The DSA-2000: A Radio Survey Camera

G. Hallinan[1], V. Ravi[1], S. Weinreb[1], J. Kocz[1], Y. Huang[1], D. P. Woody[1], J. Lamb[1], J. Hickish[1], K. L. Bouman[1], L. D'Addario[1], M. W. Hodges[1], M. Catha[1], J. Shi[1], C. Law[1], G. Hellbourg[1], D. Simard[1], M. Fleming[1], S. R. Kulkarni[1], E. S. Phinney[1], H. Sun[1]

M. A. McLaughlin[2], S. M. Ransom[2], X. Siemens[2], J. M. Cordes[2], R. S. Lynch[2], D. L. Kaplan[2], S. Chatterjee[2], J. Lazio[2], A. Brazier[2]

S. Bhatnagar[3], S. T. Myers[3], F. Walter[4,3], B. M. Gaensler[5]

[1] *DSA Collaboration*
[2] *The NANOGrav Collaboration*
[3] *NRAO, 1003 Lopezville Road, Socorro, NM 87801, USA*
[4] *Max Planck Institute for Astronomy, Königstuhl 17, D-69117 Heidelberg, Germany*
[5] *Dunlap Institute, University of Toronto, 50 St. George Street, Toronto, ON M5S 3H4, Canada*

Talk Agenda

i) The DSA concept and baseline specifications

ii) DSA-2000 key science

iii) Pathfinders: DSA-10 and DSA-110

iv) DSA-2000 reference design

v) RMS panel questions of interest

The 2020s is the Decade of Surveys

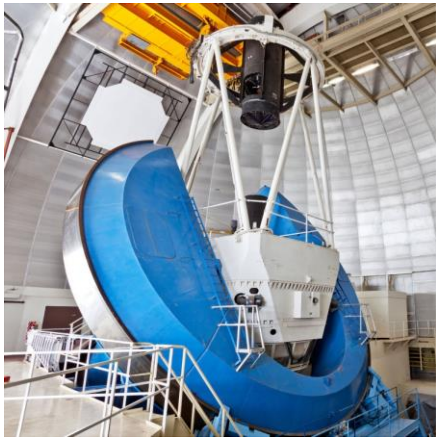
Sphere-X: 2024

WFIRST: 2025

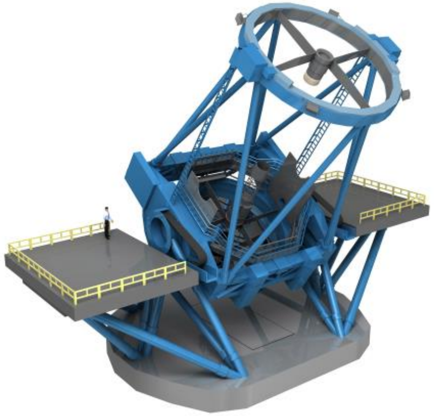
Euclid: 2022

SRG/eROSITA: 2019

ZTF: 2018



DESI: 2019

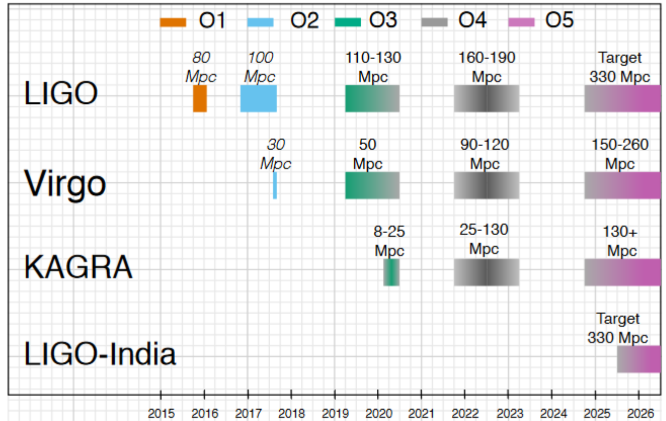


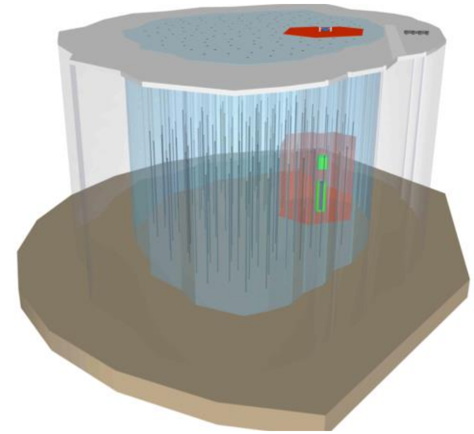
PFS: 2022

PFS: 2023

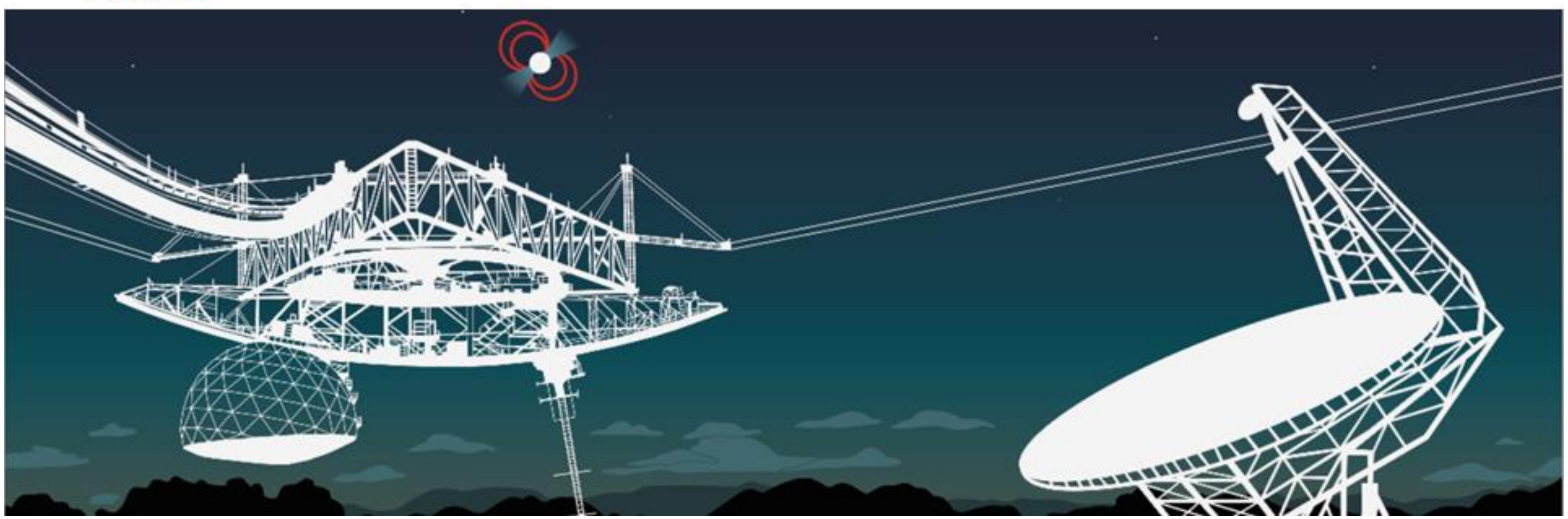
LIGO/Virgo/KAGRA

IceCube Gen2





The North American Nanohertz Observatory for Gravitational Waves



The DSA-2000: A Radio Survey Camera

- A 2000-dish array optimized for unprecedented survey speed (0.7 - 2 GHz)
- Prime phase: 2026 - 2031
- Will survey 30,000 deg^2 to 500 nJy; 2,000 deg^2 to 200 nJy/beam; 30 deg^2 to 50 (100) nJy/beam
- Will increase the number of cataloged radio sources to 1 billion (>30 million detections in HI)
- Serve as the principal instrument for the US pulsar timing array community
- Will provide search and monitoring of LIGO/Virgo/KAGRA compact binary mergers
- Will detect and localize 10^4 FRBs

