ngVLA: Project Technical Overview

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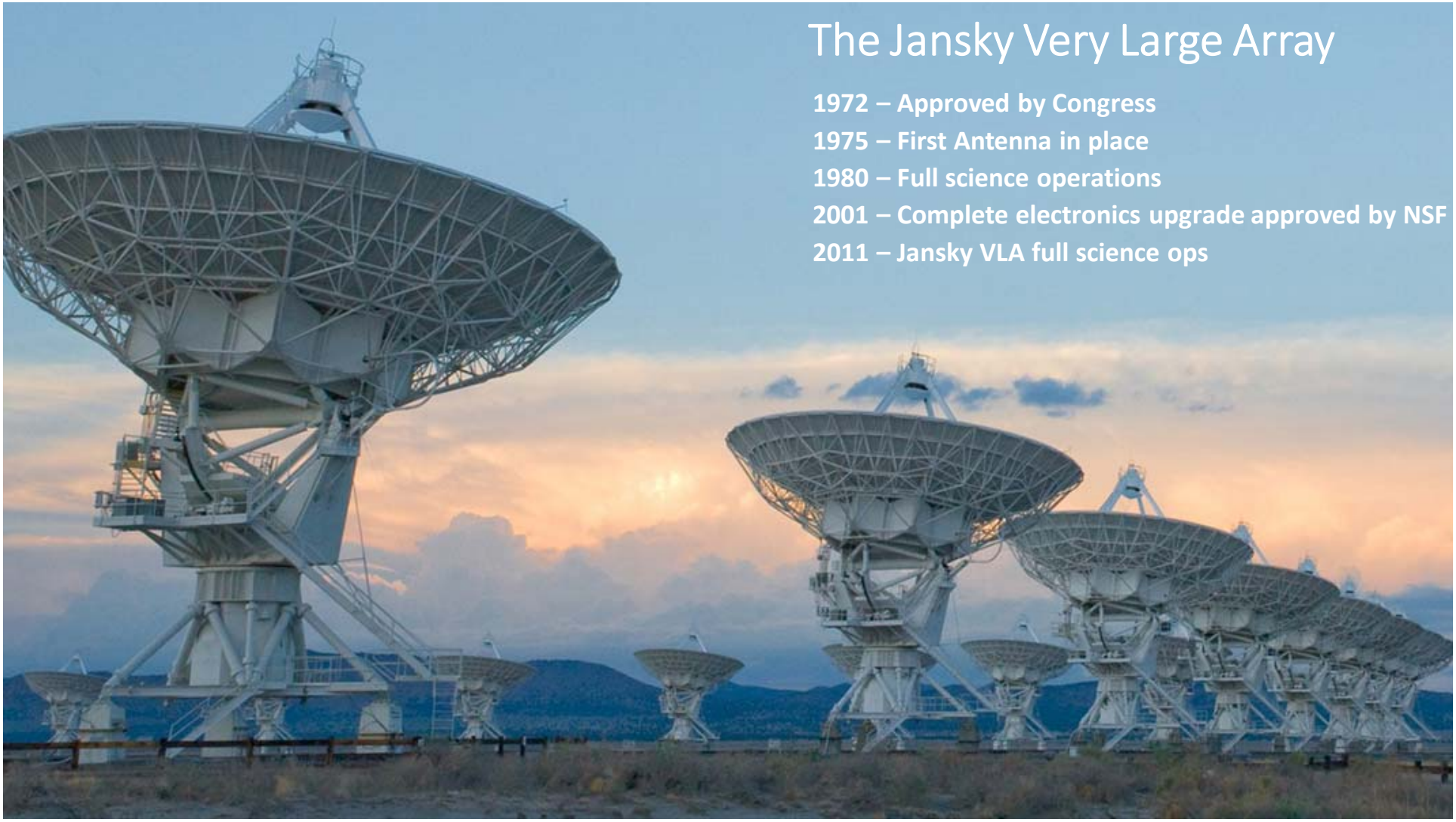
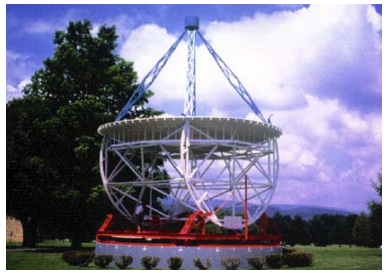

The Jansky Very Large Array
1972 – Approved by Congress
1975 – First Antenna in place
1980 – Full science operations
2001 – Complete electronics upgrade approved by NSF
2011 – Jansky VLA full science ops


The Very Long Baseline Array

Theory of Operation (1)

Single Dish: Resolution proportional to dish diameter and frequency. Sensitivity proportional to area.

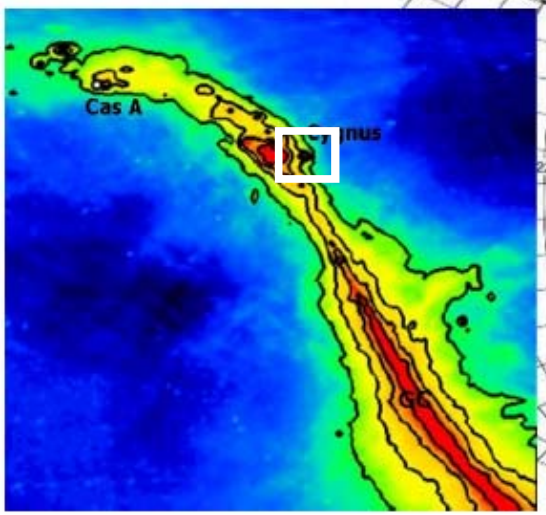
BG: 160 MHz, 9.5m Dish, G. Reber, 1944
FG: 1400 MHz, 100m Dish, W. Reich



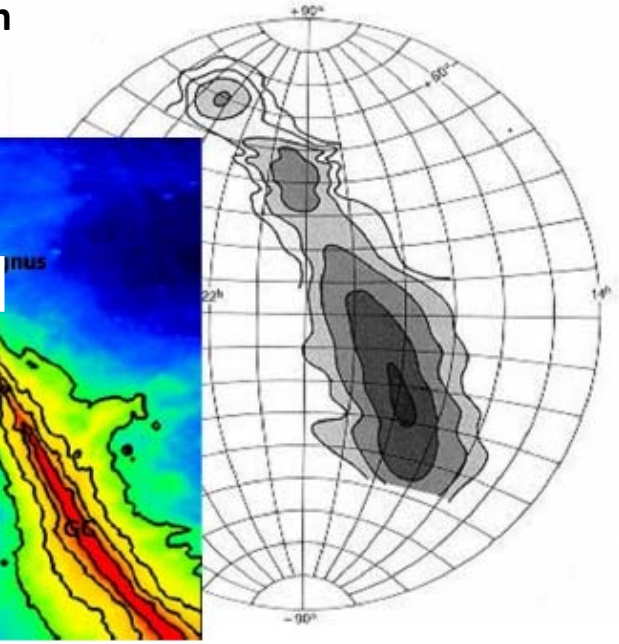
Reber 9.5m

Effelsberg 100m

Cygnus Single Dish Images:



W. Reich, 1988

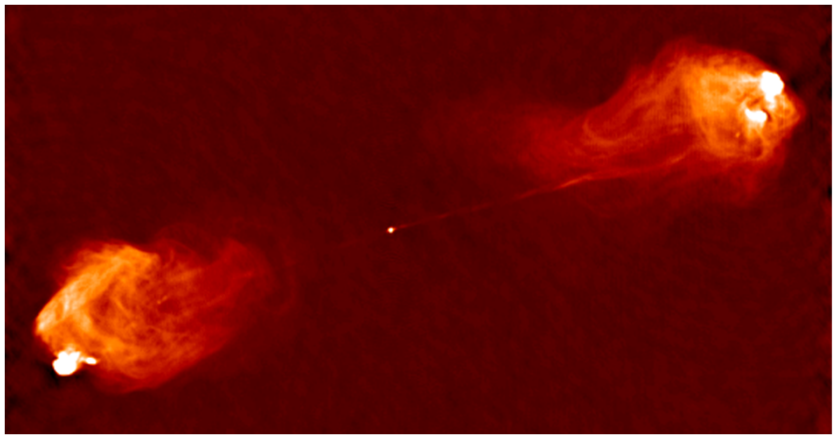


Reber, 1944

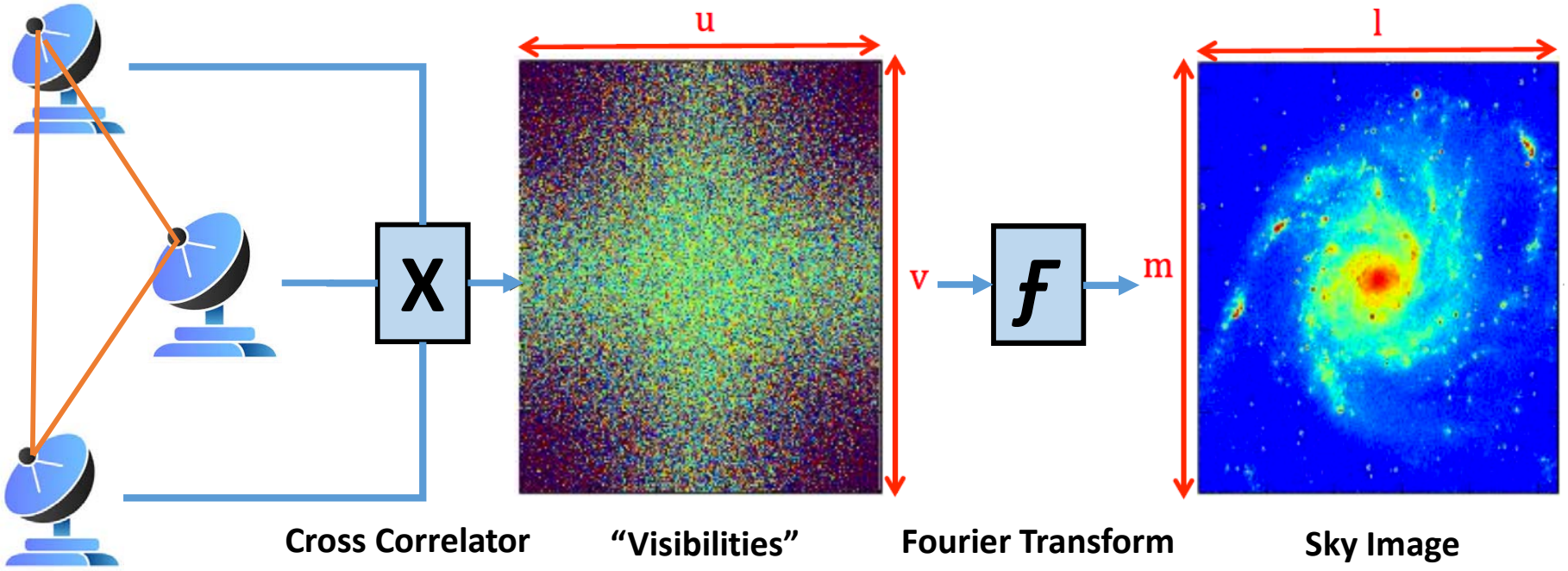
Theory of Operation (3)

Interferometer: Resolution proportional to dish *spacing* (aka “baseline”) and frequency.

