Present and Future Array Design: ngVLA

NRAO Synthesis Imaging Workshop

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ngVLA.nrao.edu

Version History

- This talk is largely based on Craig Walker's talk in 2020
  - Which was based on the 2018 lecture workshop
  - Which was in part on the 2008 lecture by Aaron Cohen

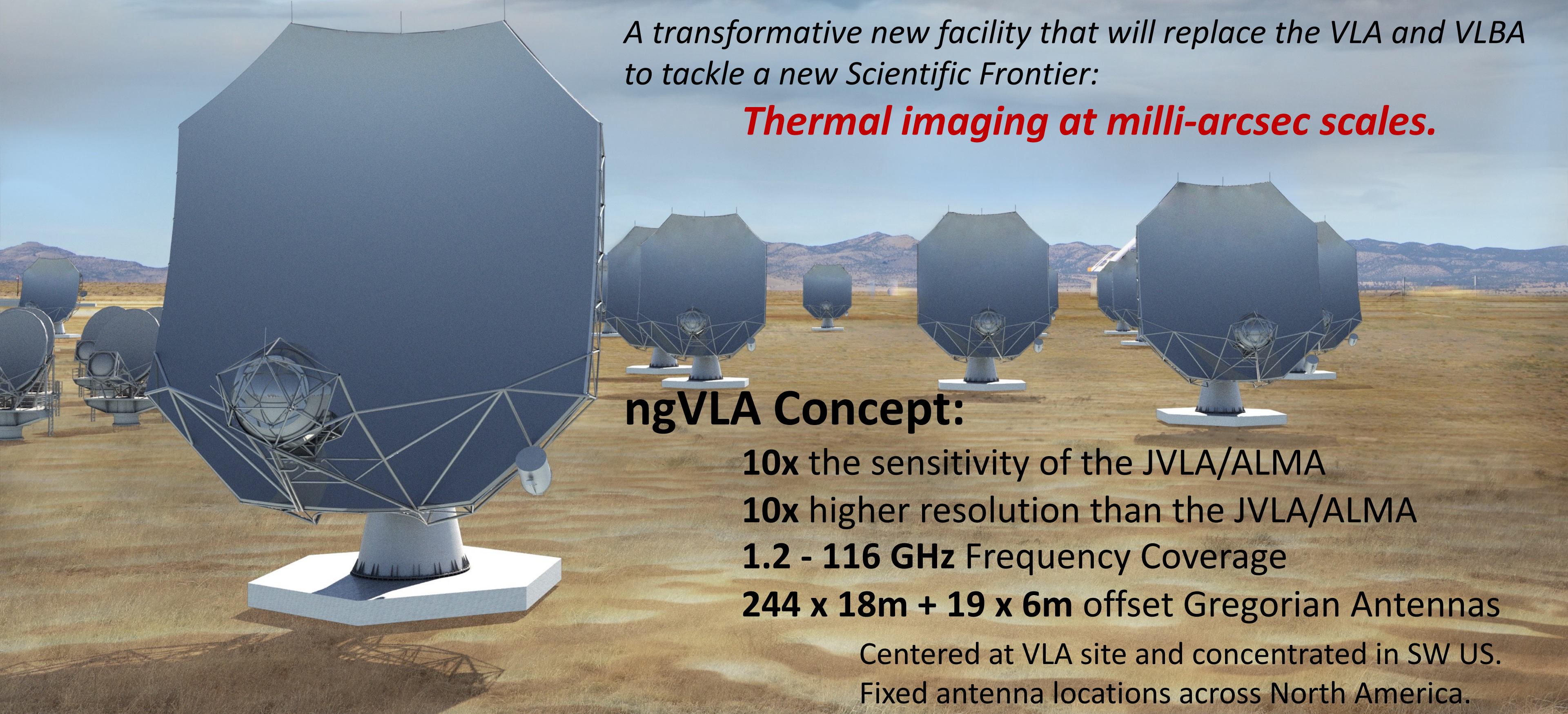
Designing an Array

- *How* we build is defined by *Why* we build – **Define the science case!**
- **Define the technical capabilities required to achieve the science**
  - E.g., Frequency range, field of view, sensitivity, survey speed, resolution, etc.
- **Define the technical specifications to achieve the technical capabilities**
  - E.g., Antenna (size/number/perf.); Electronics (receivers/data trans/correlator); Site/config characteristics; Observing Modes; Calibration Strategy; Compute/Data storage size, etc.
- **Design/prototype the hardware/software to meet the technical specifications**
  - E.g., Antennas, FE electronics, Pipelines
  - Demonstrate that array meets requirements (e.g., via simulations)
- ***Additional Design Requirements***
  - Define Commissioning and Operations Plans
  - Estimate the total cost (Construction + Operations)

Case Study:
The next-generation Very Large Array (ngVLA)

A transformative new facility that will replace the VLA and VLBA to tackle a new Scientific Frontier:

Thermal imaging at milli-arcsec scales.



ngVLA Concept:

10x the sensitivity of the JVLA/ALMA

10x higher resolution than the JVLA/ALMA

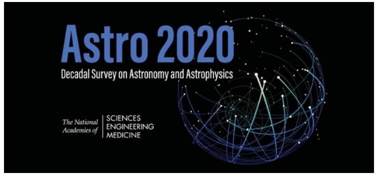
1.2 - 116 GHz Frequency Coverage

244 x 18m + 19 x 6m offset Gregorian Antennas

Centered at VLA site and concentrated in SW US.

Fixed antenna locations across North America.

Last 6 years: Pathway to Astro2020



2015

Inaugural ngVLA Technical Workshop

ngVLA Science White Papers Published

1st Radio Futures Kavli Meeting (Chicago)

2016

ngVLA Project Office Established

ngVLA SAC Established

2nd Radio Futures Kavli Meeting

2017

ngVLA TAC Established

Science & Tech Meeting (Socorro)

Reference Design Memo Posted

Key Science Goals Memo Posted

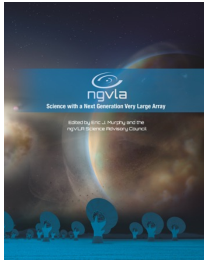
ngVLA Development Funding ($11M)

3rd Kavli Meeting (Berkeley)

2018

2nd Science Meeting (Portland)

ngVLA Science Book Published



2019

3rd ngVLA Science Meeting (Cville)

APC White Paper Submitted to Astro2020

Reference Design published

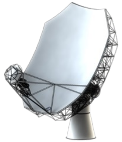
ngVLA CSA Created

2020

Presentation to Astro2020 RMS Panel

ngVLA Summer Talk Series

4th ngVLA Science Meeting (virtual)



2021

ngVLA Endorsed by Canadian LRP

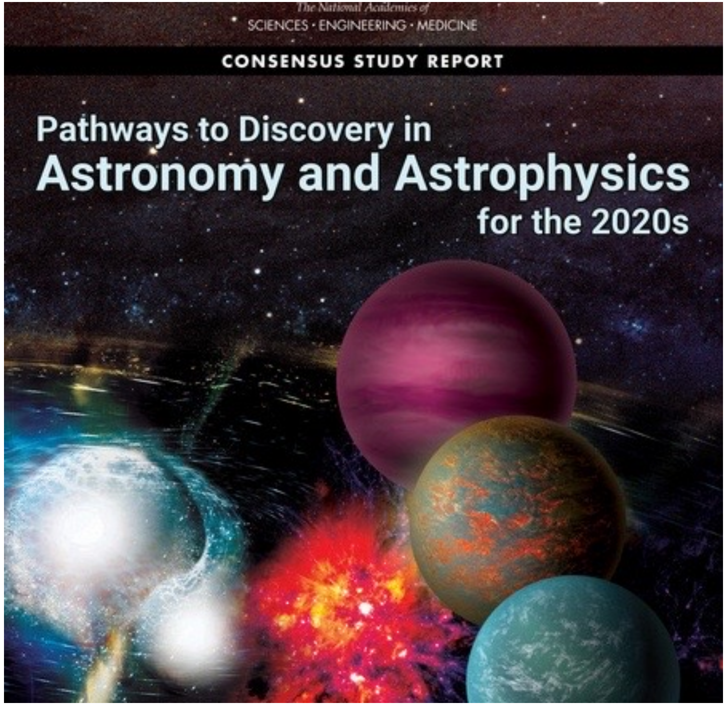
ngVLA- Japan Website Launched

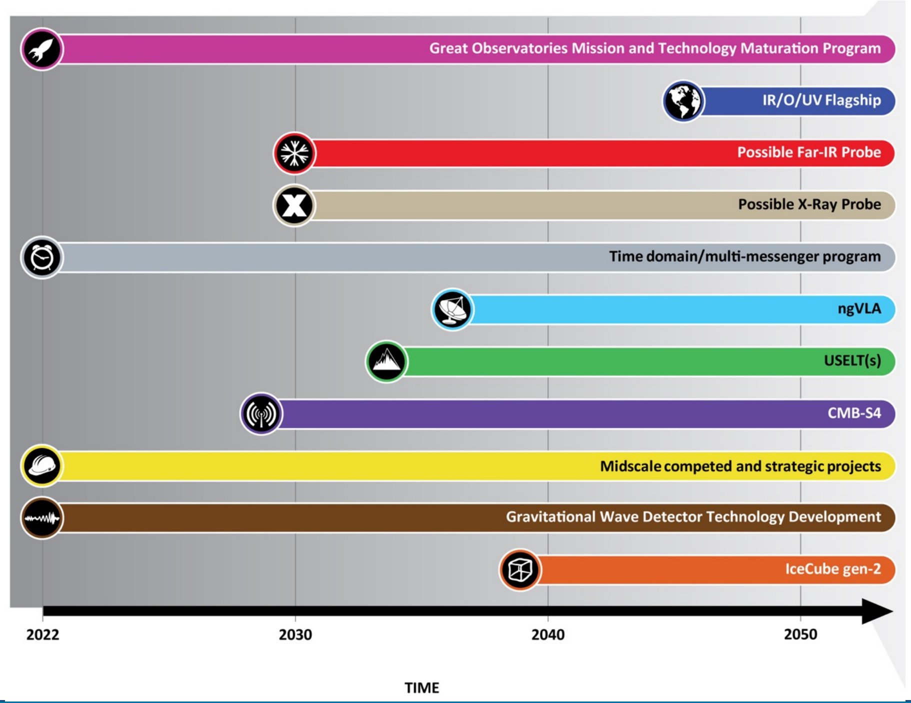
NRAO Contracts mtex for Antenna Dev.

NSF awards prototype funding ($23M)

Astro2020 Report Published – **ngVLA Strongly Endorsed**

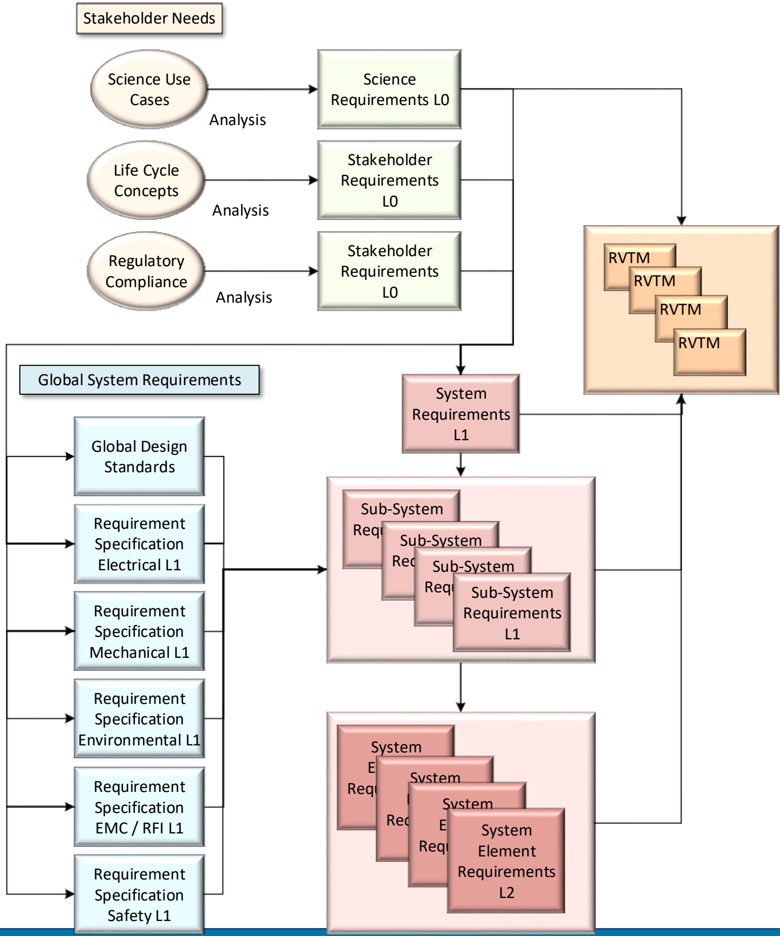
Astro2020 identified the ngVLA as a high-priority large, ground-based facility whose construction should start this decade.





