ngvla

Next Generation Very Large Array

A next-generation Very Large Array (ngVLA)

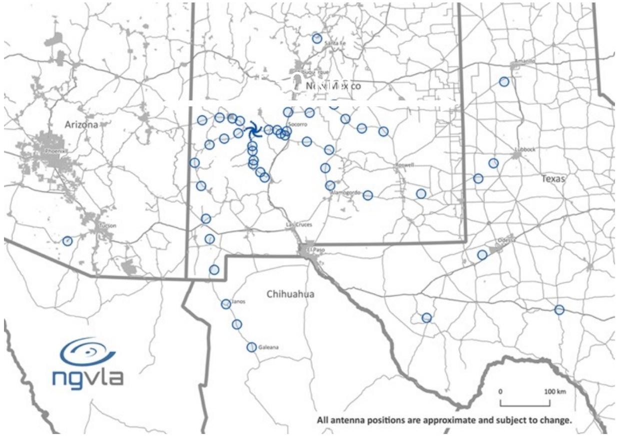
Eric J. Murphy – ngVLA Project Scientist

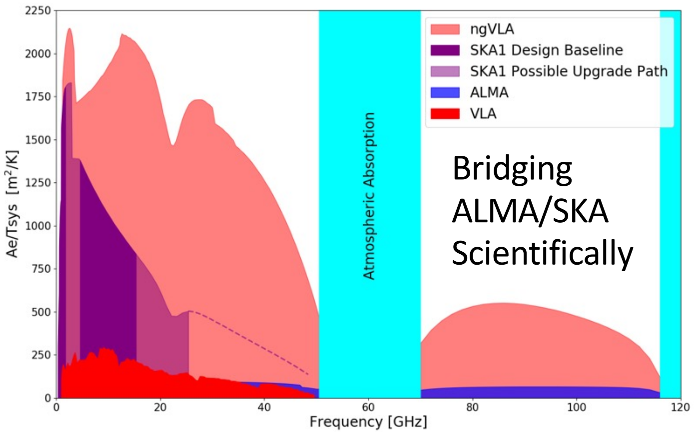
ngVLA.nrao.edu

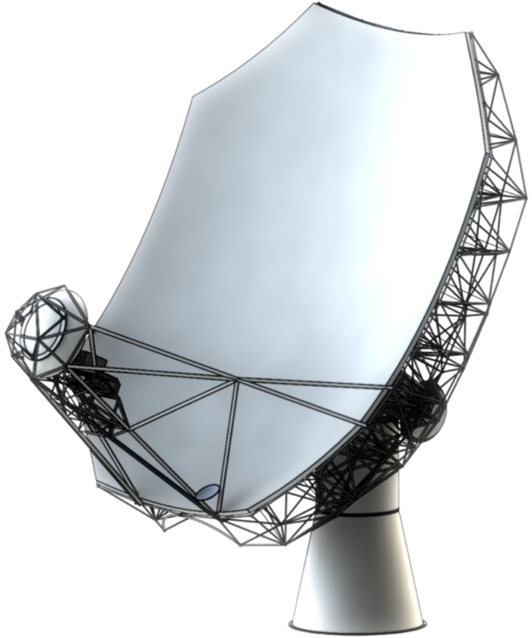
NSF AUI NRAO

A next-generation Very Large Array (ngVLA)

- Scientific Frontier: ***Thermal imaging at milli-arcsec resolution***
- Sensitivity/Resolution Goal: ***10x sensitivity & resolution of JVLA/ALMA***
- Frequency range: ***1.2 –116 GHz***
- Located in Southwest U.S. (NM, TX, AZ) & MX, centered on VLA
- Low technical risk (reasonable step beyond state of the art)







Complementary suite of meter-to-submm arrays for the mid-21st century

- **< 0.3 cm:** ALMA 2030
- **0.3 to 3 cm: ngVLA**
- **> 3 cm:** SKA

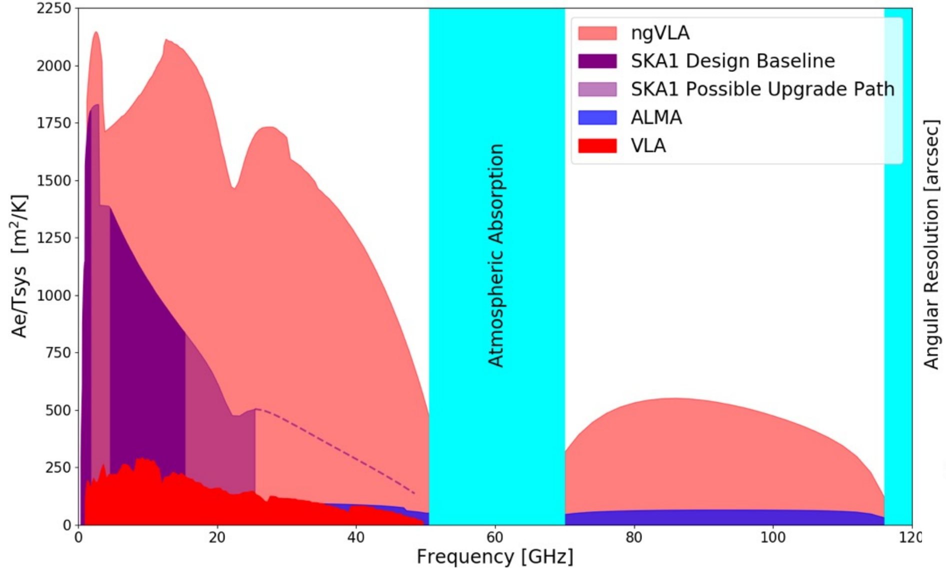
http://ngvla.nrao.edu

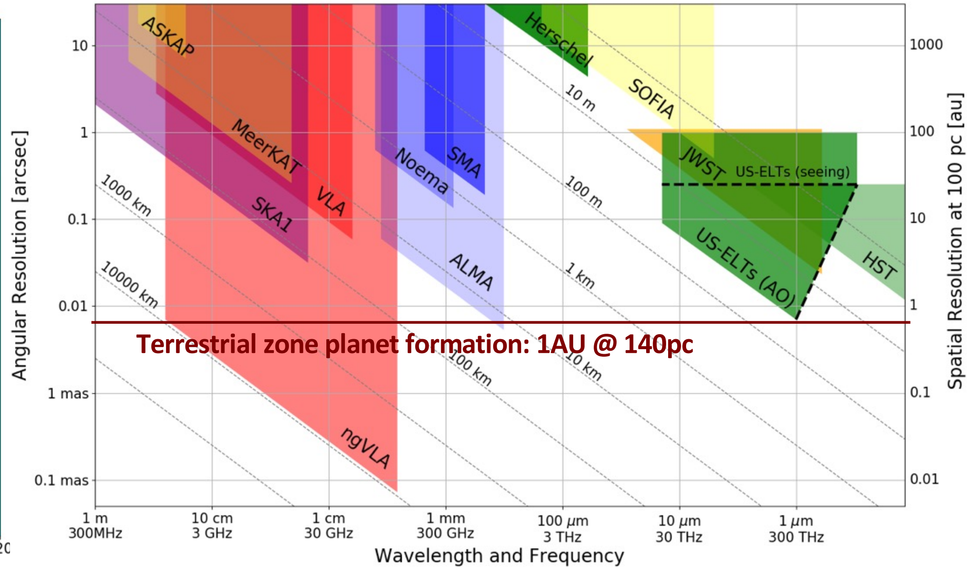
ngVLA Key Science Goals (ngVLA memo #19)

1. *Unveiling the Formation of Solar System Analogues on Terrestrial Scales*
2. *Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry*
3. *Charting the Assembly, Structure, and Evolution of Galaxies Over Cosmic Time*
4. *Using Pulsars in the Galactic Center as Fundamental Tests of Gravity*
5. *Understanding the Formation and Evolution of Stellar and Supermassive BH's in the Era of Multi-Messenger Astronomy*

Bridging SKA & ALMA Scientifically

Thermal Imaging on mas Scales at λ ~ 0.3cm to 3cm





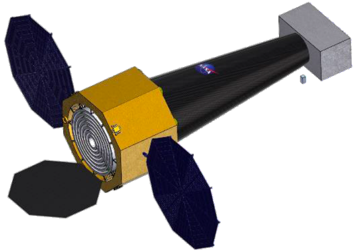
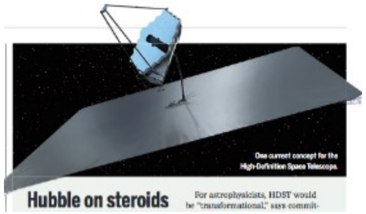
Complementary suite from cm to submm arrays for the mid-21st century

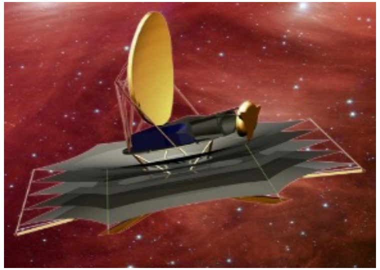
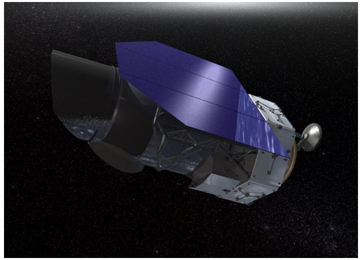
- **< 0.3cm:** ALMA 2030 superb for chemistry, dust, fine structure lines
- **0.3 to 3cm:** ngVLA superb for terrestrial planet formation, dense gas history, baryon cycling
- **> 3cm:** SKA superb for pulsars, reionization, HI + continuum surveys

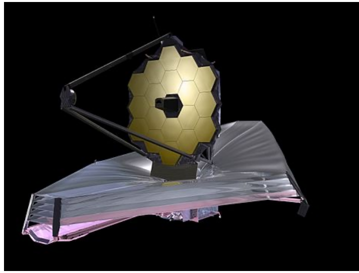
Highly Synergistic with Other Facilities on Similar Timescales