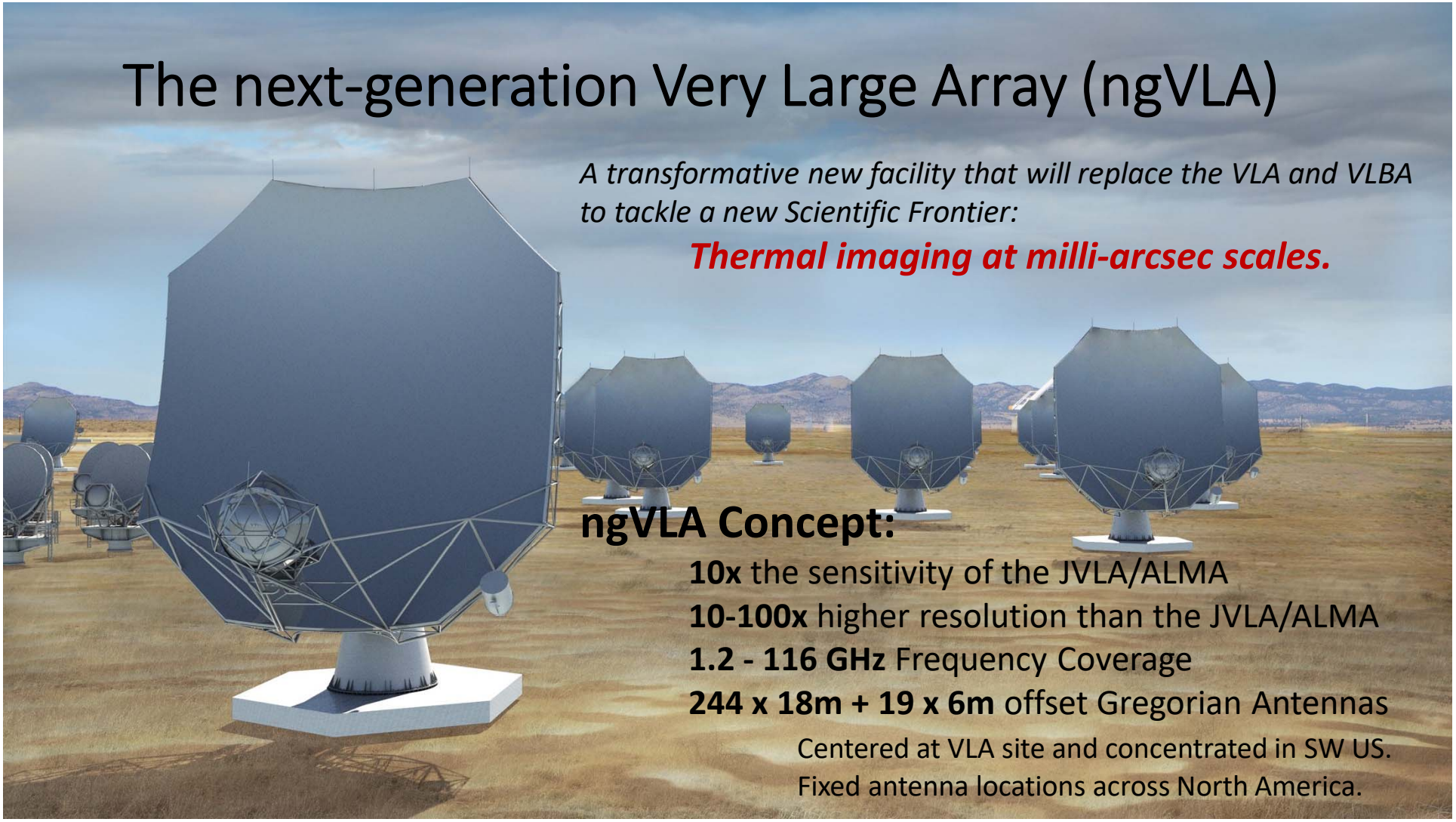
5000 MHz, 38 km Interferometer, R. Perley, 1983.



Theory of Operation (3)



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

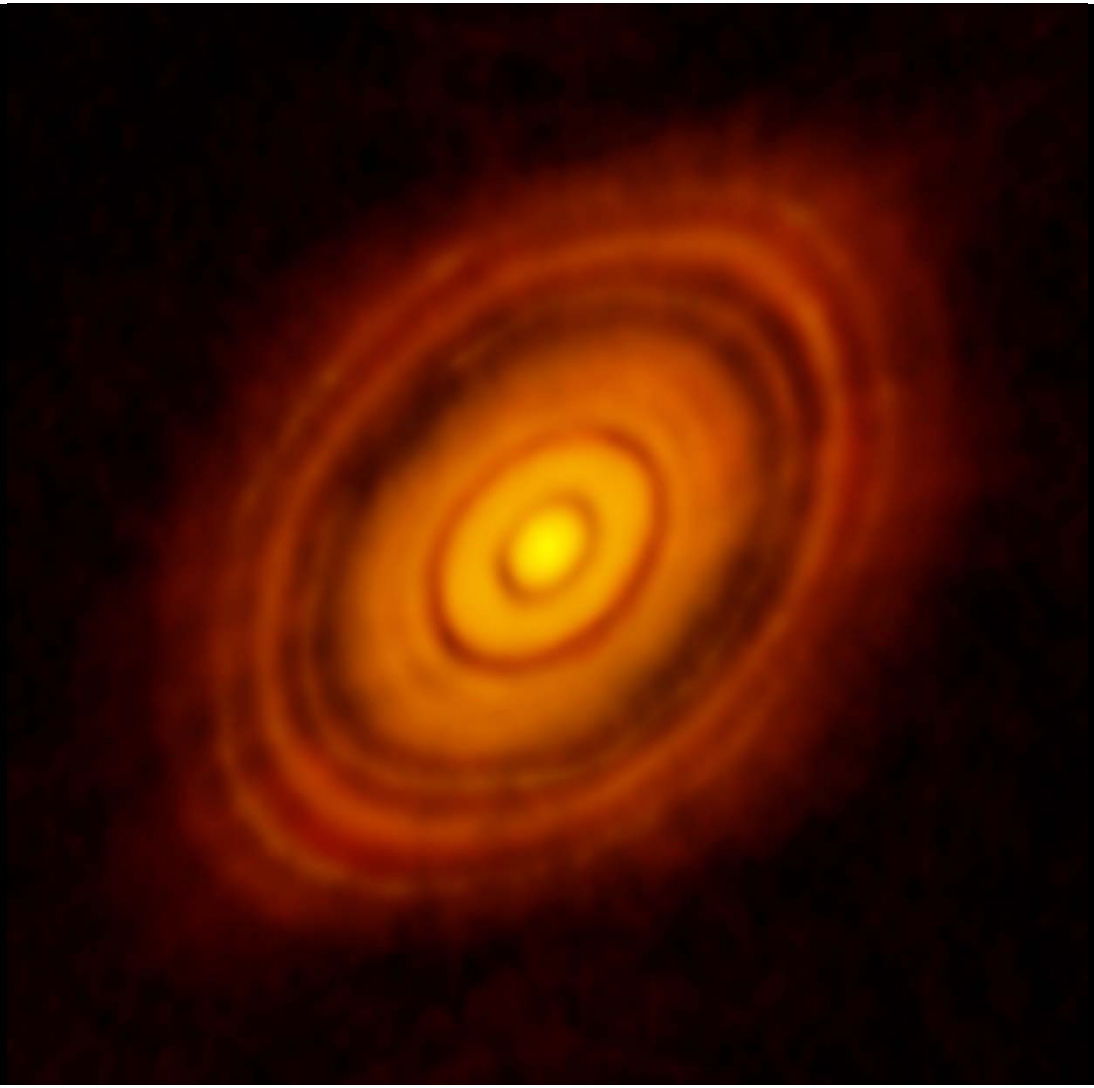
10-100x higher resolution than the JVLA/ALMA

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.



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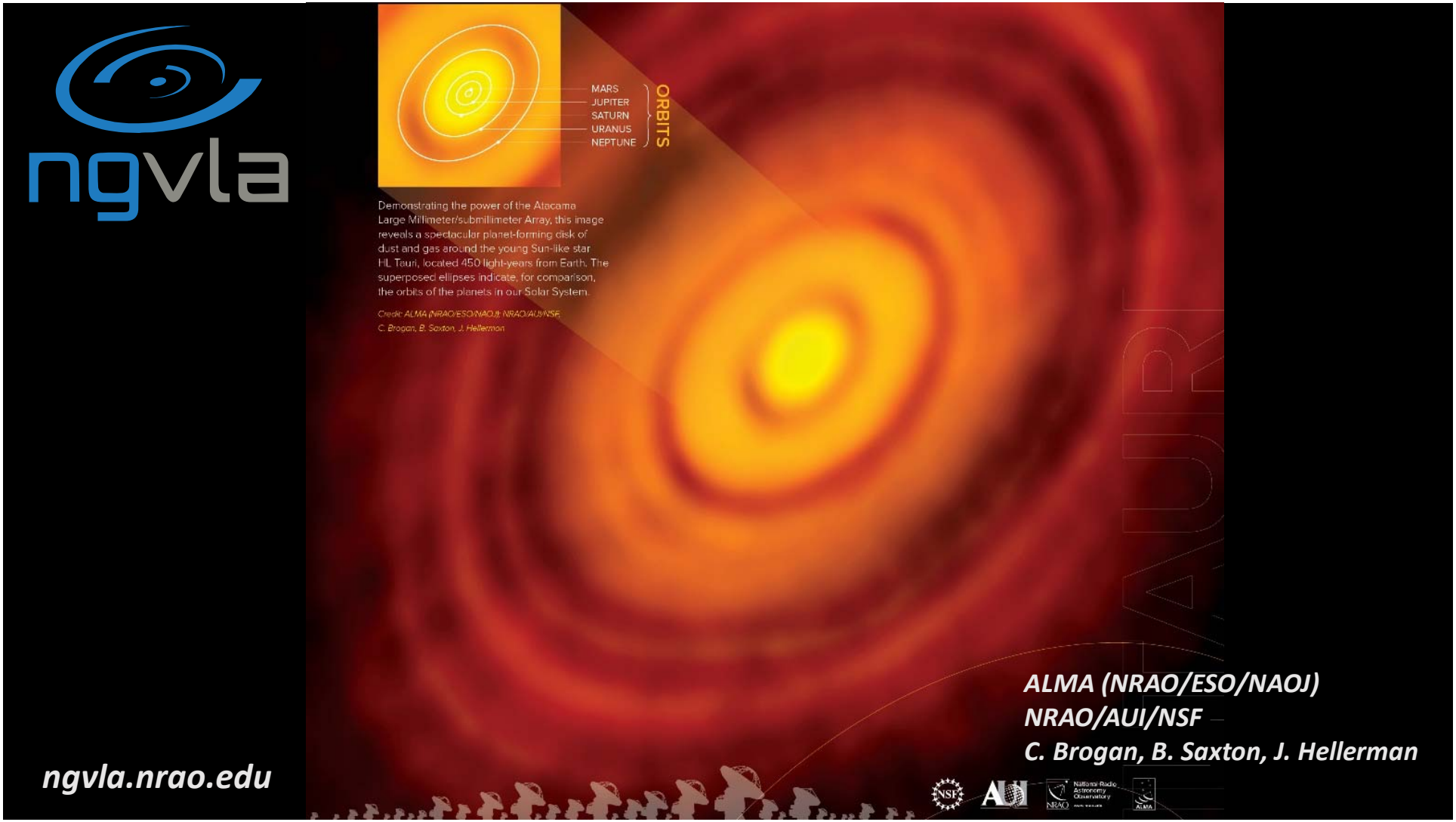
ALMA(ESO/NAOJ/NRAO)
C. Brogan, 2014