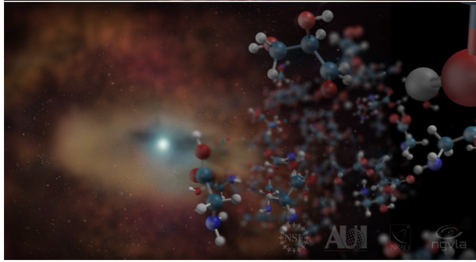
How is defined by Why

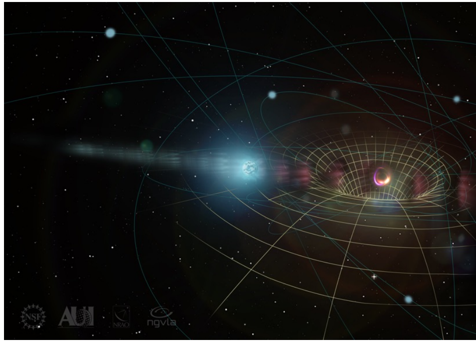
- It all comes down to ***Science***
  - **Level 0 Science Requirements**:
    - provide the initial foundation for all that follows.
  - **Technical Requirements**
    - Level 1 & 2 Req. translated from Sci Reqs.
  - **Technical Design**
    - Design hardware to meet technical specs
  - ***Build***
    - *Requires substantial community/political support*
  - ***Operate***
    - *Deliver on the initial science goals*



ngvla
Next Generation Very Large Array

Defining the Science Requirements



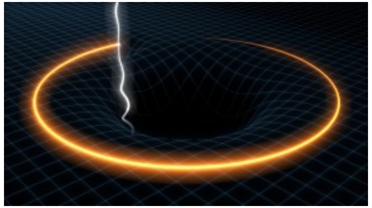


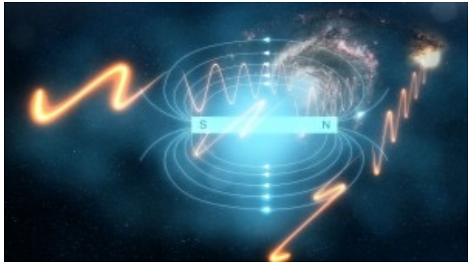
- Identify the Key Science Goals of the Array
  - NB: Different for an experiment (e.g., EHT, HERA, etc.) vs. ***general-use facility*** (e.g., ngVLA, SKA, TMT)
- Ideally, one wants:
  - Exciting topics with broad appeal
  - A manageable number that represent the full range of desired capabilities
  - Document the goals in a compelling and convincing manner
    - White papers, science books, talks
- Use the goals to sell the array to astronomers and the public
  - Required for funding
- Use the goals to specify the technical characteristics
- Show the goals can be met with a feasible and affordable array

CASE STUDY: ngVLA
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*

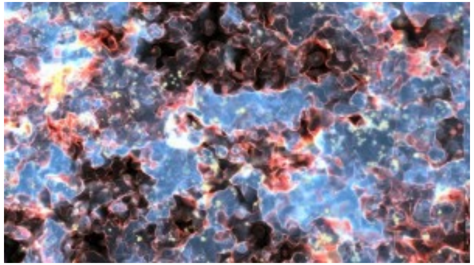
For Comparison: SKA Key Science Drivers (circa 2007)





SKA project identified 5 key science drivers:

1. Cradle of Life
   - Astrobiology, planet detection, SETI
2. Probing the Dark Ages
   - Epoch of reionization, redshifted CO, first AGNs
3. The origin and evolution of Cosmic Magnetism
4. Strong field tests of gravity using pulsars and black holes
5. Galaxy evolution, cosmology and dark ages
6. (Exploration of the Unknown)



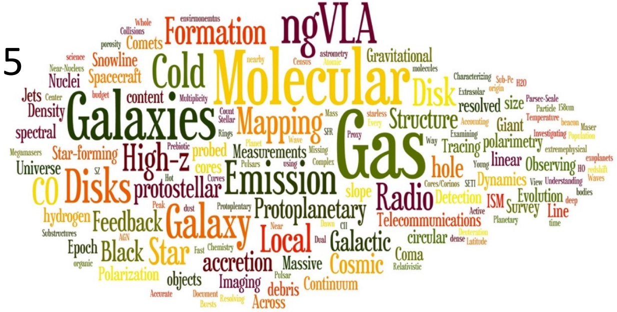
(Schilizzi et al, 2007, SKA Memo 100)

NB: In 2015 SKA Prioritized Science Goals (Deployment vs. Baseline Design)

Developing the ngVLA Science Case

Community-Driven, Growing, and Evolving

- Numerous Science and Technical meetings, starting from Jan 2015 AAS
- Initial Science Working Group reports covering 4 broad areas, Nov .2015 (*http://library.nrao.edu/ngvla.shtml*)
  - ***Cradle of Life: CoL*** *(Isella et al):* Terrestrial-zone planet formation, Massive Stars, etc.
  - ***Galaxy Ecosystems: GEco*** *(Leroy et al):* wide field, high resolution/sensitive imaging
  - ***Galaxy Formation: GFor*** *(Casey et al): Dense gas history of the Universe*
  - ***Time domain, Cosmology, and Physics: TdCP*** *(Bower et al):* Plasma physics, Exo-space weather, Strong Lensing



- **Community Studies Program**: 38 studies approved over 2 Rounds, *financially supported by NRAO (http://ngvla.nrao.edu/page/commstudiesprogram)*
- **Community-Led Science Use Cases**: 80 submitted for ‘Reqs to Specs’ process (ngVLA memo # 18)

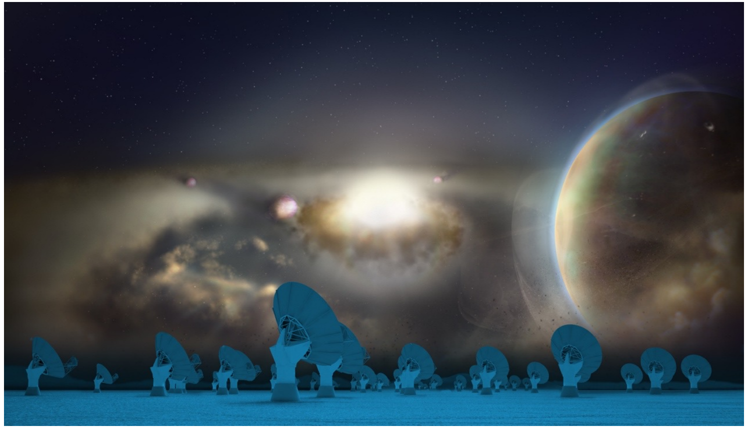
- ***All gathered to report out and build toward a consensus vision last week of June in Socorro***

Defining the Key Science Goals

- Observatory or Community-driven?
  - If the ultimate goal is to get array built, which needs community support, better let them help steer the ship from the beginning.

- Work with the Community to Build the Science Case
  - Science Use-Case Capture exercise
    - https://ngvla.nrao.edu/page/scicase
    - ***Used to derive Technical Specifications***
  - For ngVLA, process built upon NASA Flagship and SKA capture exercises
  - *Continuous process… We still have use cases submitted every few months!*

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

Executive Committee

Brenda Matthews (NRC–Vic: **co-Chair/SWG1**)
David Wilner (CfA/SAO: **co-Chair/SWG1**)
Brett McGuire (MIT: **SWG2 Chair**
Fabian Walter (MPIA: **SWG3 Chair**)
Megan DeCesar (George Mason: **SWG4 Chair**)
Rachel Osten (STScI: **SWG5 Chair**)
Andrew Baker (Rutgers)
Alberto Bolatto (Maryland: ex-officio)
Andrea Isella (Rice: ex-officio)

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

Capture Necessary Technical Specifications

- From the required Scientific Requirements, set the Technical Specifications
  - Frequency range: antenna accuracy, receivers, site
  - Field of view: antenna size, multi-beam feeds, frequency resolution
  - Sensitivity: total collecting area (antenna size and number) receiver quality, bandwidth
  - Resolution: maximum baseline length, frequency, site
  - Dynamic range: number of antennas, calibration style
  - Polarization: feeds, receiver, antenna
  - Spectral resolution: correlator

ngVLA Science Use Case Capture: *Narrative*

- **Science Goal(s):** *Briefly summarize the key science goal(s) for this science case.*
- **Scientific Rationale:**
  - **Scientific Importance:** *Provide a brief discussion on the scientific importance for this science case.*
  - **Measurements Required:** *Provide a description of the necessary measurements to be carried out by the ngVLA to adequately address this science case.*
  - **Uniqueness to ngVLA Capabilities (e.g., frequency coverage, resolution, etc.):** *Is this science case uniquely addressed by the ngVLA? Can other facilities address this science and reach the same conclusion?*
  - **Longevity/Durability: with respect to existing and planned (>2025) facilities:** *Describe potential synergies/complementarities between this ngVLA science case and those from future facilities at all wavelengths.*

ngVLA Science Use Case Capture: *Technical Specs*

(A) 'TARGETS' OF OBSERVATIONS

Type of observation (what defines a 'target')		Individual pointings per object
		Individual fields-of-view with multiple objects
		Mosaics of multiple fields of view
		Non-imaging pointings
Number of targets		
Position range of targets (RA/Dec.)		
Field of view (arcmin^2)		
Rapidly changing sky position? (e.g., comet, planet)		YES [details:]
		NO
Time Critical?		YES [details:]
		NO
Required rms (μJy/bm) [per km/s for lines]		
Peak brightness (μJy/bm)		
Expected polarized flux density (expressed as % of total)		

(B) OBSERVATIONAL SETUP

	Tunin g 1	Tuning 2	Tuning 3	…
Central Sky Frequency(ies) (GHz)				
Instantaneous Bandwidth for each Sky Frequency (GHz/pol; max 40GHz)				
Spectral resolution(s) [km/s or kHz]				
Temporal resolution (in seconds)		YES [details:]		
		NO [set by time/bandwidth smearing considerations]		
Subarrays	(y/n; number):			
VLBI		YES [details, including phased field of view:]		
		NO		

ngVLA Science Use Case Capture: *Technical Specs*

(D) IMAGING CONSIDERATIONS (Continuum & Line, Including VLBI Observations)		
Required angular resolution (mas) (single value or range)		
Largest angular scale required (arcsec)		
Mapped image size ($arcmin^2$)		
Required pixel resolution (mas)		
Number of output/image channels		
Output bandwidth (minimum and maximum frequency - GHz) [Continuum]		
Channel width (km/s or kHz) [Spectral line]		
Required rms (µJy/bm) [per channel for spectral line] (if polarization products required define for each)		
Dynamic range within image (if polarization products required define for each)		
Polarization accuracy (%)		
Required polarization angle accuracy (deg)		
Zero spacing/total power required?	(y/n)	
Required flux density scale calibration accuracy		1-3%
		5%
		10%
		20-50%
		n/a

Results

- More than 80 use-cases submitted
  - Equated to ~190 specific observations
  - Prioritized by ngVLA SAC
    - Driving, Related, Identified
- Analyzed in ngVLA Memo #18