DSA-2000: a paradigm shift in technology

- 1) Breaking the radio antenna cost equation
  - Small antennas and mounts, leveraging COTS hardware where possible
- 2) Low-cost, ambient temperature receiver package – no cryogenics
- 3) Signal transport via low-cost RFoF links and single-mode optical fiber
- 4) “Radio camera” digital backend - delivers science-ready image data 10^6 smaller in volume than equivalent visibility data

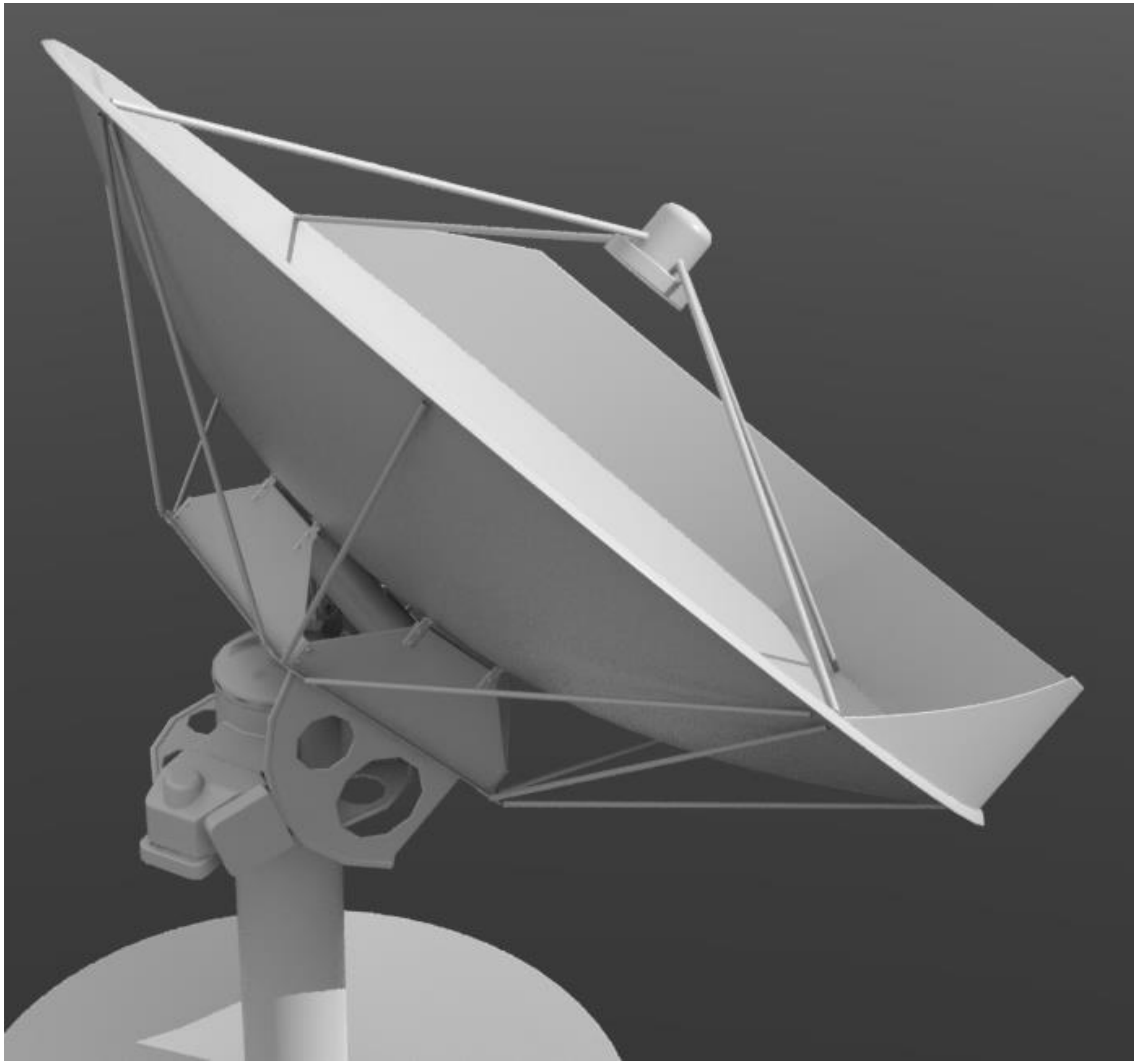
DSA Antenna Evolution

September 2013

September 2017

September 2019

DSA-2000 Antenna Reference Design



DSA-2000 Baseline Specifications

Table 1 Baseline DSA-2000 specifications. Assumes 65% usable bandwidth and 20% time overheads.

Quantity	Value
Reflectors	$2000 \times$ 5-m dishes
Frequency Coverage	0.7–2 GHz
Bandwidth	1.3 GHz
Field of View	10.6 deg^2
Spatial Resolution	3.5 arcsec
System Temperature	25 K
Aperture Efficiency	70%
System-Equivalent Flux Density (SEFD)	2.5 Jy
Survey Speed Figure of Merit	$1.3 \times 10^7\ \mathrm{deg}^2\ \mathrm{m}^4\ \mathrm{K}^{-2}$
Continuum Sensitivity (1 hour)	1 μJy
All-Sky Survey (per epoch)	$30,000\ \mathrm{deg}^2$ @ 2 μJy/bm
All-Sky Survey (combined)	$30,000\ \mathrm{deg}^2$ @ 500 nJy/beam
Pulsar Timing Fields (Intermediate)	$2000\ \mathrm{deg}^2$ @ 200 nJy/beam
Deep Drilling Fields	$30\ \mathrm{deg}^2$ @ 100 nJy/beam
Brightness Temperature (1σ)	5 mK
Number of Unique Sources	$>$ 1 billion