MARS
JUPITER
SATURN
URANUS
NEPTUNE
ORBITS
Demonstrating the power of the Atacama Large Millimeter/submillimeter Array, this image reveals a spectacular planet-forming disk of dust and gas around the young Sun-like star HL Tauri, located 450 light-years from Earth. The superposed ellipses indicate, for comparison, the orbits of the planets in our Solar System.
Credit: ALMA (NRAO/ESO/NAOJ); NRAO/AUI/NSF, C. Brogan, B. Saxton, J. Hellerman
ALMA (NRAO/ESO/NAOJ)
NRAO/AUI/NSF
C. Brogan, B. Saxton, J. Hellerman
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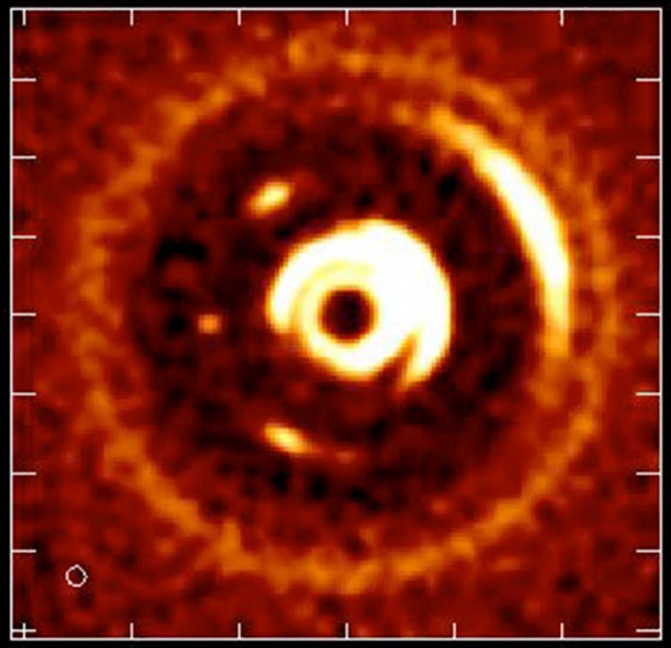
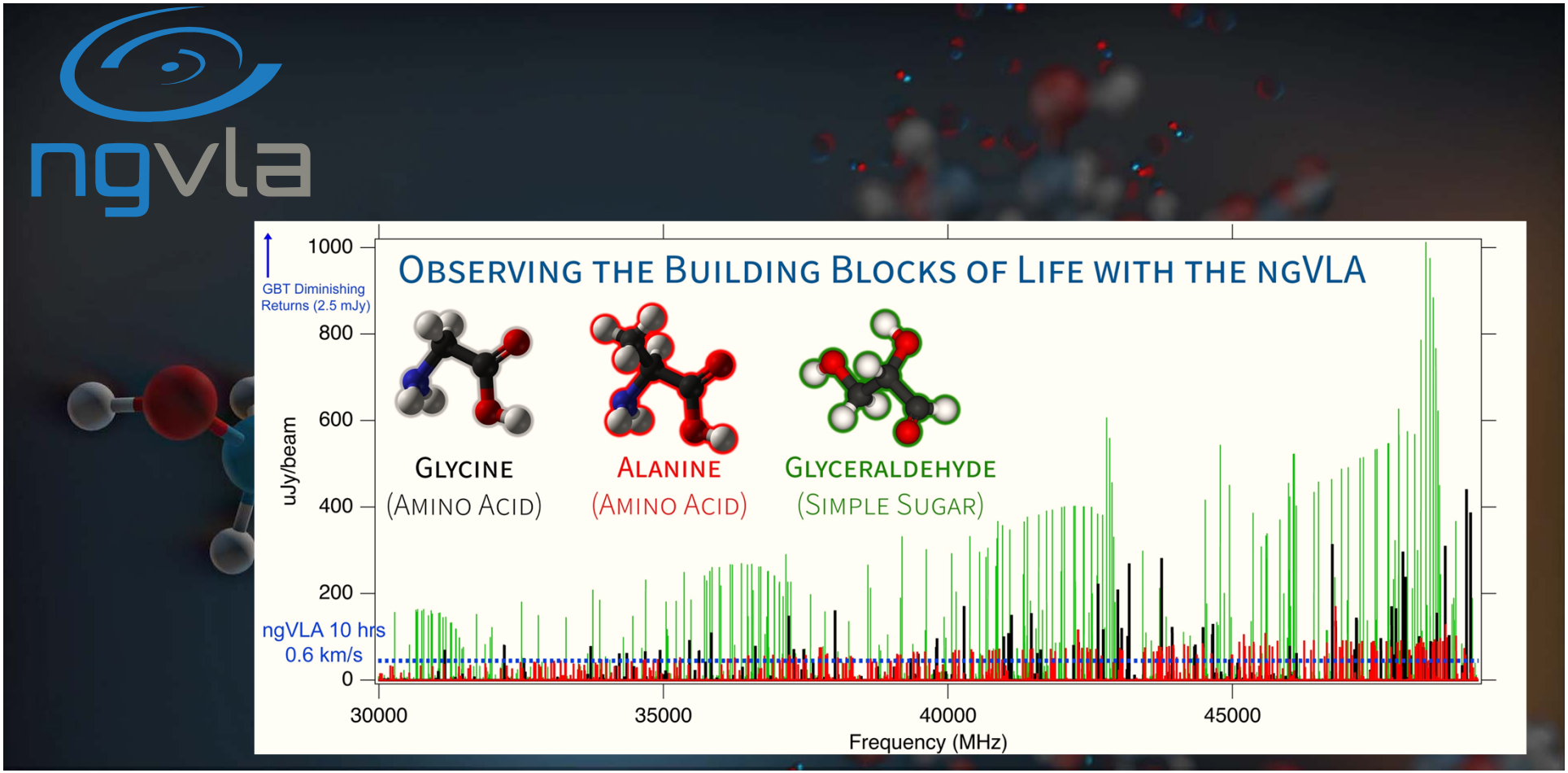


Ricci et al. (2018)



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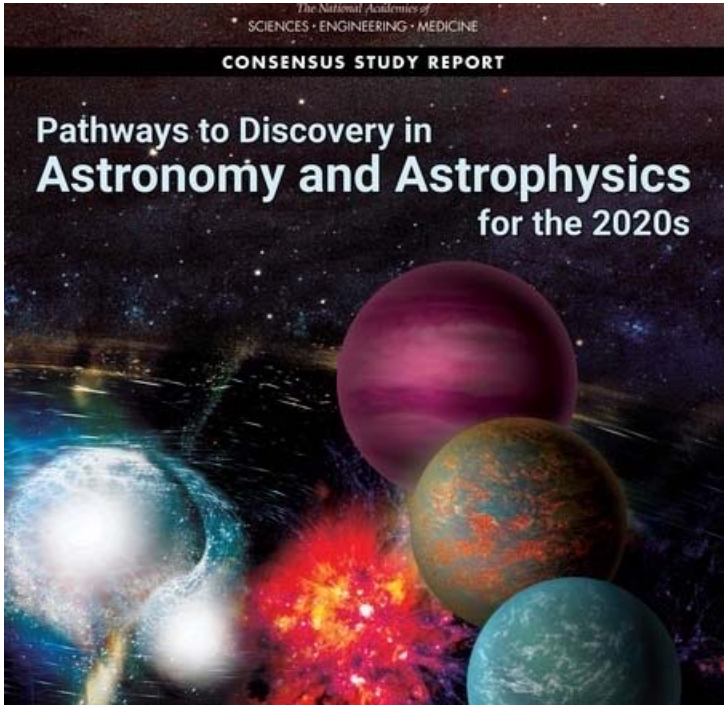
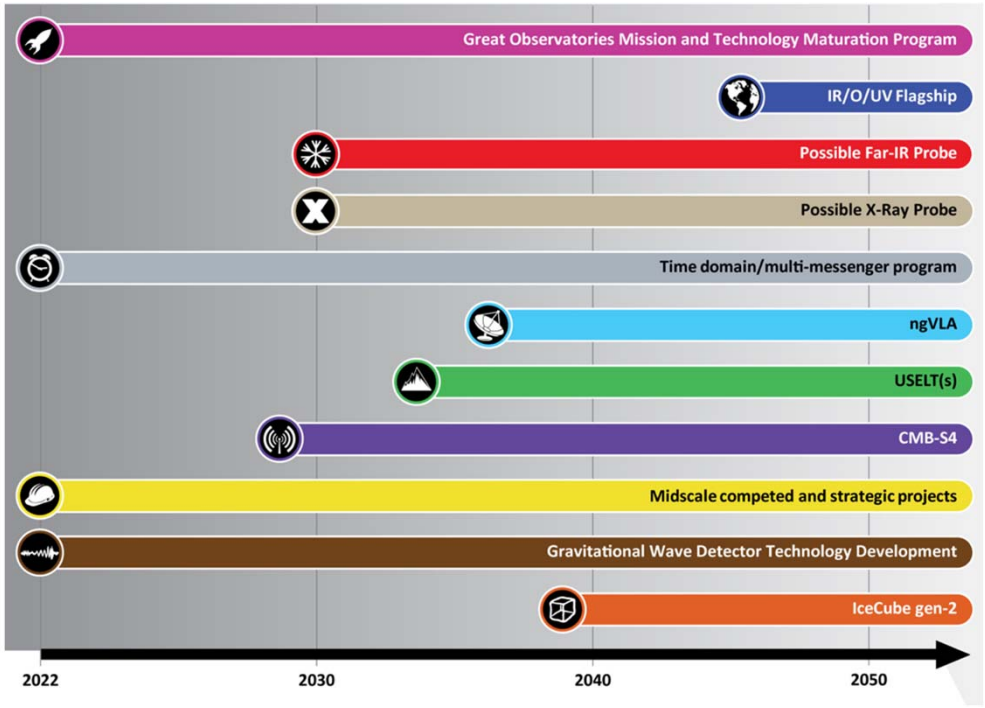
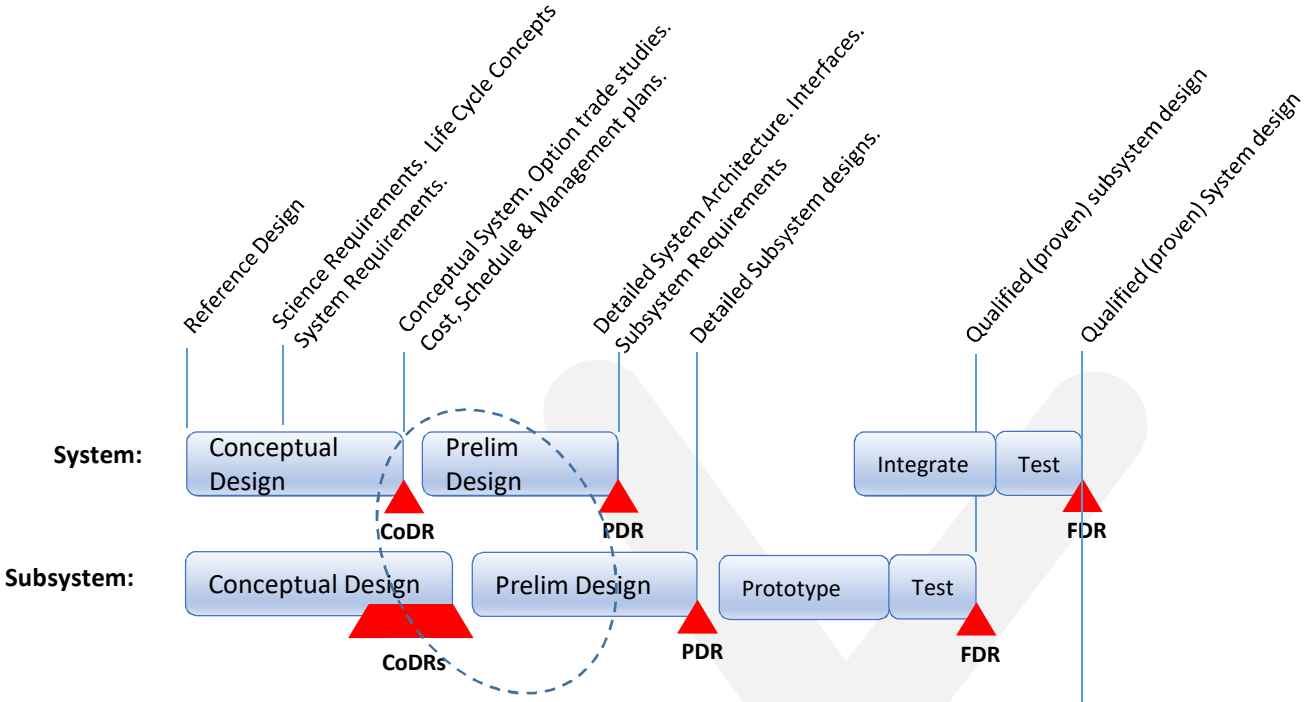
NRAO/AUI/NSF
B. Saxton, J. Hellerman