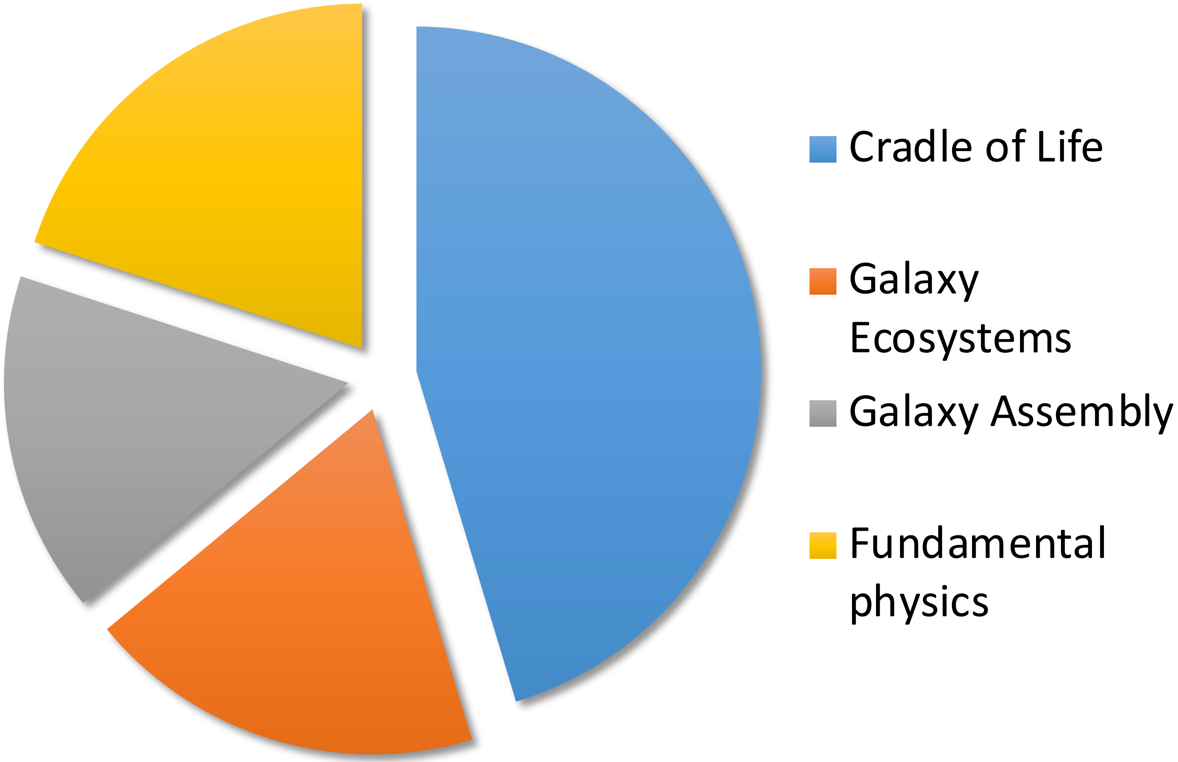
Science Use Case List

A List of Submitted ngVLA Science Use Cases

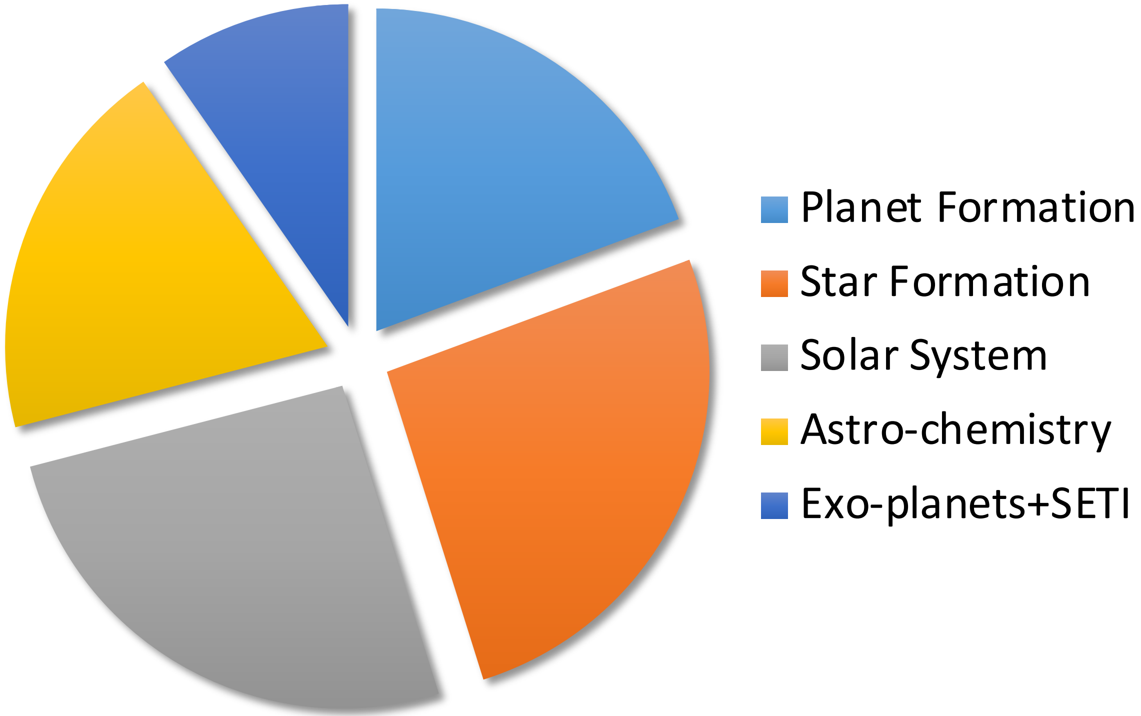
Cradle of Life Science Cases

ID	Title	First Author
PF1	Resolved Substructures in Protoplanetary Disks	Sean Andrews
PF2	Particle Evolution at the H2O Snowline	Jonathan Williams
PF3	Characterizing Planet-Disk Interactions	Paola Pinilla
PF4	Polarization of Protoplanetary Disks: The Dust Size and Porosity Distributions	Brenda Matthews
PF5	Circumplanetary Disk Detection	Zhaohuan Zhu
PF6	Disk Winds	Ilaria Pascucci
AC1	Tracing the NH3 Snowline in Protoplanetary Disks: A Proxy for Water	Edwin A. Bergin
AC2	Mapping the Organic Content in a Protoplanetary Disk Midplane	Karin I. Öberg
AC3	Complex Molecules in Hot Molecular Cores/Corinos	Maite Beltrán
AC4	Deuteration in Starless and Protostellar Cores	Rachel Friesen
AC5	Prebiotic Chemistry	Brett McGuire
AC6	Mapping Molecular Emission in the Near-Nucleus Coma of Comets	Chunhua Qi
DD1	Imaging Structure and the Spatially Resolved Spectral Slope in Debris Disks	Brenda Matthews
DD2	The Spectral Slope and Size Distribution of Grains in Debris Disks	Brenda Matthews
DD3	The Content and Origin of Hydrogen in Nearby Cometary Belts	Luca Matrà

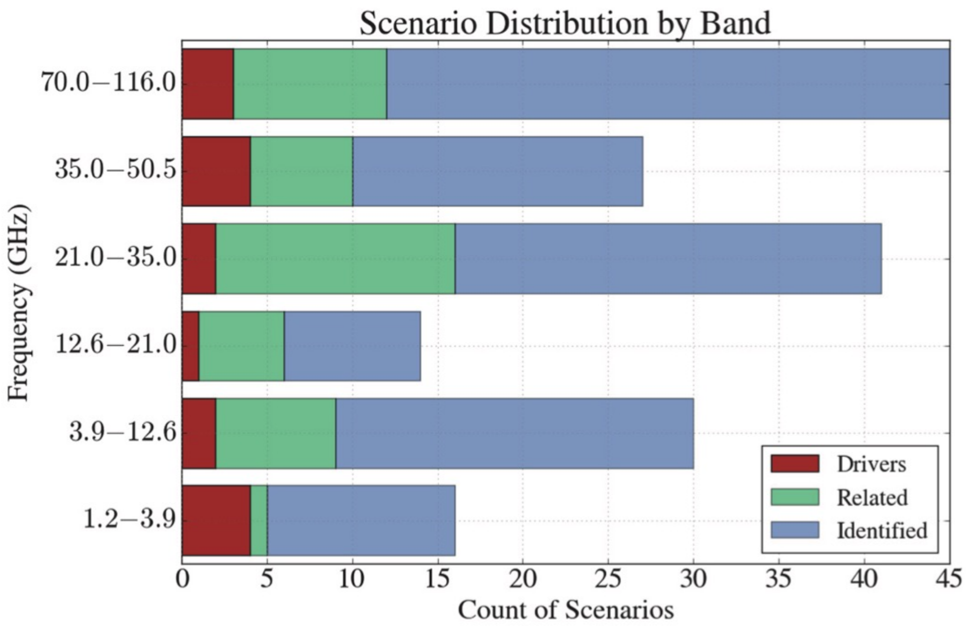
Science Use Case Summary

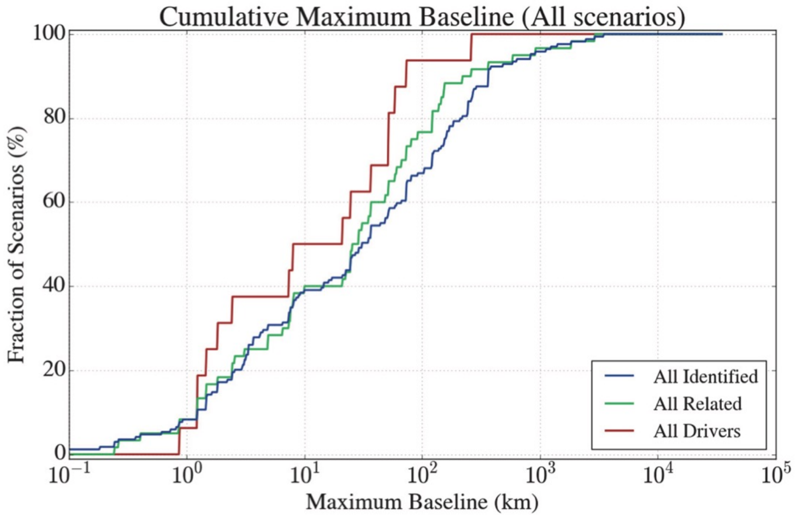


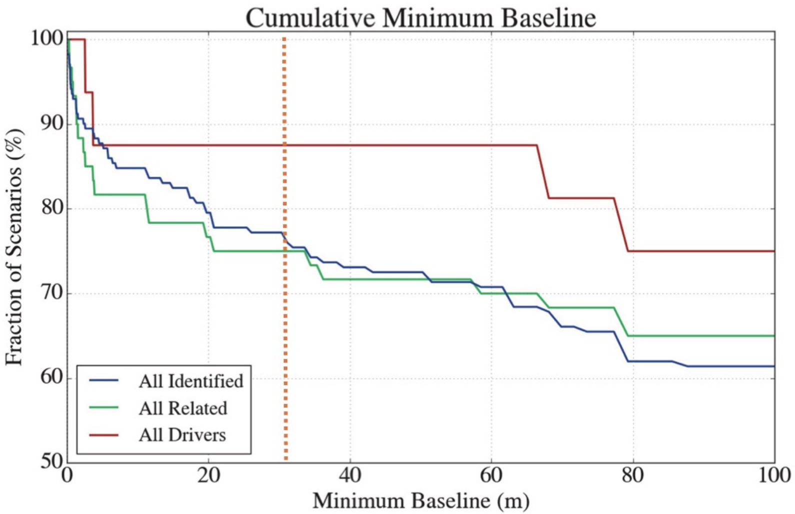
Cradle of Life



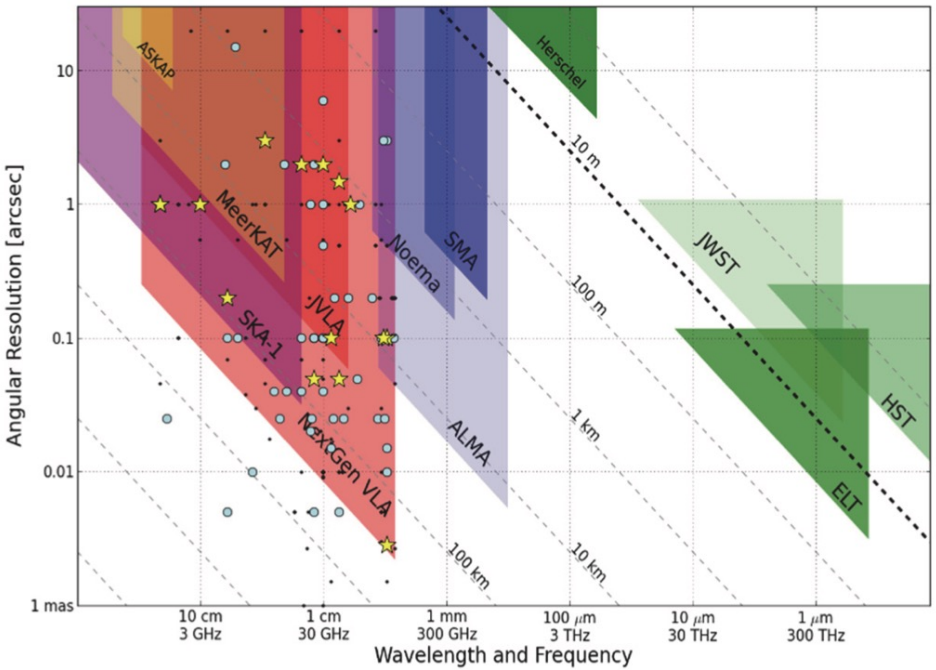
Parameterization or Use Cases







Users want to do everything…



- Users want a Proposal-Driven Telescope
  - Point and click
- Different from Roman/Rubin
  - Survey/data driven

- ***Design needs to be flexible***

But… Never done!
Continue to Engage the Community

Broad Participation Largely Dominated by Early Career Astronomers

ngvla Next Generation Very Large Array

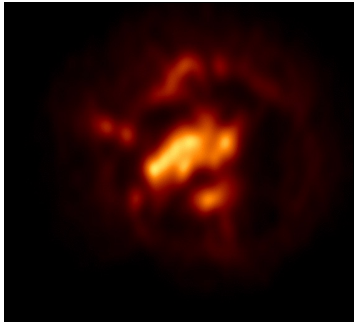
http://go.nrao.edu/ngVLA18

http://go.nrao.edu/ngVLA19

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

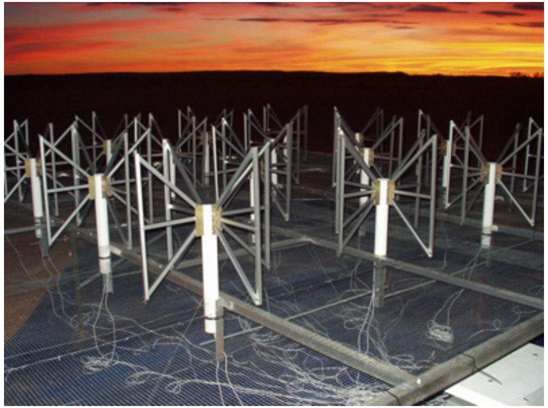
ngVLA Short Talk Series

NSF AUI National Radio Astronomy Observatory NRAO ngvla



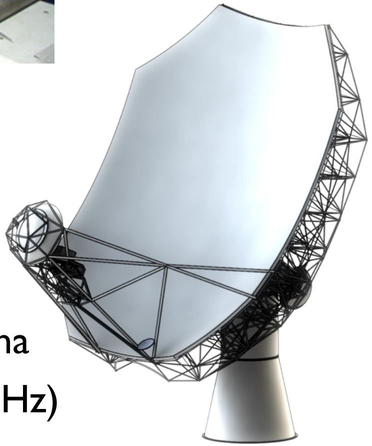
Frequency Range: Antenna Design Implications

- The frequency range strongly influences the type and cost of the antennas and receivers
  - Low frequencies (< 3 GHz very roughly)
    - Less demanding for accuracy
    - Can get large collecting area at low cost
    - Can use aperture arrays of fixed elements at $\lesssim$ 1.5 GHz
  - High frequencies (> 3 GHz very roughly)
    - Will use dishes and cryogenic receivers
    - High surface accuracy
    - High pointing accuracy
    - Offset feed designs provide low Tsys and high efficiency



MWA 80-300 MHz.