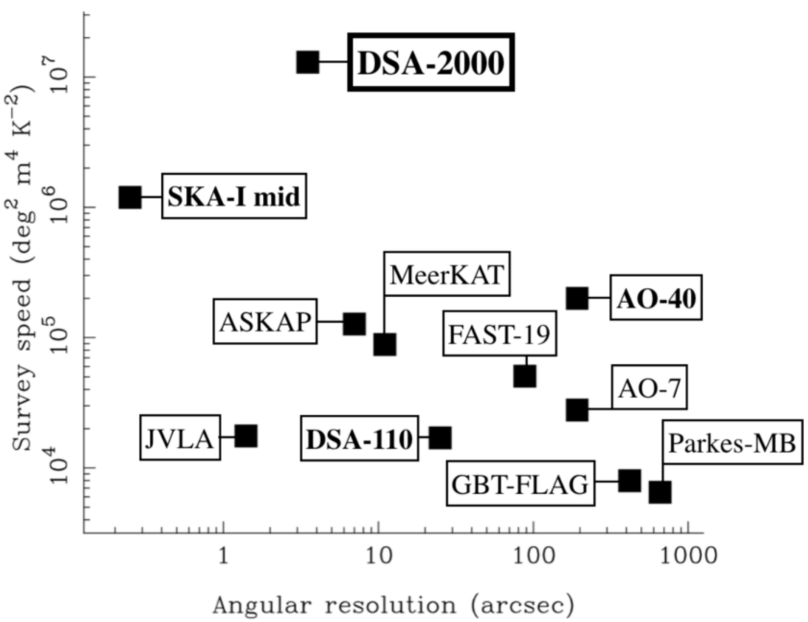
Synoptic surveys, multi-messenger science

Cadenced All-Sky Survey (CASS) (65%):
16 epochs to 2 uJy rms per epoch (500 nJy final)
All sky north of DEC -30 deg

The DSA-2000 is envisaged as a radio survey camera and multi-messenger discovery engine. Pre-designed time-domain surveys of the radio and gravitational-wave sky will be served to the community,

Pulsar timing for gravitational-wave detection (25%):
Approx. 200 MSPs timed approx. bi-weekly.
NANOGrav managed.

PSR: a commensal imaging survey during pulsar timing.
140 nJy median rms.
2000 square deg.



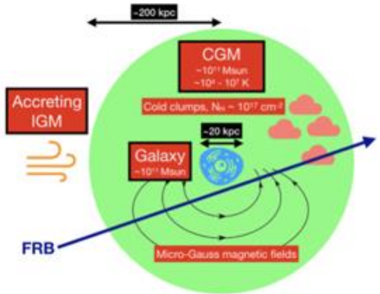
GW-detected compact object mergers (5%):
1 hr per day dedicated to discovering and monitoring NS-merger afterglows.

LSST Deep Drilling fields (5%):
3 deep fields daily to 2 uJy rms.
E.g., XMM-LSS, ECDFS, COSMOS.

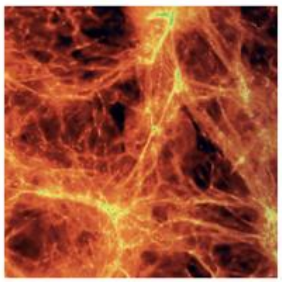
FRB searching:
Subset of array (approx. inner km) used for image-plane FRB search.
Localization with voltage buffers.

DSA-2000 in the time domain: FRBs and exploration

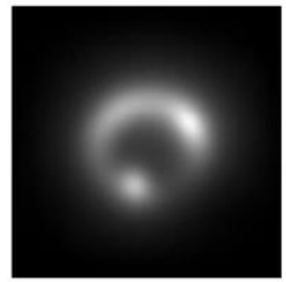
10^3 - 10^4 FRBs
Detection of CGM — CGM cooling models — compact-object dark matter models



10^4 - 10^5 FRBs
Cosmic-web IGM density and B-fields — HeII reionization — DM-space clustering



> 10^5 FRBs
Improve kSZ measurements — extragalactic micro- and nano-lenses

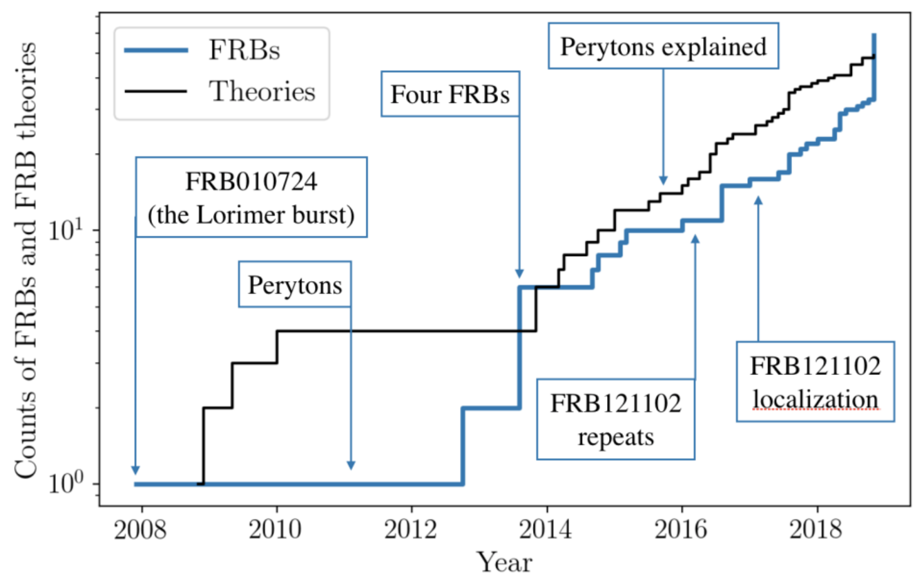


FRBs are anticipated to revolutionize the study of unseen matter in the Universe.

- Total matter content and physical conditions in CGM/IGM.
- Compact object dark matter models.

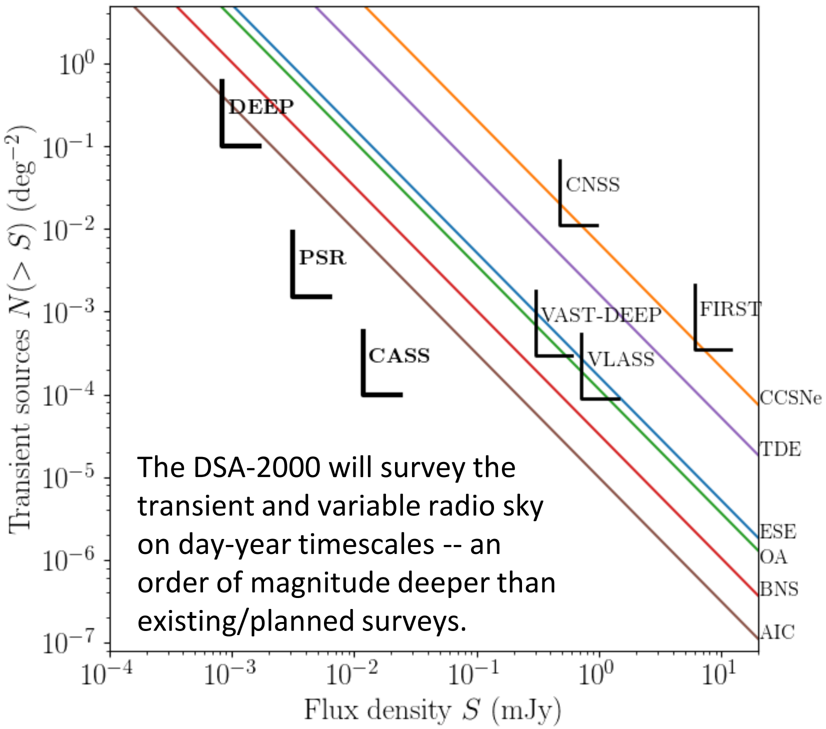
We will likely have solved the FRB progenitor question before DSA-2000.