- SKA/Lynx
  - Atomic/non-thermal
  - *Molecular/thermal*
- ALMA
  - Warm/star-forming
  - *Cold/dense fuel for SF*
- LUVOIR/HabEx
  - Image earth-like planets
  - *Image terrestrial-zone planets forming*
- OST (FIR surveyor)
  - C/WNM & WIM
  - *Cold Molecular Medium*
- TMT/GMT
  - *Stellar Mass and Unobscured SF*
  - *Dense Gas and Obscured SF*
- JWST/WFIRST
  - *Continuing its legacy in many areas of astrophysics*



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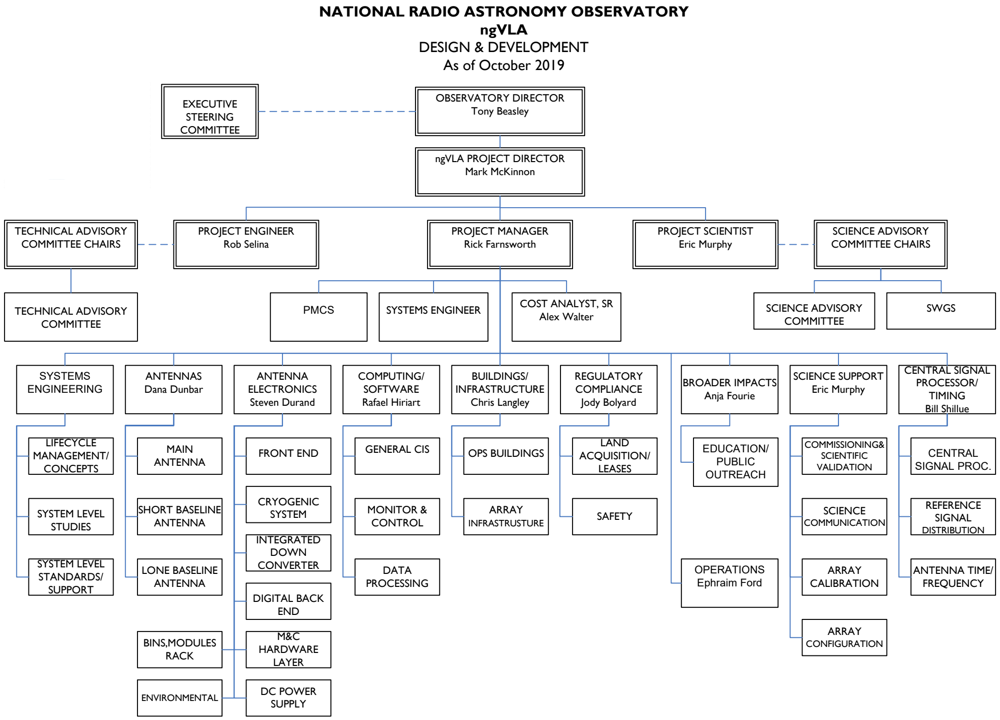
ngVLA Project

- Project Office leadership team:
  - Project Director: Mark McKinnon
  - Project Manager: *Chris Langley*
  - Project Scientist: Eric Murphy
  - Project Engineer: Rob Selina
  - Cost Analyst: Alexia Nalewaik
  - System Engineer: Thomas Kusel



- 10 Integrated Product Teams (IPTs).
- MREFC-style project definition.
- Actively engaged science and technical advisory councils.

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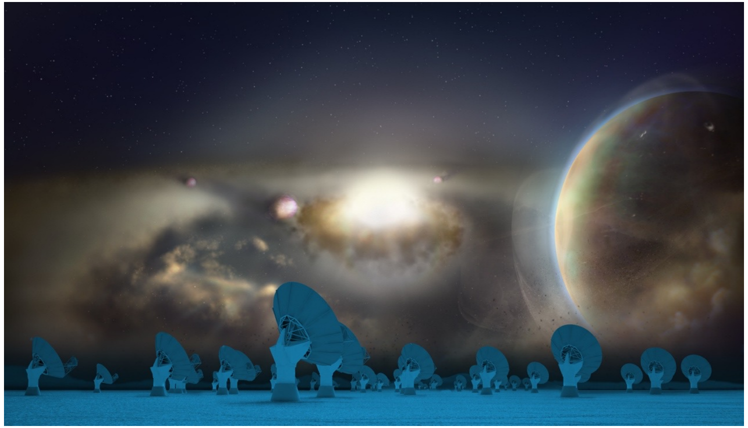
ngVLA Science Advisory Council



- Interface between the Community & NRAO -- Est. Sept 2016
- Recent/Current Activities:
  - Lead SWGs: science use cases → telescope requirements
  - SOC for science meeting in June 2017/2018/2019
  - Lead Science case development → 'Science Book' & Astro2020 White Papers
  - Document Review: e.g., Sci Reqs, Ops Con, Ref Observing Program, etc.
  - Help with preparation of Astro2020 APC white papers

International Participation

東京大学 THE UNIVERSITY OF TOKYO · NRC-CNRC Canada · ASIAA · RIKEN · UNIVERSITY OF ALBERTA · Universidad Nacional Autónoma de México · Max-Planck-Institut für Astronomie Heidelberg

Executive Committee

Alberto Bolatto (Maryland: **co-Chair**)
Andrea Isella (Rice: **co-Chair**)
Brenda Matthews (NRC–Vic: **SWG1 Chair**)
Danny Dale (Wyoming: **SWG2 Chair**)
Dominik Riechers (Cornell: **SWG3 Chair**)
Joseph Lazio (JPL: **SWG4 Chair**)
Shri Kulkarni (Caltech)
James Di Francesco (NRC–Vic)

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Strong Community Participation

Jet Propulsion Laboratory
Johns Hopkins University
University of Virginia
Ohio State
The University of New Mexico
California State University Northridge
Cornell University
NOAO
University of Maryland
The George Washington University Washington, DC
BYU Brigham Young University
Michigan State
University of Wyoming
LSST Large Synoptic Survey Telescope
Rice
Green Bank Observatory
Texas Tech University
Harvard-Smithsonian Center for Astrophysics
Berkeley University of California
Texas The University of Texas at Austin
The University of Arizona
The University of Iowa
UC San Diego
West Virginia University
STScI Space Telescope Science Institute
Caltech

mtex | antenna technology
MT Mechatronics
Vertex
Raytheon Technologies
General Dynamics Mission Systems
EMSS Antennas (Pty) Ltd
Quantum Design
REhnu Next Generation Solar
LaserLaB Amsterdam
VU
Minex Engineering Corp.

NRC·CNRC Canada
ASIAA
The University of Western Australia
University of Alberta
US University of Sussex
Universidad Nacional Autónoma de México
国立天文台 NAOJ National Astronomical Observatory of Japan
東京大学 The University of Tokyo
ICRAR International Centre for Radio Astronomy Research
RIKEN
Max-Planck-Institut für Astronomie Heidelberg

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2018 Science Meeting

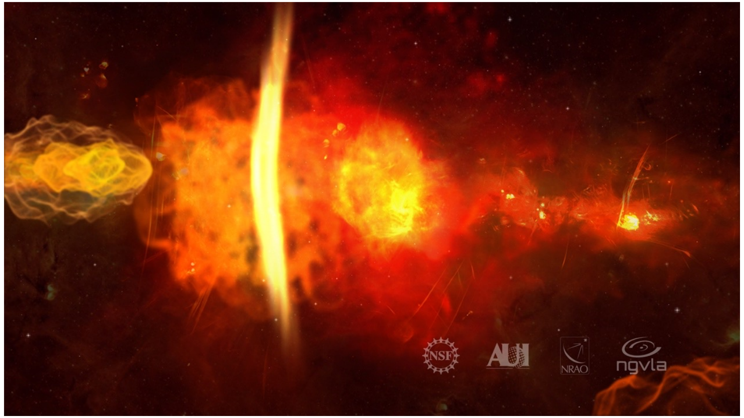
- Meeting was science-focused and wavelength agnostic
  - Brought together a broad cross—section of community
- 3 Parallel Sessions:
  - Origins of Exoplanets and Protoplanetary Disks
  - Mechanisms of Galaxy Evolution
  - Black Holes and Transient Phenomena
- 200+ registrants and ***70+ students*!** **-** We are creating our next-generation of users

2019 Science Meeting: Radio/mm Astrophysical Frontiers in the Next Decade

- 25-27 June, 2019 in Charlottesville: http://go.nrao.edu/ngVLA19

- Focus on compelling Astro2020 Science WPs requiring cm/mm observations.

- Early Career participation strongly encouraged
    - Housing covered for presenting students



First Internationally-Led Science Meeting!

Broad Participation Largely Dominated by Early Career Astronomers

- NAOJ-ngVLA Science Meeting: September 16-20, 2019 in Mitaka, Japan
- ***~100 Participants!***
- Forward looking talks covering broad scientific interests.