Steered by phasing fixed elements



mtex design for ngVLA antenna

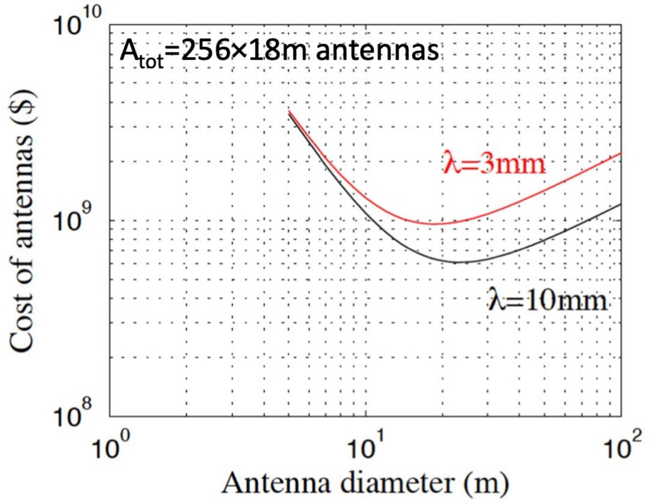
Offset low feed (1.2 to 116 GHz)

Cost vs. Antenna Diameter

Cost of all antennas = $N\times[1.5(D/18\text{m})^{8/3}(\lambda/10\text{mm})^{-1/2} + 1]$ \$M

↑ Number of antennas ↑ Structure, panels etc. ↑ Servo, installation

- Need realistic model of cost vs N_{ant} and D
- Traditional dish antenna cost scales as **$C \propto D^{2.7}$**
- For constant area, Number of antennas scales as **$N_{ant} \propto D^{-2}$**
- Total cost for all antennas scales as **$N_{ant}C \propto D^{0.7}$**
  - *Favors smaller antennas.*
- But many items scale with N_{ant} and N_{beams}
  - Receiver electronics, LO/IF, data transmission, parts of correlator
- Other items scale with N_{ant}^2
  - Baseline sections of correlator scale, postprocessing
- Optimum has a broad minimum favoring 10 to 50 m antennas

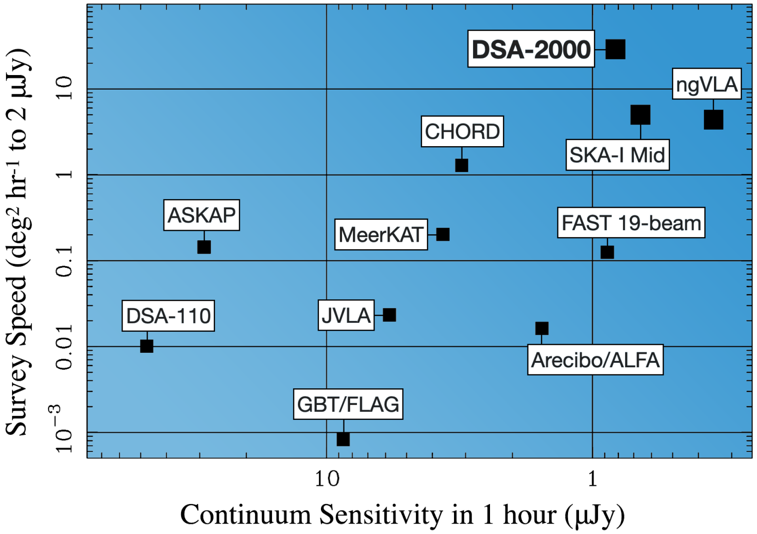


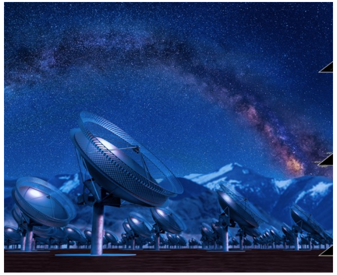
S. Padden: 4/13/15
ngVLA inaugural tech. workshop

- ***ngVLA case included 2 boundary conditions: Total Construction and Operation Cost***

Field of View

- Reasons for small fields of view:
  - Good for detailed/targeted observations of small sources
  - Imaging: Less trouble with strong, confusing sources
  - Fewer, larger antennas simplify operations
    - May also be able to afford better receivers/larger BW/etc.
  - Easier processing – fewer baselines, smaller data sets
  - *But cost scales faster than area, so don't make antennas too big*
- Reasons for large fields of view:
  - Surveys - want to cover large areas of sky
  - Large sources (e.g., galactic clouds, nearby galaxies)
  - Options for large field of view:
    - Large N / Small D: Many small antennas with large beams
    - Multiple beam receiving systems (PAF, FPAs) – a lot of electronics





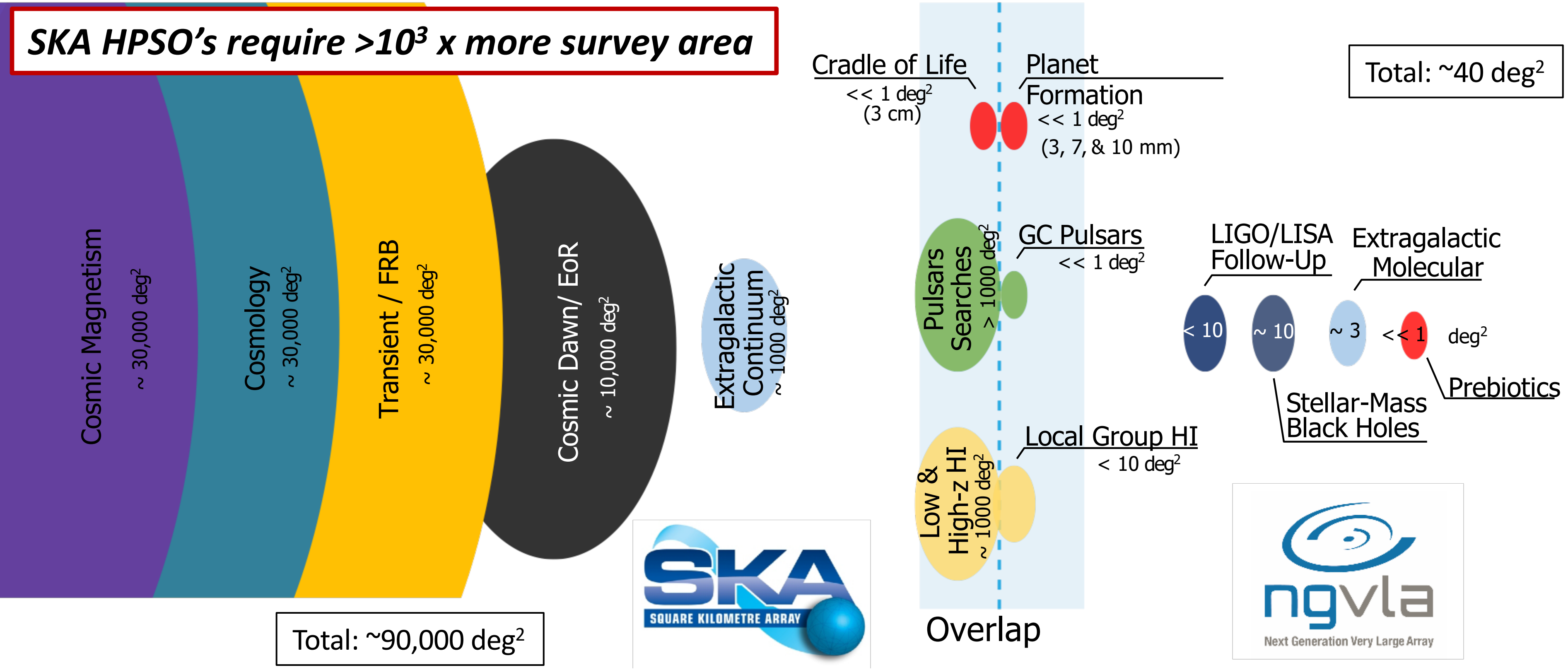
Field of View Examples

- EVLA: 25m antennas - primary beam 30’ at 1.4 GHz.
  - Good for sensitivity and wide frequency coverage
  - Slow/Moderate speed for surveys
- ALMA: 54 X 12m antennas + ACA (12 X 7m array + 4 X 12m for total power)
  - Compromise between sensitivity for extragalactic sources and ability to observe large objects
  - The ACA is used for short baselines and wide fields
- VLBA: 10 X 25m antennas
  - Not for blind surveys: Individual fields limited by delay and rate smearing
  - Can use multiple phase centers over primary beam
- LWA, MWA, LOFAR: Fixed aperture arrays. In principle, with enough electronics, could observe the whole sky.
- WSRT, ASKAP: Feed arrays on dish antennas for multiple beaming
- **ngVLA**: 214 X 18m antennas + SBA (19 X 6m array) + TPA (4 X 18m for total power)
  - Designed for good point source
  - Relatively fast survey speed

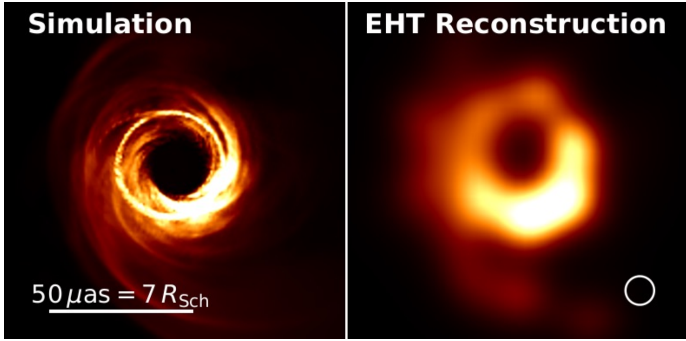
Sensitivity and Survey Speed

- The sensitivity spec is the desired noise level in single fields
  - Important for detecting weak sources and for high dynamic range
  - Depends on collecting area (N_{ant} D^2), system temperature (T_{sys}), integration time (t) and bandwidth ($\Delta\upsilon$)
    - Image noise $\boldsymbol{\sigma} \propto T_{sys} / (N_{ant} D^2 (t\ \Delta\upsilon)^{0.5})$
  - Integration time to reach noise $\boldsymbol{\sigma}$: $t_{\sigma} \propto T_{sys}^2 / (N_{ant}^2 D^4 \Delta\upsilon\ \boldsymbol{\sigma}^2)$
- A survey speed spec relates to time for surveys or mosaics
  - Integration time to reach noise $\boldsymbol{\sigma}$ over the full area depends on:
    - Single field sensitivity (as above)
    - Number of fields required ∝ (total area / beam area) ∝ $(D/\lambda)^2$
    - Number of simultaneous beams (N_{beams})
  - Time to survey to noise $\boldsymbol{\sigma}$: $t_s \propto t_{\sigma} (D/\lambda)^2 / N_{beams}$
  - Note a survey is faster with smaller antennas (D) for fixed sensitivity

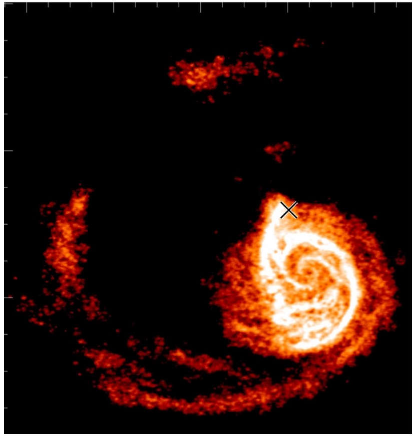
SKA and ngVLA Key Science Drivers



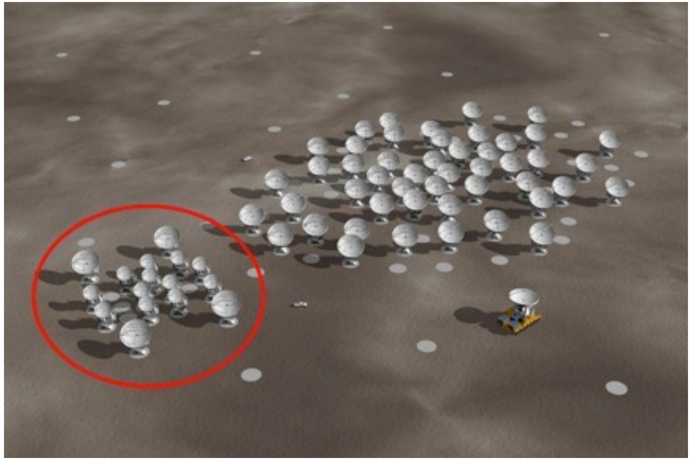
Resolution and Brightness Temperature



- Resolution $\theta \approx \lambda / B_{max}$
  - Highest resolutions use high frequencies and long baselines
  - High res. good for hot or non-thermal sources (AGN, masers …)
  - High resolution best for astrometry
- Brightness temperature (Rayleigh-Jeans limit)
  - Flux density for brightness temperature T_B: $S = 2 k T_B \Omega / \lambda^2$
  - For measured T_B, use the synth. beam solid angle $\Omega_b \propto (\lambda / B_{max})^2$
  - Then: $S \propto T_B / B_{max}^2$: Depends only on baseline, not frequency
  - For low T_B sources, need short B_{max} for detection
  - Low T_B sources include radio lobes, molecular clouds, most thermal objects
- ***A general-purpose instrument needs a wide range of resolutions!***



EXTREME BASELINE EXAMPLES



- ALMA ACA and most compact configuration
- Good for large, diffuse sources

- VLBA - Continental or more in scale
- Good for very high brightness sources and astrometry
- Space VLBI is being done

