ngVLA Project Overview

Rob Selina - ngVLA Project Engineer

South America Astronomy Coordination Committee, 04/2020

A next generation VLA

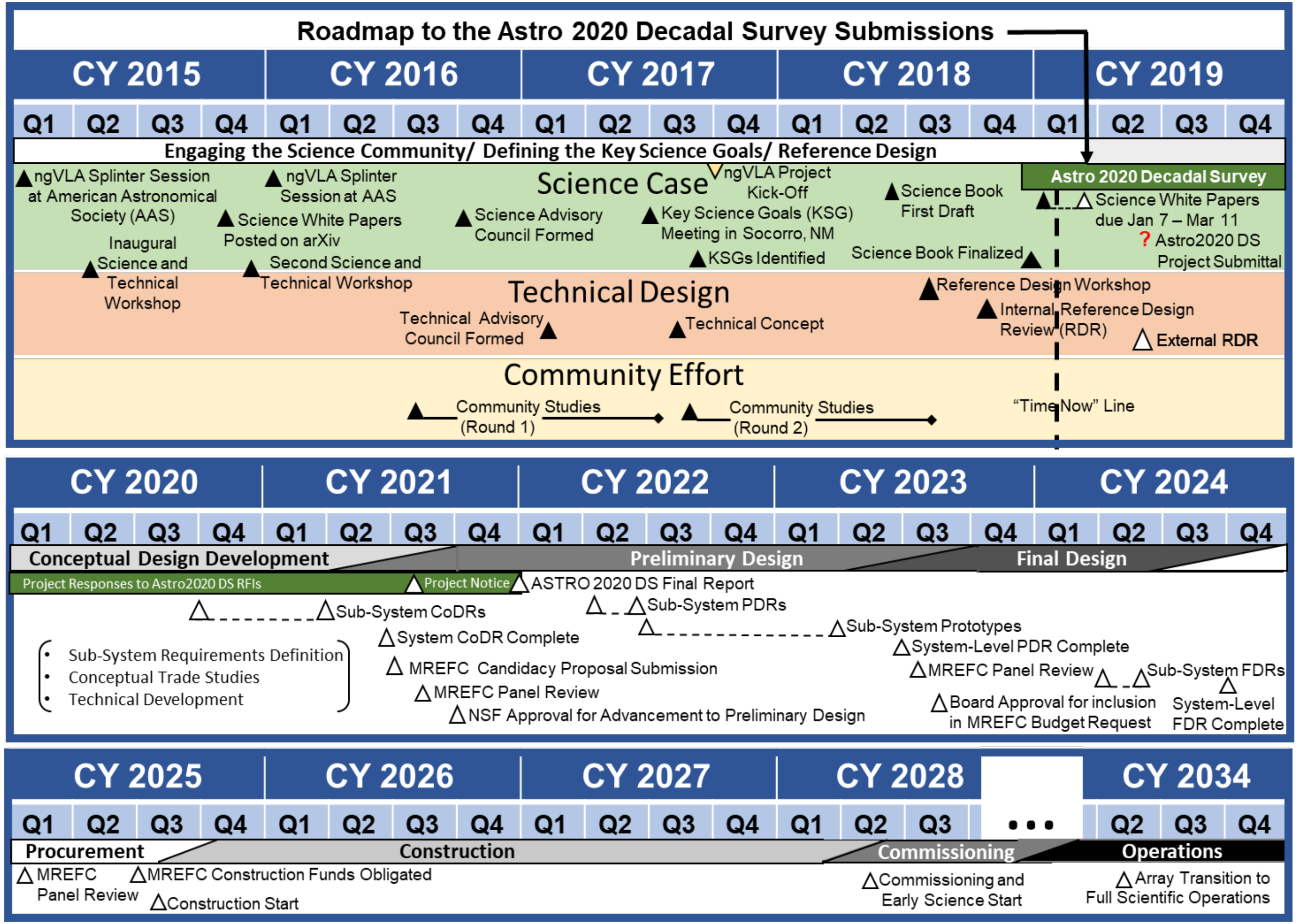
- Scientific Frontier: thermal imaging at milli-arcsecond resolution
- Goals
    - 10x effective collecting area of VLA: ~244x18m antennas
    - 10x better spatial resolution: up to ~1000km baselines
- Frequency range: 1.2-116GHz
- Locate in southwest US (AZ, NM, & TX) and MX, centered on present location of VLA
- Low technical risk
- NSF-Funded Development
- Under Evaluation by Astro2020 Decadal Survey

Next Generation Very Large Array (ngVLA) Project Timeline

As of 2/4/2019

NAS DS2020 Roadmap

NSF MREFC Roadmap

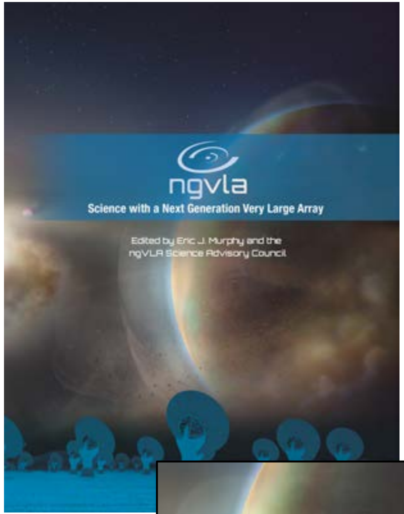


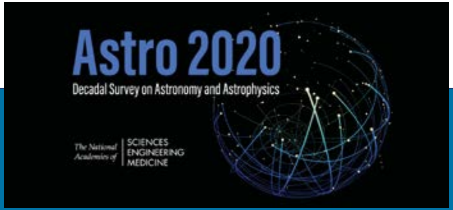
International Partnerships

- International involvement via SAC, TAC, Community Studies
  - Canada, Mexico, Japan, Germany, Netherlands, Taiwan
- Inaugural international development meeting, Socorro (May 2019)
  - Provided project overview; possible distribution of work packages
- ngVLA-SKA *Future Large Radio Telescope Alliance* meeting in Reykjavik, Iceland (Jun 2019)
  - Purpose: investigate process and possibility of a scientific alliance between SKA and ngVLA
- NAOJ-ngVLA workshop, Mitaka (Sep 2019)

Recent Highlights

- ngVLA Science Book published (Dec 2018)
- Facilitated community submission of ngVLA science white papers to Astro2020 Decadal Survey (Jan 2019)
- Submitted ngVLA facilities white paper to Astro2020 Decadal Survey (Jul 2019)
- ngVLA Reference Design Concept completed (Aug 2019)
    - https://ngvla.nrao.edu/page/refdesign



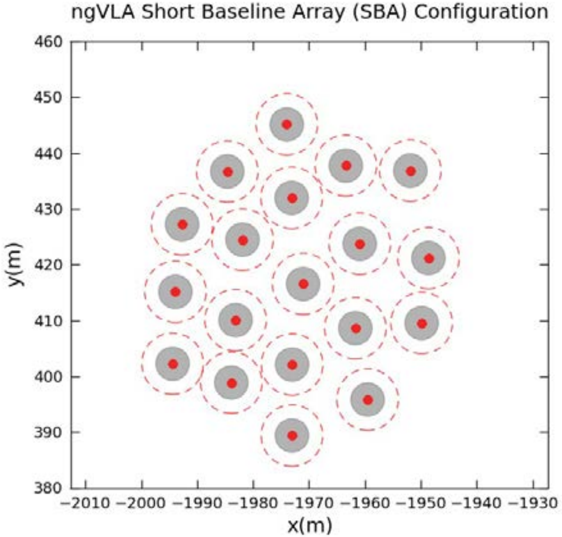


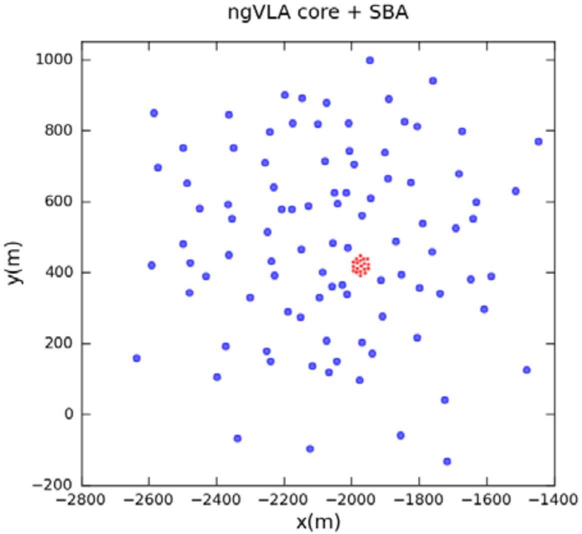
- **1.2 - 116 GHz** Frequency Coverage
- **Main Array**: 214 x 18m offset Gregorian Antennas
  - Fixed antenna locations across NM, TX, AZ, MX.
- **Short Baseline Array**: 19 x 6m offset Greg. Antenna
  - Use 4 x 18m in TP mode to fill in (*u, v*) hole
- **Long Baseline Array**: 30 x 18m antennas located across continent for baselines up to 8860km

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

Short Baseline Array (SBA)