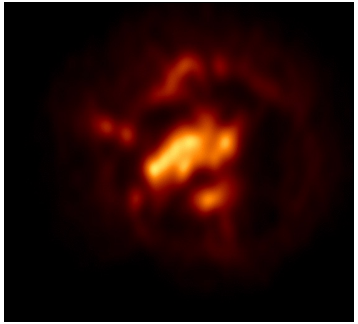
Successful Community Engagement Activities

Broad Participation Largely Dominated by Early Career Astronomers

http://go.nrao.edu/ngVLA18

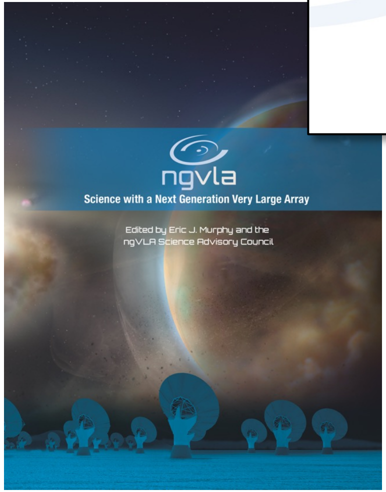
http://go.nrao.edu/ngVLA19

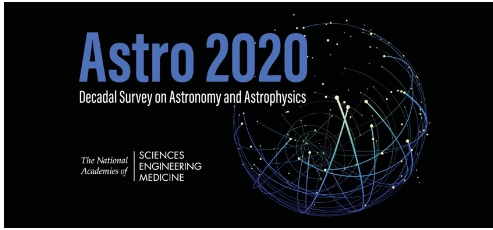
- Science Meetings
- Short Talk Series
- Community Studies
- ngVLA Town Hall



Science and Technical Documentation

- **ngVLA Science Book published** (Dec 2018)
- Facilitated community **submission of ngVLA science white papers** to Astro2020 Decadal Survey (Jan 2019)
  - 15% specifically mentioning ngVLA
- **Submitted ngVLA facilities (APC) white paper** to Astro2020 Decadal Survey (Jul 2019)
- **ngVLA Reference Design Concept completed** (Aug 2019)
  - https://ngvla.nrao.edu/page/refdesign
- **Presented to Astro2020 RMS Panel** (Dec. 2019)
- **Submitted (120 pg) Response to Astro2020** Decadal Survey RFI (Nov. 2019) + Second Response (Mar. 2020)

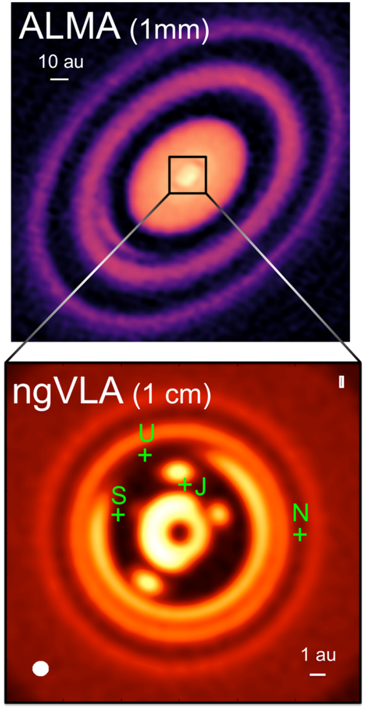


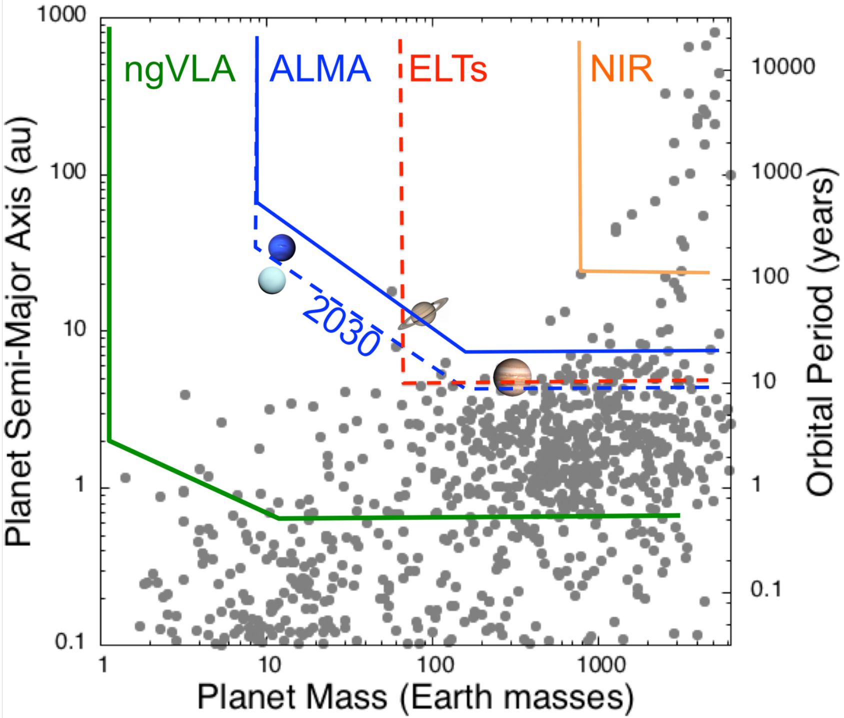


https://ngvla.nrao.edu/page/projdoc

KSG1: Unveiling the Formation of Solar System Analogues

The ngVLA will measure the planet IMF down to ~5-10 Earth masses and unveil the formation of planetary systems similar to our own Solar System.

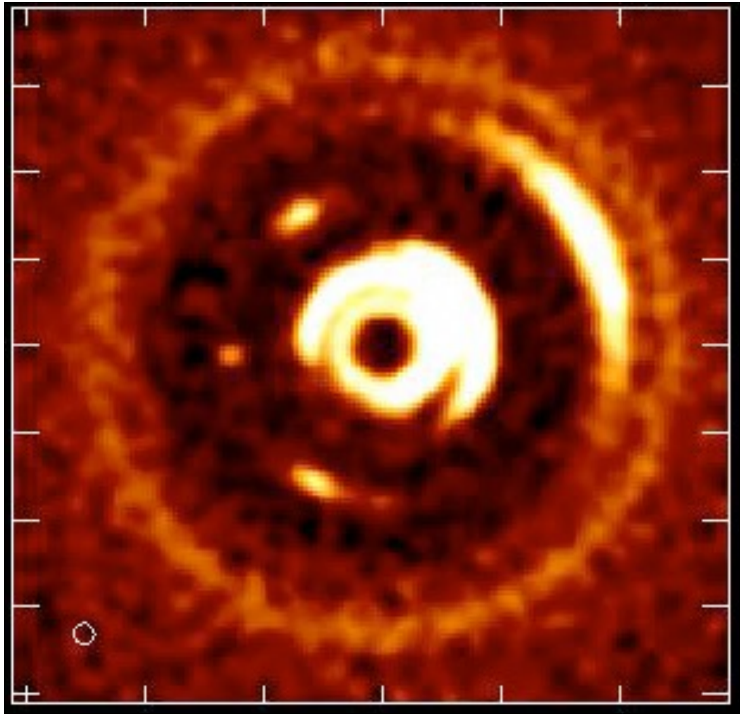




- ALMA observation of HD163296 at 1mm along with a simulated 1 cm ngVLA observations (Ricci et al. 2019) of the innermost 24 au region at 1 au resolution for Jupiter-, Saturn-, and Neptune-like planets.
- The distribution of exoplanets and young planets embedded in circumstellar disks: Then ngVLA will discover many hundreds of planets with orbital periods <10 Myr.

KSG1: Unveiling the Formation of Solar System Analogues

The ngVLA will measure the orbital motion of planets and related features on monthly timescales.



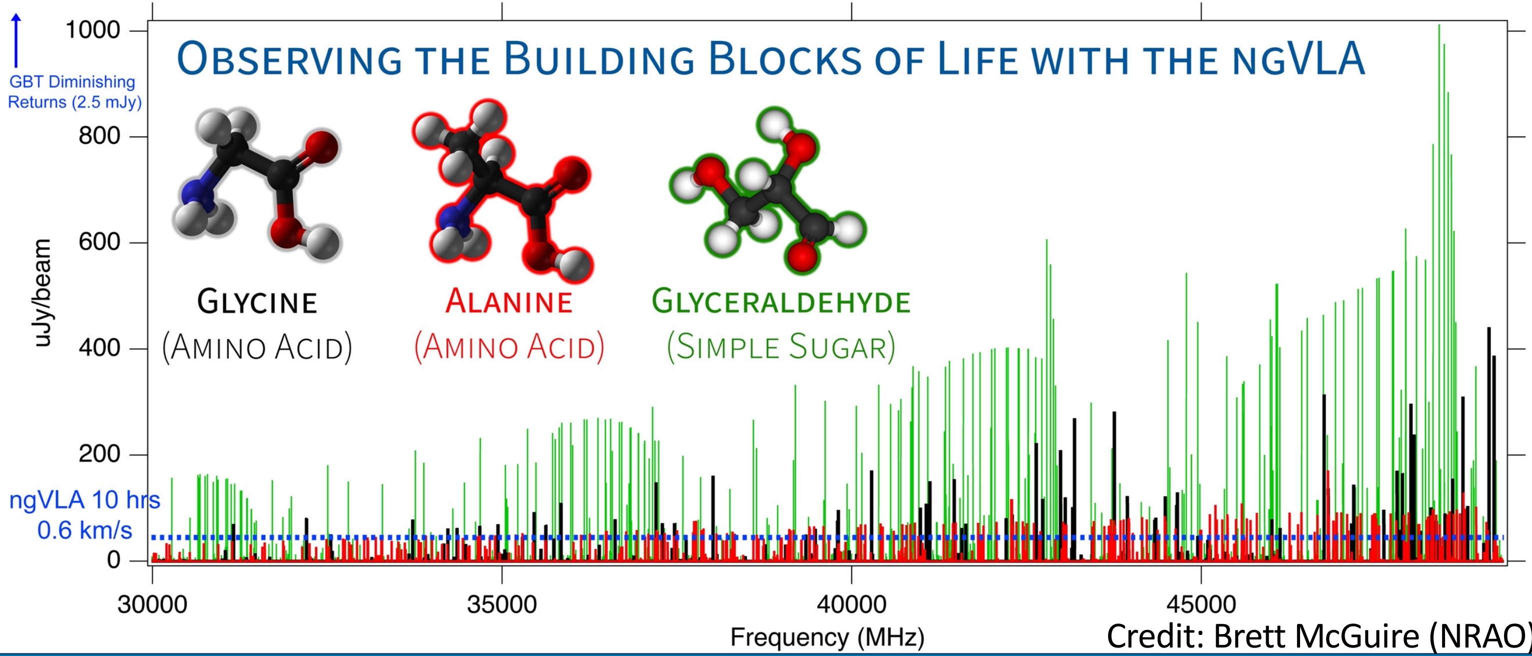
The ngVLA will measure the planet IMF down to ~5-10 Earth masses and unveil the formation of planetary systems similar to our own Solar System.