CASE STUDY: ngVLA Antenna Down Select

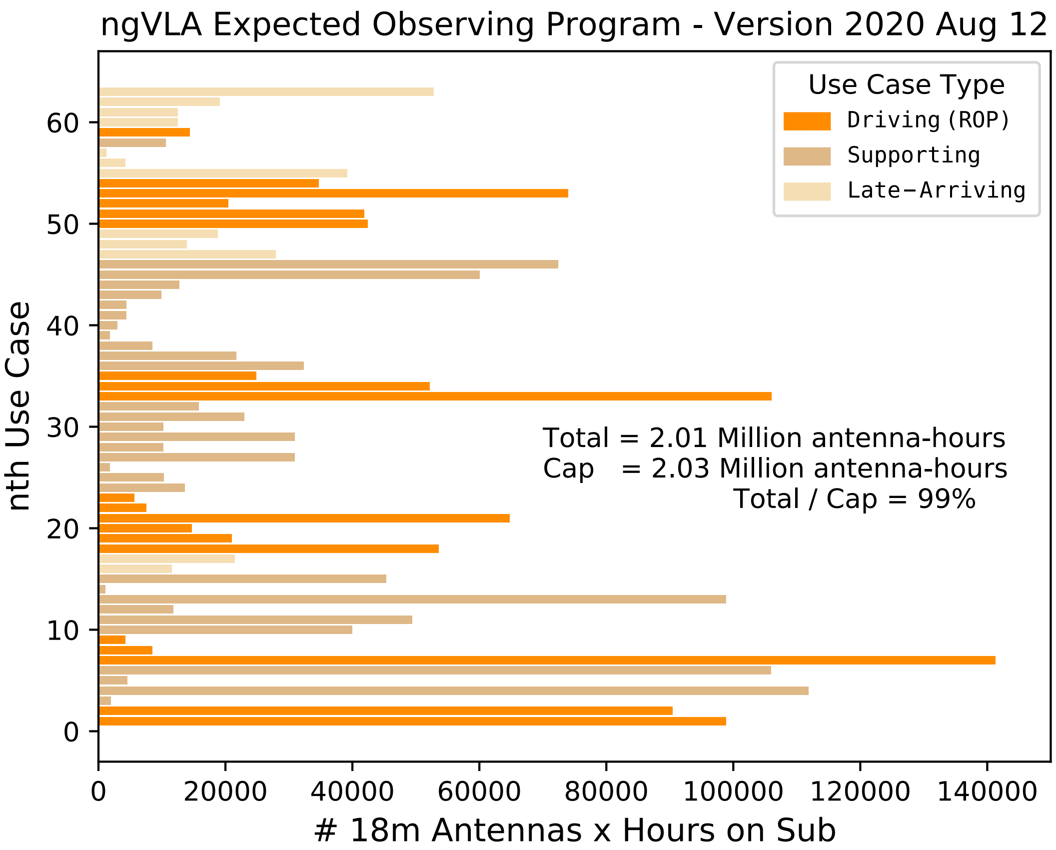
(ngVLA Antenna Memo #2)

- Bounded by 4 Key Performance Parameters
  - ***Lifecycle cost***: Total construction and (20 yr) operations costs.
  - ***Sensitivity***: System sensitivity, which is proportional to the total collecting area (i.e., $\mathbf{ND^2}$).
  - ***Survey Speed***: System survey speed, which is proportional to sensitivity squared times the field of view, which does as $\mathbf{1/D^2}$ (i.e., $\mathbf{N^2D^2}$).
  - ***Image Fidelity***: Imaging performance is (to first order) proportional to number of baselines in the array ($\mathbf{N^2}$) to ensure goo (u,v) coverage .

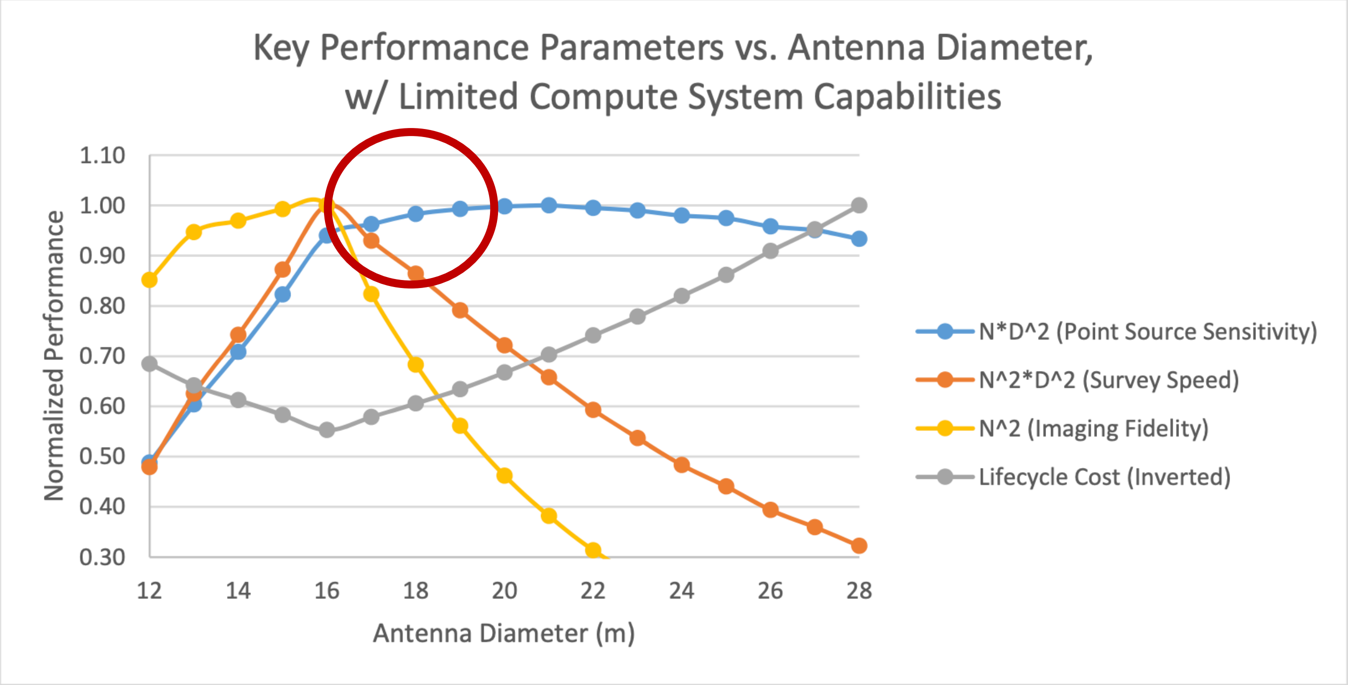
Computing Drives Cost!

- 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*

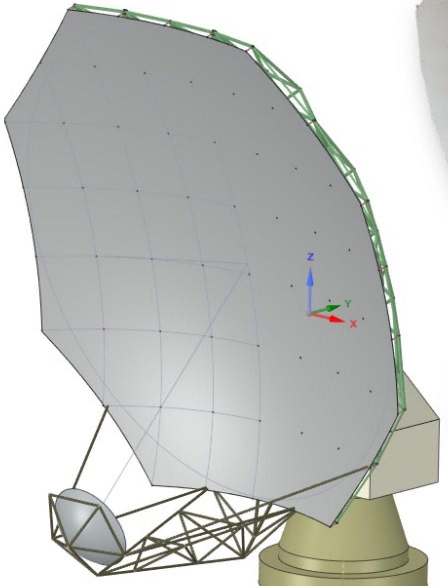


ngVLA Antenna Down Select
(ngVLA Antenna Memo #2)

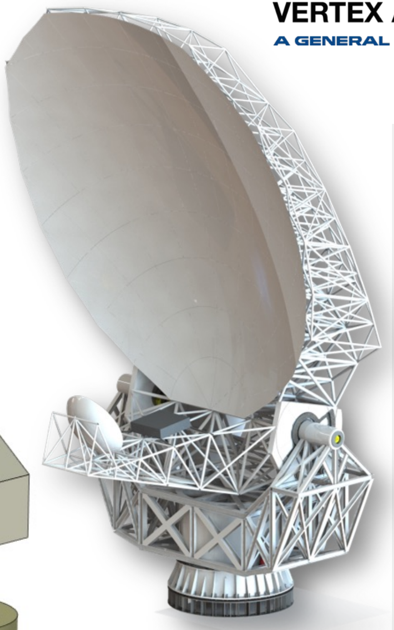


ngvla
Next Generation Very Large Array

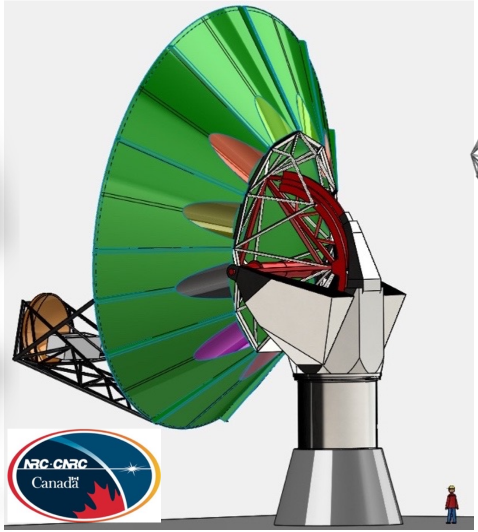
ngVLA Antenna Development

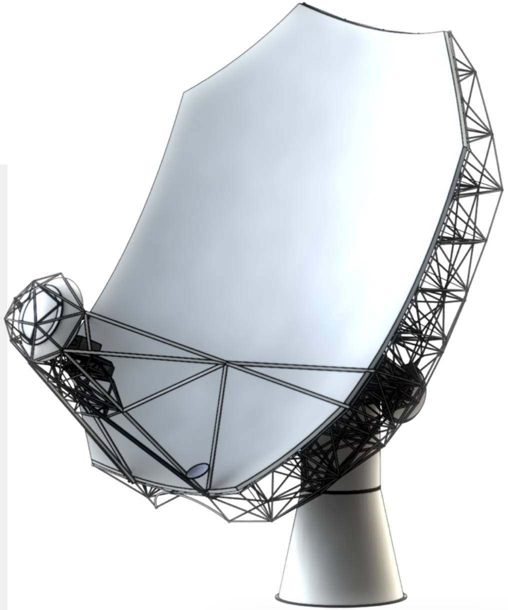


MT MECHATRONICS
An OHB Company



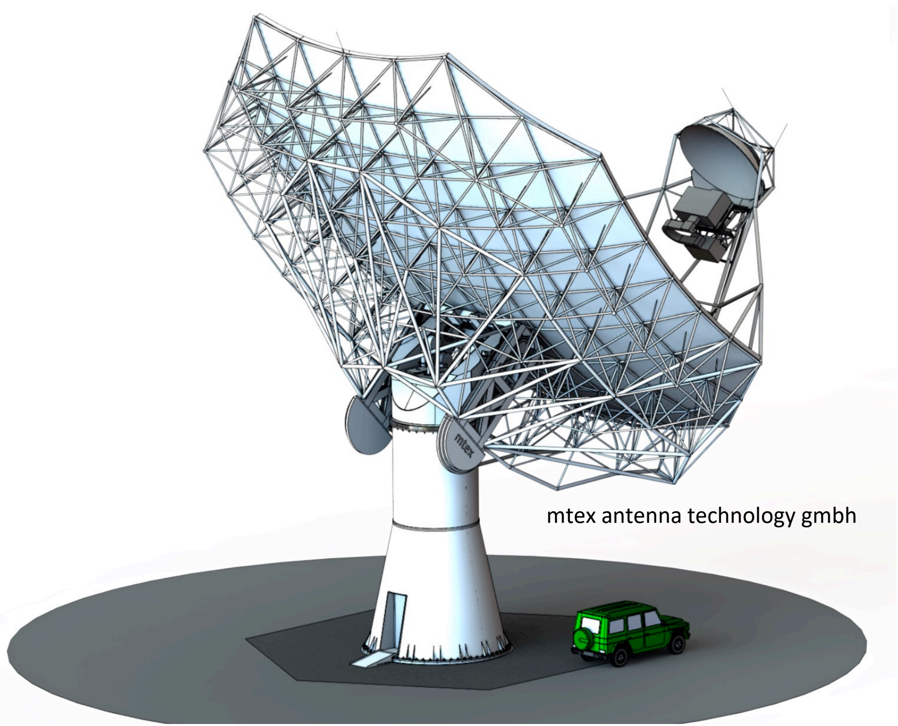
VERTEX ANTENNENTECHNIK GmbH
A GENERAL DYNAMICS COMPANY





mtex | antenna technology

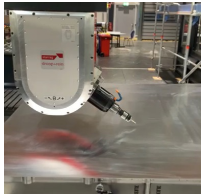
ngVLA Antenna Concept



- **Feed Low**: Maintenance requirements favor a receiver feed arm on the low side of the reflector.
- **Mount concept**: Choice of a pedestal concept for life-cycle cost.
- **Drives:** Choice of motor-gearbox for both axes of motion.
- **Materials:** Cast and post-machined Al panels with steel BUS, composite sub-reflector and mostly carbon fiber feed arm.

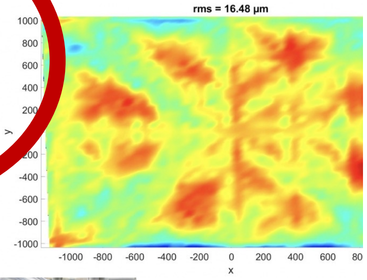
Key Specifications	
18m Aperture	Offset Gregorian
Shaped Optics	4° Slew & Settle in 10 sec
Surface: 160 µm rms	Referenced Pointing: 3” rms

Now we prototype: ngVLA Antenna Development: 1st panel



Manufacturing Req. for ngVLA is 40µm RMS!!!