We need to remain open to the possibility of new, unexpected discoveries: only possible through close community engagement.



Astro2020 SWPs DeMarines+, Fabbiano+, Kashlinsky+, Law+, Lesyna, Lynch+, Margot+, Ravi+, Shawhan+, Siemiginowska+, Wright+

DSA-2000 in the time domain: transient and variable discovery space



CASS: 30,900 deg^2 every 4 months.

PSR: 2,000 deg^2 every 2 weeks.

DEEP: 30 deg^2 every day..

2 uJy rms

3.5’’ res

(can super-resolve)

For extragalactic explosions (e.g., CCSNe, TDEs, OAs, BNSs, AIC)...

High-energy → Jets, IC

OIR, UV → Thermal ejecta

Radio → Trans-relativistic ejecta, jets

For Galactic transients (e.g., active stars, accreting compact objects, novae, flaring magnetars)...

Radio → Stellar magnetic fields, jet-launching mechanisms, ejecta calorimetry...

Astro2020 SWPs Airapetian+, Corsi+, Kao+, Law+, Salter

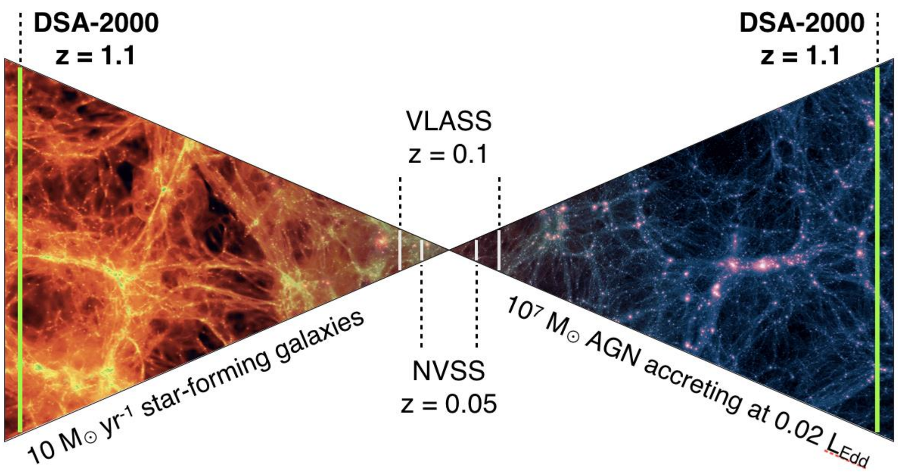
DSA-2000 continuum surveys

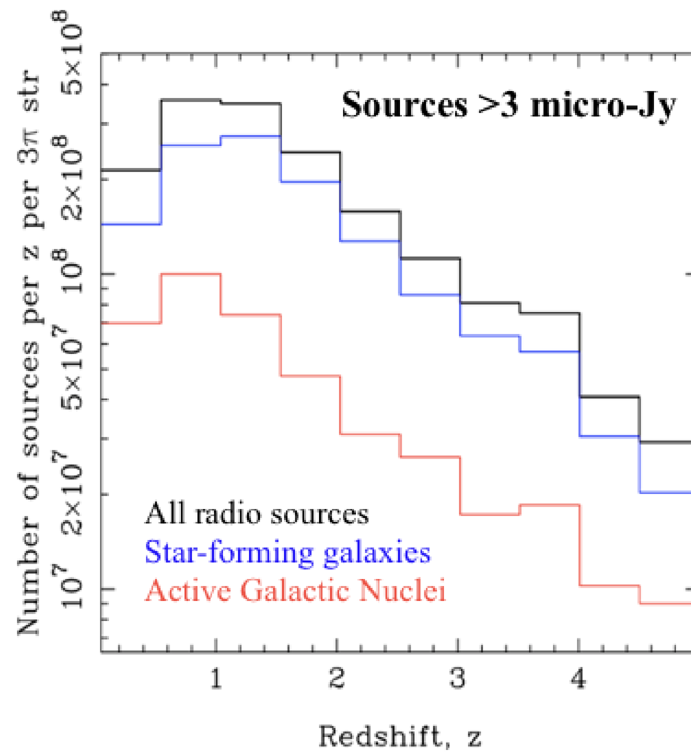
The DSA-2000 will transform our view of active and star-forming galaxies throughout cosmic time, in the context of the next generation of multi-wavelength imaging and spectroscopic surveys.

The DSA-2000 will detect z=6 star-forming galaxies @ a hundred solar masses / year, as have recently been discovered with ALMA.

The DSA-2000 will expand the sample of known radio sources by x1000 to a billion objects. Dominated by star-formation activity.

The AGN occupation fraction in dwarf galaxies probes the SMBH seed formation: CASS will detect Hen 2-10 to 200 Mpc across 3pi str.





Astro2020 SWPs Aalto+, Anderson+, Haiman, Natarajan+, Plotkin+, Pope+, Ruszkowski+

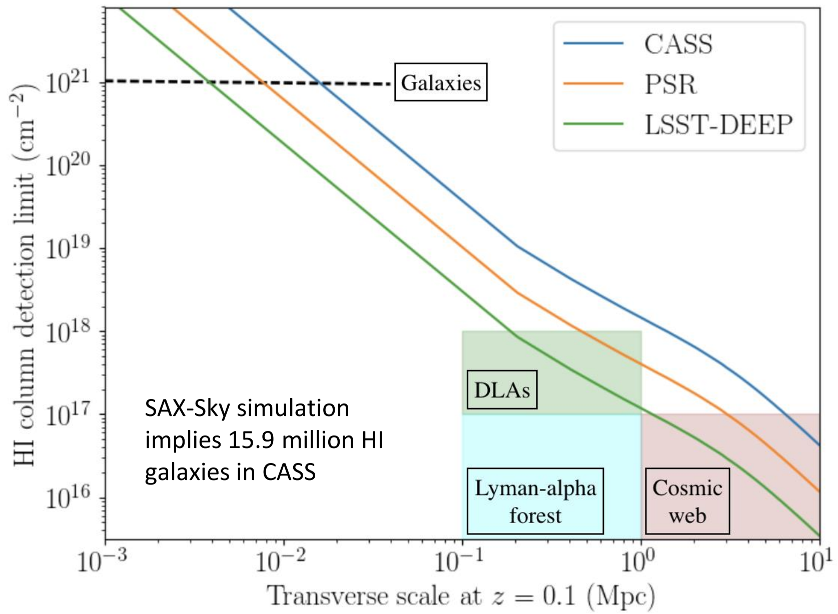
Spectral-line surveys

The DSA-2000 spectral-line data will commensally map HI to z=1 (e.g., MWs in DEEP) with angular resolutions from a few arcsec to tens of arcmin.