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

Ricci et al. (2018)

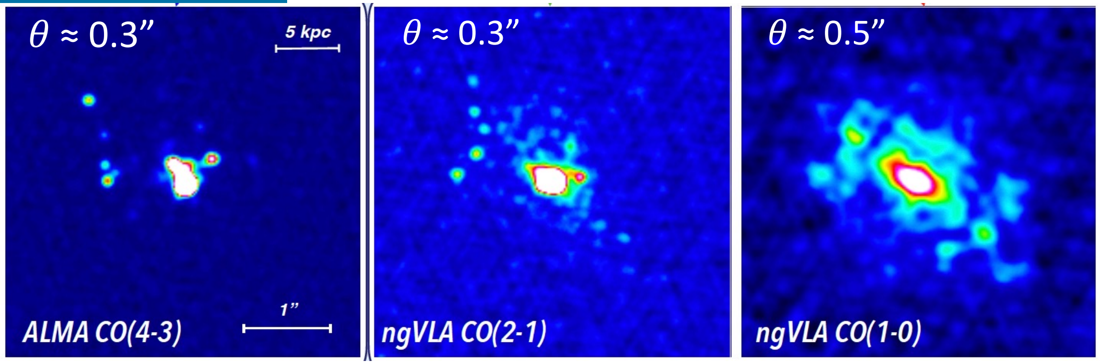
KSG2: Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry

The ngVLA can detect complex pre-biotic molecules and provide the chemical initial conditions in forming solar systems and individual planets



Credit: Brett McGuire (NRAO)

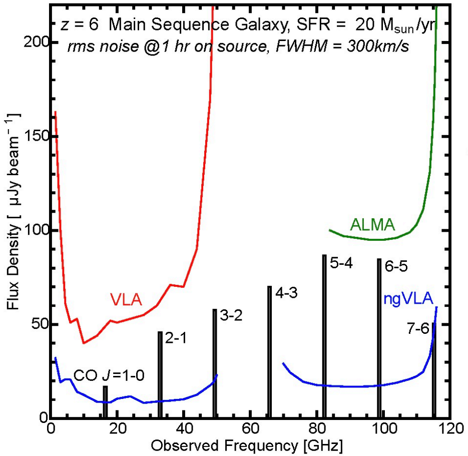
KSG3: Charting the Assembly, Structure, and Evolution of Galaxies from the First Billions Years to the Present

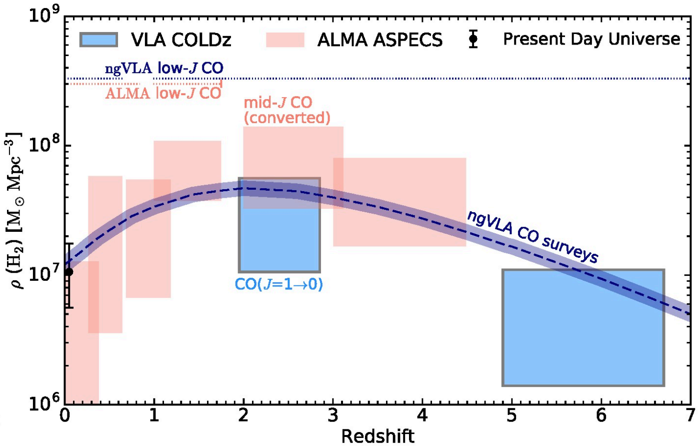


Credit: Caitlin Casey (UT Austin)

SMG at $z = 4.4$; SFR ≈ 400 $M_\odot$ /yr

Total molecular gas content largely missed by high-J lines





The ngVLA will routinely detect molecular gas in “normal” galaxies at z=6 ***via low-J transitions that remain inaccessible to ALMA***.

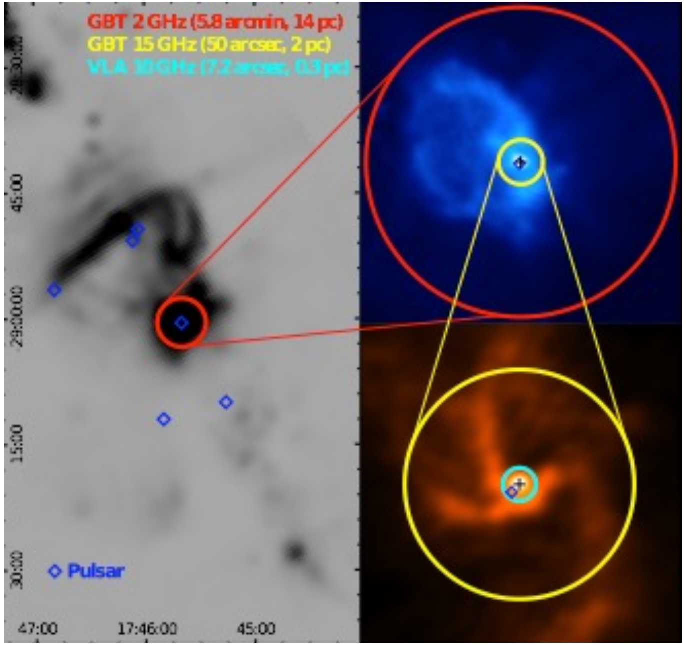
The ngVLA will provide >10x improvement in our knowledge of the cold molecular gas content throughout cosmic time.

KSG4: Using Pulsars in the Galactic Center as Fundamental Tests of Gravity

- The ngVLA sensitivity and frequency coverage will probe deeper than currently 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

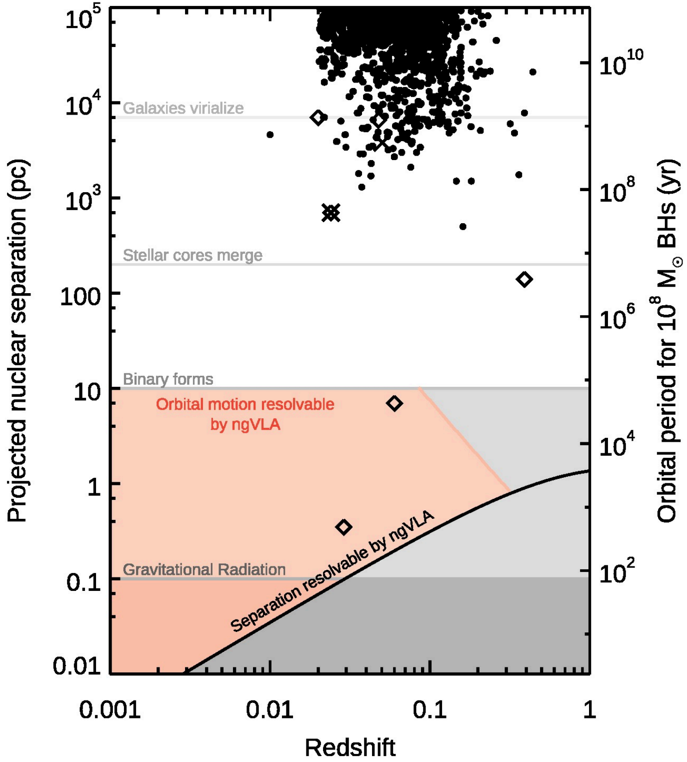
- Estimates are as high as 1,000 PSRs. Only known example is PSR J1745-2900 magnetar, which are extremely rare (<1%)



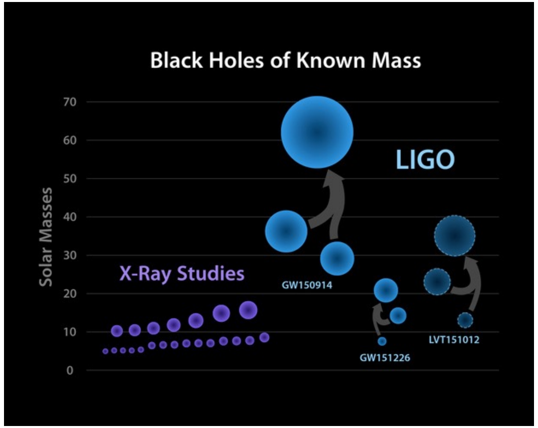
Credit: R. Wharton

KSG5: Understanding the Formation and Evolution of Black Holes in the Era of *Multi-Messenger Astronomy*

- Unaffected by dust obscuration, the ngVLA's sensitivity and angular resolution will be able to:
  - Resolve dual AGN and BH binaries.
  - Measure proper motions over 5 year periods (orange shaded region), including sources detect by GWs

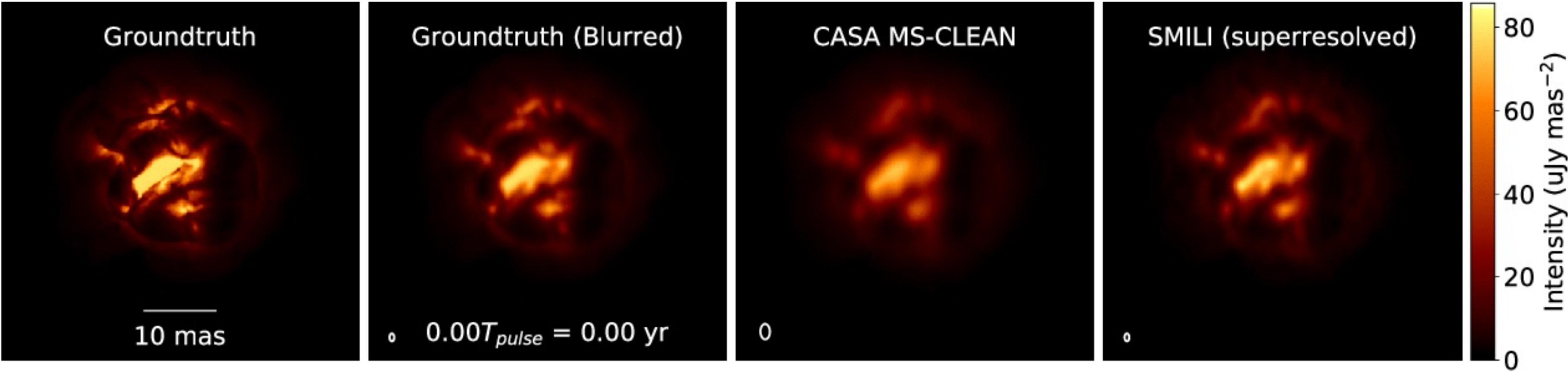


  - Search for BHs across all masses, including weakly accreting BHs in the MW via proper motions



Science Highlight: Star Formation and Stellar Evolution

The ngVLA will measure the in –situ gas motions from material shed around AGB stars.