First measurement comes out with 16.5µm RMS

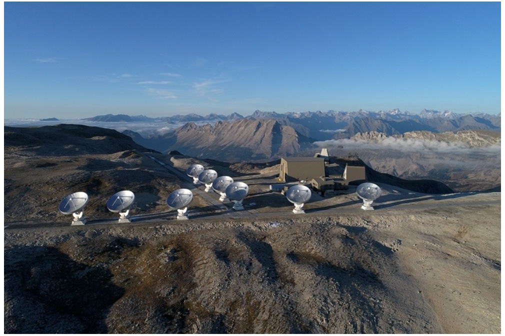


~x2 better than Manufacturing Req

a king size bed with an accuracy better than half a thickness of a human hair!

mtex | antenna technology

Site Location



NOEMA

ALMA

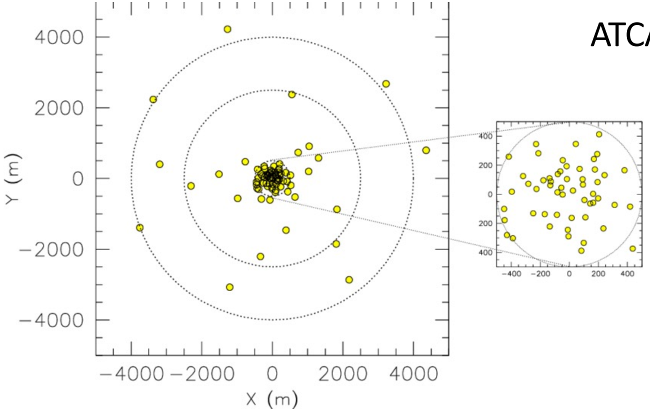
- Location has ***performance, operations, financial, and political*** impacts
- Latitude important for sky coverage, observing conditions and ionosphere
- At high frequencies, want high altitude site with a dry climate (ALMA, NOEMA)
- At low frequencies, want protection from RFI (MeerKAT, ASKAP, SKA)
- At low frequencies, avoid regions with worst ionosphere (SKA etc)
- Site must be large enough to accommodate the array
- Need ***reasonable access*** and place to live for staff and their families
    - Not everyone can work remotely
- Need ***infrastructure***: roads, power, communications
    - Expensive if need to provide own, especially to outer stations.

MeerKAT

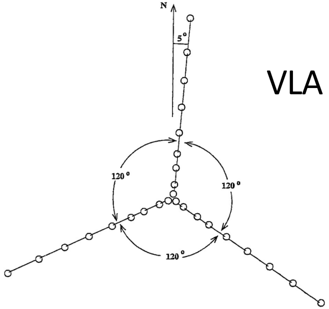
Configuration

- Where to put the individual antennas within overall site
  - Directly linked with the location of the telescope
  - Need enough area to accommodate longest baselines for science requirements
- Goals
  - Obtain adequate UV coverage to meet the scientific goals
  - Obtain the desired distribution of long and short baselines
  - Minimize cost of construction and maintenance
- Some top-level decisions
  - Centrally condensed or more uniform distribution?
  - Use reconfiguration?
  - Optimize for snapshot coverage or only for full tracks?
  - Are some antennas in clusters, especially far from core?
- Once configuration is chosen, can't freely move individual antennas
  - UV coverage depends on relative antenna locations

ATCA



MeerKAT



VLA

Reconfigure?

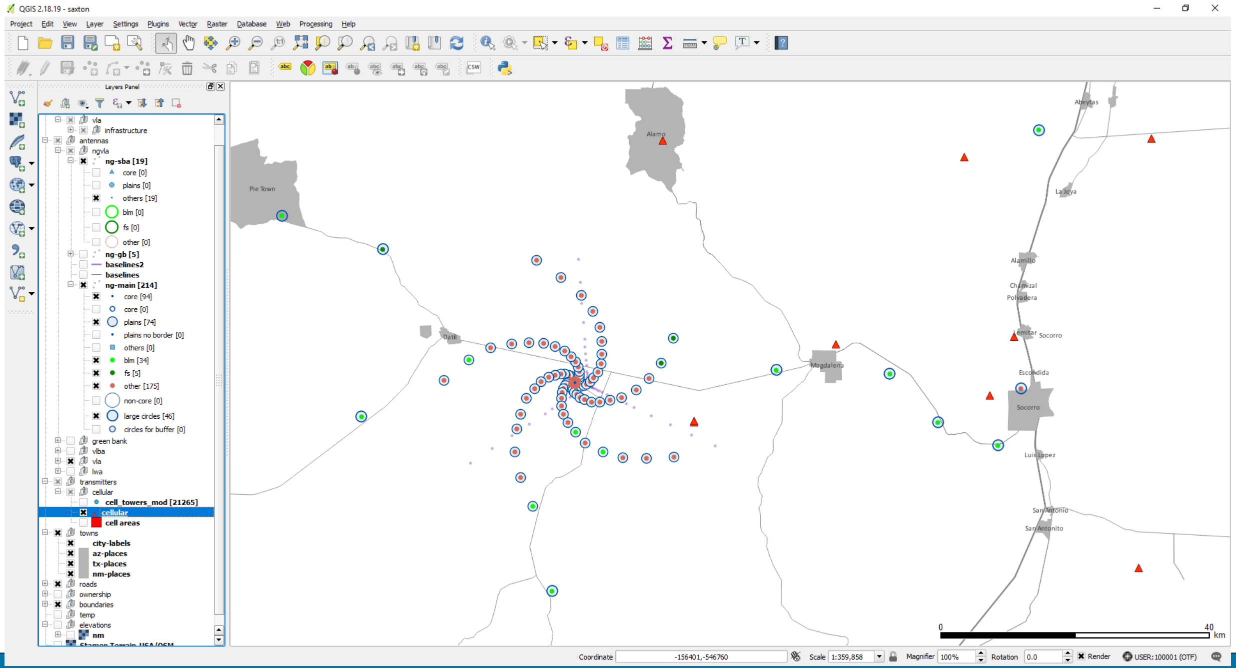
- Moving antennas allows wide baseline range with fewer antennas
  - Constrains observation dates
  - Requires transporter and roads/rails
  - Increased operations and maintenance complexity
- JVLA: 4 configurations
  - Scale by 3.28
- ALMA: 10 configurations + ACA
  - Variable scale < factor of 2
- SKA and ngVLA will not reconfigure
  - Weights and tapers for desired resolution with good imaging roughly cut sensitivity in half (1.5 – 2.4)

Antenna Site Constraints

- Antenna location constraints vary on different scales
  - For short baselines (10s of km), want large flat area
    - Full freedom to position antennas as desired
  - For about 30 to 300 km, geography has big impact
    - Need individual sites
    - Need power, communication, and road access at reasonable cost
    - Need to avoid cities, wilderness areas, military bases etc.
    - Sites need to be close (few km) to the desired position
  - For baselines over about 300 km, precise site position not critical
    - Usually can find an acceptable site close enough to desired position
    - Main constraints are major geographic features like oceans and national boundaries

USE OF GIS (Geographic Information Services)

- Can use layers for many useful types of information relating to sites
    - Antenna locations, roads, cell towers, fiber, land ownership, towns....
    - Significant help in identifying good sites, especially for longer baselines
- Free program QGIS – ngVLA example below

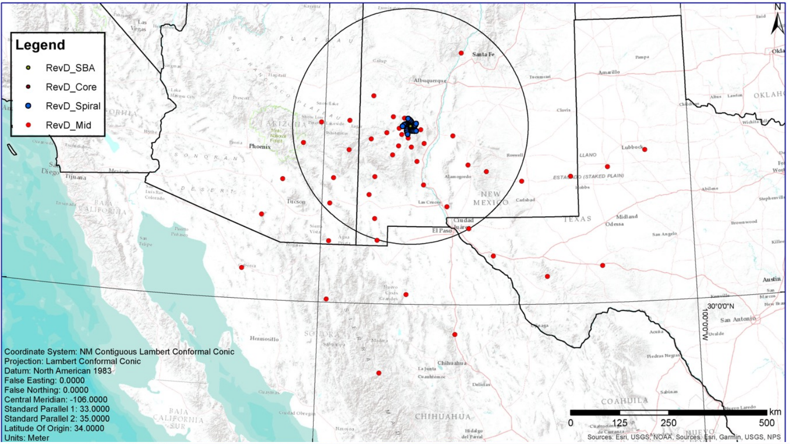


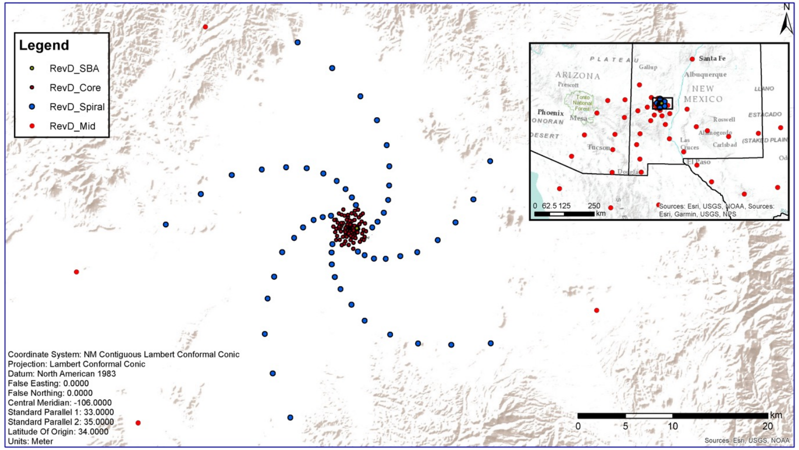
CASE STUDY: ngVLA Technical Baseline

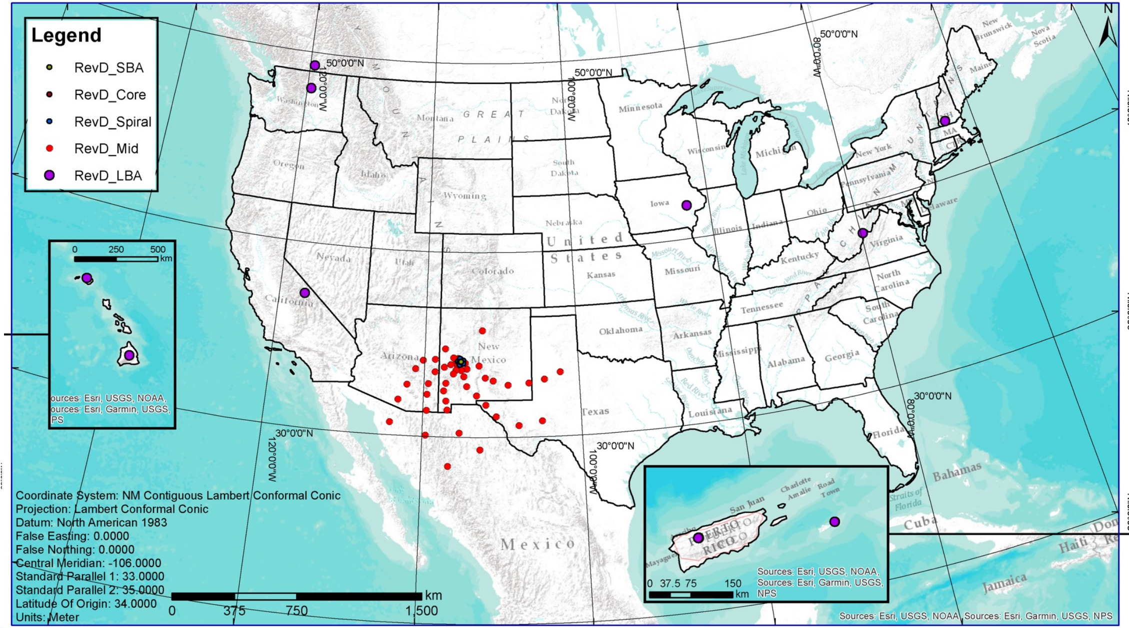
- **1.2 - 116 GHz** Frequency Coverage
- **Array Design**: 244 x 18m offset Gregorian Antennas
  - **Core**: 114 fixed antennas; B_{max} = 4.3 km
  - **Spiral**: 54 fixed antennas; B_{max} = 39 km
  - **Mid**: 46 fixed antennas spread into NM, AZ, TX, MX; B_{max} = 107 km
  - **Long**: 30 x 18m antennas located across continent; B_{max} = 8860 km
- **Short Baseline Array**: 19 x 6m offset Greg. Antennas
  - 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