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

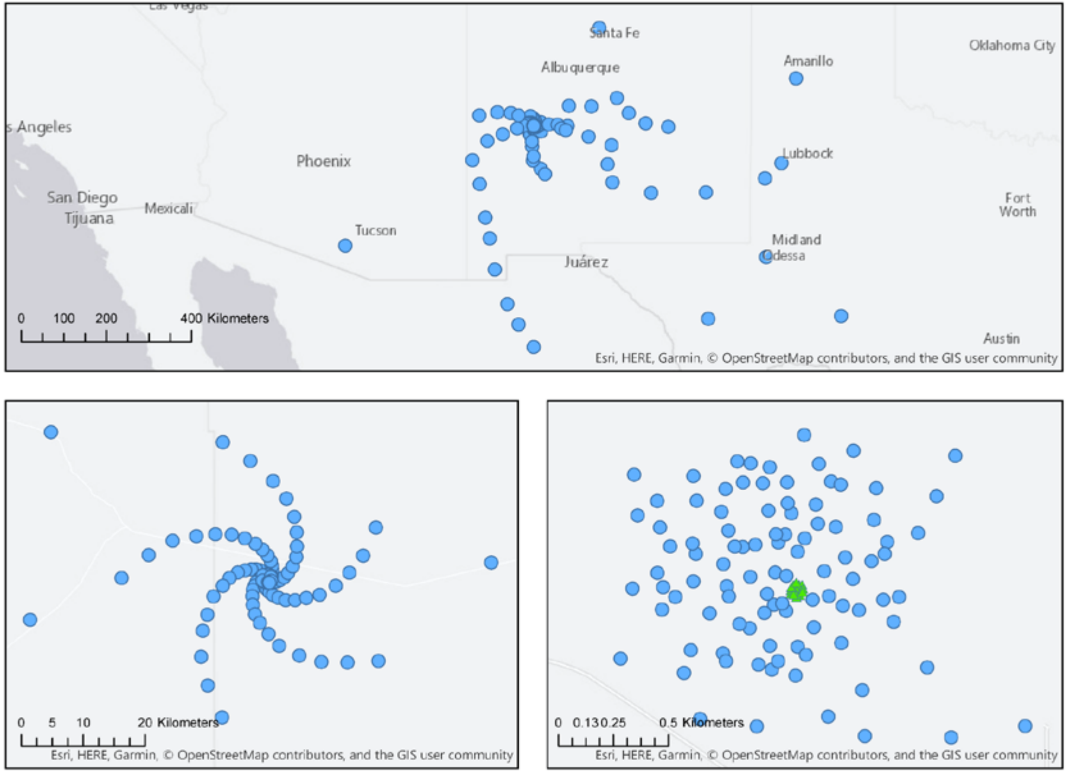




Main Array (MA) Configuration

- 214 x 18m Antennas

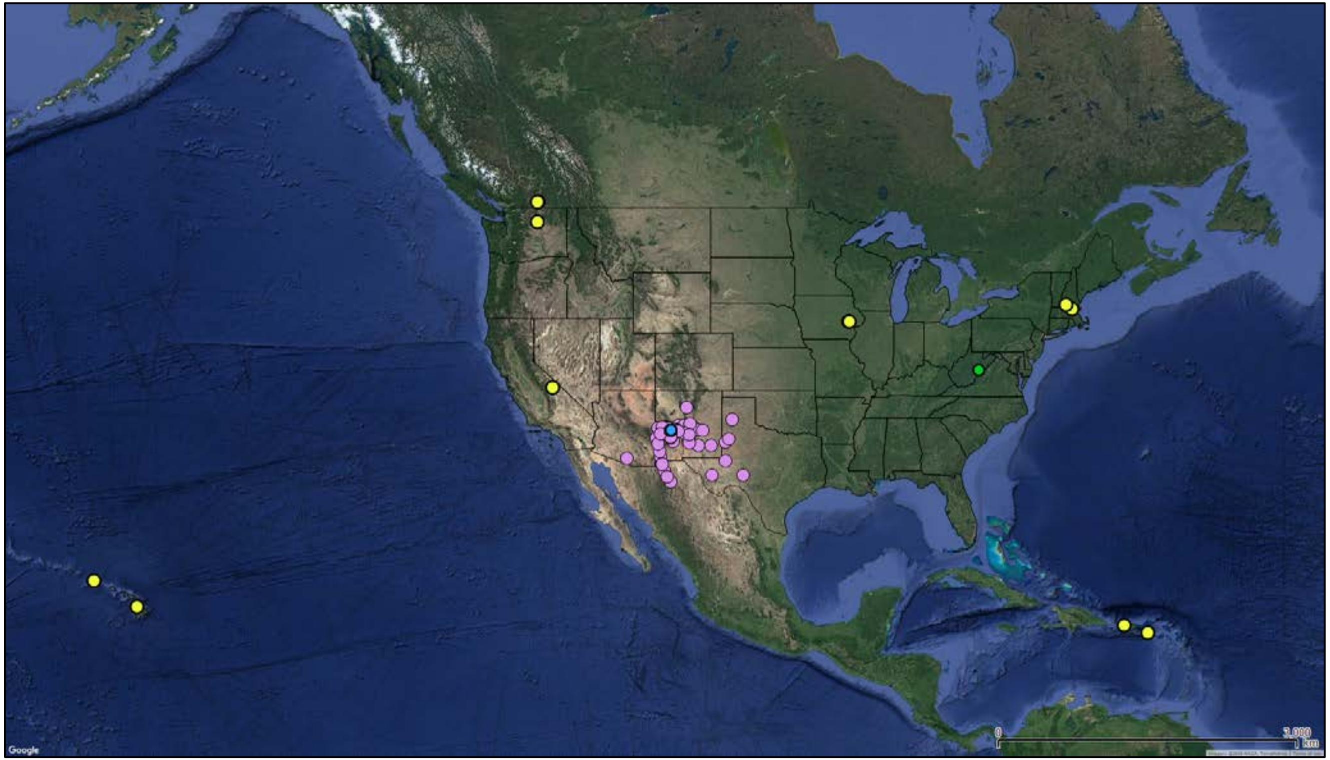
Radius	Collecting Area Fraction
0 km < R < 1.3 km	44%
1.3 km < R < 36 km	35%
36 km < R < 1000 km	21%



Long Baseline Array (LBA)

- 30 x 18m Antennas at 10 sites
- Balance between Astrometry & Imaging Use Cases

Qty	Location	*__Possible__* Site
3	Puerto Rico	Arecibo Site
3	St. Croix, US VA	VLBA Site
3	Kauai, HI	Kokee Park Geo. Obs.
3	Hawaii, HI	New Site (off MK)
2	Hancock, NH	VLBA Site
3	Westford, MA	Haystack
2	Brewster, WA	VLBA Site
3	Penticton, BC, CA	DRAO
4	North Liberty, IA	VLBA site
4	Owens Valley, CA	OVRO



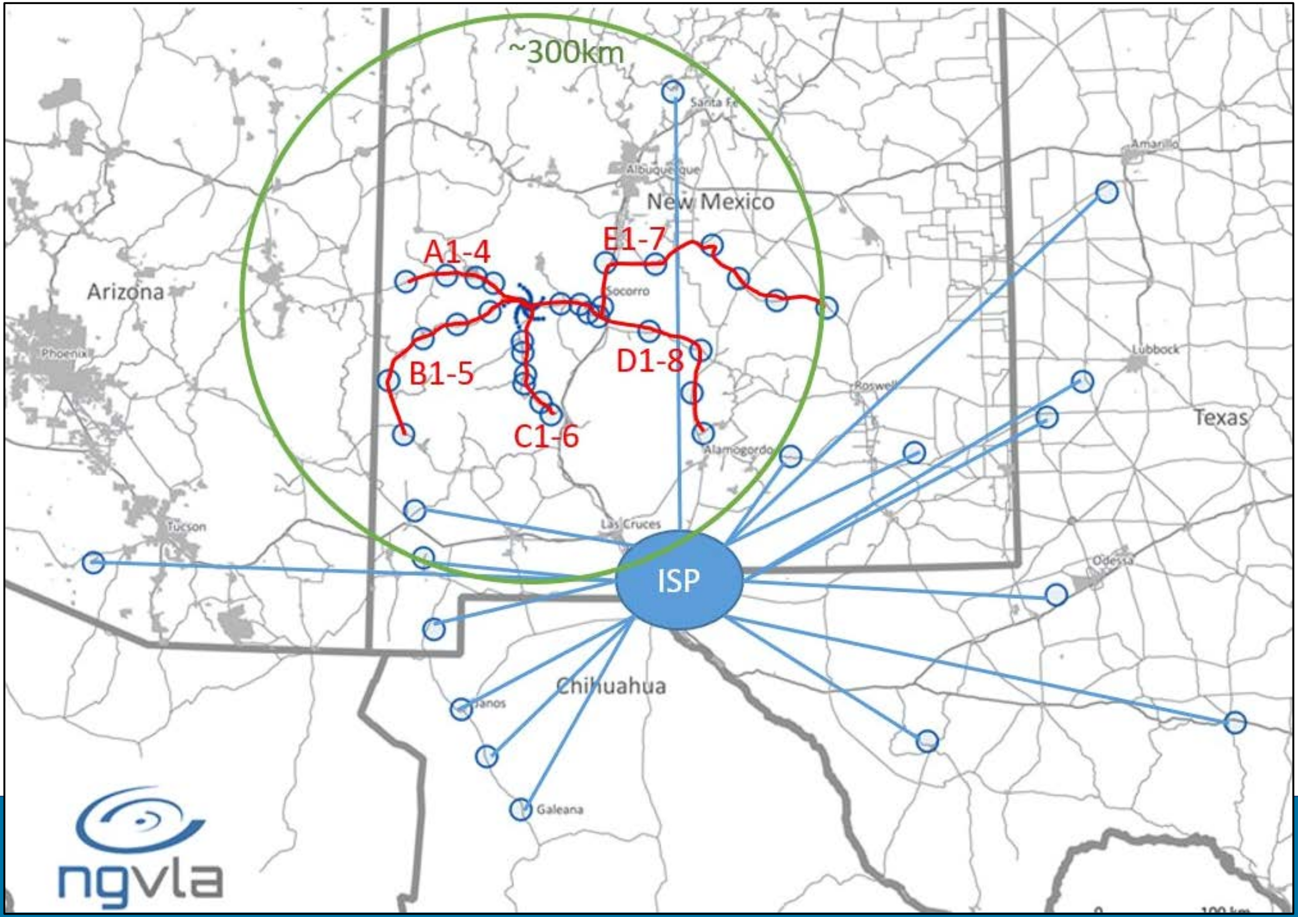
Antenna Data Rates

- Real-time correlation of all 244 array elements.
- Up to 20 GHz of instantaneous bandwidth per polarization.
- 8-bit digitization below 50 GHz.
- 4-bit digitization for 70-116 GHz band.
- Requantized and formatted for data transmission on packet-switched networks

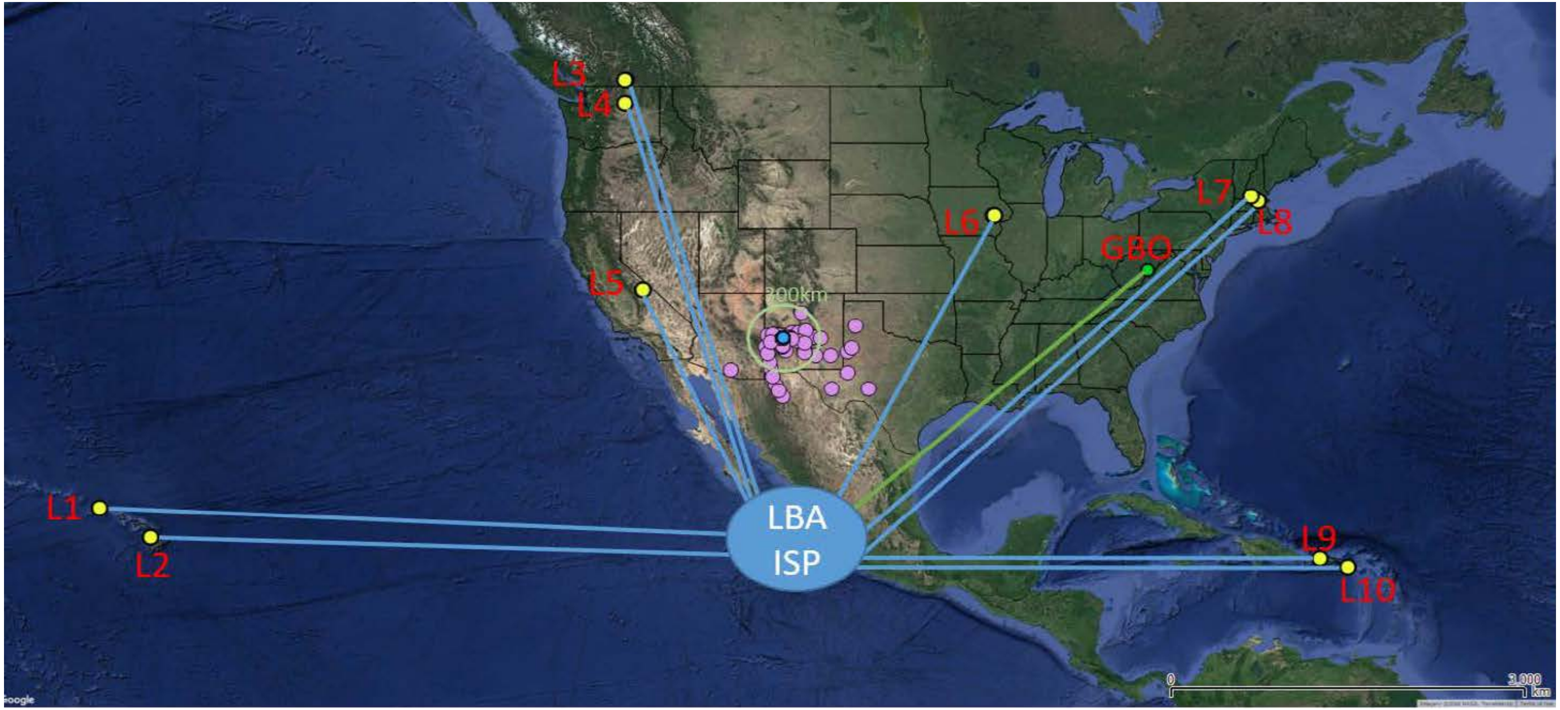
- 320 Gbps per antenna, over 4x100 Gbps links.
- ~3 antenna LBA sites = ~1 Tbps link

Main Array Fiber Optic Network

- Dedicated point-to-point fiber links for ~196 antennas in NM within ~300 km radius of core.
- ISP connected elements beyond inner stations.
- ISP connections to LBA sites.
- Leased fiber vs Leased Bandwidth (TBD)



VLB Fiber Optic Network



Facility Integration

- VLBI Recording Capabilities:
  - 3 beams, VDIF, Mark-X recorder standard
- eVLBI Integration:
  - ~260 element correlator
  - Built-in data buffers and packet re-ordering for packet switched network interfaces.
  - Real time links to GBT? LMT? ALMA? Others?

Data Processing

- **Post Processing**: storing the raw visibilities will be possible.
  - Data processing is post-facto, with system sized for average throughput.
  - Data Rates:
    - Average – 8 GB/s.
    - Peak - 128 GB/s.
- **Computing:** Challenging, but feasible with current technology.
  - Sized by time resolution, spectral resolution, and multi-faceting in imaging.
  - ~60 PFLOPS/s (inc. efficiency factors) matches average data throughput.