Census of local universe for GW counterparts.

Cosmic web/filament detections to z~0.1.

Survey of CO-dark molecular gas through OH.

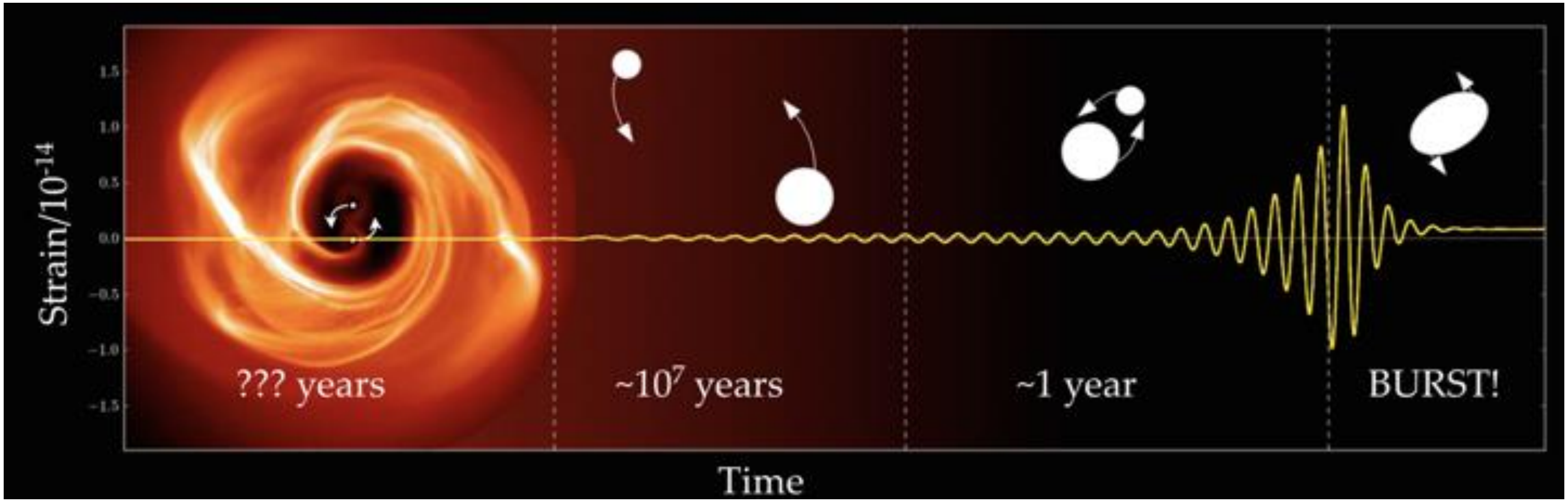


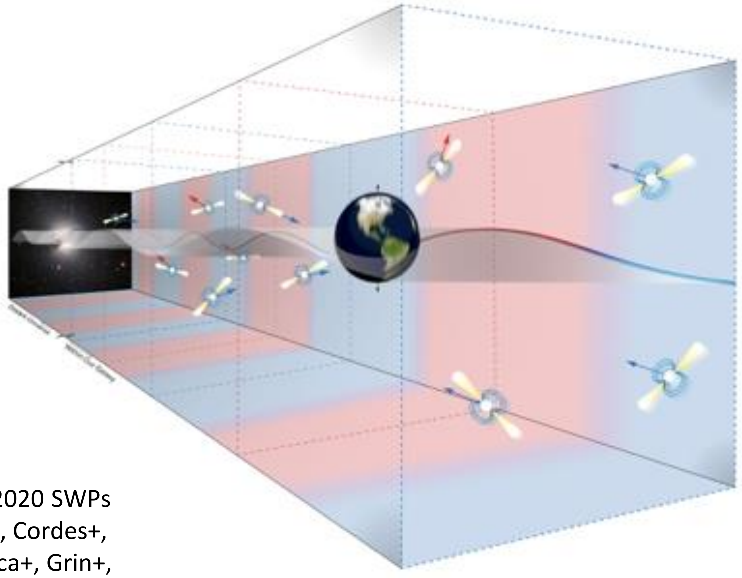
CASS data will replicate THINGS increasing the sample by orders of magnitude

Survey	Sky coverage (deg^2)	Angular resolution (arcmin)	Velocity coverage (v/c)	Velocity resolution (km/s)	SEFD / sqrt(t) (Jy/sqrt(s))
HIPASS	29,340	15.5	-0.004 to 0.043	13.2	1.6
ALFALFA	7,000	3.5	-0.007 to 0.06	11	0.6
THINGS	34 galaxies at <15Mpc	0.1	Within 150 km/s from systemic	5	0.07
WALLABY	30,900	0.5	-0.007 to 0.26	3.9	0.33
MHONGOOSE	30 galaxies at <20Mpc	0.5	Within 150 km/s from systemic	5	0.01
DSA-2000 / CASS	30,900	0.06	(a) 0 to 1 (b) -0.004 to 0.02	(a) 28 (b) 1.8	0.02

Astro2020 SWPs Anderson+, Butterfield+, Ghosh+, Lockman+, Minchin, Pisano+, Thilker+

DSA-2000 multi-messenger science: pulsar timing





Galaxy mergers are expected to result in the formation of binary supermassive black holes (SMBHs), the properties of which map to galaxy/SMBH co-evolution mechanisms.

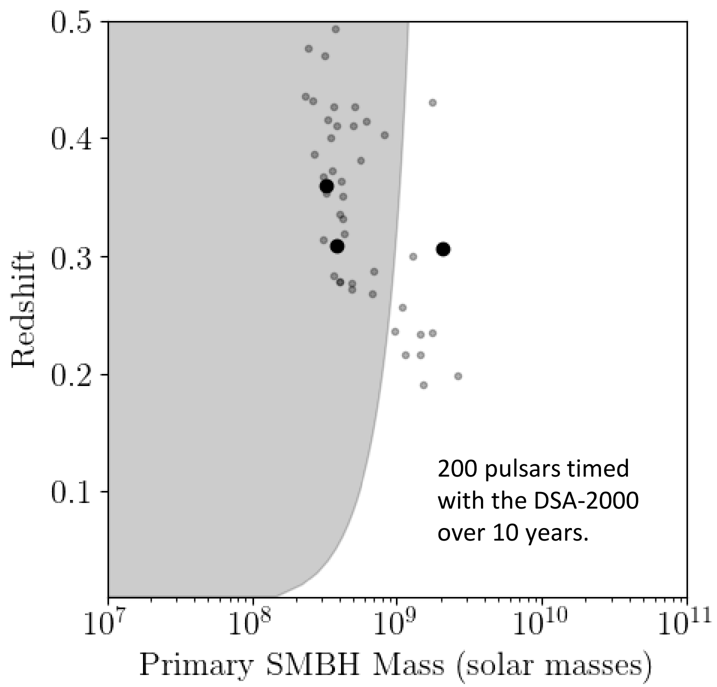
GWs from milliparsec-separation binary SMBHs will be detected in several-year timing of a sample of millisecond pulsars.