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



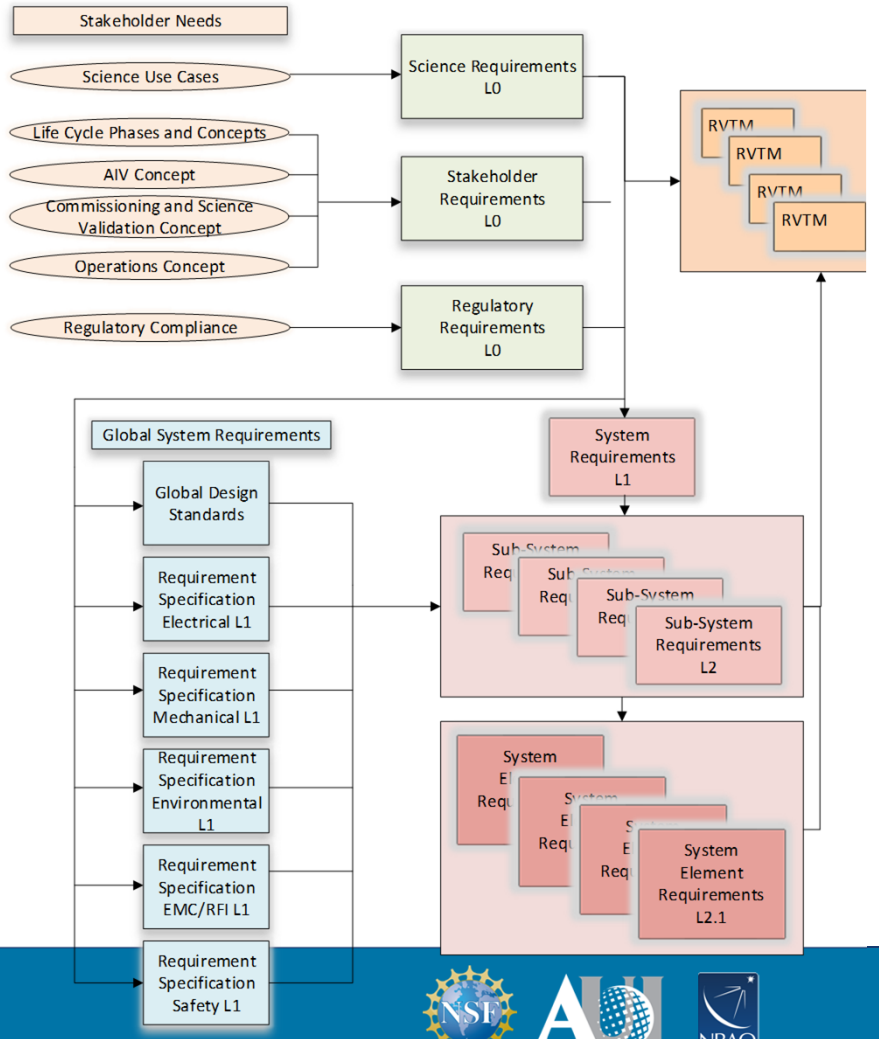


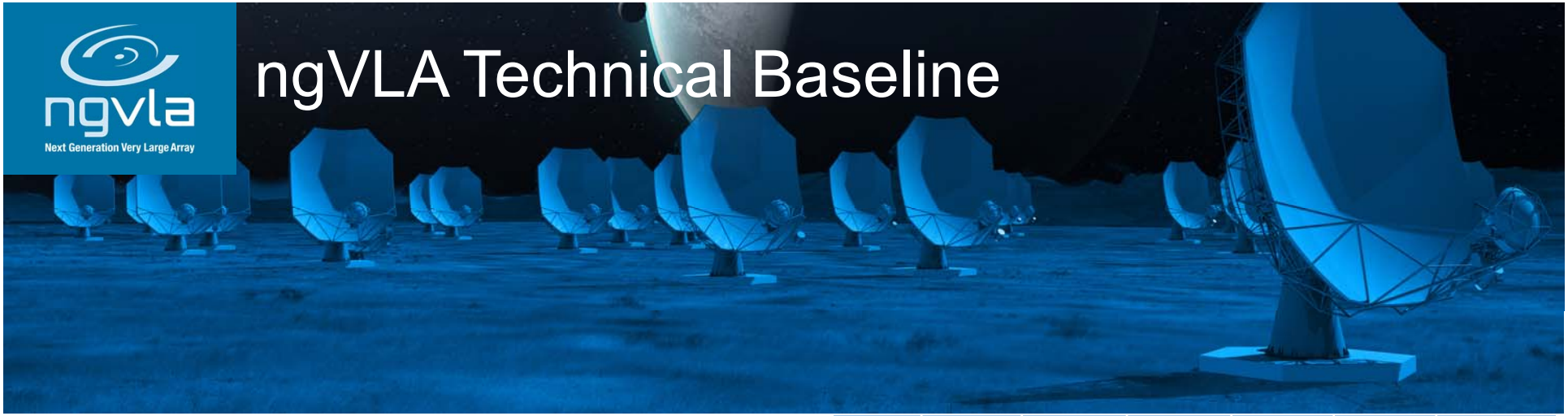
System development life cycle



Tech. Scope

- **Parametric** model: informed facility concept & architecture.
- **Bottom-up** Scope:
  - Science Requirements flow-down to System Requirements, Architecture & Sub-System Designs...
  - Full life-cycle, with supporting “concepts” for AIV, CSV, OPS…
  - End-2-End Architecture informed WBS.
- **Risk-assessment** at system and sub-system level.