Serving Data to Users

- “Science Ready Data Products” Operations Model
- Process-in-place for data to most PIs.
- Data products requested in proposal; Pipeline interaction possible.
- Low-level data products (visibilities, flagging tables)
- High-level data products for Standard Observing Modes (e..g, calibrated image cubes)
- Archive reprocessing interface for users.
- Data Reduction S/W; Data Analysis S/W

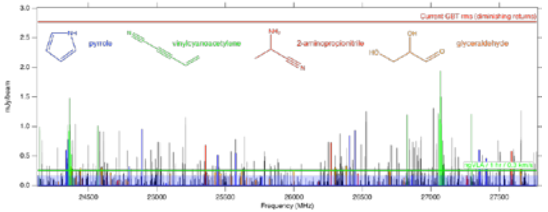
ngvla

Next Generation Very Large Array

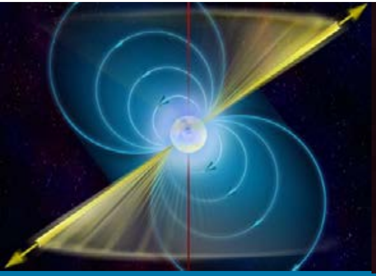
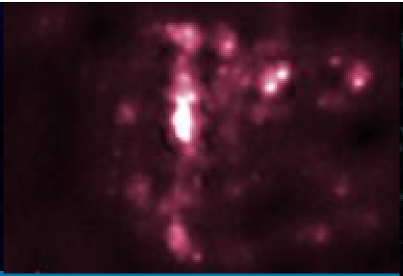
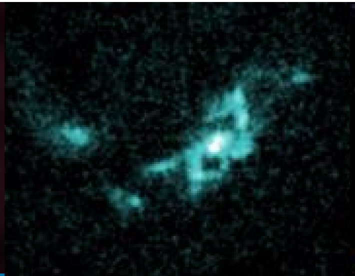
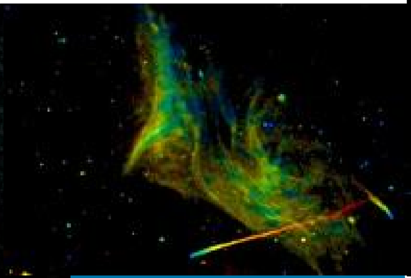
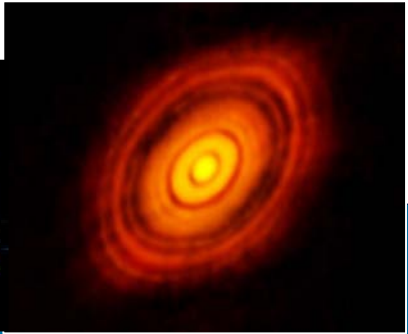
Summary

- ngVLA is being designed to tap into the astronomy community's intellectual curiosity and to enable a broad range of scientific discovery
- Key Science Goals, science use cases, and Science Book are complete
- The ngVLA Reference Design, a credibly-costed and low-technical risk concept, is complete and ready for Astro2020 Decadal Survey.
- System-level design (requirements, architecture) will be baselined in 2020 to enable sub-system conceptual design down-selects.
- Major Challenges: No major technological blockers. Challenges are in cost-performance optimizations, manufacturability and reliability.

Key Science Goals



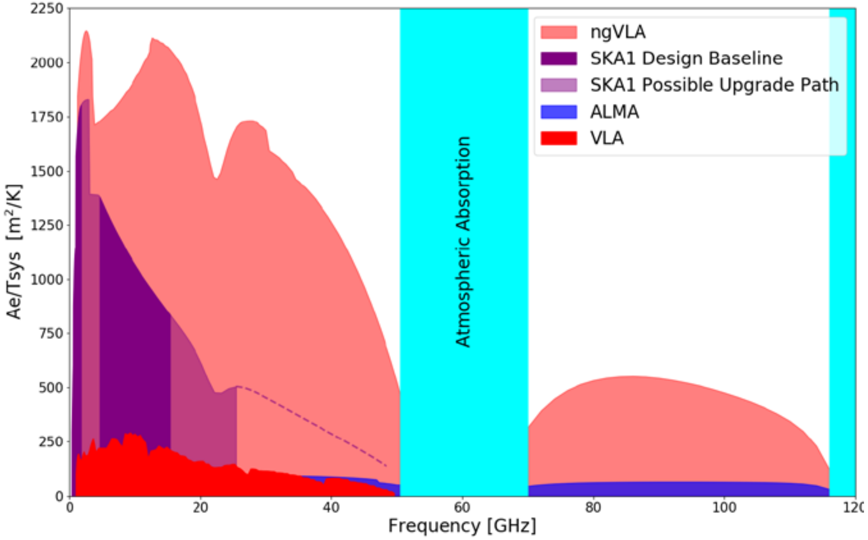
- Unveiling the Formation of Solar System Analogues
- Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry
- Using Galactic Center Pulsars as Fundamental Tests of Gravity
- Understanding the Formation and Evolution of Stellar and Supermassive BH's in the Era of Multi-Messenger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

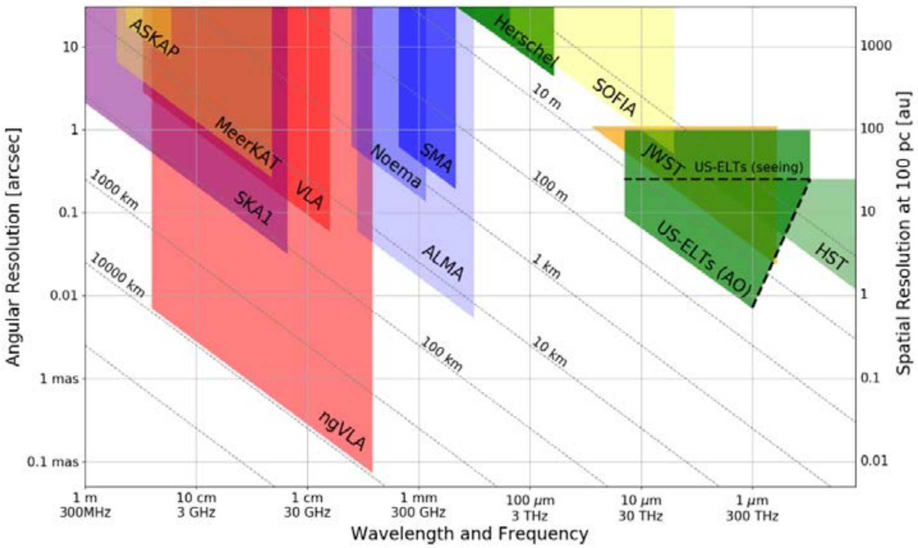
Community Engagement

- Science meetings sponsored
  - *Developing the ngVLA Science Program*, Socorro, NM (Jun 2017)
  - *The VLA Today and Tomorrow: First Molecules to Life on Exoplanets*, National Harbor, MD (Jan 2018)
  - *Astrophysical Frontiers in the Next Decade*, Portland, OR (Jun 2018)
  - *Theoretical Advances Guided by RMS Arrays*, Seattle, WA (Jan 2019)
  - *Radio/Millimeter Astrophysical Frontiers in the Next Decade*, Charlottesville, VA (Jun 2019)

Performance Comparison



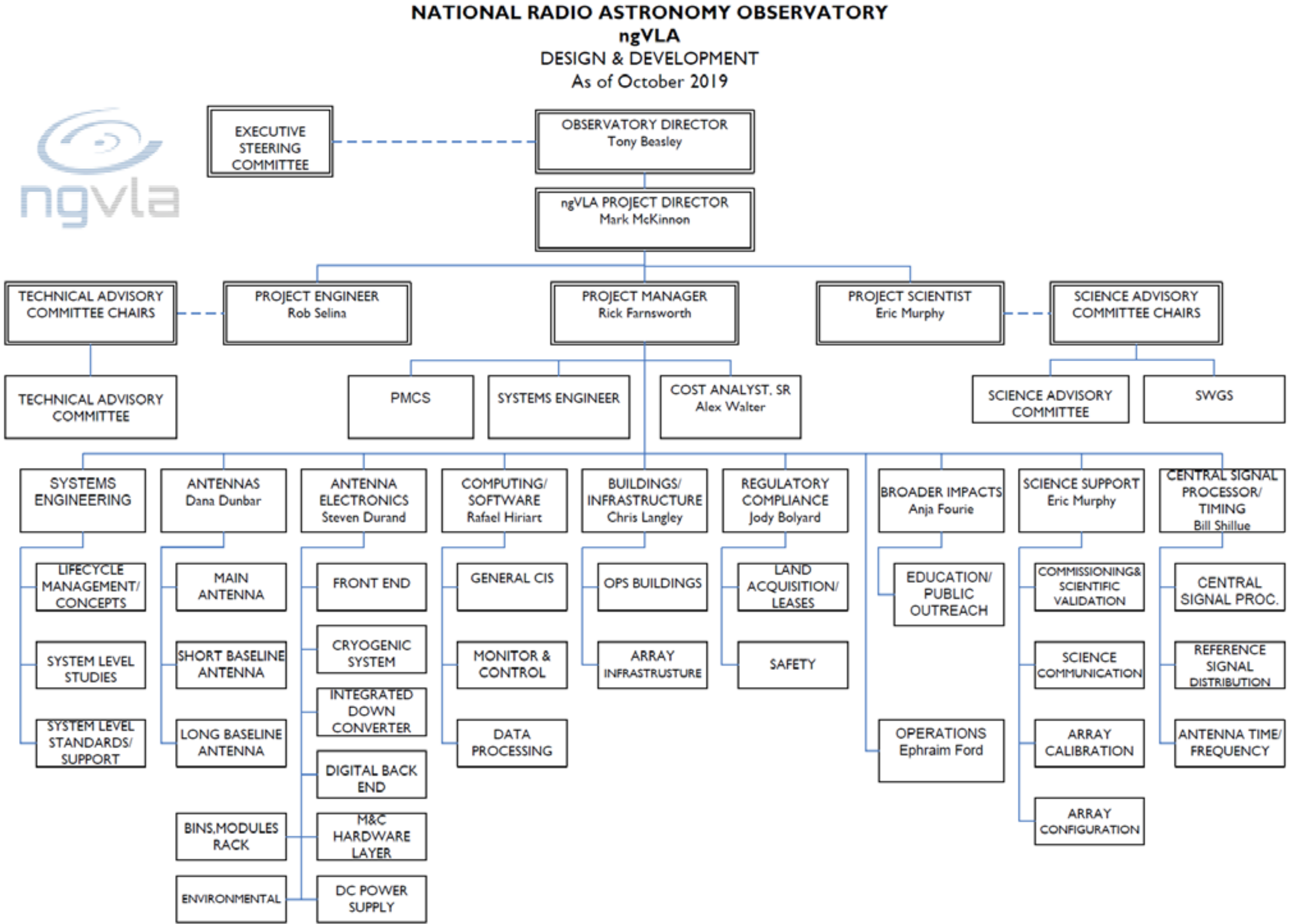
Sensitivity



Angular resolution

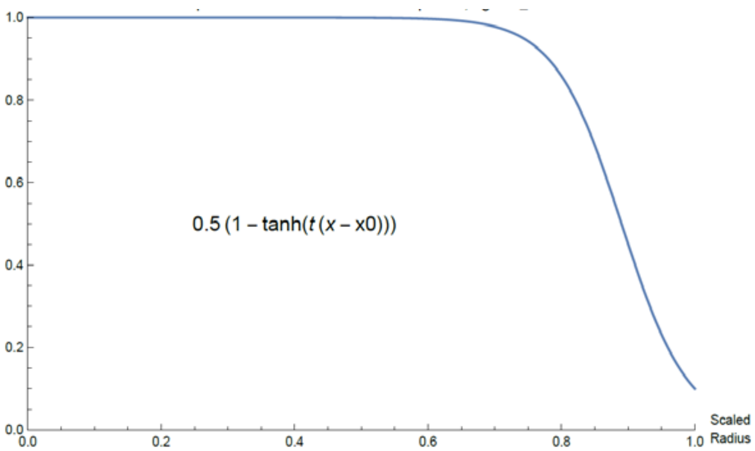
Project Organization

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

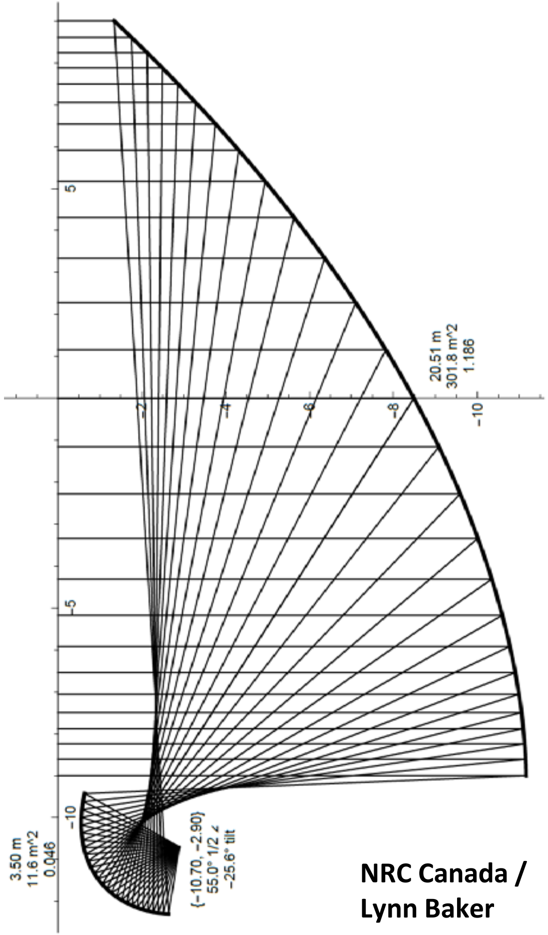


18m Antenna Optics

- **Offset Gregorian**: Wide subtended angle of the subreflector for small feeds. Likely lowest cost for required A/T. (Ant. Memo #1)
- **18m Aperture**: Based on cost and performance modeling (Ant. Memo #2)
- **Shaped:** Aperture efficiency optimized for single pixel feeds.



