF capabilities (ngLOBO)
    o 5 – 150 MHz: multi-beam dipole arrays alongside ngVLA long-baseline stations (e.g., LWA style).
    o 150 – 800 MHz commensal prime focus feeds on ngVLA antennas (e.g., VLITE style)

• U.S. VLBI Expansion of Capabilities (Brisken)
  • Replace existing VLBI antennas/infrastructure with ngVLA technology
  • Introduce new ~1000 km baseline stations to bridge gap between ngVLA & existing VLBA baselines
  • Cross correlate VLBI antennas with phased ngVLA
Five Key ngVLA Science Cases

- Unveiling the Formation of Solar System Analogues
- Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry
- Charting the Assembly, Structure, and Evolution of Galaxies from the First Billion Years to Present
- Using Pulsars in the Galactic Center as Fundamental Tests of Gravity
- Understanding the Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy

http://library.nrao.edu/public/memos/ngvla/NGVLA_19.pdf
ngVLA Science Use Cases

- Cradle of Life
- Galaxy Ecosystems
- Galaxy Assembly
- Fundamental physics
- Planet Formation
- Star Formation
- Solar System
- SETI
- Astrochemistry
Frequency Distribution of ngVLA Science Cases

Scenario Distribution by Band

| Frequency (GHz) | Count of Scenarios |
|----------------|--------------------|
| 70.0–116.0     | 45                 |
| 30.0–50.0      | 30                 |
| 18.0–30.0      | 20                 |
| 11.0–18.0      | 10                 |
| 3.6–10.8       | 5                  |
| 1.2–3.6        | 5                  |

Drivers | Related | Identified

Band 6
Band 5
Band 4
Band 3
Band 2
Band 1
Next Generation Very Large Array

Receiver Band Distribution over Baseline

Frequency (GHz)

1.2–3.6
3.6–10.8
11.0–18.0
18.0–30.0
30.0–50.0
70.0–116.0

Maximum Baseline (km)

10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4}

Band 1
Band 2
Band 3
Band 4
Band 5
Band 6
• 90% of ngVLA science use cases require max baselines of 100 km or less
• ngVLA workshop feedback from key science drivers found that 1-30 km baselines are desirable/essential
Charting the Assembly, Structure, and Evolution of Galaxies from the First Billions Years to the Present

- Understanding How Galaxies Produce New Generations of Stars
  - The ngVLA can study extended atomic reservoirs and large samples of GMC populations
  - Unique windows into the physical and chemical properties of accretion, transport, phase change, and excretion processes

NGC 628: THINGS HI (12", blue), PHANGS ALMA CO (1", red), IRAC 4.5 um (green)
Using Pulsars in the Galactic Center as Fundamental Tests of Gravity

- The ngVLA sensitivity and frequency coverage will probe deeper than possible into the GC area looking for pulsars, which are moving clocks in the space-time potential of Sgr A*
- New tests of theories of gravity, constraints on exotic binaries, SF history, stellar dynamics and evolution, and ISM at the GC
- Estimates are as high as 1,000 PSRs. Only know example is PSR J1745-2900 magnetar
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Understanding the Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy

- Unaffected by dust obscuration and with the angular resolution to separate Galactic sources from background objects using proper motions, the ngVLA will enable a search for accreting black holes across the entire Galaxy.
- Key to understanding GW discoveries
The Next Generation Very Large Array

Understanding the Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messanger Astronomy

- The ngVLA, with its deep high resolution imaging capabilities, will enable discovery of many supermassive black holes.

- Synergies to LISA and Pulsar Timing Arrays.

22 GHz VLBA image of binary SMBH

VLBA Image Courtesy of NRAO/AUI/NSF, from Taylor 2014
## Summary of Requirements from Key Science Cases

| Key Science Use Case                              | Frequency Coverage | Angular Resolution | Sensitivity       |
|--------------------------------------------------|--------------------|--------------------|-------------------|
| 1. Terrestrial Zone Planet Formation             | 20-40, 90-110      | <10                | 0.5 uJy/beam      |
| 2. Initial Conditions for Planetary Systems and Life | 16-50              | 50-200             | 30 uJy/beam/km/s  |
| 3. Assembly and Structure of Galaxies            | 5-50               | 100-3000           | 10 uJy/beam/km/s  |
| 4. Understanding how Galaxies Produce Stars      | 1.2-1.4, 80-120    | 100-60000          | 8 uJy/beam/km/s   |
| 5. Pulsars in the Galactic Center                | 2-26               |                    | 0.05 uJy/beam     |

Driving cases for sensitivity requirements

http://library.nrao.edu/public/memos/ngvla/NGVLA_19.pdf
The SAC was formed to provide science direction:

- represents the external community (no NRAO members): US + five int’l
- Currently 23 members, including B. Matthews and J. Di Francesco

For practical reasons, SAC split into Science Working Groups

- Cradle of Life (sub-GMC scales including the Solar System)
- Galactic Ecosystems (from Milky Way to nearby galaxies)
- Galaxy Assembly (the high-redshift universe)
- Fundamental Physics (time domain, Cosmology, Physics)
- SWGs are open: community members can participate in SWGs
The TAC was formed to provide technical direction:

- represents the external community (no NRAO members)
- currently 10 members, including M. Rupen and S. Dougherty

Activities

- Review of cost model
- Identification of areas in need of additional study
- Analysis of key science use cases and associated requirements
- Review of key specification documents (e.g., antenna)
- Development phase proposal input
ngVLA Construction Cost Distribution