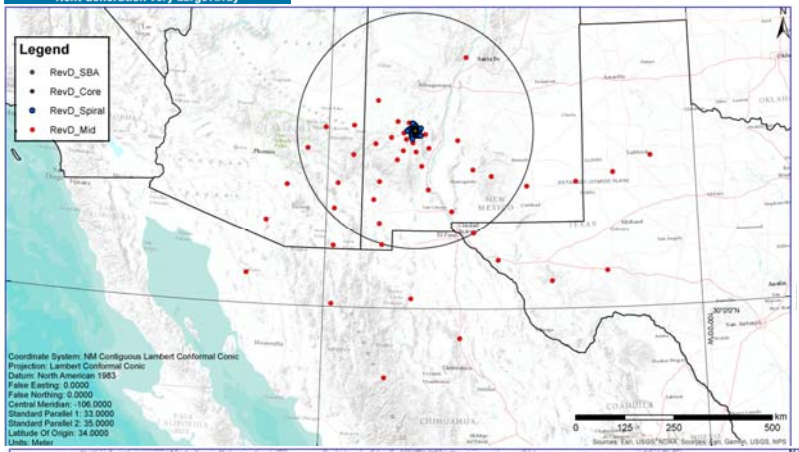


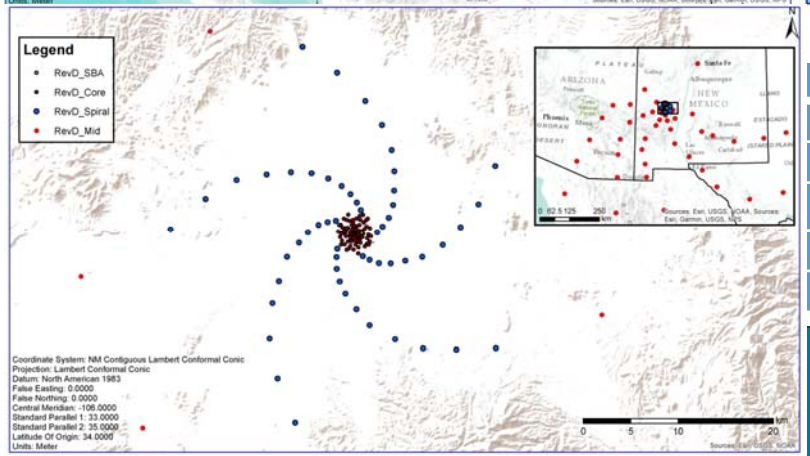
ngVLA Technical Baseline

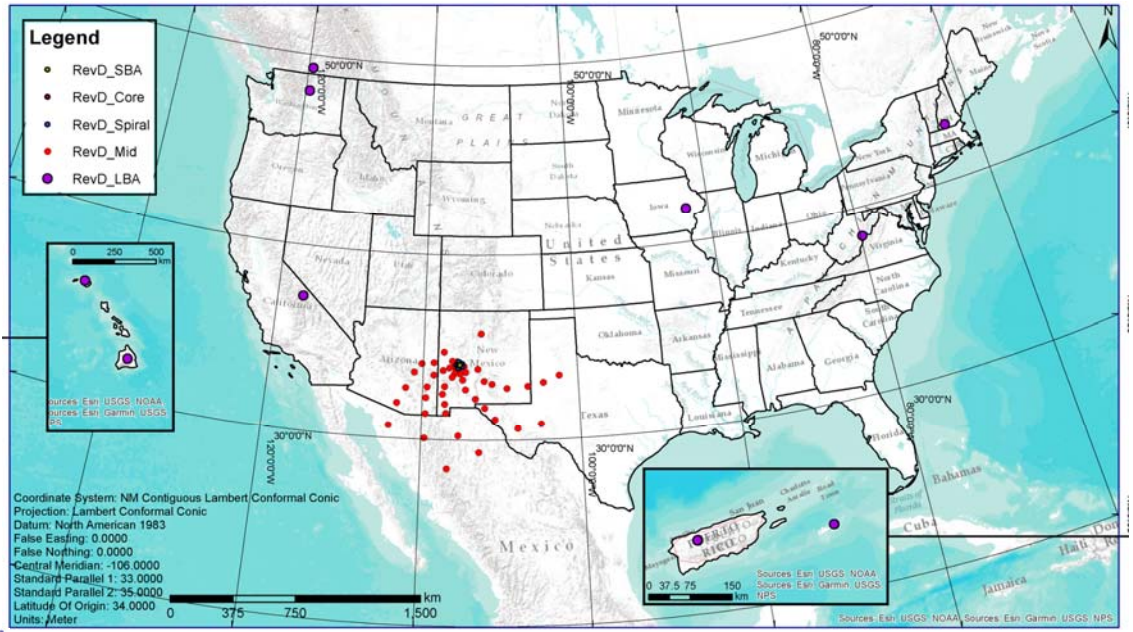
- **1.2 - 116 GHz** Frequency Coverage
- **Array Design**: 244 x 18m offset Gregorian Antennas
  - **Core**: 114 fixed antennas; B_{max} = 4.3 km
  - **Spiral**: 54 fixed antennas; B_{max} = 39 km
  - **Mid**: 46 fixed antennas spread into NM, AZ, TX, MX; B_{max} = 1070 km
  - **Long**: 30 x 18m antennas 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

Array Configuration





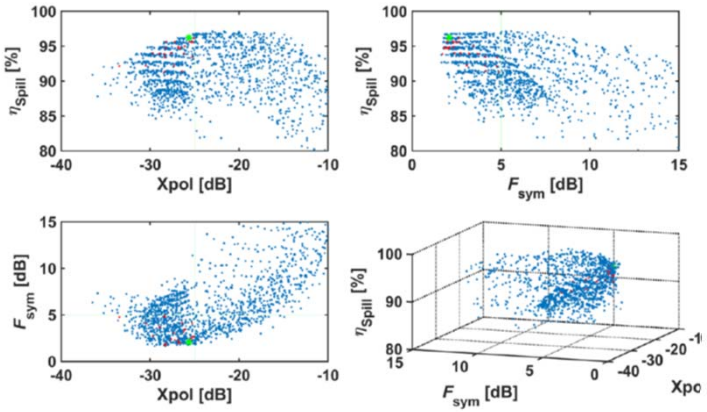


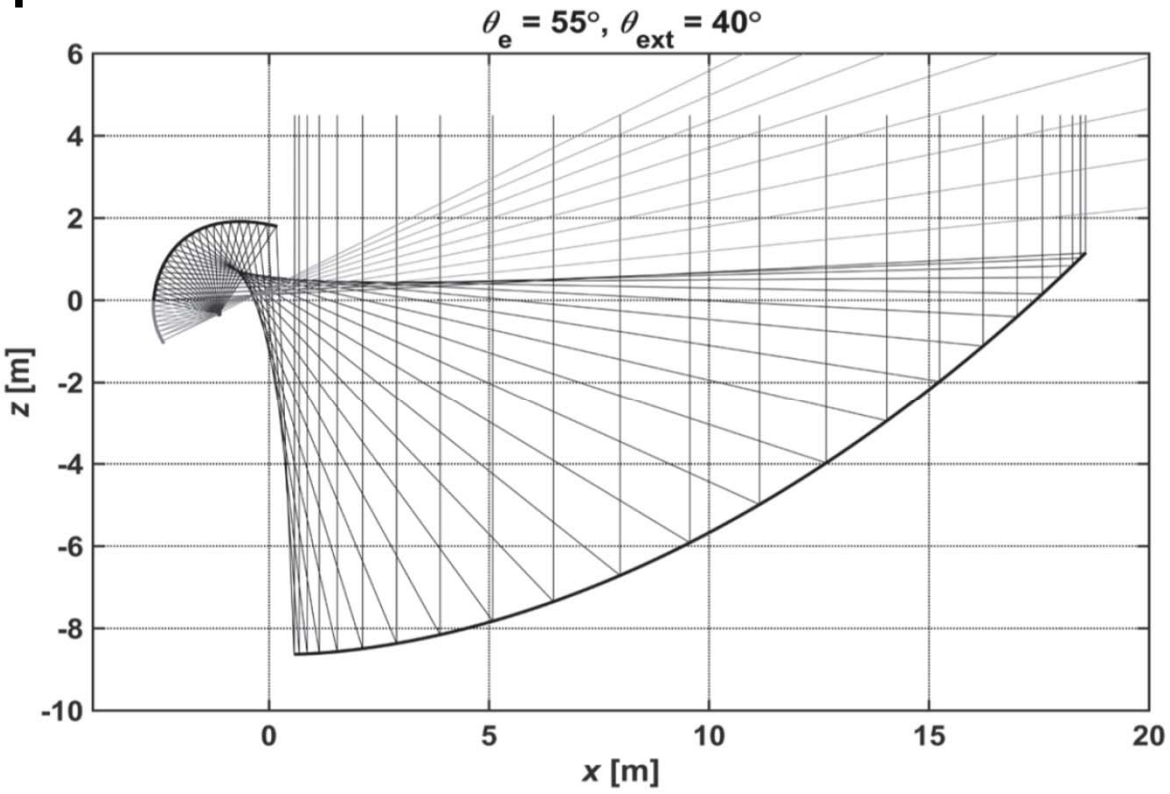
Long Baseline Antenna Locations

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

Antenna Optics

- 18m dual-offset Gregorian w secondary extension
- 110° subtended angle at focus
- Optically shaped, for optimum Aeff/Tsys at 30 GHz (Band 4)
- Illumination efficiency ~96% at 30 GHz; > 93% for all of Band 4



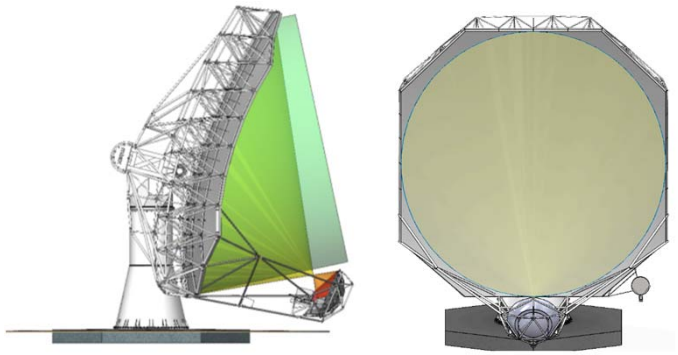


mtex ngVLA 18m Antenna Design

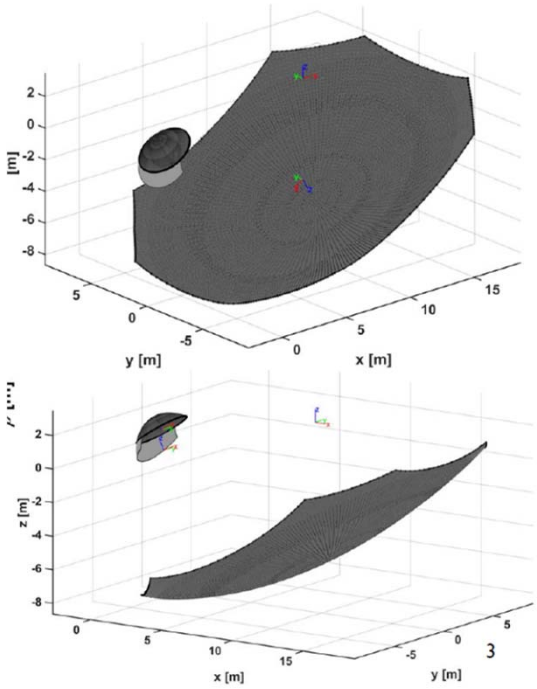
mtex | antenna technology

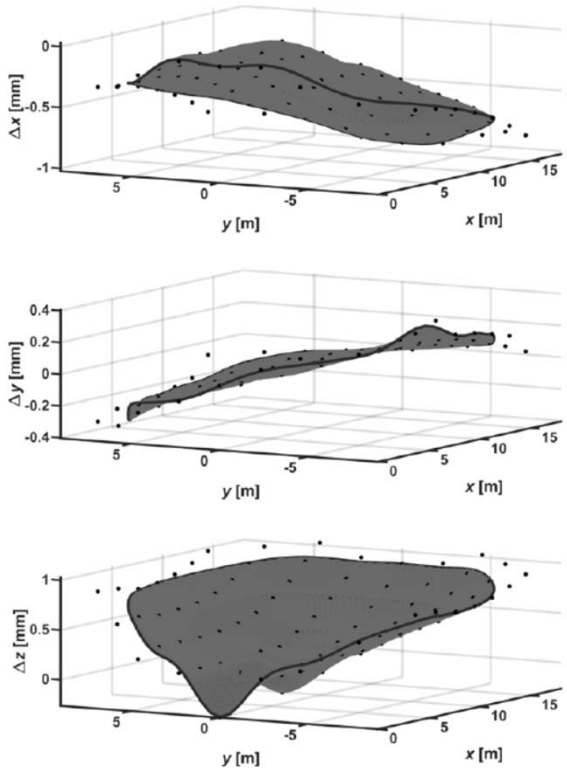
Key Specifications	
18m Aperture	Offset Gregorian
Shaped Optics	3° Slew & Settle in 7 sec
Surface: 160 µm rms	Referenced Pointing: 3” rms