- **3.5m Subreflector**
- **55° Half Angle**
- **95% Illum. Eff.**
- **-16dB Edge Taper**
- **-19dB First Side Lobe**
- **-27dB Second Side Lobe**

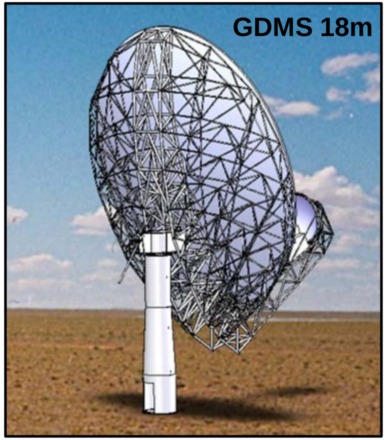


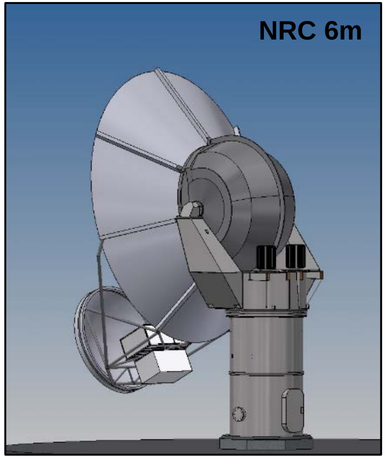
NRC Canada / Lynn Baker

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.

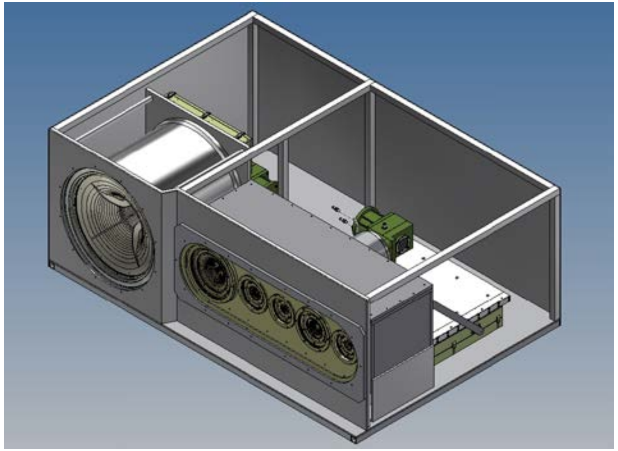
Key Specifications	
18m Aperture	Offset Gregorian
Shaped Optics	4° Slew & Settle in 10 sec
Surface: 160 μm rms	Referenced Pointing: 3” rms

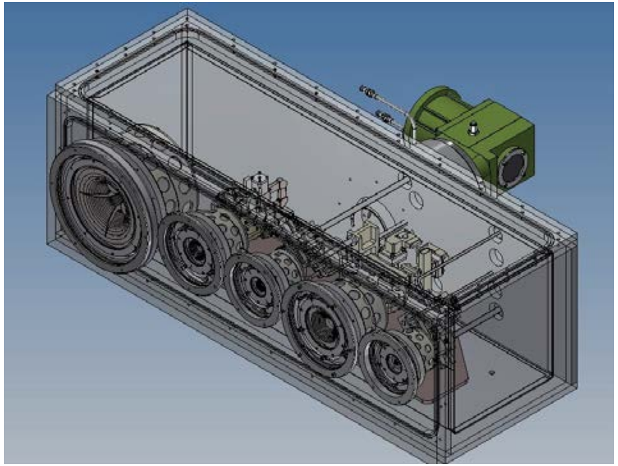




Front End Concept

- 6 Bands in 2 Cryogenic Dewars
- 1.2-3.5 GHz and 3.5-12.3 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 using modular devices @ FE.
- Two-stage Gifford-McMahon cryogenic system with variable-speed cryocoolers and compressors for reference design.

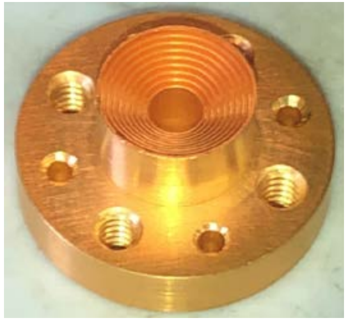




ASU/Caltech Band 1 Prototype Cryostat

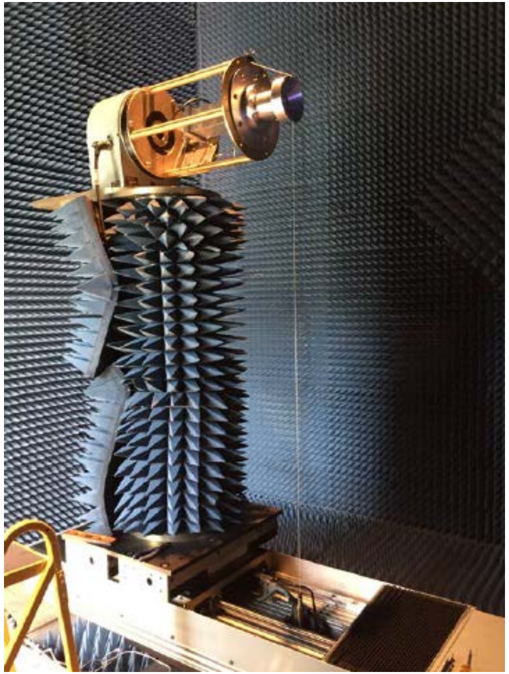
(Credit: Sander Weinreb, Caltech & Hamdi Mani, ASU)

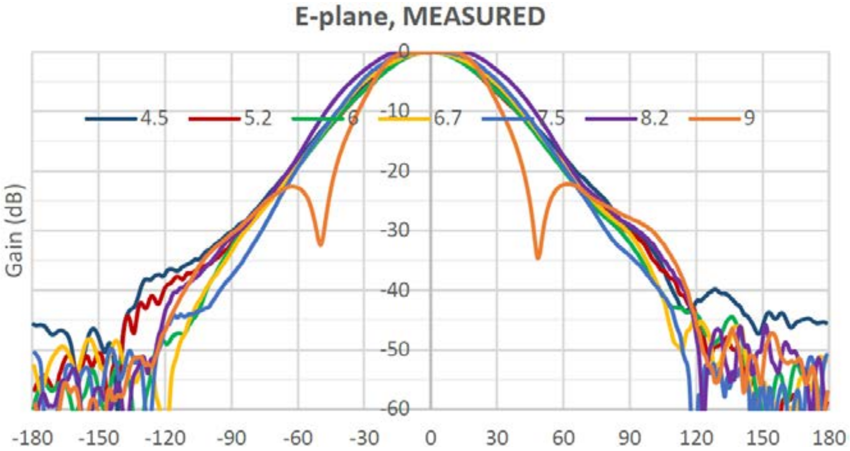
Feed Development

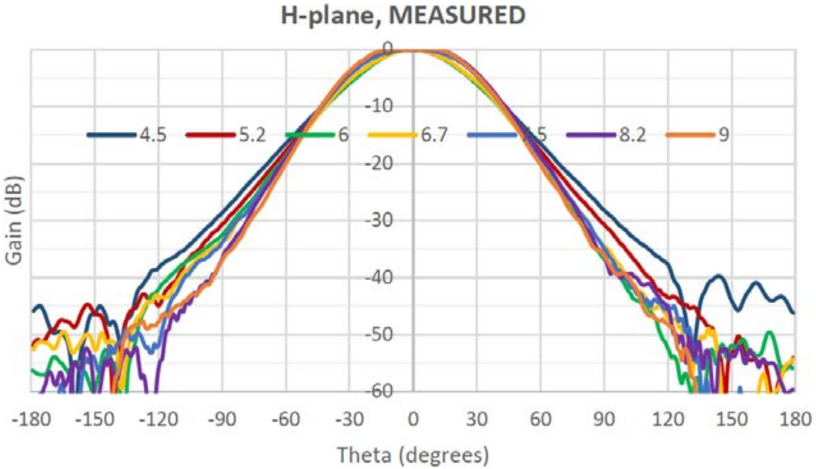


(courtesy S. Srikanth, NRAO CDL)

(courtesy R. Lehmensiek, EMSS)







Orthomode Transducer (OMT)

- Developed by NAOJ for ALMA Band 2+3 (67 – 116 GHz)
- Modified Boifot double-ridged waveguide junction
- Highly compact
- Very low loss, excellent port match
- Readily manufactured with conventional CNC mills
- Directly applicable on Band 6
- Design will scale for Bands 3 – 5

(courtesy Alvaro Gonzalez and Shinichiro Asayama, NAOJ)

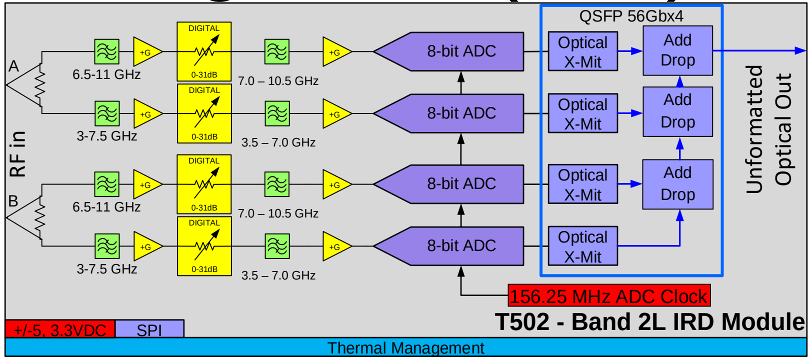
Compressor Development by Sumitomo

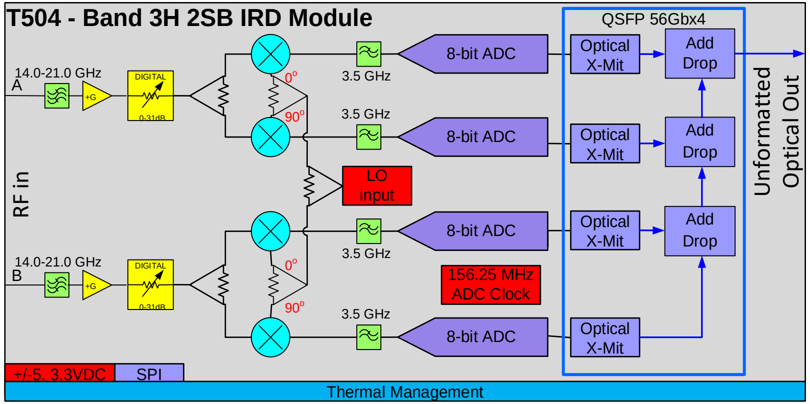
FA40 Integration into
FA70 outdoor enclosure

- **Phase 1:**
  - Build FA40 prototype with VFD (completed)
  - Measure the performance: flow vs power (completed)
  - Measure RFI and design shielded enclosure for electronics (pending)
- **Phase 2**:
  - Integrate FA40 capsule into a FA70 outdoor enclosure
  - Relocate control/power electronics to an outdoor-rated RFI enclosure (ngVLA prototype)

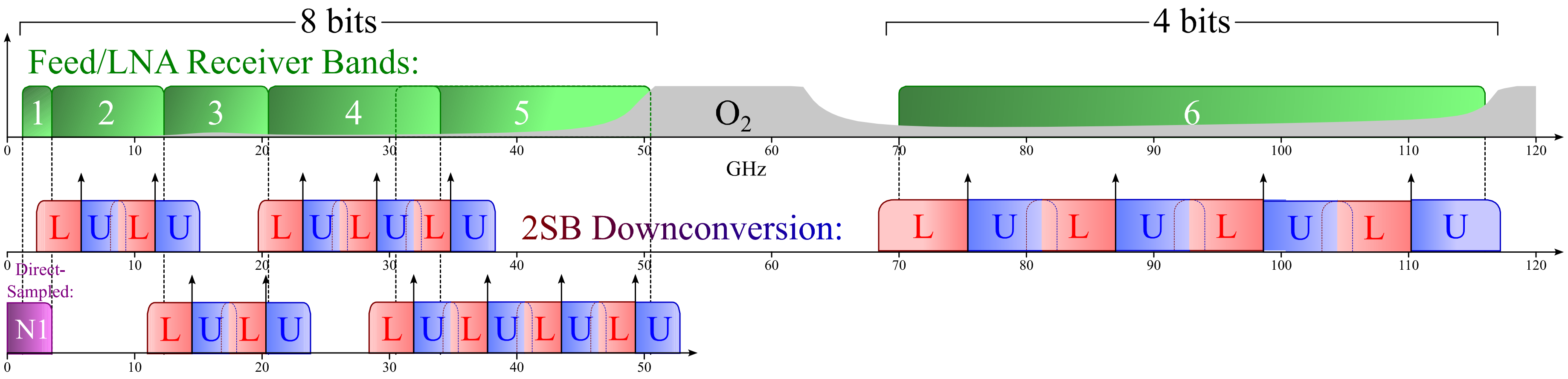
Integrated Receiver Digitizers (IRD)

- Small integrated modules mounted at secondary focus near the front ends
- Direct sampling for 1.2 – 3.5 GHz
- Downconverted sideband separating sampling for 3.5 – 116 GHz
- Custom digitizer IC in development:
  - 8 bit, 7 Gsps for bands 1-5
  - 4 bit, 14 Gsps for band 6
- Output on multiple 56 Gbps unformatted optical data streams





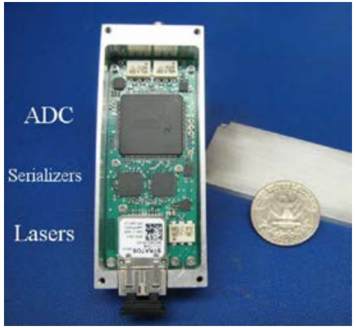
Integrated Receiver Digitizers (IRD)

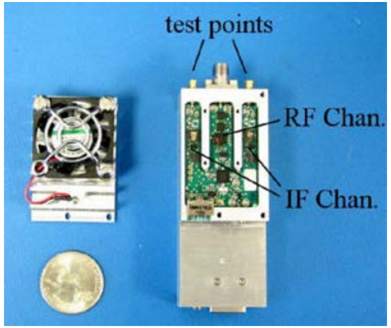


- Side-Band Separating Sampling for Bands 2-6.
- All Local Oscillator (LO) Signals are harmonics of **2.9 GHz**.
- **3.5 GHz** Sampler Clocks provide overlapping side-bands.