Simulation based on 3D hydrodynamic model of AGB star Atmosphere from Freytag et al. (2017):

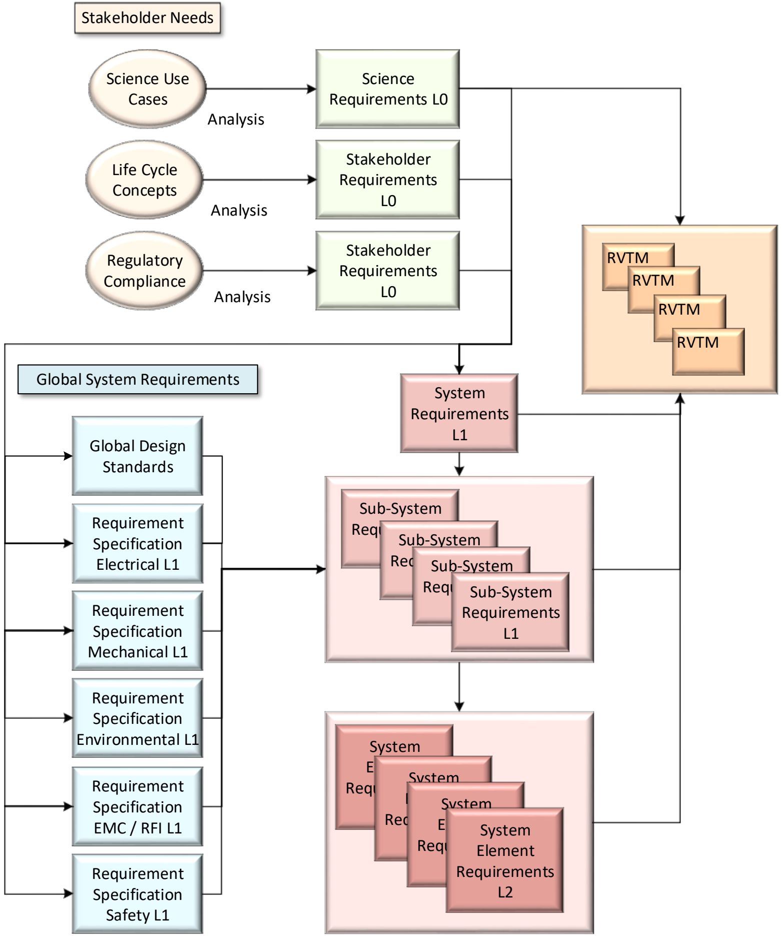
- ngVLA Main Array at 46 GHz
- 1.5 mas ~ 0.04 stellar radii at d=150pc
- 1.3 year pulse period
- Observed every 2-3 weeks

ngVLA Memo #66

Credit: K. Akiyama & L. Matthews
based on models from B. Freytag
Supported by ngVLA Comm Study Program

Requirements Flow-Down

- Begins with Science Use Cases (>80)
  - Distilled into ~200 unique observations
- Prioritization by SAC
  - 5 KSGs born out of various use cases
- Converted into Level 0 Science Reqs.
  - 37 Requirements to support KSGs
    - 18 Functional Reqs.
    - 19 Performance Reqs.
- Translated into Level 1 Technical Reqs.
  - 180+ System Level Reqs.
- **Next Step: Full Level 2 Technical Reqs.**



ngVLA Technical Baseline

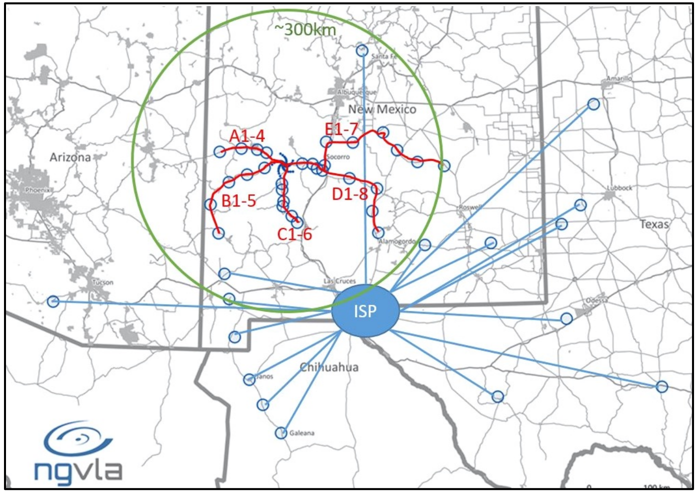
- **1.2 - 116 GHz** Frequency Coverage
- **Main Array**: 214 x 18m offset Gregorian Antennas.
  - Fixed antenna locations across NM, TX, AZ, MX.
- **Short Baseline Array**: 19 x 6m offset Greg. Ant.
  - Use 4 x 18m in TP mode to fill in (*u, v*) hole.

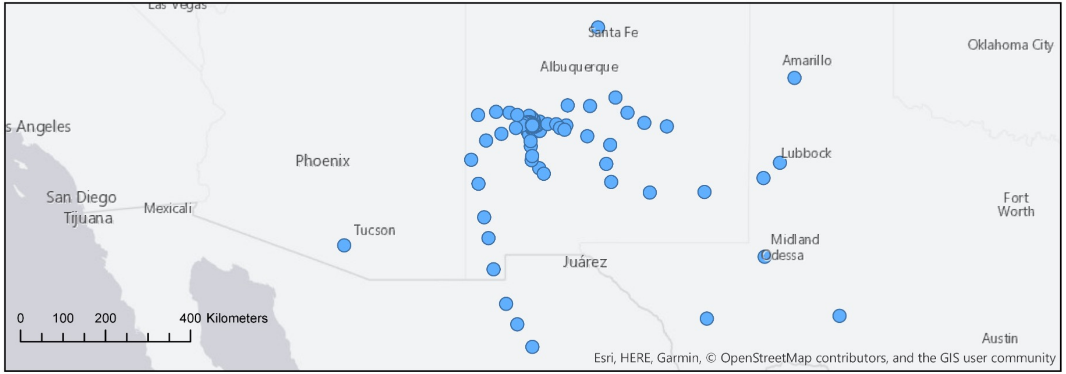
Band #	Dewar	f_L GHz	f_M GHz	f_H GHz	f_H: f_L	BW GHz
1	A	1.2	2.35	3.5	2.91	2.3
2	B	3.5	7.90	12.3	3.51	8.8
3	B	12.3	16.4	20.5	1.67	8.2
4	B	20.5	27.3	34.0	1.66	13.5
5	B	30.5	40.5	50.5	1.66	20.0
6	B	70.0	93.0	116	1.66	46.0

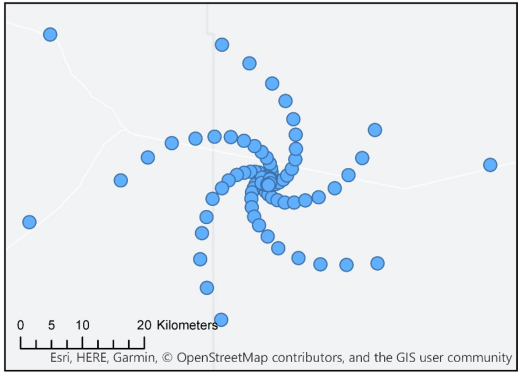
- **Long Baseline Array**: 30 x 18m antennas located across continent for baselines up to 8860km.

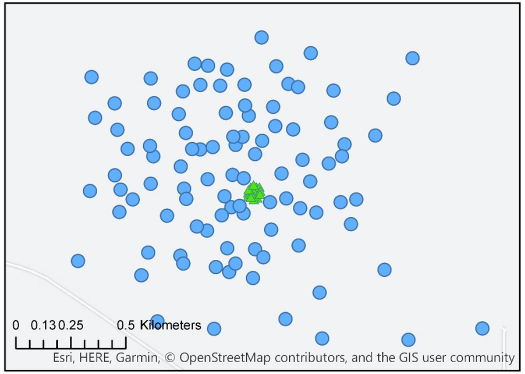
The Main Array (MA) Configuration

Radius	Collecting Area Fraction
0 km < R < 1.3 km	44%
1.3 km < R < 36 km	35%
36 km < R < 1000 km	21%