Antenna subsystem is the construction cost driver

- Antennas 53.1
- Antenna Electronics 18.0
- Array Infrastructure 9.4
- Computing & Software 4.3
- Project Management & Administration 3.8
- Buildings 3.0
- Correlator 2.7
- Central/Distribution Electronics (LO, DTS) 2.2
- Commissioning & Scientific Validation (CSV) 1.9
- Systems Engineering 0.9
- IT Infrastructure 0.7
## Key ngVLA Antenna Specs and Comparison

| Antenna | Primary Aperture Diameter (meters) | Secondary angle of illumination angle (degrees) | f/D | shaped/unshaped | surface accuracy (microns) Precision conditions | surface accuracy (microns) Standard conditions | pointing accuracy rms (arcsec) Precision conditions | pointing accuracy rms (arcsec) Standard conditions |
|---------|-----------------------------------|-----------------------------------------------|-----|-----------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| MeerKAT | 13.5                              | 100                                          | 0.55 | unshaped        | 600                                           | 600                                           | 5                                             | 25                                             |
| DVA-2   | 15                                | 110                                          | 0.8  | shaped          | 335                                           | ?                                             | 10                                            | 180                                            |
| ALMA    | 12                                | 7.16                                         | 0.4  | unshaped        | 25                                            | 25                                            | 2                                             | 2                                              |
| SKA     | 15                                | 110                                          | 0.36 | shaped          | 500                                           | 500                                           | 5                                             | 10                                             |
| ngVLA   | 18                                |                                               |      | shaped          | 160                                           | 300                                           | 2.7                                           | 4.2                                            |

Antenna requirements are reasonable when compared to other radio telescope projects in development, study coming soon to improve cost model.

Note: Data shown for constructed antennas is requirements, not actual performance. Nighttime/no wind (precision) conditions and daytime (normal) conditions differ for each system.
## ngVLA Concept

| Parameter                  | Value                                      |
|----------------------------|--------------------------------------------|
| Antenna Diameter           | 18m Homogeneous Array                      |
| Number of Antennas         | 214                                        |
| Antenna Optics             | Offset Gregorian, Feed Low, Shaped         |
| Frequency Range            | 1.2 GHz – 50.5 GHz, 70 GHz – 116 GHz       |
| Front Ends                 | Single Pixel Feeds, Dual Linear Polarization|
| Instantaneous Bandwidth    | Up to 20 GHz / pol.                        |
### ngVLA Concept

### ngVLA Configuration

| Parameter                              | Value                                                                 |
|----------------------------------------|----------------------------------------------------------------------|
| Antenna Locations                      | Fixed Configuration                                                 |
| (Minimum) Array Extent                 | 500 km + (Evaluating 500-1000km scales)                              |
| Radial Distribution of Collecting Area | 40/40/20 % at 2/50/500 km scales                                     |

![Map of ngVLA Configuration](image-url)
ngVLA Concept

Antenna Concept

- **18m Aperture**: Based on cost and performance modeling.
- **Offset Gregorian**: Off-axis geometry minimizes scattering, spillover, and sidelobe pickup
- **Feed Low**: Performance and maintenance requirements favor a receiver feed arm on the low side of the reflector
- **Mount concept**: TBD.
  - Evaluating pedestal mount vs wheel and track.
  - Pointing specification is a design driver.
- **Will pursue antenna reference design this fall.**
Receiver/Feed Configuration Concept

- 6 Bands in 2 Cryogenic Dewars
- 1.2-3.9 GHz and 3.9-12.6 GHz Quad-Ridge Horns, 3.25:1 bandwidth, coaxial LNAs.
- 12.6-50.5 GHz using three 1.67:1 BW corrugated horns and waveguide LNAs.
- 70-116 GHz 1.67:1 BW corrugated horn and waveguide LNAs with block down conversion.
- Single stage down-conversion to baseband for 5 bands. Direct SSB or IQ sampling using modular devices @ FE.
ngVLA Concept

Correlator, Back Ends, Pipelines

- FX Correlator Architecture
  - FPGA vs. ASICs
  - Dev $ vs. Ops $
  - Evaluating distributed F-Engine

- Down to 1 msec. dump times to BE
- Up to 64k spectral channels to BE

- Basic Data Products
  - Uncalibrated Visibilities (to Archive)
  - Calibration & Flagging Tables

- Advanced Data Products
  - VLA and ALMA “Science Ready Data Products” pipelines as a pathfinder.
ngVLA Concept

Phase Calibration

• Three Options Under Consideration:
  • Fast Switching
  • Water Vapour Radiometry
  • Auxiliary Array

• Optimize for Sensitivity & Efficiency per $\:
  • \((\text{uJy/beam})/\delta_{\text{sys}}/T_{\text{clock}}\)
  • Across all bands

• **Fast Switching** more technically challenging with larger dishes.

• **WVR** likely lowest cost solution, with longer switching cycles for instrumental calibration & recovery of the dry term.

• **Aux. Array** a contingency option.
ngVLA Concept

Recovering Total Flux / Large Scale Structure

- Existing Large Single Dish
- New Large Single Dish
- Short Spacing Array + 18m Total Power Mode
Longest Baselines

• Evaluating extending the array beyond 500km scale.
• 500-1000km baseline stations (e.g., Texas) bridge the UV-gap between the ngVLA & existing VLBA baselines.