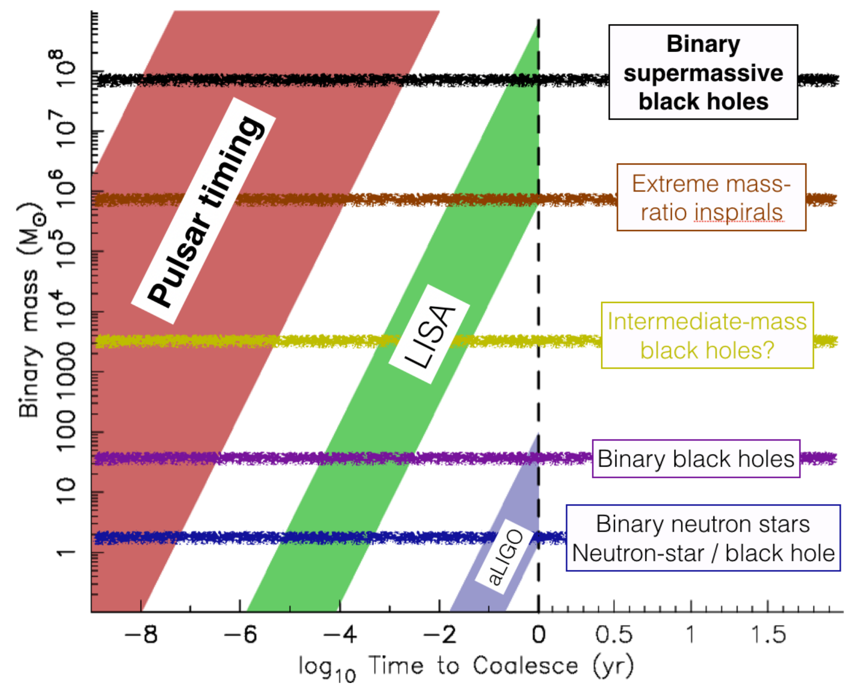
Astro2020 SWPs
Colpi+, Cordes+, Fonseca+, Grin+, Kelley+, Lynch+, Siemens+, Stinebring+, Taylor+

DSA-2000 multi-messenger science: pulsar timing

In the mid-2020s, NANOGrav will be in the regime of **characterizing** the GW background from all binary SMBHs. The DSA-2000 will **detect** individual binary SMBHs in the nearby Universe, **localized** to tens of square degrees.

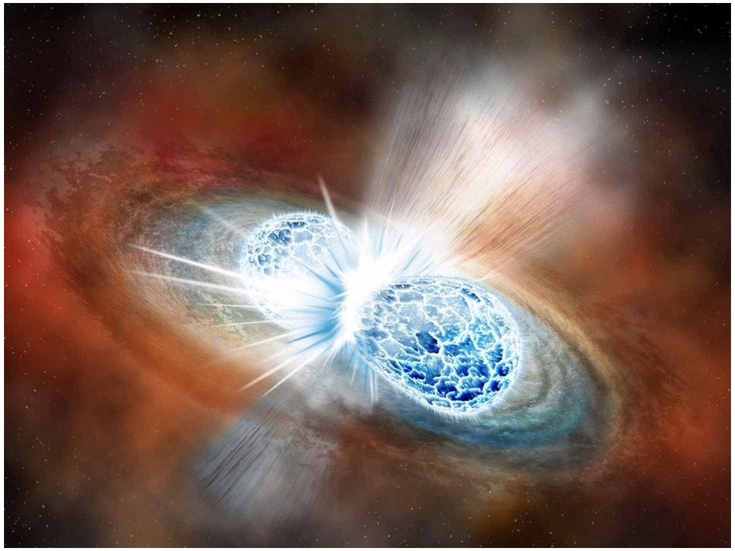
Pulsar timing arrays are scientifically complementary to LISA, tracing the formation of GW-dominated binary SMBHs.
Pulsar timing also results in significant constraints on dark matter models.





Astro2020 SWPs Colpi+, Cordes+, Fonseca+, Grin+, Kelley+, Lynch+, Siemens+, Stinebring+, Taylor+

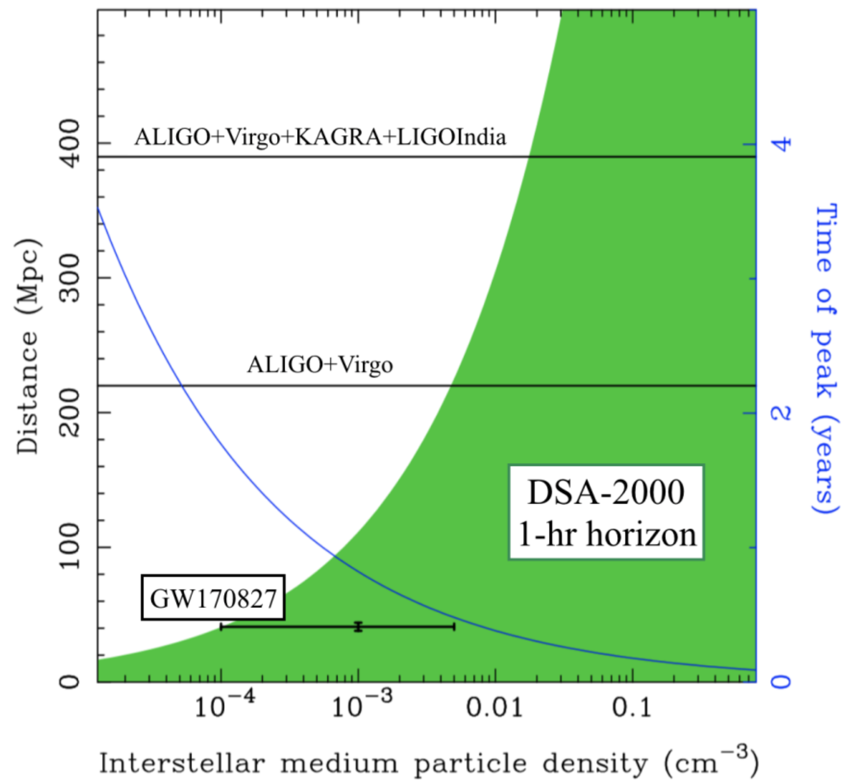
DSA-2000 multi-messenger science: compact-object merger afterglow discovery



The discovery and characterization of the EM counterparts to GW-detected NS - compact object mergers is transformational science.
NS composition, NS formation, relativistic astrophysics, origin of elements...

DSA-2000 will:

(a) detect GW170817-like events to 200 Mpc
(b) even in the absence of jets, identify sub-relativistic ejecta in several cases.