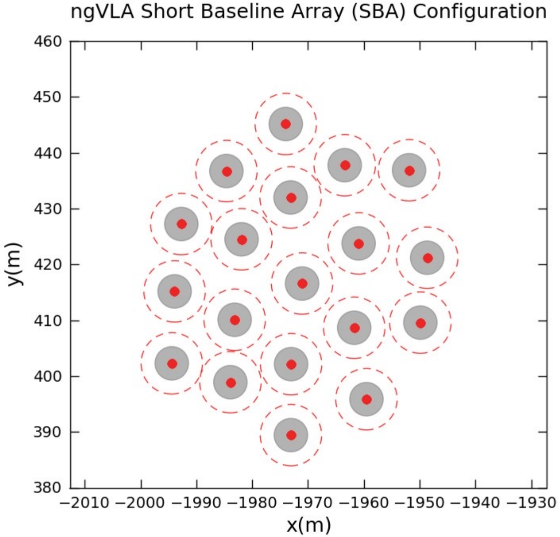


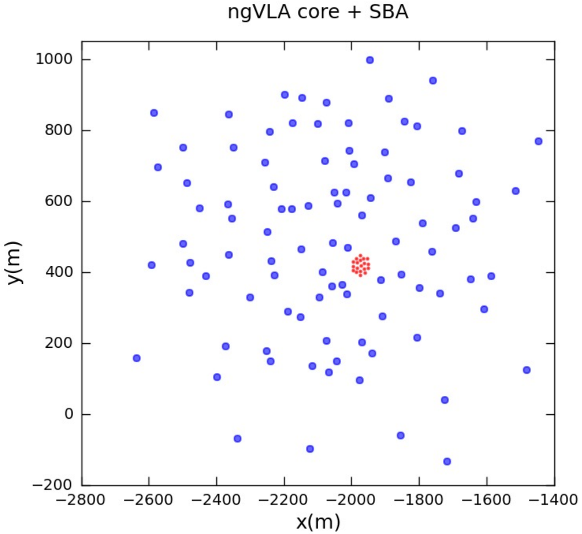


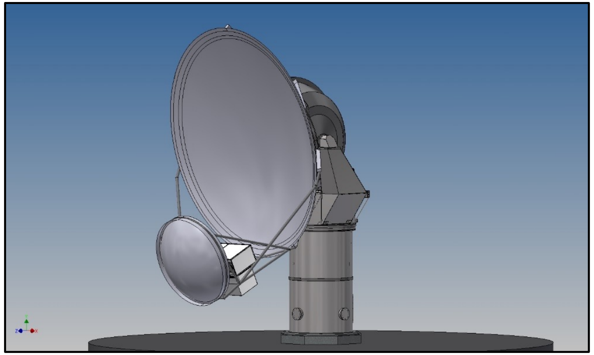


Short Baseline Array (SBA)

- SBA of 19 x 6m
- Total Power Array of 4 x 18m (included as part of the 214 main array).



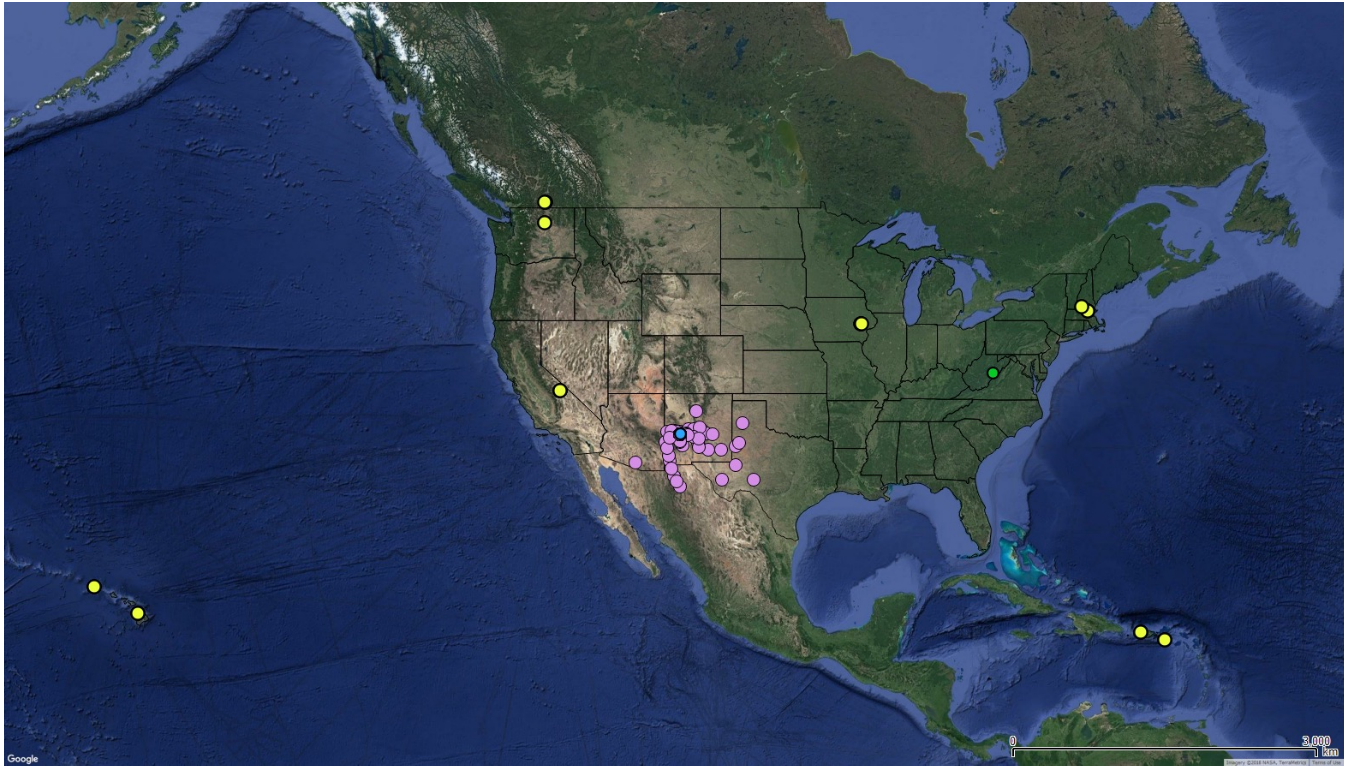




Long Baseline Array (LBA)

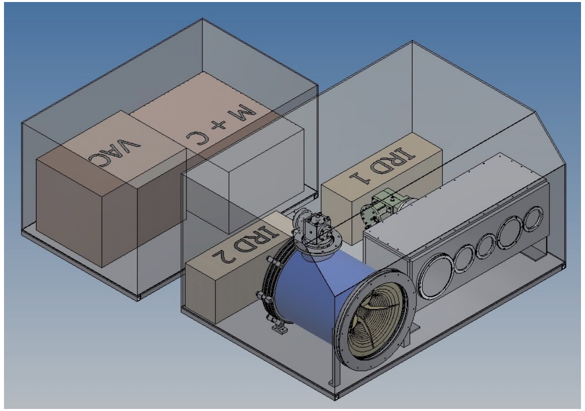
- 30 Antennas at 10 sites.
- Balance between Astrometry & Imaging Use Cases.

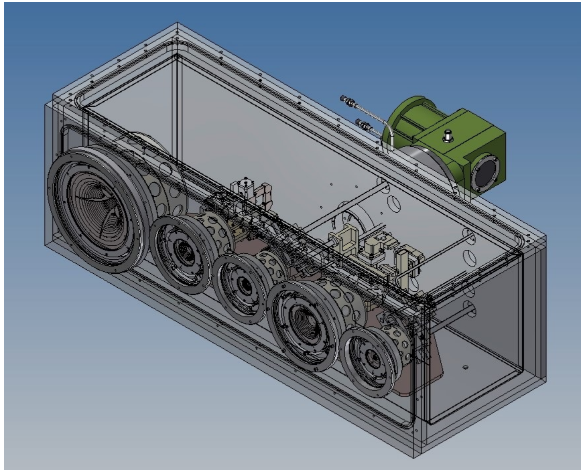
Qty	Location	Notes
3	Puerto Rico	Arecibo Site
3	St. Croix	Existing VLBA Site
3	Kauai, Hawaii	Kokee Park Geo. Obs.
3	Hawaii, Hawaii	Not MK Site
2	Hancock, NH	Existing VLBA Site
3	Green Bank, WV	GBO
2	Brewster, WA	Existing VLBA Site
3	Penticton, BC	DRAO
4	North Liberty, IA	Existing VLBA site.
4	Owens Valley, CA	Existing VLBA site.



Front End Concept

- 6 Bands in 2 Cryogenic Dewars
- 1.2-3.5 GHz and 3.5-12.3 GHz Quad-Ridge Horns, 3.25:1 bandwidth, coaxial LNAs.
- 12.3-50.5 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.
- Two-stage Gifford-McMahon cryogenic system with variable-speed cryocoolers and compressors for reference design.

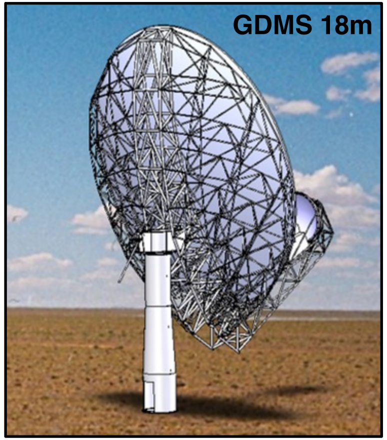


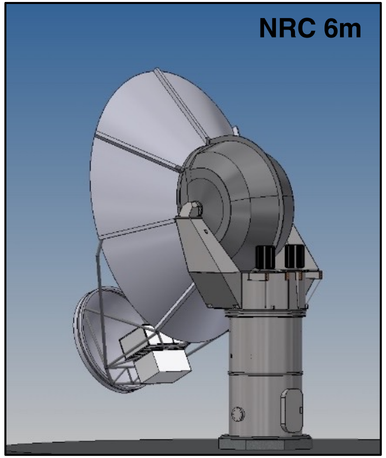


Antenna Concept

- **Feed Low**: Maintenance requirements favor a receiver feed arm on the low side of the reflector.
- **Mount concept**: Leaning towards pedestal concepts for life-cycle cost. W/T under evaluation.
- **Drives:** All motor-gearbox; gearbox and linear drives; all direct drive, etc.
- **Materials:** Traditional Al panels & steel BUS; composite reflector and mix of steel and carbon BUS.