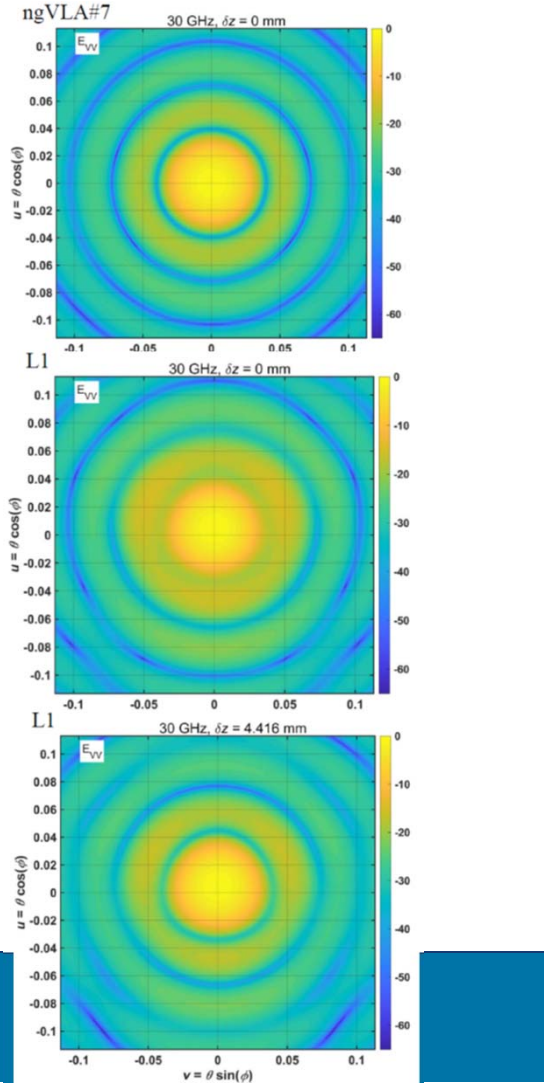
Ray trace of 18m Optics - side and front view



FEA <-> RF Simulations







Main Reflector Panels

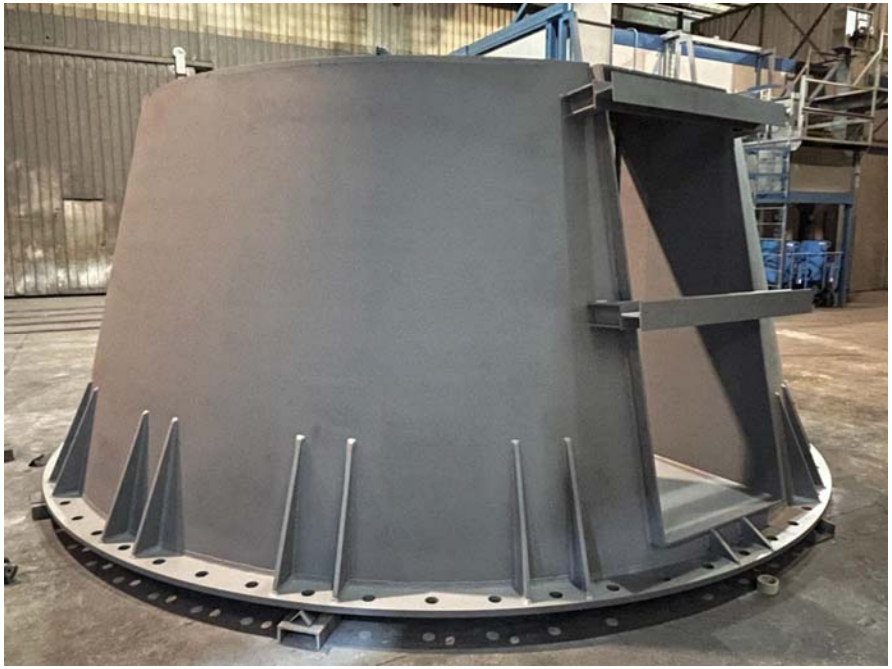
- 76 panels (68 rect.)
- ~2.5m x 2.1m
- 20 µm RMS Surface
- Diffusive surface treatment

Main Reflector Backup Structure

Subreflector Assembly

Sub reflector was adjusted with photogrammetry to <30 µm RMS

Pedestal

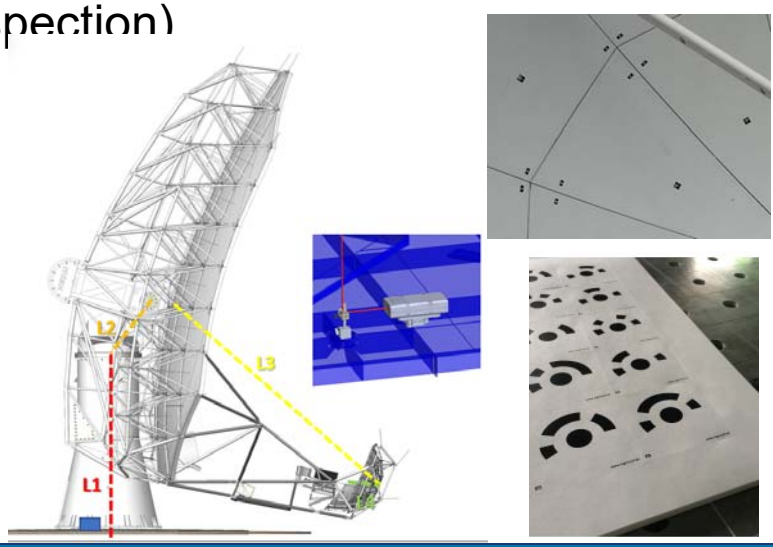


Turnhead Assembly

Vendor (mtex) Qualification

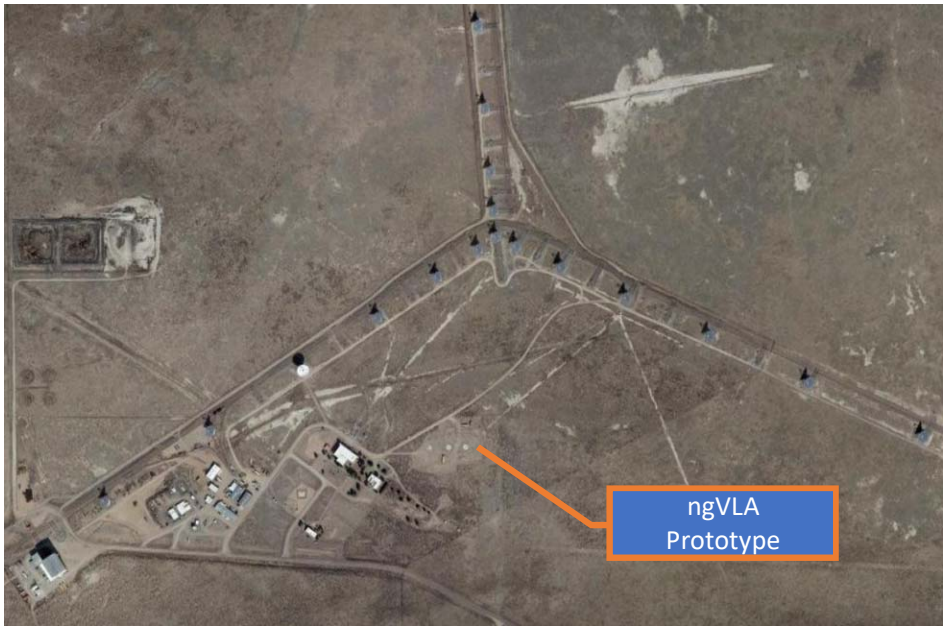
- Incremental integration and verification:

- Compliance Matrix: 378 Requirements, 23 verified by FAT, 18 verified by SAT. (Others by design or inspection)
- Only Non-radiometric tests:
  - Servo tuning and preliminary verification of pointing, tracking, slewing by encoder read-out only.
  - Surface setting and optical alignment by photogrammetry.
  - Delay stability tested incrementally with laser metrology.



Customer (NRAO) Qualification

- All radiometric & interferometric tests conducted in this phase.
- Single dish tests limited to early functional tests and accelerated lifetime (MTBF determination, etc).
- All performance tests (Surface, Pointing, Tracking, etc.) are interferometric with the VLA.
- X-band and Q-band receivers installed. VLA signal chain electronics.



NRAO Antenna Testing: Jan 2025+
VLA D-Config: Feb-May 2025 (2025A)
Many short baselines for testing!

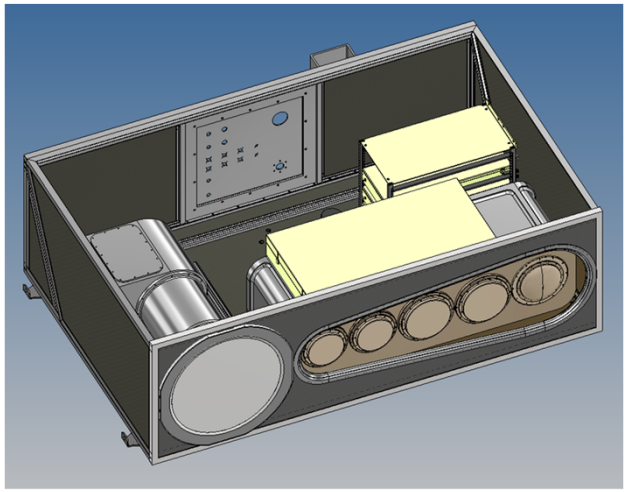
Site Infrastructure Preparation

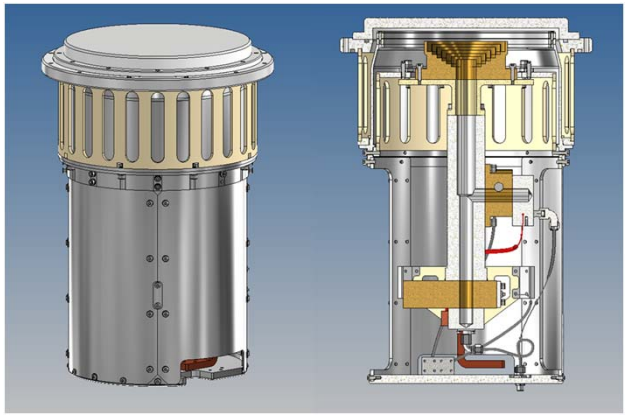
Updated medium-voltage electrical services, foundation anchors, grounding, and fiber optics


2024-04-08 13:01:03

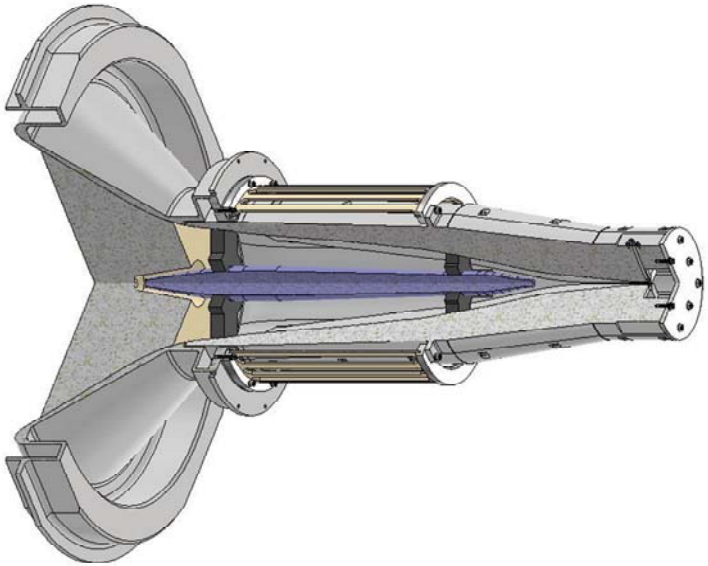
Front End Concept

- 6 Bands in 2 Cryogenic Dewars
- 1.2-3.5 GHz and 3.4-12.3 GHz Quad-Ridge Horns, 3.5:1 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.
- Single stage down-conversion to baseband for 5 bands. Direct SSB or IQ sampling (8-bit) using modular devices @ FE.
- Two-stage Gifford-McMahon cryogenic system with variable-speed cryocoolers and compressors.