Antenna Electronics Development

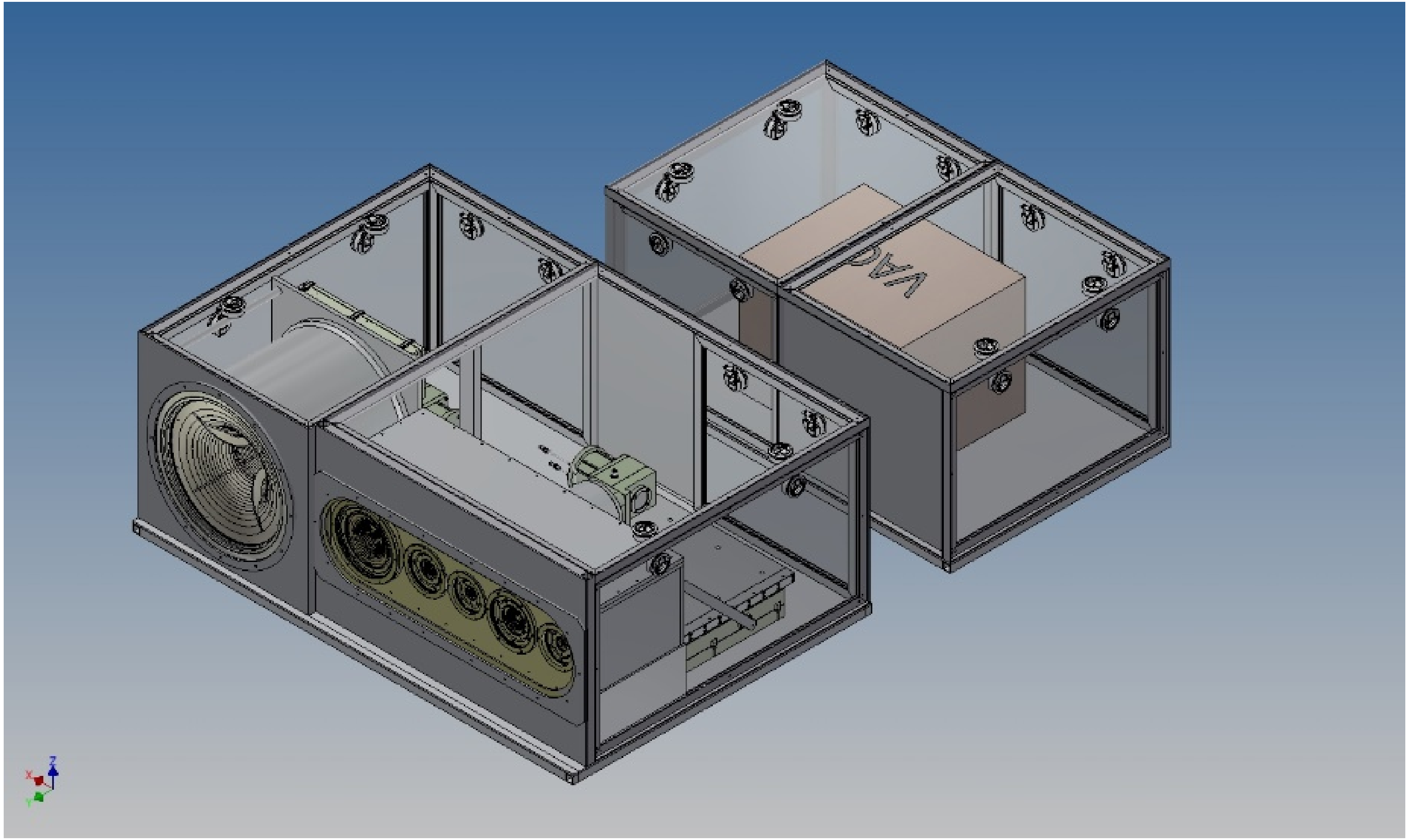
- Digitizer-Serializer ASIC Prototype.
- Custom MMIC chips for Band 5, 6 (Post Amps).
- IRD Deserialization Code.
- WVR Test Platform Using Integrated MMIC Modules.





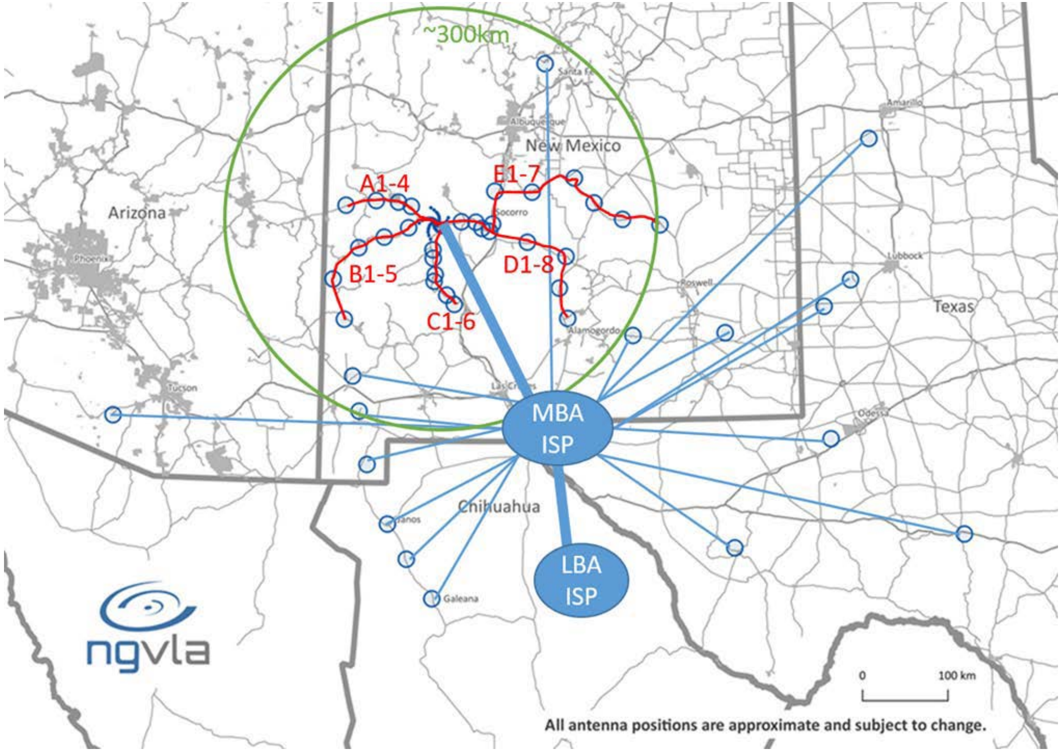
FE:

1.5 m
x
1.0 m
x
0.6 m



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-Baseline Antennas + LBA:
    - Local clocks and LO generation.
    - Fallback: Local primary references (e.g., Active Hydrogen Maser & GPS)

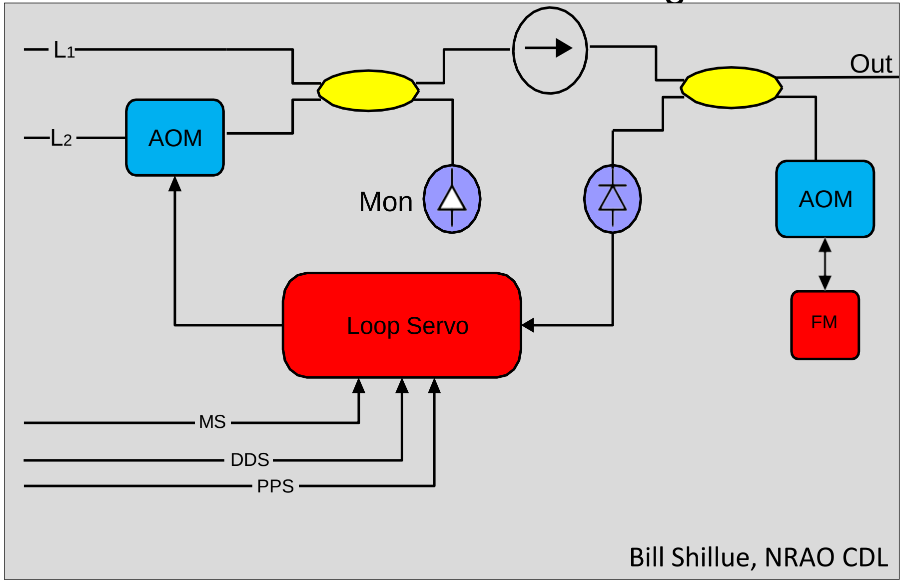


Frequency Reference Distribution

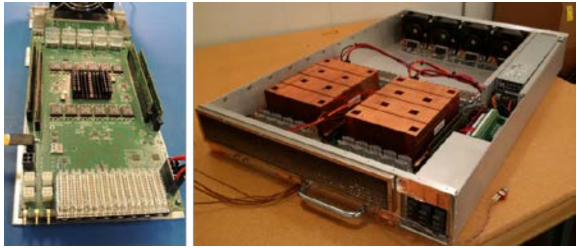
- Based on SKA1-MID Implementation, uses image reject receiver principle first developed by [Hitoshi Kiuchi, 2011]
  - Dual optical carrier transmission of reference & timing to antennas
    - L_1: Laser source
    - L_2: L_1 offset by 5.8 GHz + DDS
    - DDS offset is per antenna
  - MS: microwave shift frequency = 5.8 GHz (RF)
  - 1 PPS embedded timing signal
  - Provides for round trip phase stabilization

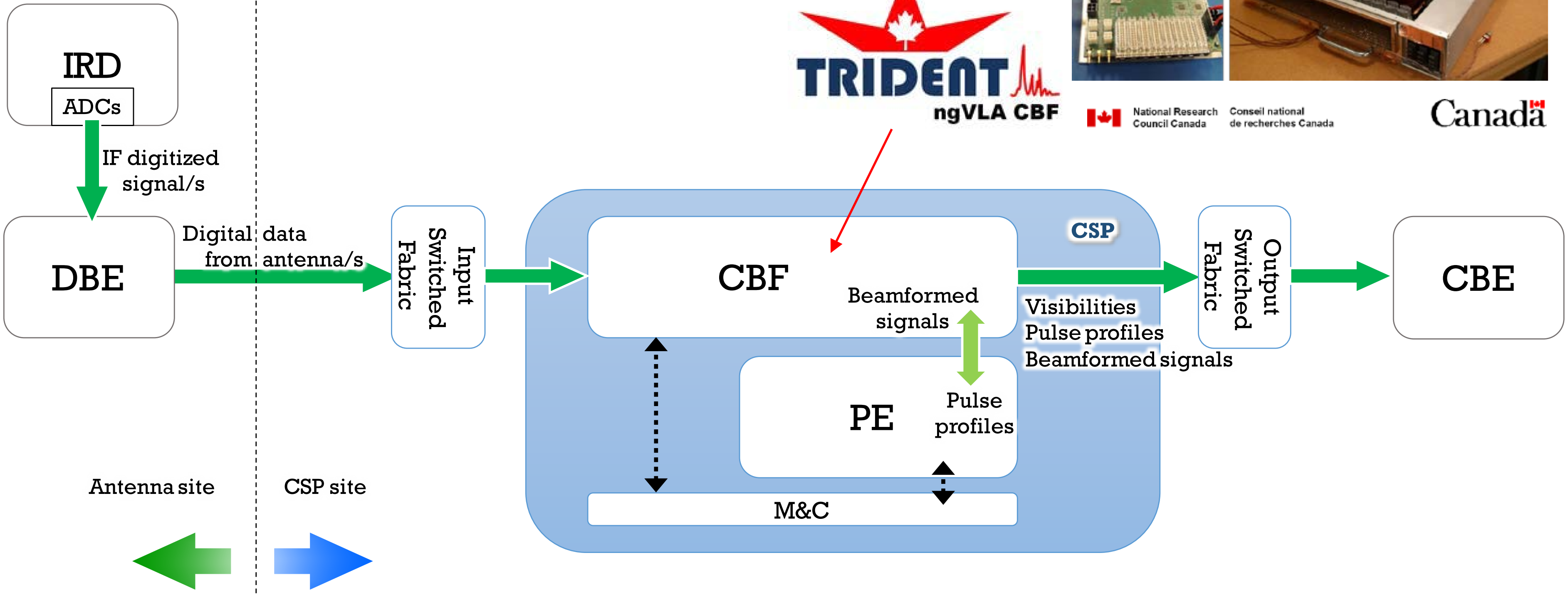
[Hitoshi Kiuchi, 2011] "Optical transmission signal phase compensation method using an Image Rejection Mixer," IEEE Photonics Journal, Vol.3, No.1, pp.89-99, 2011.