Key Specifications	
18m Aperture	Offset Gregorian
Shaped Optics	4° Slew & Settle in 10 sec
Surface: 160 µm rms	Referenced Pointing: 3” rms





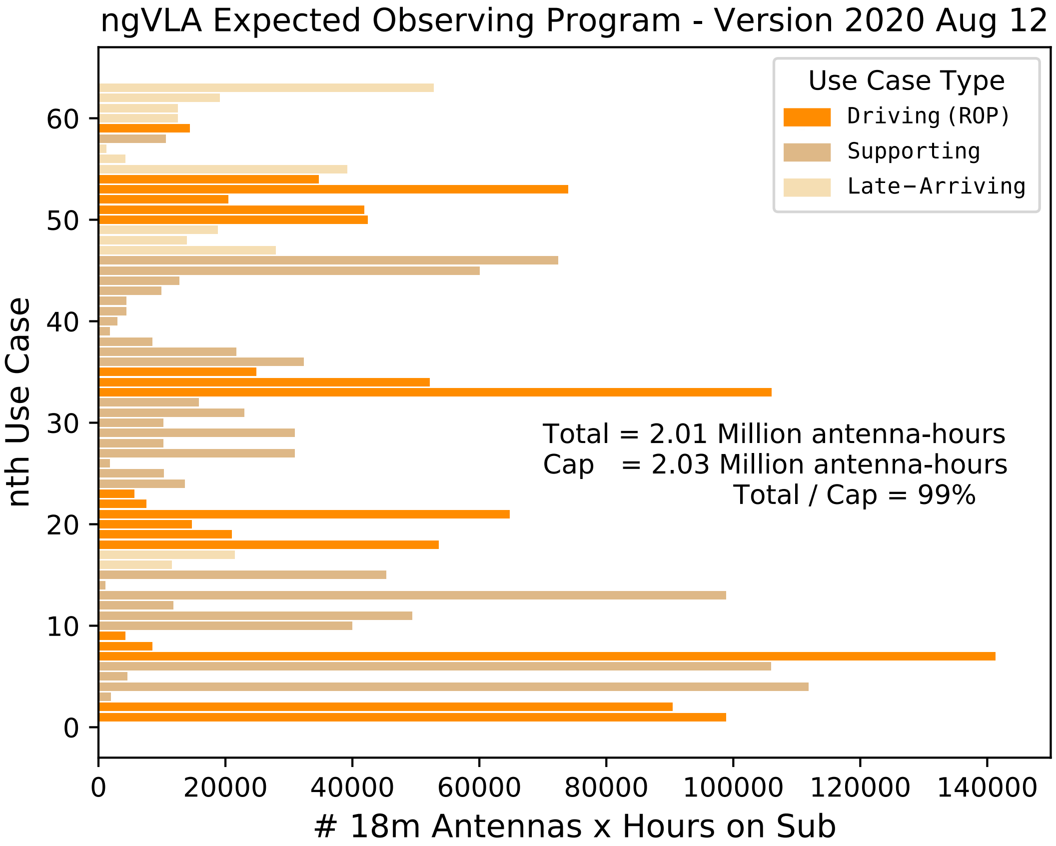
S/W and Computing Considerations

- **Operations Concept**: SRDP (Science Ready Data Products) Telescope
  - Both for 1st Observations and Archive projects.
- **Post Processing**: Analysis shows that storing the raw visibilities will be tractable when ngVLA goes into operations.
  - Data processing is post-facto, with system sized for average throughput.
  - Average Data Rate – 7.6 GB/s. Designed for 320 GB/s peak.
  - 4 hr. observation – 109 TB. Requires ~1000 cores to process in a few days.
- **Computing:** 2B Core-hr: Challenging, but can be met w/ COTS cluster.
  - Set by time resolution, spectral resolution, and multi-faceting in imaging
  - Some low-frequency, full-beam, AW-projection cases restricted in early operations.

Anticipated Usage

- Built a **Reference Observing Program** (ROP) for a 70% "learning" year
  - Driving use cases only
  - Filled ~ 2000 hours
  - For Astro2020
  - *Demonstrates we can achieve KSGs*

- Build an **Envelope Observing Program** (EOP) for a 95% "typical" year
  - All use cases
  - Fill 8330 hours
  - *To inform Computing needs and Ops Concept*



Current Goals & Initiatives

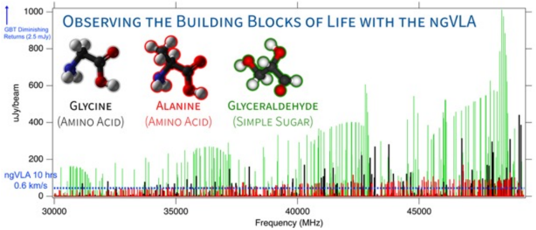
- Current goals:
  - Be ready to react to a positive Astro2020 Decadal Survey outcome.
    - Currently expected this month (June 2021)
  - Advance the ngVLA Conceptual Design for NSF MREFC Candidacy

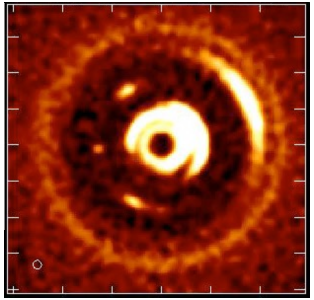
- Current initiatives:
  - Continue to build and hone the ngVLA science case
    - Driven by the community and coordinated by NRAO
    - Update/incorporate additional science cases to ngVLA Science Book
  - Develop ngVLA Conceptual Design and Requirements Baseline
    - Finalize antenna design and prototype
    - Work towards a finalized Conceptual Design to be external reviewed in Q1 FY22

Status & Performance

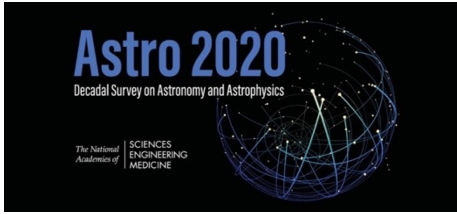
- ngVLA now funded through its own Cooperative Support Agreement with NSF
- Continue strong community engagement and participation through ngVLA SAC and sponsored events
- Updating requirements and retiring existing risks through management and systems engineering
- Awaiting NSF/MSIP award to fund prototype antenna.
- Continuing to identify and develop Broader Impact/Participation Opportunities with IPTs vis a strategic communication plan.

FY20 Activities

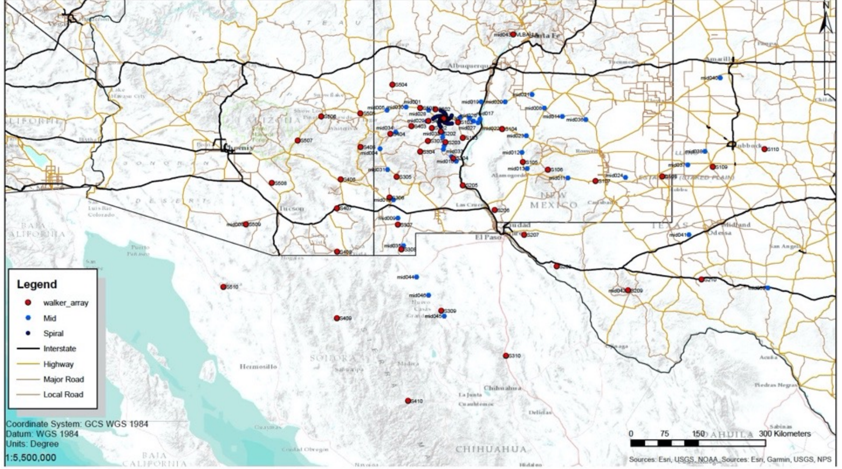




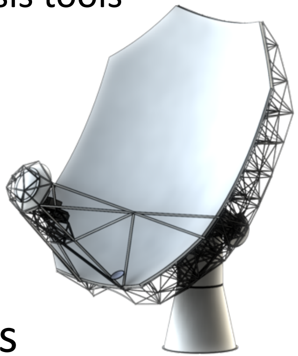
- ✓ **Respond/Present to Astro2020** Program Panel RFIs
  - Presented to RMS Panel (Feb. 2020) + Response to 2nd RFI (Mar. 2020)
- ✓ **Submit MSIP proposal for antenna detailed design and prototype**
  - Validated antenna used to support ongoing university-based intensity mapping experiment (i.e., Caltech/COMAP-*EoR*)
- ✓ **Conduct System Requirements external review**
- ✓ **Support ngVLA technical meetings**
  - SPIE Astronomical Telescopes & Instrumentation, *San Diego (Dec 13-18)*
  - NARSM 2020, Montreal (July 5-10 – *Virtual*)
- ✓ **Support ngVLA science meetings**
  - *Compact Objects in the Multi-Messenger Era,*
    - ***Virtual** (July 14 – 15, 2020)* ~~*+ Saint Paul MN (Jun 23 – 25, 2021)*~~
- **Test 5 WVRs on VLA Antennas w/ new Tipping Radiometer**
- **Continue to Develop ngVLA Broader Impact/Participation Plan**