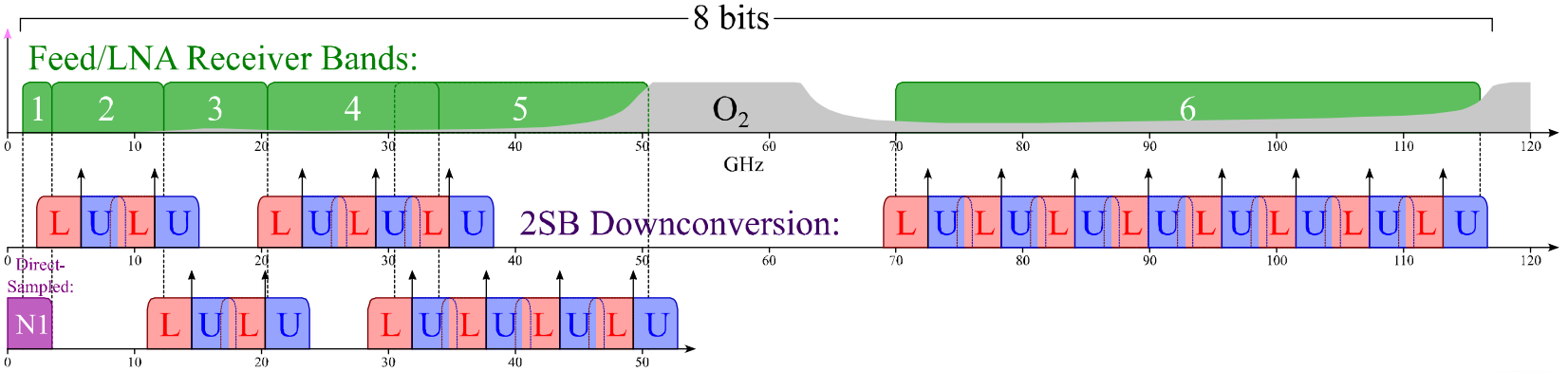




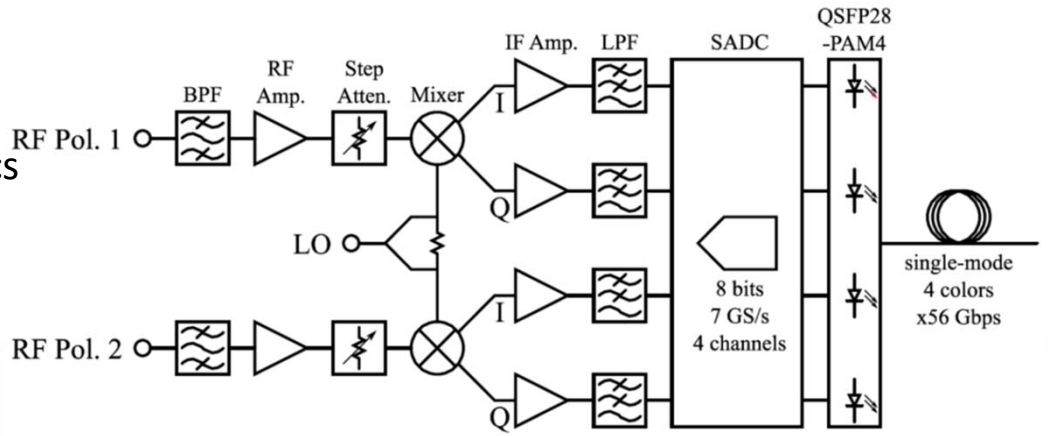
Feed horn prototypes (Band 1)



Integrated Receiver Digitizers (IRD)



- Direct-Sampled Band 1. Side-Band Separating Sampling for Bands 2-6.
- All Local Oscillator (LO) Signals are harmonics of **2.9 GHz**.
- **7.0 GHz** Sampler Clocks provide overlapping side-bands.



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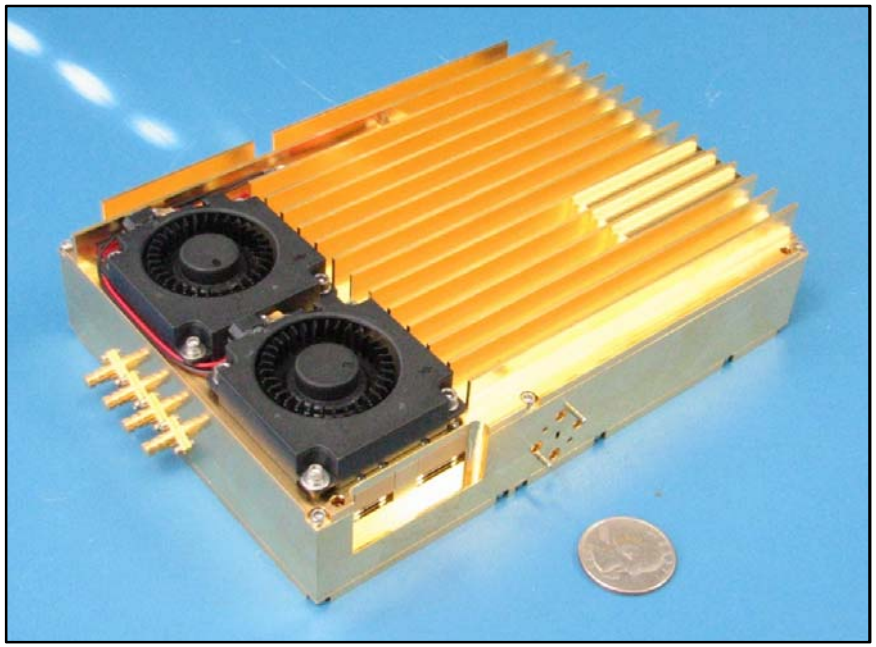
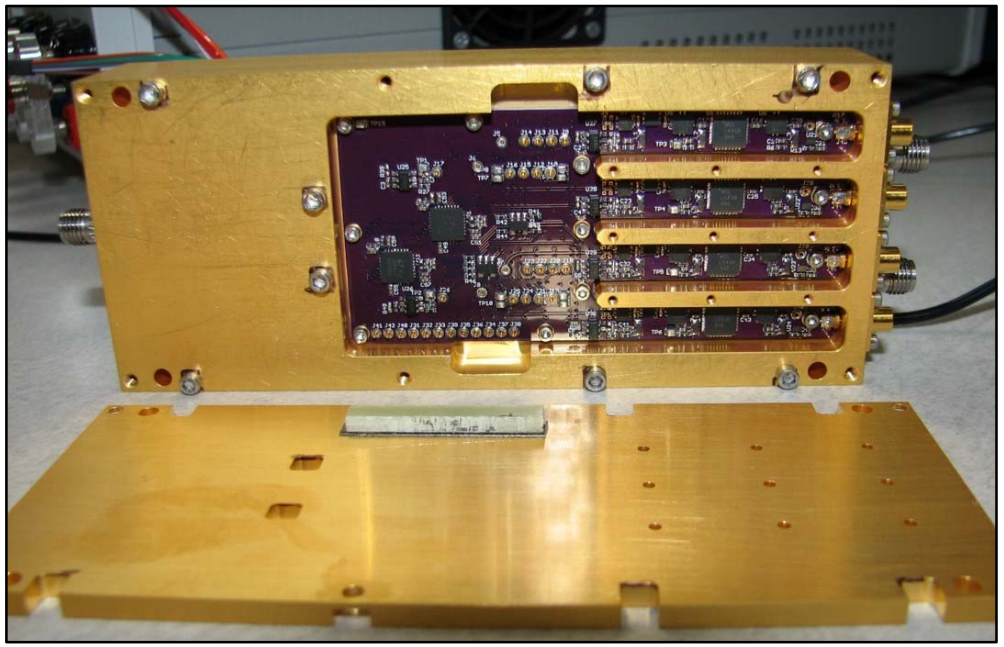




Data Transmission System

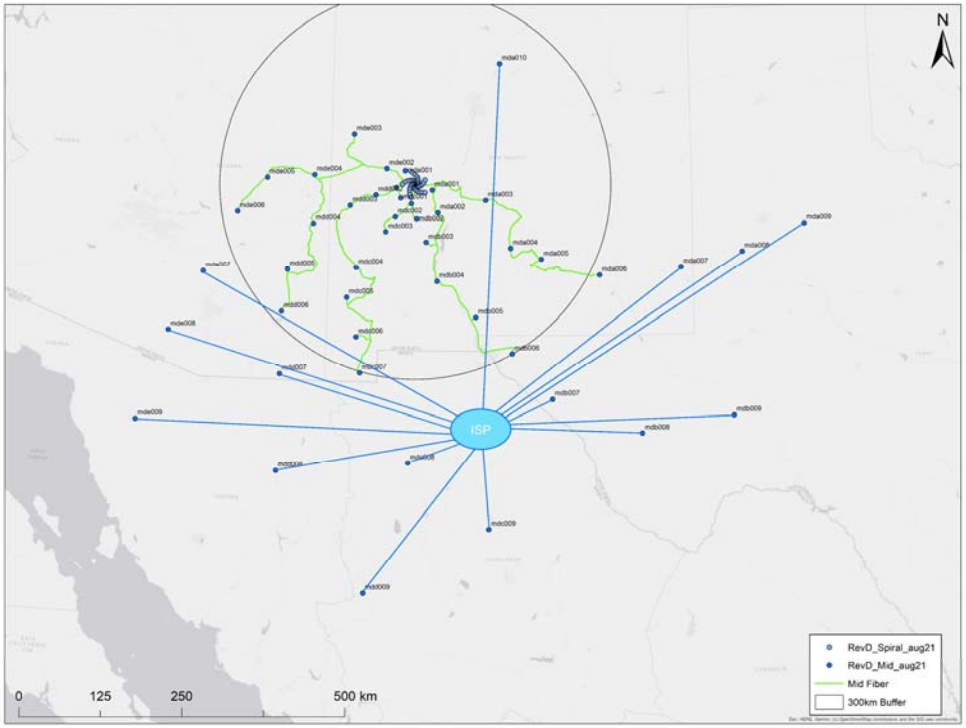
- 720 Gbps per antenna (Typical, sustained)
- 23.7 TB/sec across array

- 800 Gbps fiber optic links.
- Tunable data rates for the most distant antennas; scaleable architecture.