Transmitter module design



Central Signal Processor



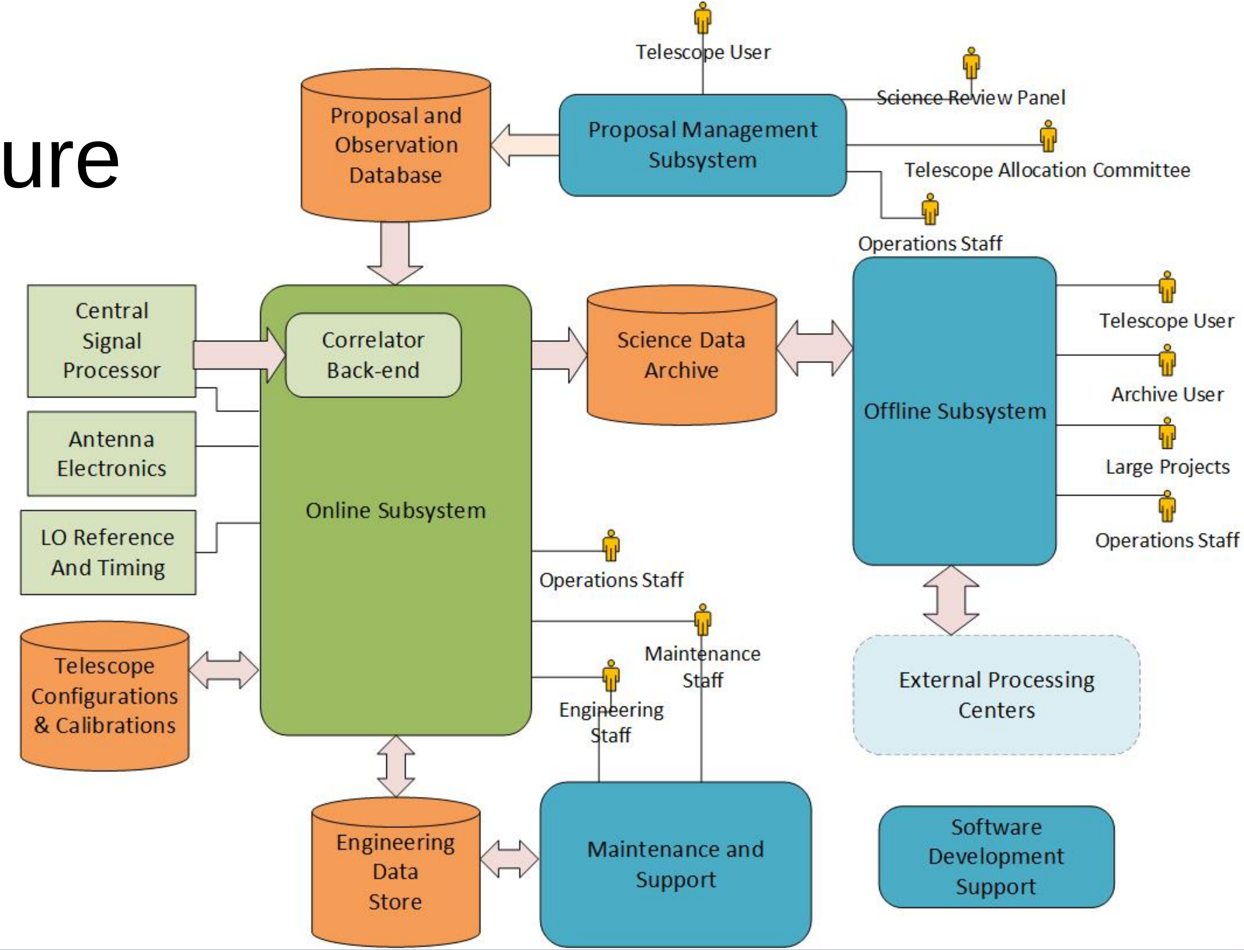


Data Processing

- **Post Processing**: storing the raw visibilities will be possible.
  - Data processing is post-facto, with system sized for average throughput.
  - Data Rates
    - Average – 8 GB/s.
    - Peak - 128 GB/s.
  - Based on CASA.
- **Computing:** Challenging, but feasible with current technology.
  - Sized by time resolution, spectral resolution, and multi-faceting in imaging.
  - ~60 PFLOPS/s (inc. efficiency factors) matches average data throughput.

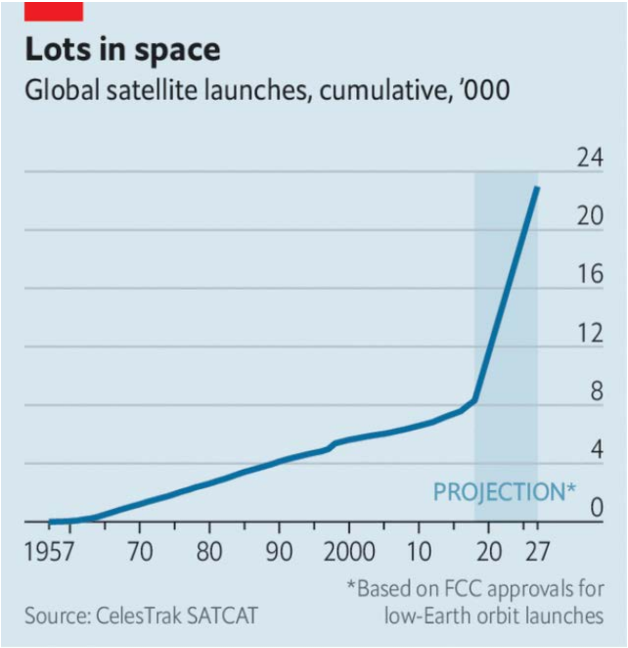
S/W Architecture

- First decomposition:
  - 5 subsystems
  - 4 datastores
- Integrates with external on-going projects: TTA, SRDP, ngCASA, HTC, etc.
- Proposal Mgt. and Offline subsystems expected to be substantially inherited (ngCASA based).



Technical Risks

- Moore's Law
  - Don't need transistor density to continue to increase, but do need Oper./$ trends to continue.
  - Parallelization efficiency is a concern.
- The new RFI environment
  - LEO satellite revolution will impact all ground based facilities.
- Cost vs. Risk Curve - Choices
  - E.g., integrated receiver ASIC, composite reflectors



The Economist

Summary

- The project has developed a coherent technical concept to achieve the identified science.
- The project and international partners are developing novel technologies to a suitable level of technical readiness prior to conceptual design down-selects.
- Technical risks are understood. Project should exploit technical opportunities to improve cost and/or technical performance.

ngvla

Next Generation Very Large Array

ngvla
Next Generation Very Large Array

RFI Mitigation:

- Scheduler
- RFI-DB
- DBE
- CBE
- Post Proc.

Voltage Streams (antenna based)

- Detect strong RFI in real time

- Best for local RFI

- Catch impulsive broad-band RFI before the FFT

Detection : Median / MAD / MoM / Kurtosis etc… w/wo FFT.

Action :
- Add to RFI monitoring database but don't edit data

- Remove/replace samples containing RFI (and adjust weight)

Correlation/ Detection (visibilties in the CBE)

- High time resolution (u-m sec)

- Intermittent RFI that benefits from some averaging

- RFI phase structure is preserved in visibilities

Detection :
- Matrix decomposition (PCA)
- Imaging (RealFast) / Peeling
- Any post-processing algo (if useful at this timescale)
(– RFI source location)

Action :
- Subtraction (subspace projection / PCA methods)

- Remove samples that go into the next integration step and adjust weight

Averaging for storage (post-processing)

- Time-persistent RFI that requires analysis along some other axes.

- Weak RFI that becomes visible only after averaging

Detection :
- Look at plots of data

- Use prior information (online flagcmds, database queries, tsys tables, cal solutions, etc)

- Autoflag on visibilities (rflag, tfcrop, uvbinflag)

Action :
- Remove from further processing (flagging).

NSF AUI NRAO

Operations Drivers

- **SRDP (Science Ready Data Products) Telescope**
  - Data must be processable with a standard pipeline.
  - Data calibration can/should drive the design.
  - Repeatability & stability in analog system, finite tuning choices.
  - Flexible sub-array management, but fixed sub-array definitions.
  - Service calibrations, impact on data model.

- **"Large N" Array & Life-cycle Cost**
  - Manufacturability & maintainability.
  - Automation of routine calibrations, data validations.
  - Expert system for maintenance prediction & issue resolution.
  - Reduced parts count, parts integration.
  - Power consumption.

Science Drivers

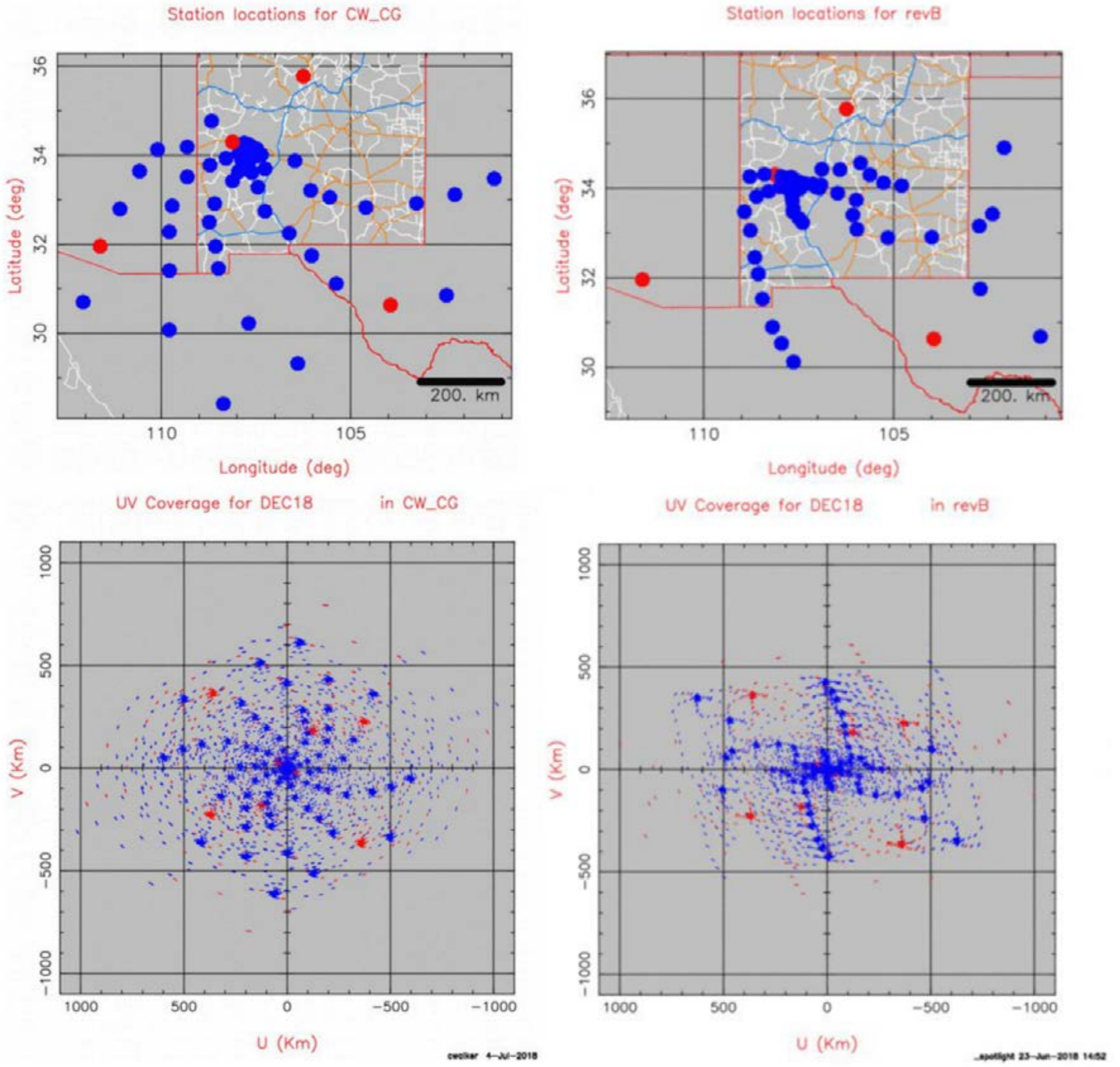
- **Frequency Coverage**: 1.2 to 116 GHz, both edges drive design.
- **Sensitivity**: Area, Tsys, bandwidth, deconvolution algorithms.
- **Resolution**: 400km+ minimum extent, 8000km+ for multi-messenger.
- **Image Fidelity:** Even sampling of (u, v)-plane from 10s of meters to 100s of km.
- **Dynamic range**: pointing, phase cal, electronic stability.
- **Large-N**: central archive and compute. High level data product delivery pipelines.