Astro2020 SWPs Corsi+, Shawhan+

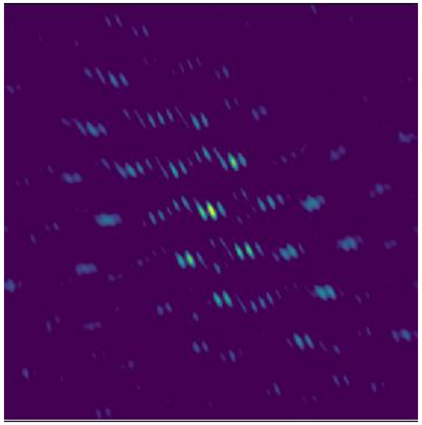
The DSA-10 FRB 190523

Ravi+19, Kocz+19

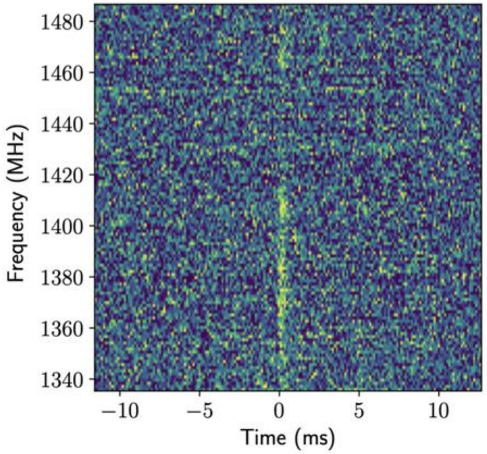
The DSA-10 (2016-2019) prototype demonstrated the basic viability of the DSA concept: streamlined, well-designed receiving elements served by a fiber and power network, complemented by sophisticated digital engineering. The coup de grace was the discovery of the z=0.66 FRB 190523.

Field of view	7 x 7 deg (null to null)
Frequency range	1280 — 1530 MHz 2048 channels
Search sensitivity	SEFD of 6200 Jy 65 Jy ms (1 ms)
Localization accuracy	<5'', depending on S/N & position

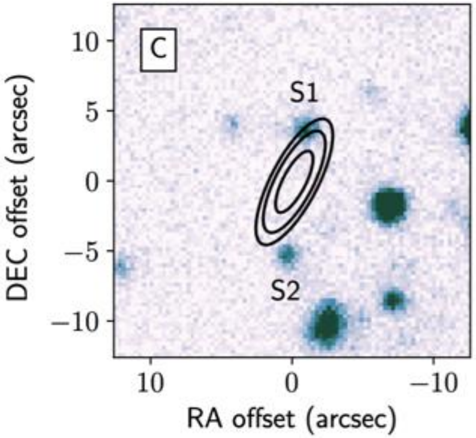
0.5 x 0.5 deg image of FRB 190523, 0.13 ms frame



De-dispersed dynamic spectrum of FRB 190523

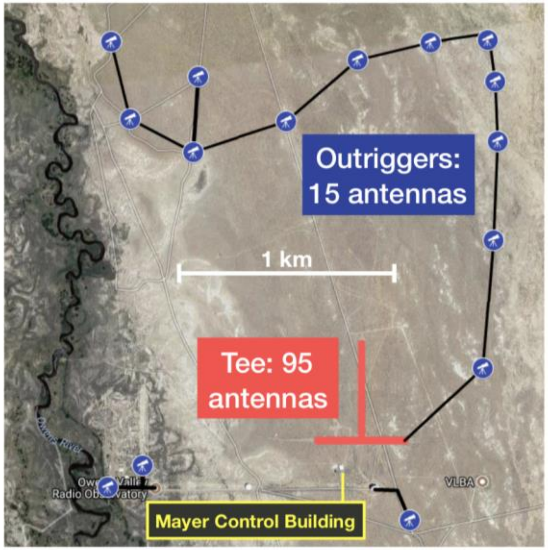


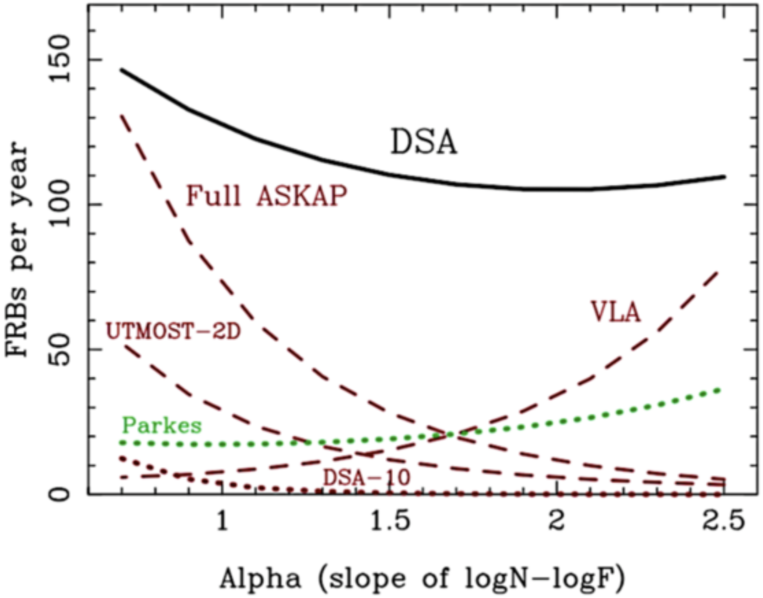
Keck g-band image; galaxy S1 is the only object within the 99% confidence region



The DSA-110

What are the sources of FRBs?
What is the nature of the medium through which they propagate?