Distribution of Antennas





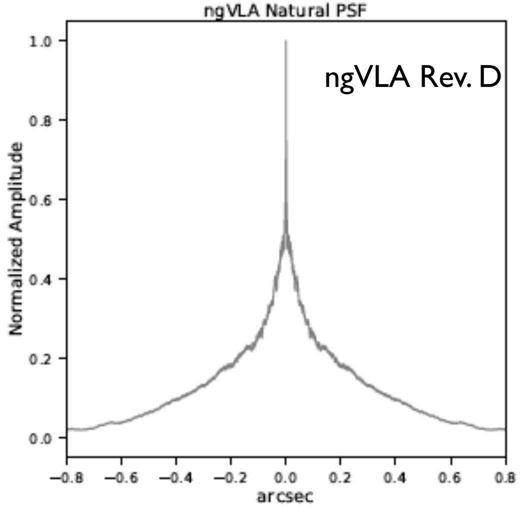


Long Baseline Antenna Locations

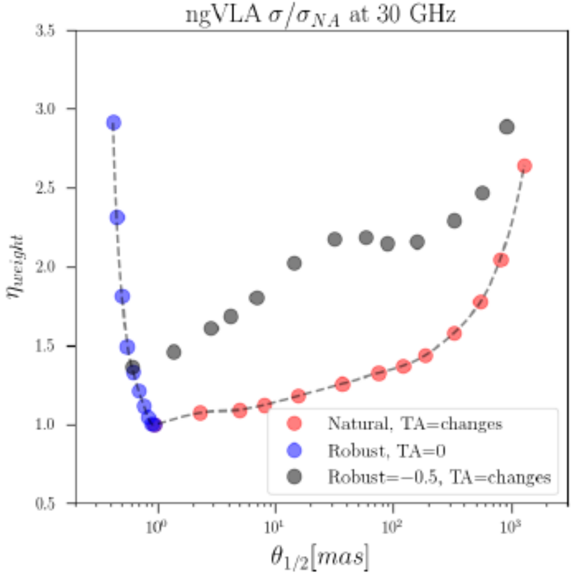
Qty	Location	Notes	Qty	Location	Notes
3	Puerto Rico	Arecibo Site	3	Green Bank, WV	GBO
3	St. Croix	VLBA Site	3	Brewster, WA	VLBA Site
3	Kauai, HI	Kokee Park Obs.	3	Penticton, BC	DRAO
3	Hawaii, HI	Not MK Site	3	North Liberty, IA	VLBA site
3	Hancock, NH	VLBA Site	3	Owens Valley, CA	VLBA site

ngVLA: The price of not reconfiguring –
the synthesized beam of centrally concentrated array

- Natural weight
- N-S beam cut 30 GHz
- Fit beam 13.0 X 17.0 mas
- Large skirt from dominant short baselines
- Noise 0.14 μJy/beam in 4 hr
- T_B Noise 0.85 K in 4 hr
- Adjust beam with weights and taper
  - E.g., beams from 1 – 1400 mas
  - Some loss of sensitivity (1.5-2.4)



See Rosero ngVLA Memo #55

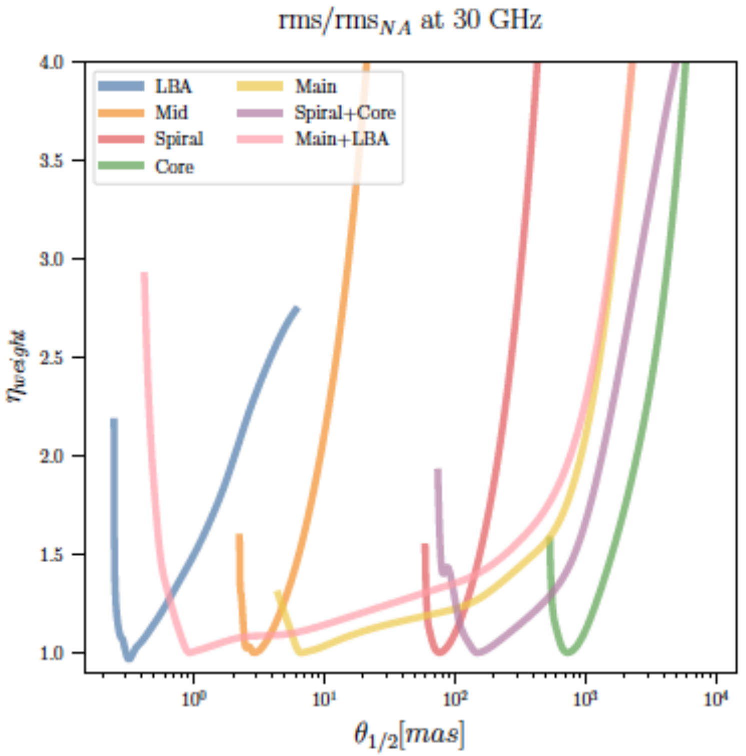


Use of Subarrays

See Rosero ngVLA Memo #55

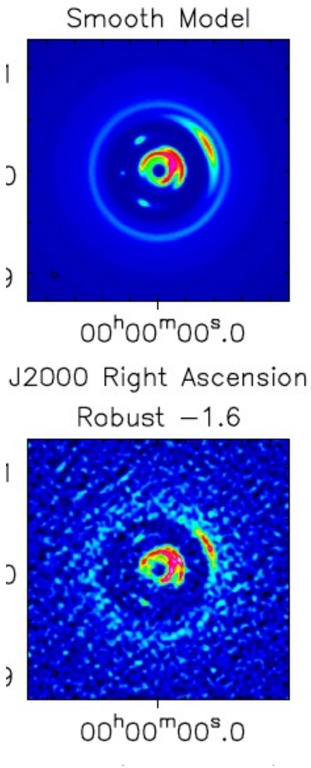
- Given the large range of angular scales supported by ngVLA, observations to be taken in sub-arrays:

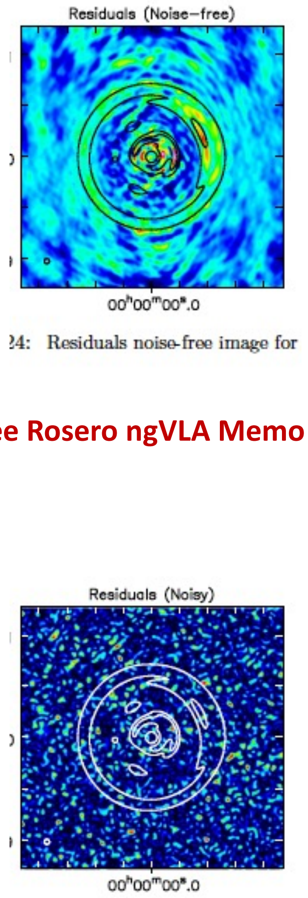
Component/ Subarray	# Ant.	B_{max} [km]	B_{min} [m]
Main+LBA	244	8857.2	36.4
LBA	30	8857.2	36.4
Main	214	1068.3	39.4
Mid	46	1068.3	17147.1
Spiral+Core	168	39.3	39.4
Core	114	4.3	39.4
Spiral	54	39.3	811.0



SIMULATIONS

- Purpose of simulations:
  - Help set specifications needed by key science
  - Confirm that the key science can be done
  - Help build support for funding
  - ***See numerous memos by ngVLA Carilli, Rosero, and Mason***
- Steps for a simulation:
  - Generate models of the sky representing realistic key science targets
  - Simulate data, adding increasing levels of reality
    - Receiver noise
    - Atmospheric and ionospheric phase fluctuations and absorption
    - Antenna pointing errors and efficiency
    - Instrumental bandpass and polarization variations
  - Process simulated data to make images or extract other science
    - Might use multiple methods
  - Compare results with known input model – tests image fidelity





See Rosero ngVLA Memo #65

Some Questions to Address with Simulations

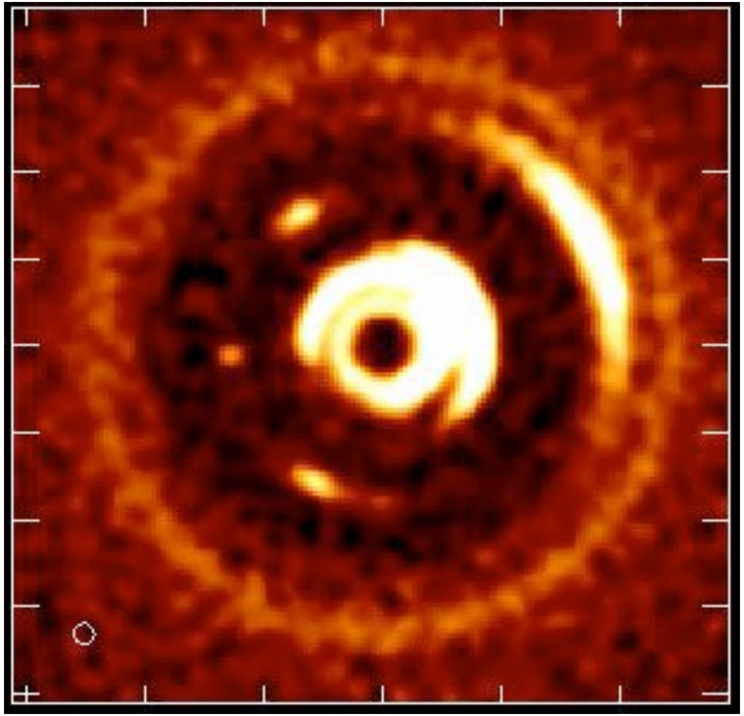
- Will the array do the key science specified?
  - Is there adequate sensitivity on the required scales?
  - Is there adequate brightness sensitivity on the required scales?
  - Is the array able to image large enough sources?
  - Is the array able to observe polarization adequately?
- What is the best distribution of long vs short baselines?
- What calibration strategies should be supported?
  - Are the slew rates and source switch times adequately fast?
  - Should antennas be paired?
  - Should an array of smaller calibration antennas be built?
  - Are water vapor radiometers needed?
  - Is a separate instrument needed to measure short spacings?
    - Single dish or array of smaller antennas?

Simulation Software

- Simulation software creates model data sets
  - Use model image, array configuration, and observing style
  - Include effects of noise, troposphere, ionosphere
  - Mimic instrument properties (bandpass polarization etc).
- The imaging is generally done with standard software
- Most analysis packages have basic simulation capabilities. Examples:
  - AIPS - Basic fake data creation with full imaging and analysis
  - MeqTrees - Implements measurement equations (Mainly LOFAR)
  - ASKAPSoft - includes support for multi-beam systems
  - IRAM/GILDAS ALMA simulator
  - **CASA - SIMOBSERVE can model many arrays**
    - **Used for ngVLA simulations – new functionality added to support heterogenous array needs**

Examples: KSG1: Unveiling the Formation of Solar System Analogues

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



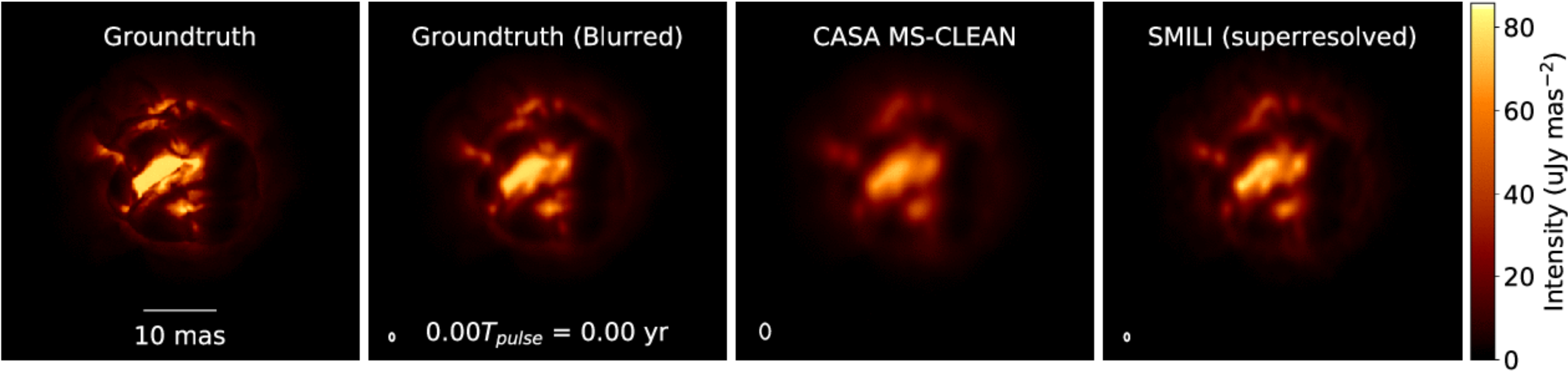
The ngVLA will measure the planet IMF down to ~5-10 Earth masses and unveil the formation of planetary systems similar to our own Solar System.