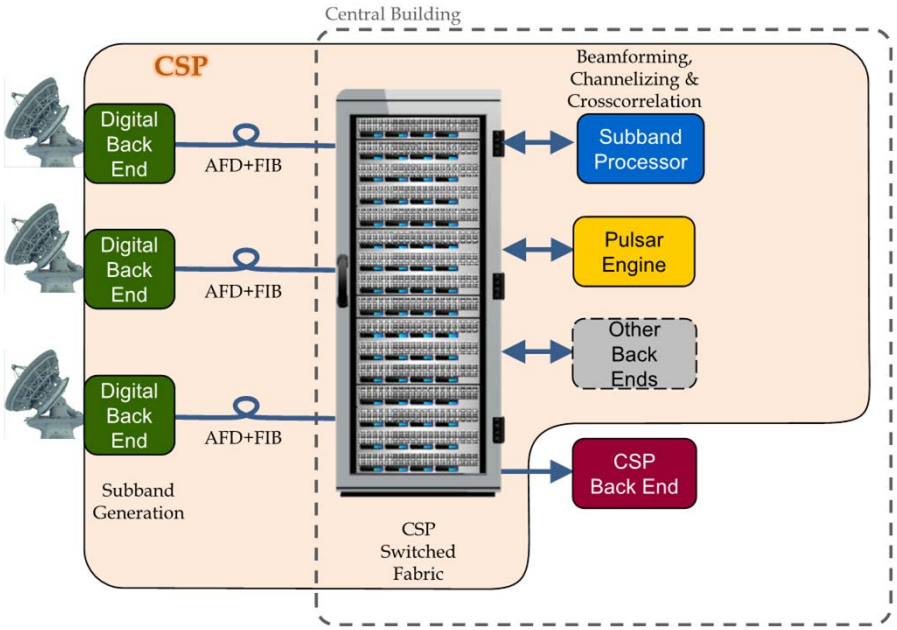
- (263 Ant)
- (20 Ghz)
- (8 bits)
- (2 Nyquist Sampling)
- (9/8 Resampler/Filter)
- (2 Pol)
- 189.4 Tbps or 23.7 TB/s

Time & Frequency References

- 187 Antennas on Plains of San Agustin:
  - Central clock and LO generation. Within 40 km point-to-point.
  - Fiber optic links to Front End.
- 30 Mid-baseline Antennas:
  - Synchronous Time & Frequency Reference Distribution to ~300 km.
  - Repeaters and EDFAs.
- 16 Mid & Long Baseline Antennas:
  - Local primary references (e.g., Active Hydrogen Maser & GPS)

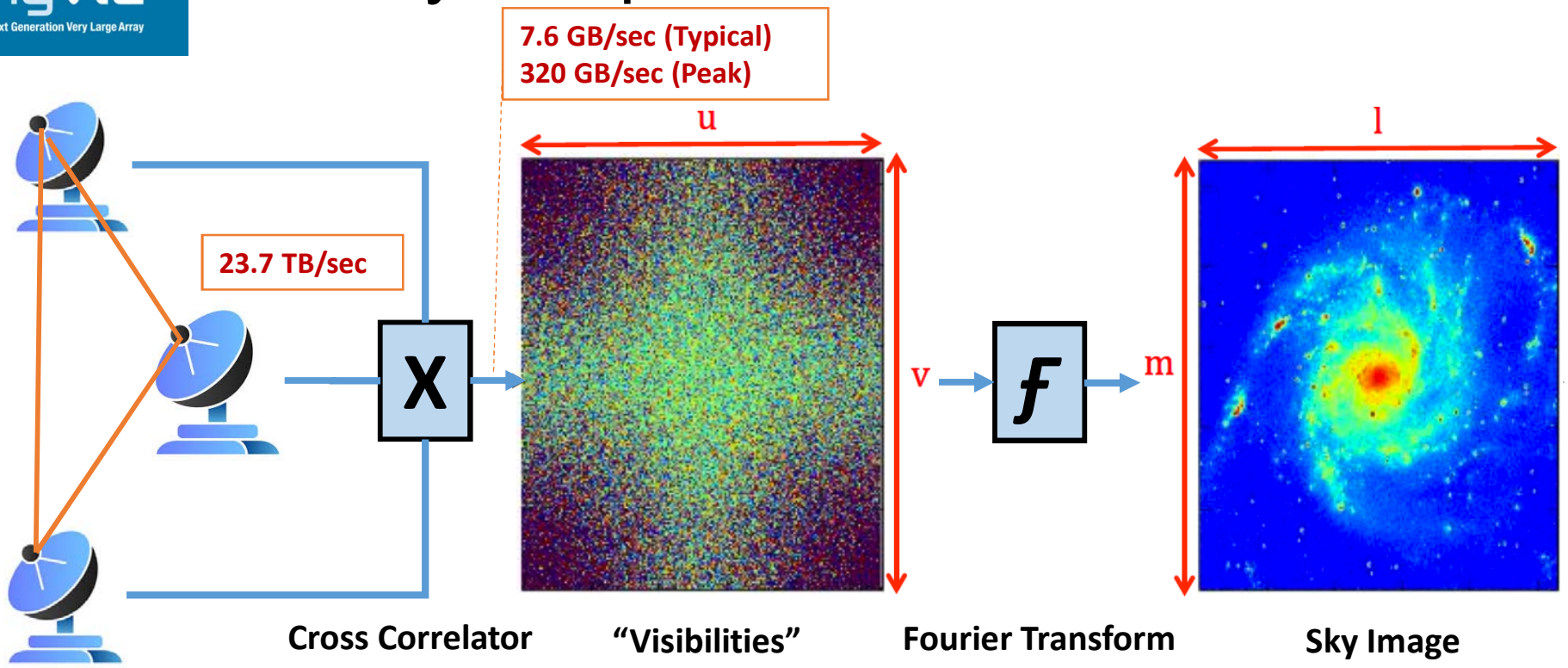


Central Signal Processor



Requirement Description	Specification
Number of Connected Antennas	263 total (minimum)
Maximum Baseline Length	8,800 km
Maximum Instantaneous Bandwidth	20 GHz per polarization in interferometric mode concurrent with 8 GHz in beamformed mode.
Maximum Number of Channels	≥240,000 channels minimum (2M channel goal)
Highest Frequency Resolution	1kHz, goal of 400 Hz, corresponding to 0.1 km/s resolution at 1.2 GHz. (15.625 kHz default resolution at full processed bandwidth)
Pulsar Search Beamforming	≥10 beams ≤700 km diameter sub-array
Pulsar Timing Beamforming	≥5 beams ≤700 km diameter sub-array

Theory of Operation



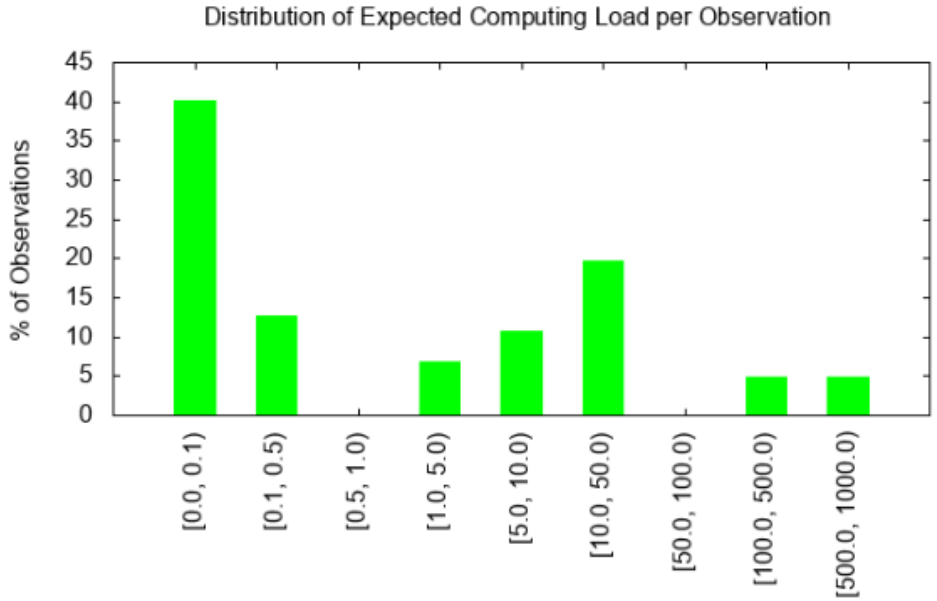
S/W and Computing Considerations

- **Operations Concept**: HLDP (High-Level Data Product) 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.

Post Processing Estimates

Table 6: Measured parameter summary.

Algorithm	Operations per Visibility (FLOPs/Vis)	Arithmetic Intensity (FLOPs/Byte)
Standard Gridding	1280.8	40
A-projection	7472.8	233
W-projection	21768.4	670
AW-projection	39704.8	1240



Science Case	Time	Vis Per Hour	Data Rate	Storage Rate
KSG1 Driving Cont. Band 6 e.g. Taurus disk	9%	73.19 GVis	0.081 GB/s	0.21 PB/Month
KSG1 Driving Cont. Band 4 e.g. Taurus disk	4%	216.28 GVis	0.240 GB/s	0.63 PB/Month
KSG2 Driving Line Band 5 e.g. Sgr. B2(N)	4%	97241.83 GVis	108.046 GB/s	284.14 PB/Month
KSG2 Driving Line Band 4 e.g. Sgr. B2(N)	1%	72129.85 GVis	80.144 GB/s	210.76 PB/Month
KSG2 Driving Line Band 3 e.g. Sgr. B2(N)	1%	119342.01 GVis	132.602 GB/s	348.72 PB/Month
KSG3 Driving Line Band 5 e.g. COSMOS	4%	5985.35 GVis	6.650 GB/s	17.49 PB/Month
KSG3 Driving Line Band 4 e.g. COSMOS	1%	2996.82 GVis	3.330 GB/s	8.76 PB/Month
KSG3 Driving Line Band 3 e.g. COSMOS	1%	3030.45 GVis	3.367 GB/s	8.85 PB/Month
KSG3 Driving Line Band 6 e.g. Spiderweb galaxy	2%	11.16 GVis	0.012 GB/s	0.03 PB/Month
KSG3 Driving Line Band 5 e.g. Spiderweb galaxy	1%	11.16 GVis	0.012 GB/s	0.03 PB/Month
KSG3 Driving Line Band 4 e.g. Spiderweb galaxy	1%	5.58 GVis	0.006 GB/s	0.02 PB/Month
KSG3 Driving Line Band 6 e.g. Virgo Cluster	7%	3232.05 GVis	3.591 GB/s	9.44 PB/Month
KSG3 Driving Line Band 1 e.g. M81 Group	11%	149.48 GVis	0.166 GB/s	0.44 PB/Month
KSG3 Driving Line Band 1 e.g. M81 Group	13%	4.66 GVis	0.005 GB/s	0.01 PB/Month
KSG5 Driving Cont. Band 1 OTF Find LIGO event	7%	7347.53 GVis	8.164 GB/s	21.47 PB/Month
KSG5 Driving Cont. Band 4 OTF Find LISA event	7%	1090.82 GVis	1.212 GB/s	3.19 PB/Month
KSG5+4 Driving Cont. Band 2 OTF Find BHs + Possible Pulsars	4%	2034.17 GVis	2.260 GB/s	5.94 PB/Month
KSG5 Driving Cont. Band 3 Gw170817@200Mpc	24%	4.18 GVis	0.005 GB/s	0.01 PB/Month
Avg.:		**6898.09 GVis**	**7.665 GB/s**	**20.16 PB/Month**

High-Throughput Gridder