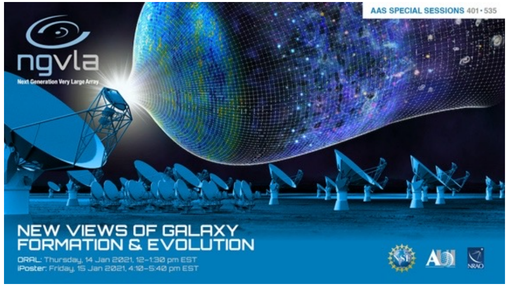


FY21 Activities



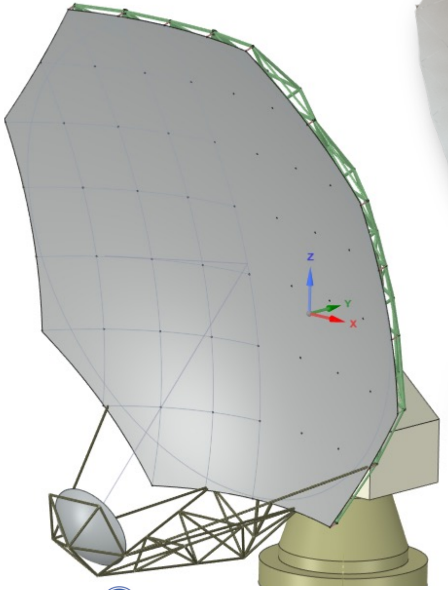
- Hosted Special Session at AAS
- Supporting ngVLA Community Studies
  - 7 approved and 4 funded
- Hired new ngVLA Research Associate
- Document Prep. for FY22 Conceptual Design Review ***(Requirements Baselined)***
  - Substantial update to the configuration and simulation analysis tools
  - CSV Test Planning
  - Software Requirements Capture
  - Observing Mode Calibration Strategy
  - …
- Awaiting MSIP Funding for Antenna Final Design and Prototype Kickoff
- Ramp up on Preliminary Design on all major systems





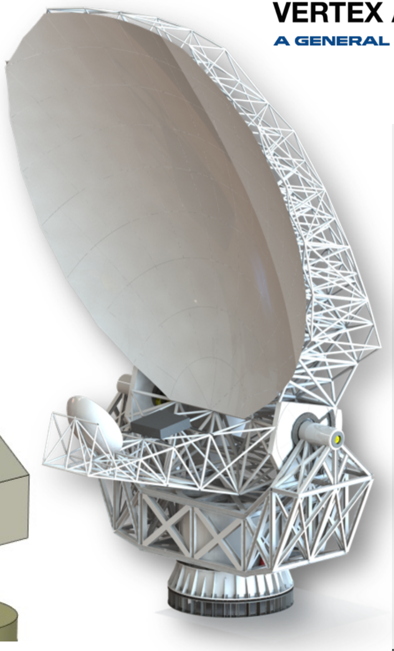
ngVLA Antenna Development

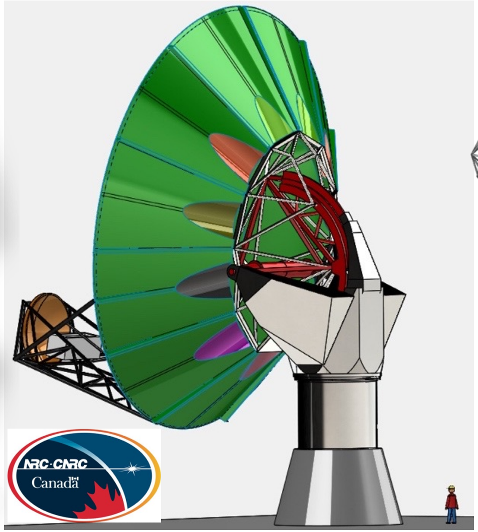
ngvla
Next Generation Very Large Array



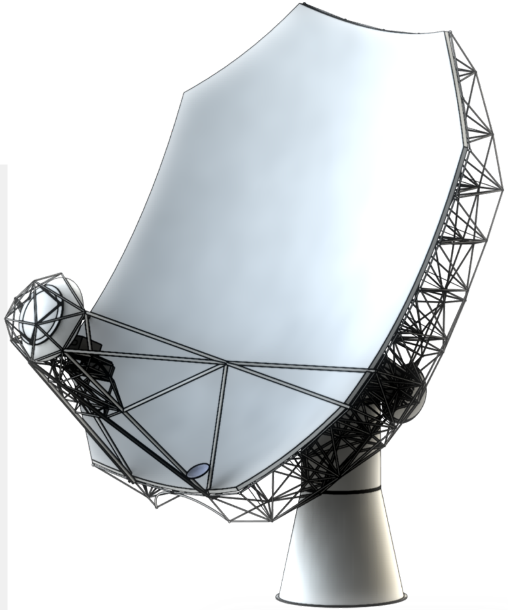
MT MECHATRONICS
An OHB Company

VERTEX ANTENNENTECHNIK GmbH
A GENERAL DYNAMICS COMPANY



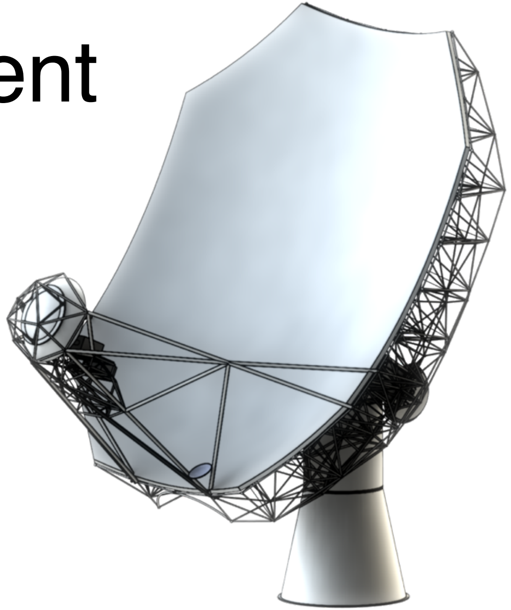


NRC·CNRC
Canada



mtex | antenna technology

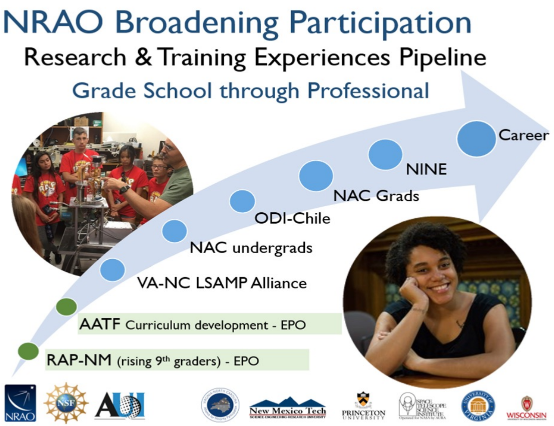
ngVLA Antenna Development

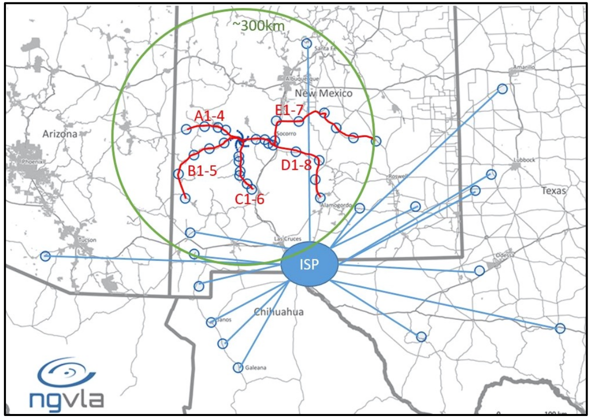


- Contract Awarded to mtex
- Antenna contract contains 4 options
  - Baseline – Preliminary Design Phase 1
  - Option 1 - Preliminary Design Phase 2
  - Option 2 - Prototype Development
  - Option 3 – Final Design
- FY21 antenna budget supports the Baseline option
- NSF MSIP funding supports the 3 remaining options
  - Does not include Project Office Funding

Broader Initiatives

- Supporting Astro2020 Decadal Survey (TRACE)
- Building University, Industrial and International Partnerships
- Education and Public Outreach Campaign.
- Broadening Participation
- Fostering Broader Impacts to the Community (e.g. Rural Broadband)





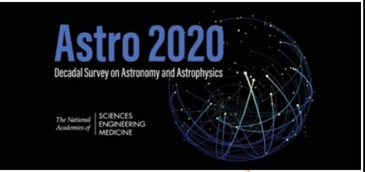
Cost Estimate: Const. & Ops.

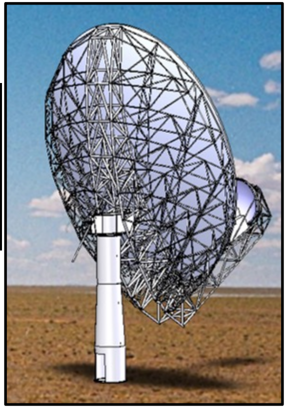
- Most recent cost estimate for construction:
  - **$1.9B** in 2018 base-year dollar point estimate, **$2.25B** risk adjusted.
  - Seeking ~25% International Partner Contributions (discussions underway),

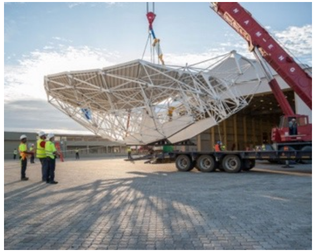
    $\Rightarrow$ ***<2018$1.4B U.S. Contribution to ngVLA,*** *<$1.7B risk adjusted*

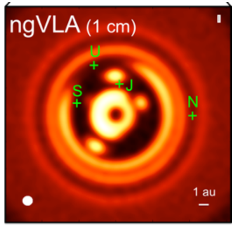
- Target operations budget of **2018$92.7M/yr** (core: 85M/yr + extended: 8M/yr).
  - Operations, maintenance, computing, archiving, etc. Optimize as part of design.
  - Expect changes to Observatory-wide administration & science operations model.

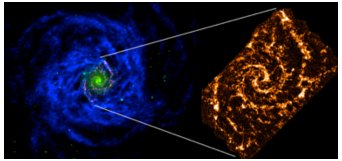
Project Timeline











2019 2021 2023 2025 2028 2034

ngVLA Submission to Astro2020

Astro2020 Recommendation Published

Submit ngVLA Proposal to NSF/MREFC

Prototype Delivered to VLA Site

Complete NSF/MREFC FDR

ngVLA Construction →

Initiate ngVLA Early Science (> VLA capabilities)

Achieve Full Science Operations

ngvla

Next Generation Very Large Array