S/W and Computing Considerations

- **Code Development**: Approx. 2.6M new lines of code expected.
  - ALMA / VLA SLOC – 4.77M / 4.35M (Actual)
  - ngVLA SLOC – 5.75M (Projected).
  - Reuse estimated on each element of logical architecture.
  - 54% Average Reuse Projected – 2.63M new SLOC.
- **Risks**:
  - Depends upon continuation of the historic trend in cost of storage and compute capacity.
  - Uncertainty in time spent on cases (4 of 25 use cases) that need w-projection.
  - Uncertainty in algorithmic compute scaling for specific use cases.

	ALMA (SLOC)	EVLA (SLOC)	Estimation (MSLOC)	Estimated reuse (%)	Effort Size (MSLOC)
Online Subsystem					
Calibration	109,798	9,857	0.100	40%	0.060
Common	431,125	16,863			
Control	222,233	439,876			
Correlator	710,860	846,112			
Diagnostic and Engineering Tools	18,721	66,833	1.400	30%	0.980
Metadata Capturer	46,135	8,998	0.050	0%	0.050
Monitoring	15,517	24,365	0.050	50%	0.025
Observation	114,279	49,285	0.100	20%	0.080
Operation	88,177	52,934	0.200	0%	0.200
Quick-Look	31,547	-	0.050		0.050
Scheduling	37,085	3,127	0.050	30%	0.035
Telescope Configuration	85,584	2,019	0.100	0%	0.100
Offline Subsystem					
Archive & Observatory Interfaces	504,545	303,035	1.000	80%	0.200
Data Processing	2,078,245	2,078,245	2.000	70%	0.600
Proposal Management Subsystem					
Proposal Management	279,728	444,527	0.500	80%	0.100
Maintenance, Support & Development					
CMMS Integration	-	-	0.100	0%	0.100
Simulation	-	-	0.050	0%	0.050
Total	**4,773,579**	**4,346,076**	**5.750**	**54%**	**2.630**

Mid-Scale Baseline Optimization: the Walker Configuration



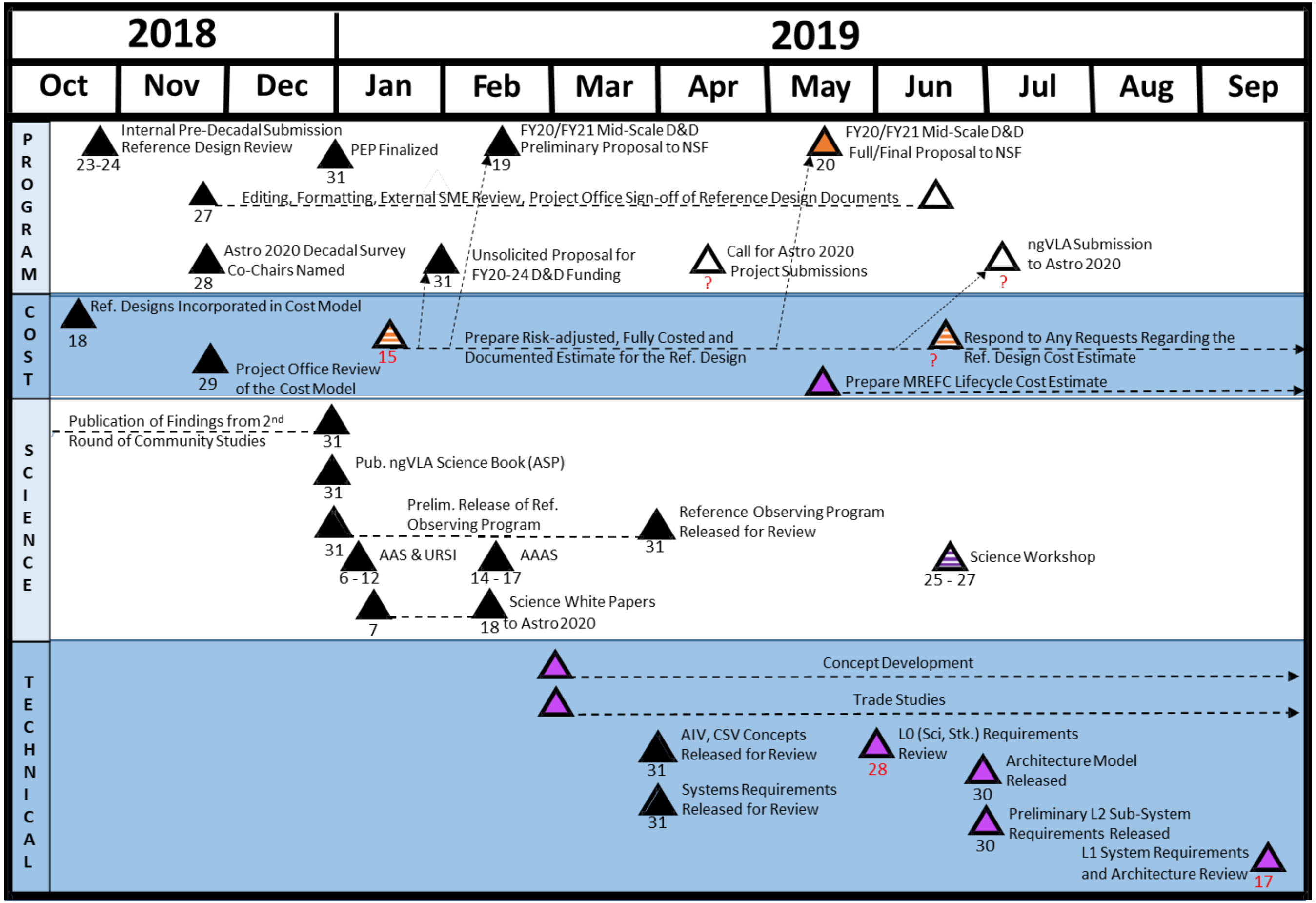
ngvla
Next Generation Very Large Array

= In Support of Astro 2020 Decadal Survey

= In Support of Concept Development/MREFC

= Solicitation of Project Funding

= Completed Effort *(as 4/20/2019)*

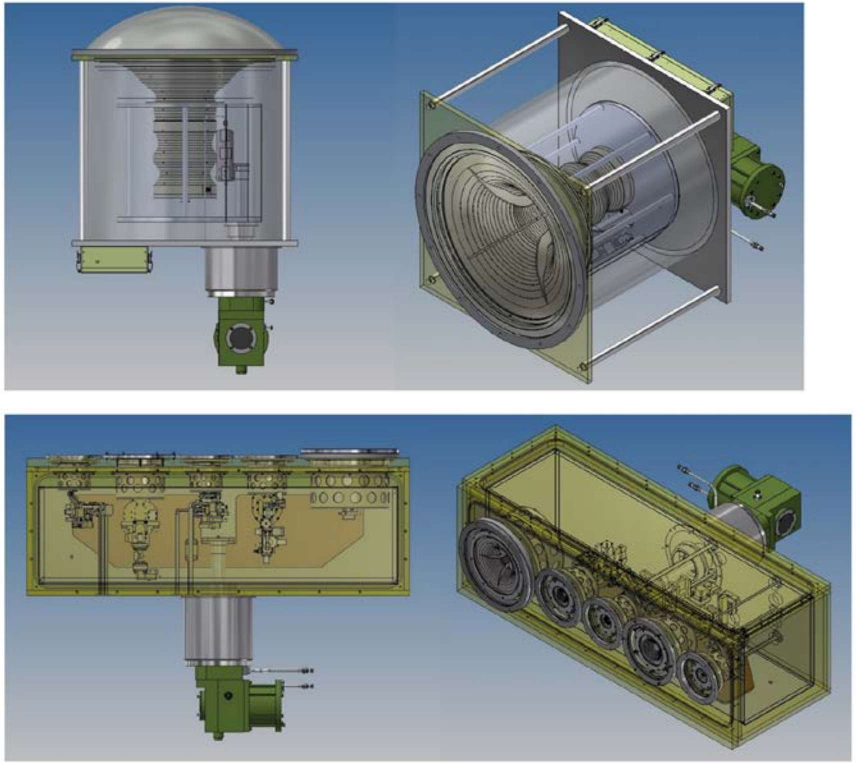


Electronics Design Philosophies

- Digitize as close as possible to the receiver.
  - Short, stable signal path. Minimize frequency conversion steps.
- Utilize highly integrated, manufacturable sub-assemblies.
  - Reduced parts count, mechanical connectors.
  - Limited number of Line Replaceable Units (LRUs).
- Emphasize low power, high reliability designs.
- Provide advanced remote diagnostic & fault prediction capability
  - Know which LRU has failed before visiting an antenna: swap & return.
  - Predict what's about to fail to better schedule maintenance visits.

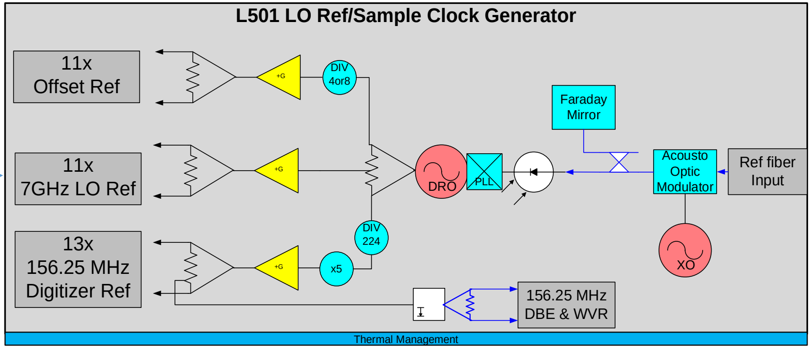
Front Ends / Dewars

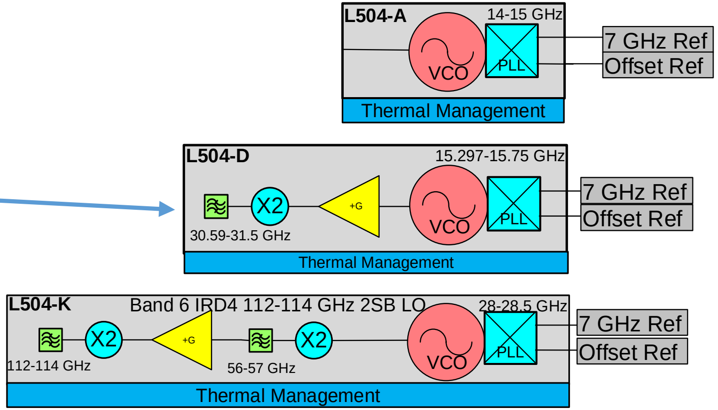
- 6 receivers in 2 dewars
  - Covering 1.2 – 116 GHz
  - Compact, cooled feeds
  - Linear polarization
  - Total mass ~120 Kg
  - RF output at sky frequency



Local Oscillator & Clocks

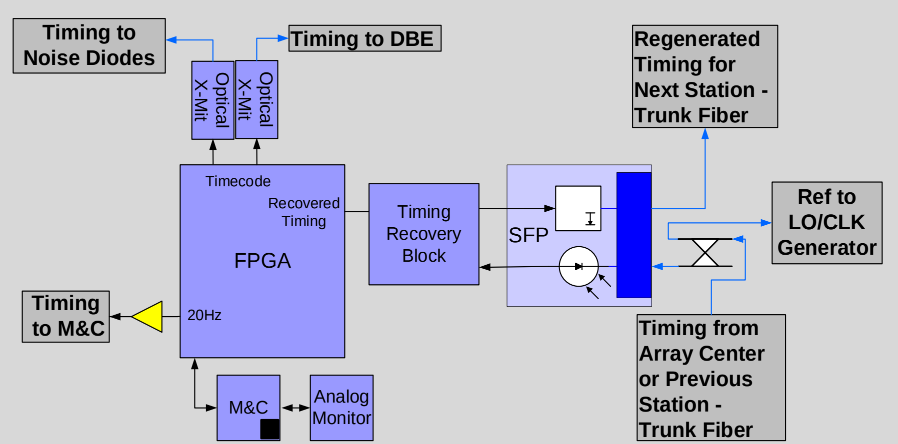
- **Secondary Focus Enclosure:**
  - Reference generator:
    - Recovered signal locks 7 GHz reference oscillator
    - An offset reference is generated by dividing reference by 2, 4, or 8
    - 156.25 MHz digitizer clock reference
  - LO Modules:
    - Co-located with each 2SB IRD
    - Use 7GHz & offset reference to generated coarse tunable LO’s for the mixers in the IRD modules