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)

Examples: 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

Imaging Simulations: Complicated Extended Sources

Model
(PHANGS N4321)

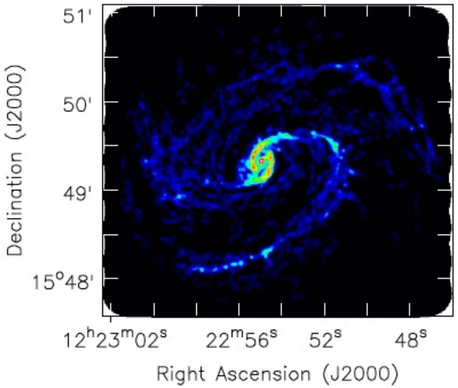
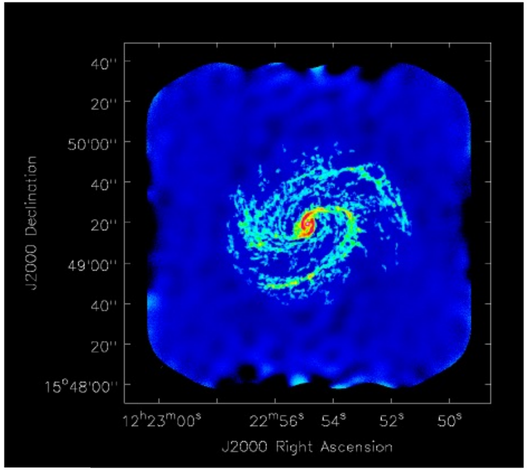
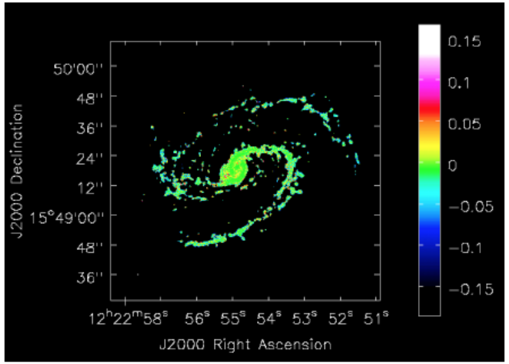
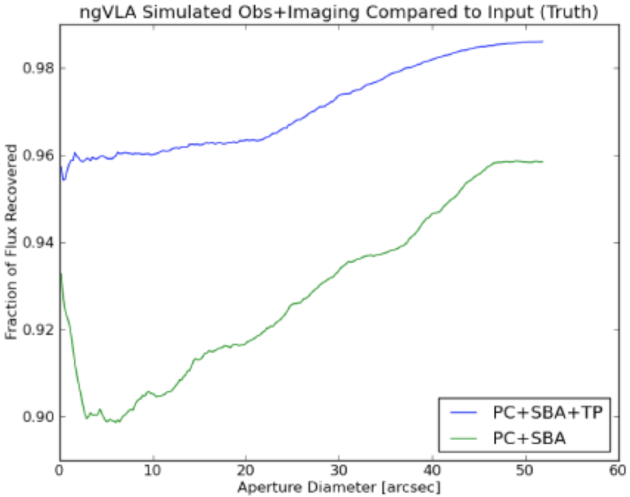


Image
(18m + SBA + Core)





(Image – Model) /
(Model)

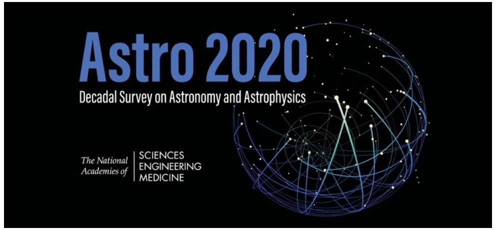


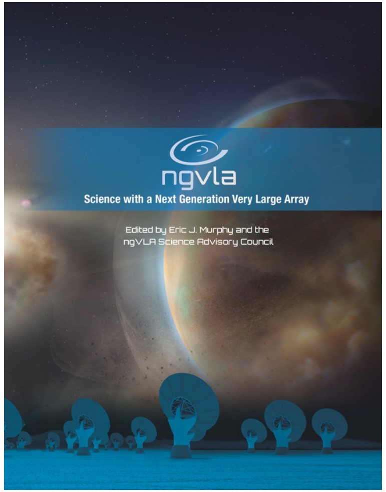
Simulating image fidelity

- Use model image to simulate UV data and image in normal way
- Subtract model to examine residual image errors

Simulation shows that image fidelity requirement for extended large source met when both SBA and TP data included in the imaging

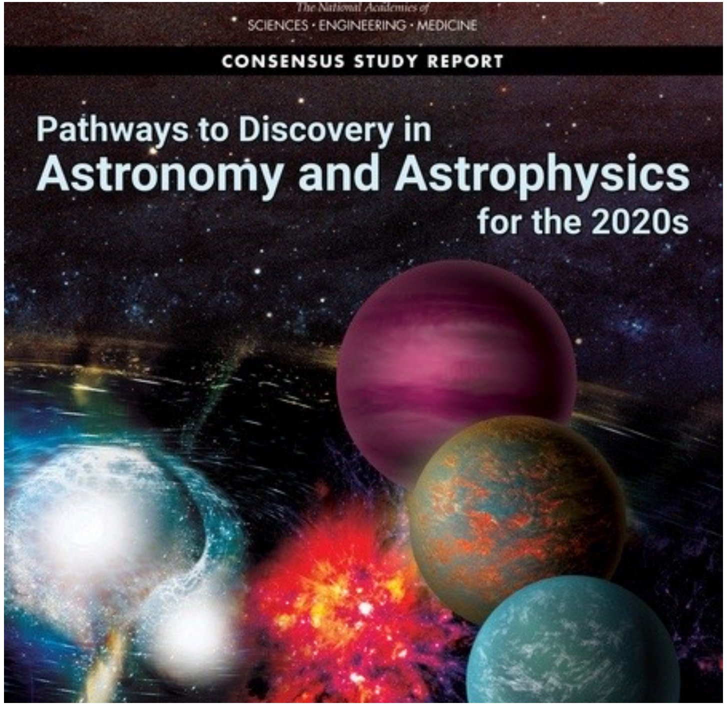
Key Astro2020 Project Documentation

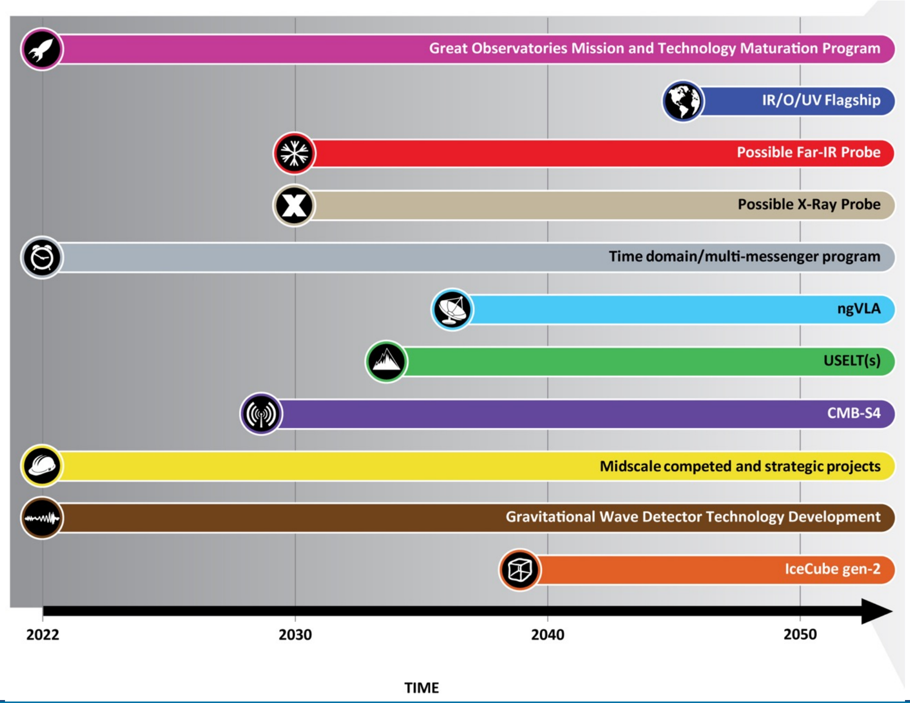




- ngVLA Science Book published (Dec 2018)
  - https://ngvla.nrao.edu/page/scibook
- Facilitated community submission of ngVLA science white papers to Astro2020 Decadal Survey (Jan 2019)
  - *15% specifically mentioning ngVLA*
- Submitted ngVLA facilities (APC) white paper to Astro2020 Decadal Survey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

Astro2020 identified the ngVLA as a high-priority large, ground-based facility whose construction should start this decade.

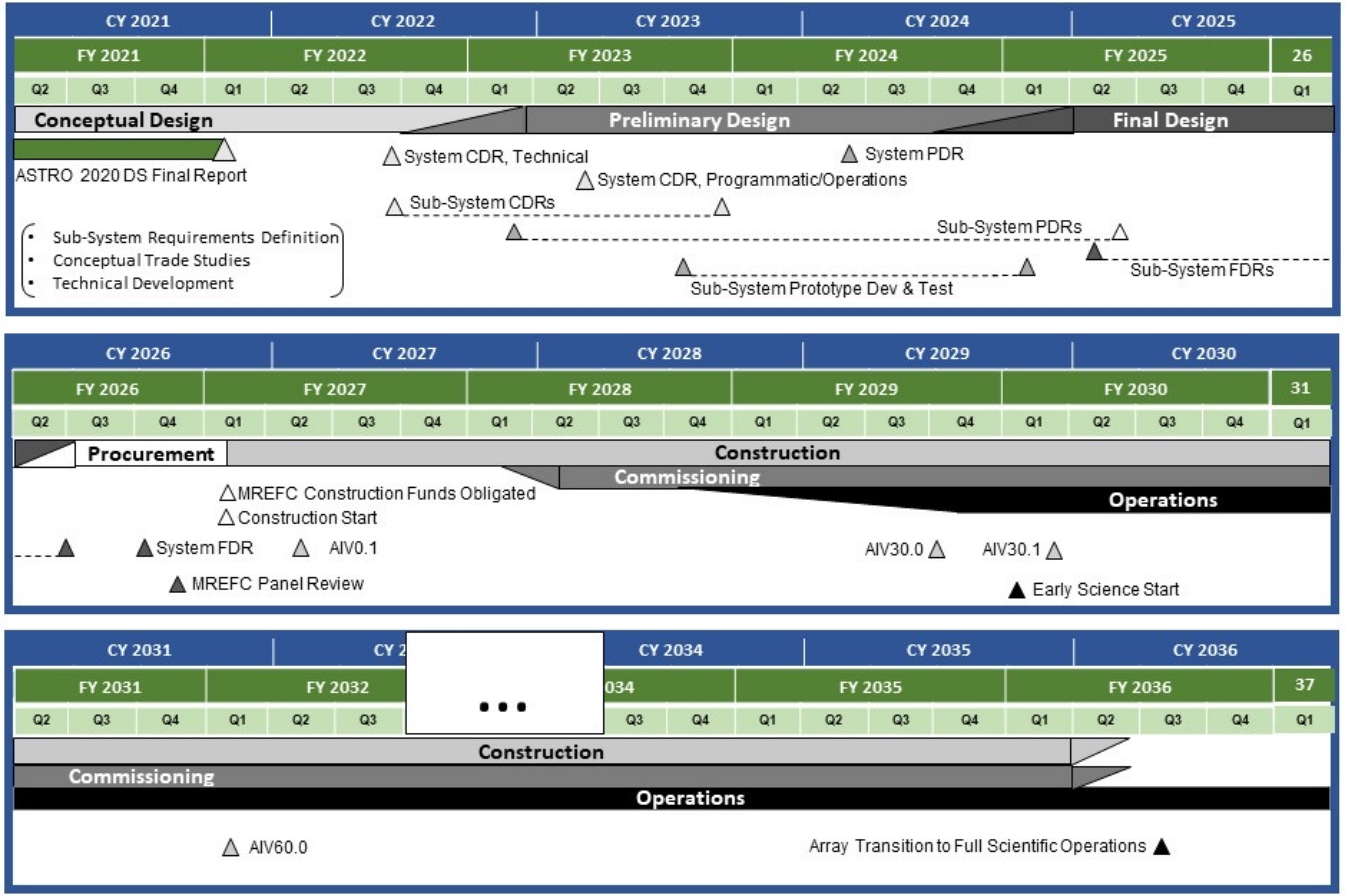




Still Not done! – Complete Design/Development

- Project Declared MREFC Candidate by NSF
- Proposal for design-phase funding (FY23-FY26)
- Project (Tech/Prog) Conceptual Design Review (CDR) in FY22/FY23.
- Secure international partnership contributions for final design and construction. Baseline plan and work package distribution by PDR.
- Preliminary and Final Design Reviews in FY24 and FY26.

Next Generation Very Large Array (ngVLA) Project Timeline

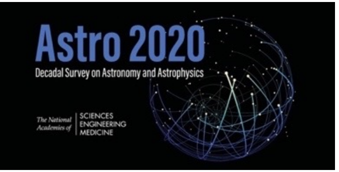


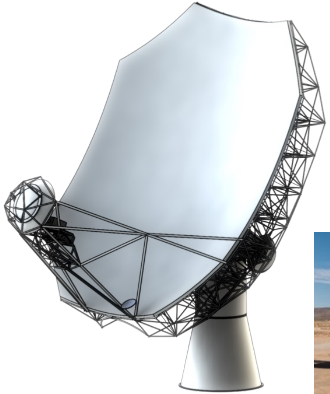
Note: Construction and Operation Phases are Rough Estimates

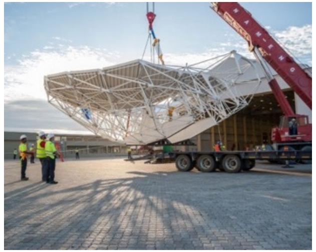
As of 18April2022

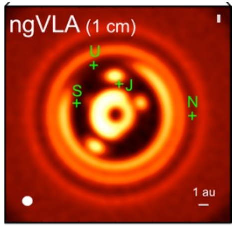
Milestone	Date
Technical CDR	**7/22**
Programmatic CDR	**4/23**
System PDR	**4/24**
System FDR	**9/26**
Construction Start	2027
Early Science CfP	2029
Full Science CfP	2035

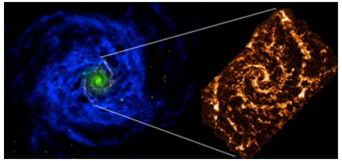
Project Timeline

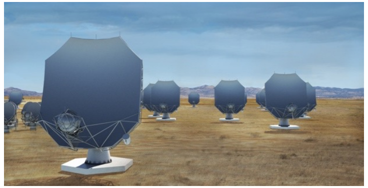












2019 — ngVLA Submission to Astro2020

2021 — Astro2020 Recommendation Published

Submit ngVLA Proposal to NSF/MREFC

2023 — Prototype Delivered to VLA Site

Complete NSF/MREFC FDR

2026 — ngVLA Construction →

2029 — Initiate ngVLA Early Science (> VLA capabilities)

2035 — Achieve Full Science Operations

ngvla

Next Generation Very Large Array