Reference & Timing Distribution

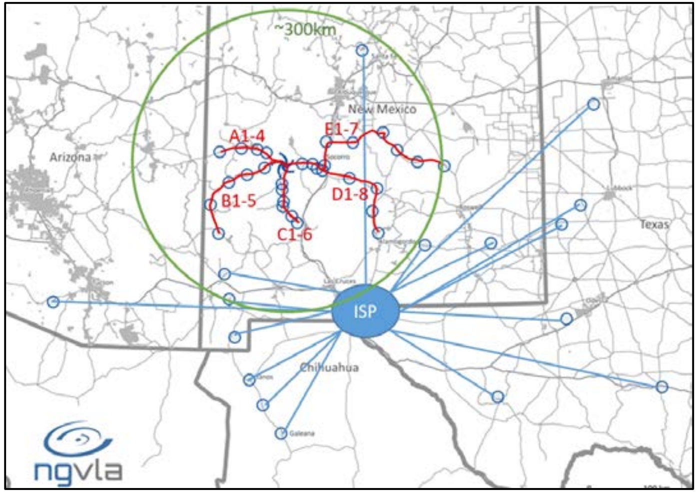
- Reference signals from array center are sent to two locations for timing recovery & local oscillator (LO) / sample clock generation
- **Pedestal rack:** PPS timing signal is recovered and used along with NTP in an FPGA to generate:
  - Timecode for Digital Back End (DBE)
  - Timing signal(s) for local M&C
  - Switching signal for front end noise diodes
  - Timing signal may also be regenerated for transmission to next station

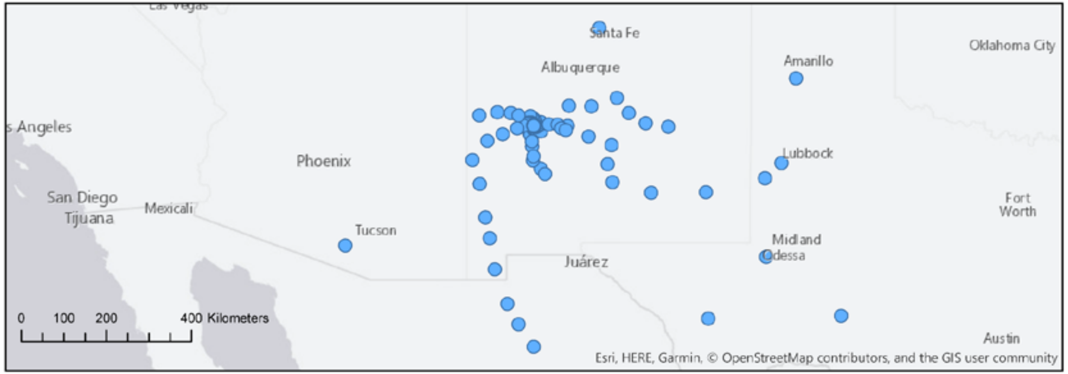


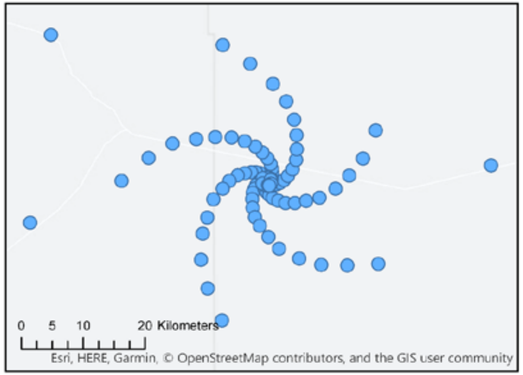
L503 - Reference Recv, Generator and Distribution

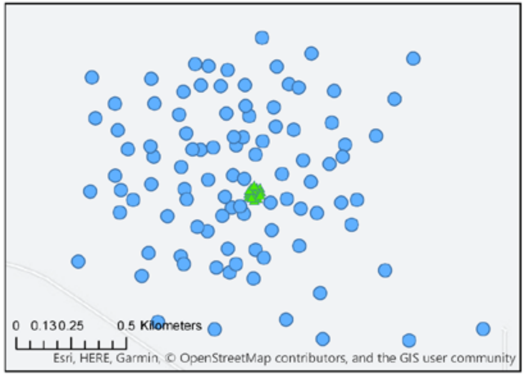
The Main Array (MA) Configuration

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



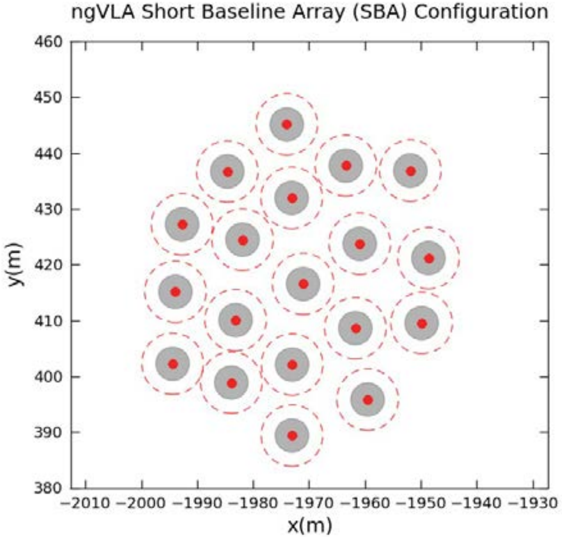


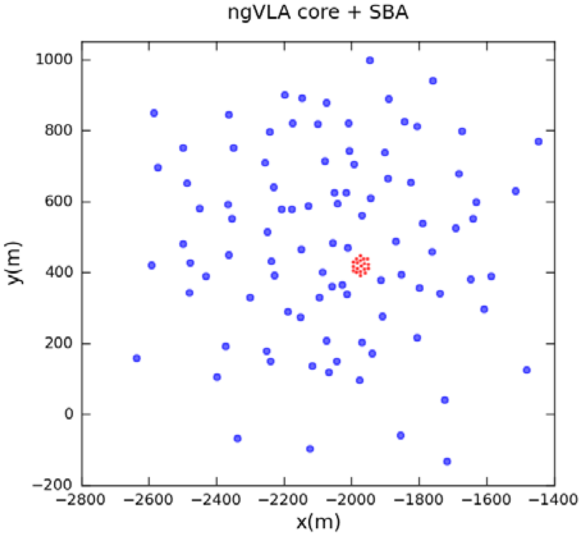




Short Baseline Array (SBA)

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

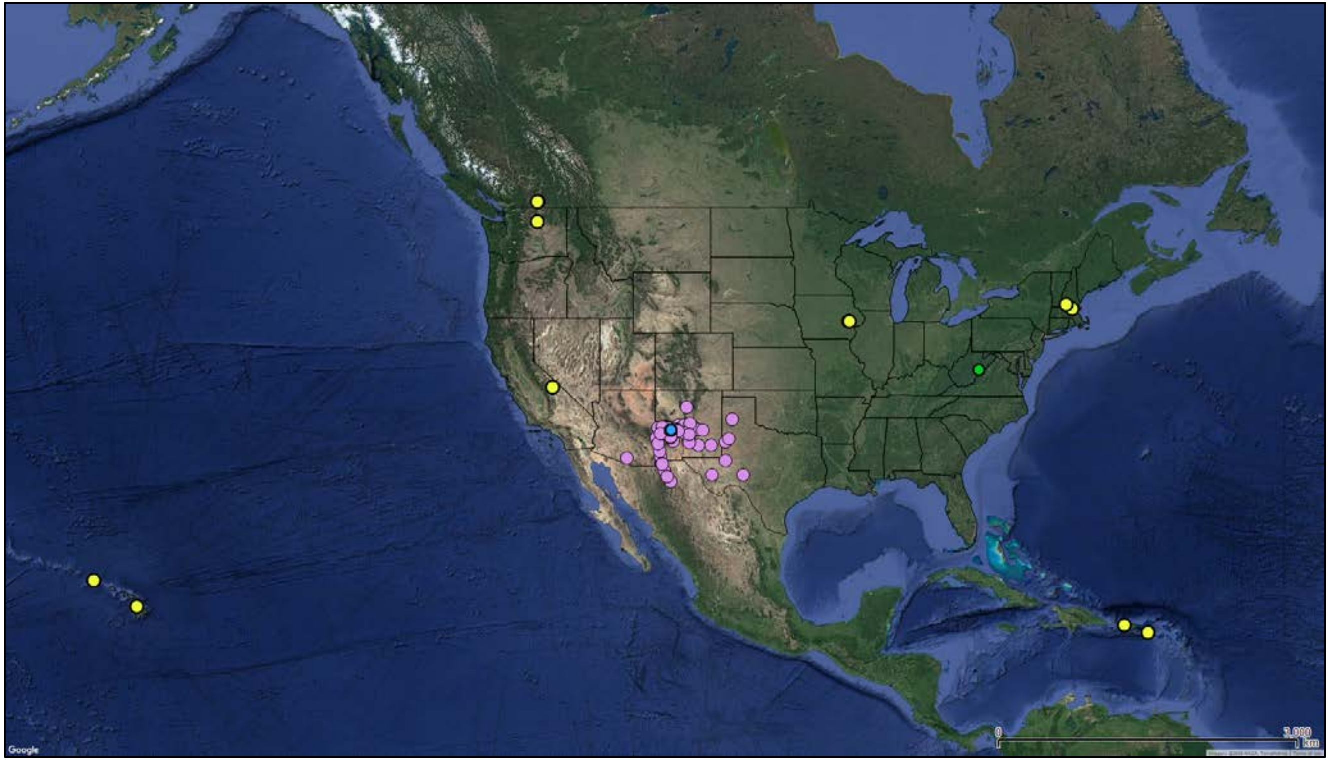




Long Baseline Array (LBA)

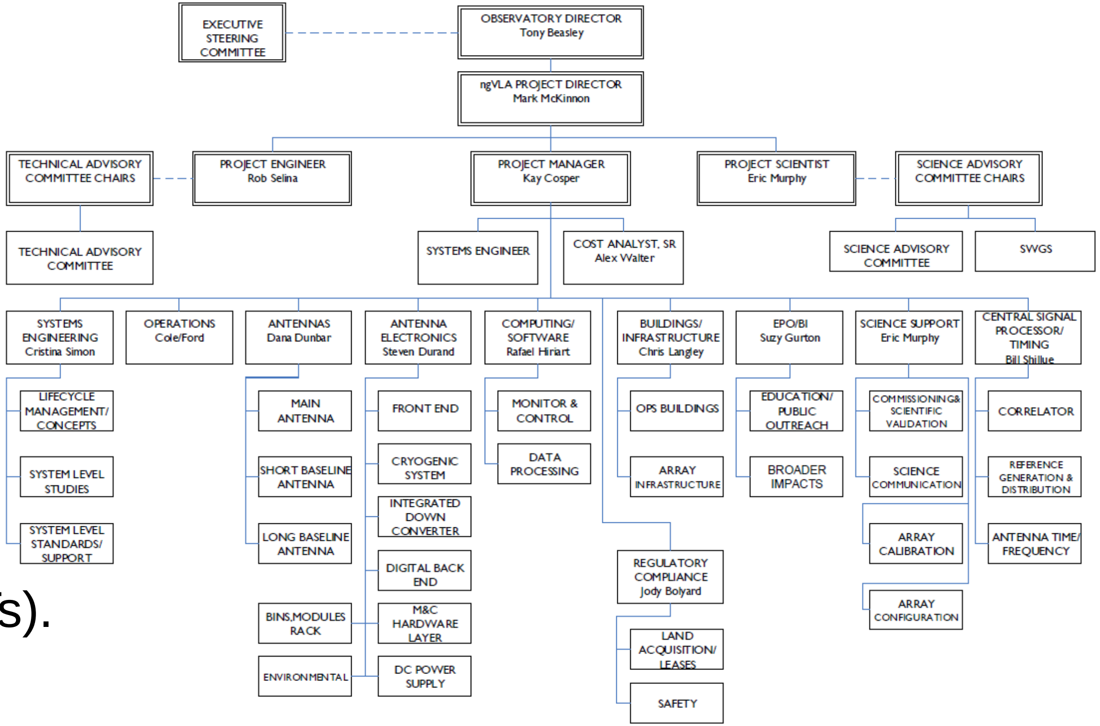
- 30 x 18m Antennas at 10 sites.
- Balance between Astrometry & Imaging Use Cases.

Qty	Location	*Possible* Site
3	Puerto Rico	Arecibo Site
3	St. Croix, US VA	VLBA Site
3	Kauai, HI	Kokee Park Geo. Obs.
3	Hawaii, HI	New Site (off MK)
2	Hancock, NH	VLBA Site
3	Westford, MA	Haystack
2	Brewster, WA	VLBA Site
3	Penticton, BC, CA	DRAO
4	North Liberty, IA	VLBA site
4	Owens Valley, CA	OVRO



ngVLA Project

- Project Office leadership team:
  - Project Director: Dr. Mark McKinnon
  - Project Manager: Kay Cosper
  - Project Scientist: Dr. Eric Murphy
  - Project Engineer: Rob Selina
  - Cost Analyst – Alex Walter
- 10 Integrated Product Teams (IPTs).
- MREFC-style project definition.
- Actively engaged science and technical advisory councils.



Astro2020: ngVLA Reference Design

- A baseline design with known cost and low technical risk. Technical & cost basis of the Astro2020 Decadal Survey proposal.
- 1500 page, 75 document package that describes end-2-end system design.
- Bottom-up supporting cost estimate.