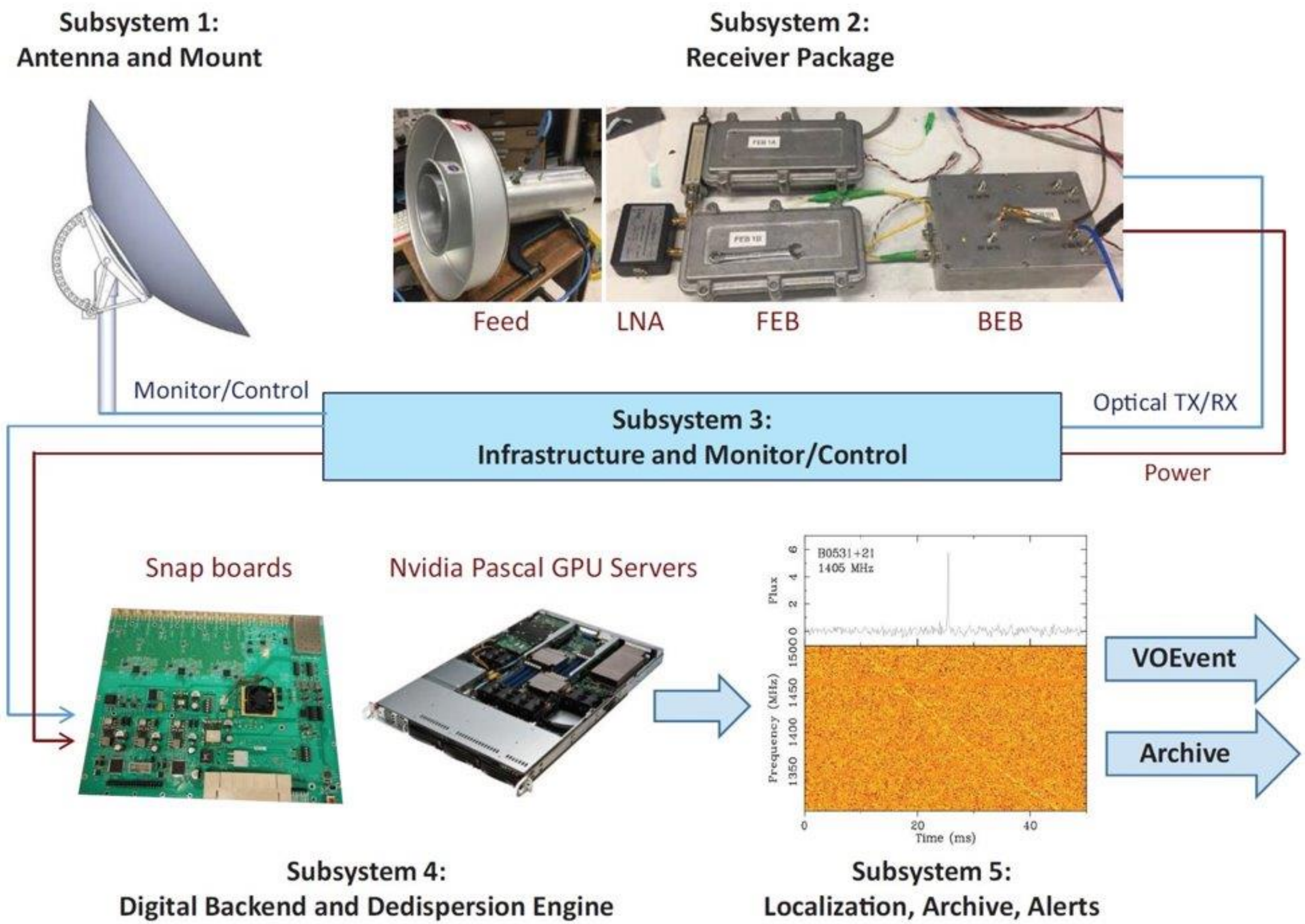




Fully funded for construction+operations - NSF MSIP grant ($5.3M).

Alerts with <3'' localizations will be distributed to the community via the FRB VOEvent protocol within 60s, with refined localizations to follow. A **public data archive** will serve as a repository for high-time-res and localidation data. *Community engagement is critical in the search for multi-wavelength counterparts, which are predicted by leading FRB models.*

The DSA-110


Subsystem 1:
Antenna and Mount
Subsystem 2:
Receiver Package
Feed
LNA
FEB
BEB
Monitor/Control
Subsystem 3:
Infrastructure and Monitor/Control
Optical TX/RX
Power
Snap boards
Nvidia Pascal GPU Servers
B0531+21
1405 MHz
Flux
Frequency (MHz)
Time (ms)
VOEvent
Archive
Subsystem 4:
Digital Backend and Dedispersion Engine
Subsystem 5:
Localization, Archive, Alerts

DSA-110 Specifications

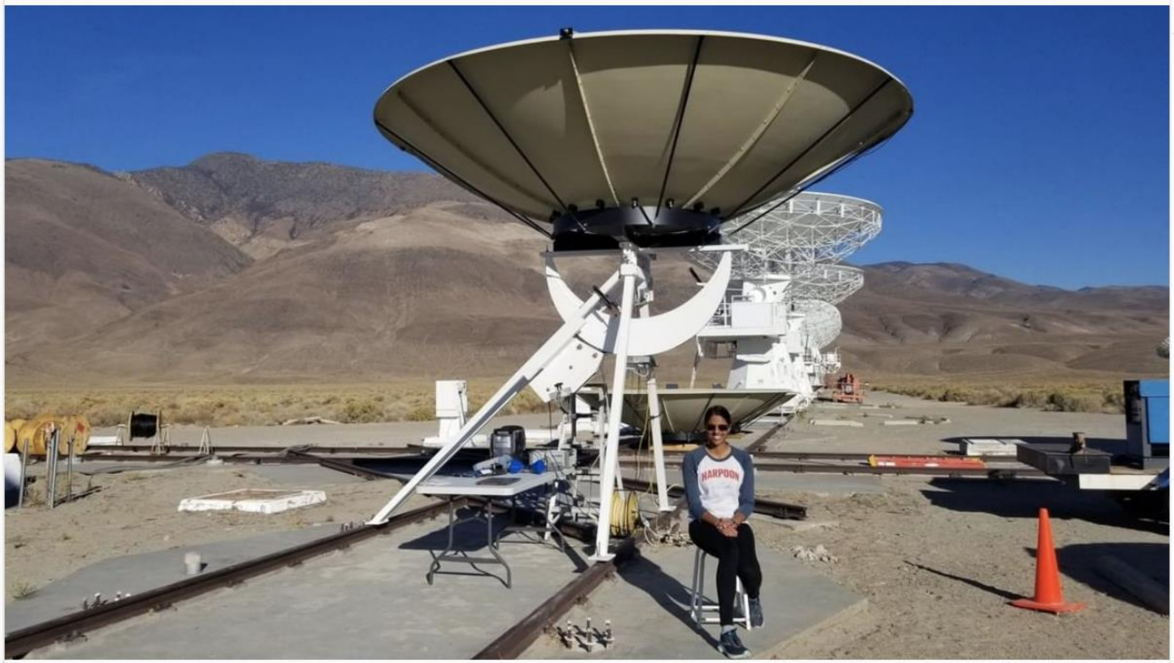
Parameter	Specification	Goal	Comments	Ref.
Frequency range	1.28–1.53 GHz	1.28–1.53 GHz		
Frequency resolution	122.07 kHz	122.07 kHz	Resolution for dispersion meas.	[1]
System temperature	< 45 K	25 K	Zenith; good weather	[2]
Aperture efficiency	0.62	0.70		
Gain stability	±0.1 dB over 6 h			[3]
Passband amplitude	±0.1 dB/10 MHz			
Passband phase	±5.0°		Diff. between antennas	[3]
# antennas (core)	85	95		[4]
# antennas (outrigger)	15			
Minimum baseline, E–W	5.75 m			[4]
Minimum baseline, N–S	8.627 m			[4]
Maximum baseline	2.25 km	2.25 km		
Antenna diameter	4.65 m		Effective collecting area; rim roll outside ok	[4]
Elevation range	25°–145°		Includes NCP	[4]
Pointing accuracy	± 0.2°	± 0.1°		[4]
Antenna location accuracy (core)	± 0.160 m		Relative to design w.r.t. on-site fiducial	[5]
Antenna location accuracy (outer)	± 1.6 m	± 0.8 m	Relative to design w.r.t. on-site fiducial	[5]
Phase drift	± 1.7°.h^{-1}		8 calibrators/day average	

DSA-110 Progress: Antenna

Instagram

Search

Log In Sign Up



Caltech

caltechedu • Follow

caltechedu A #FieldworkFriday from #OVRO (aka Owens Valley Radio #Observatory), by Caltech grad student Nitika Yadlapalli! "Here's the very first dish for our new array, the DSA-110. One day, it'll be finding fast radio bursts but until then, I'll be here testing all sorts of stuff out on it. Exciting days ahead!!" Learn more about OVRO at ovro.caltech.edu!

#astronomy #telescopes

828 likes

OCTOBER 18

Log in to like or comment.

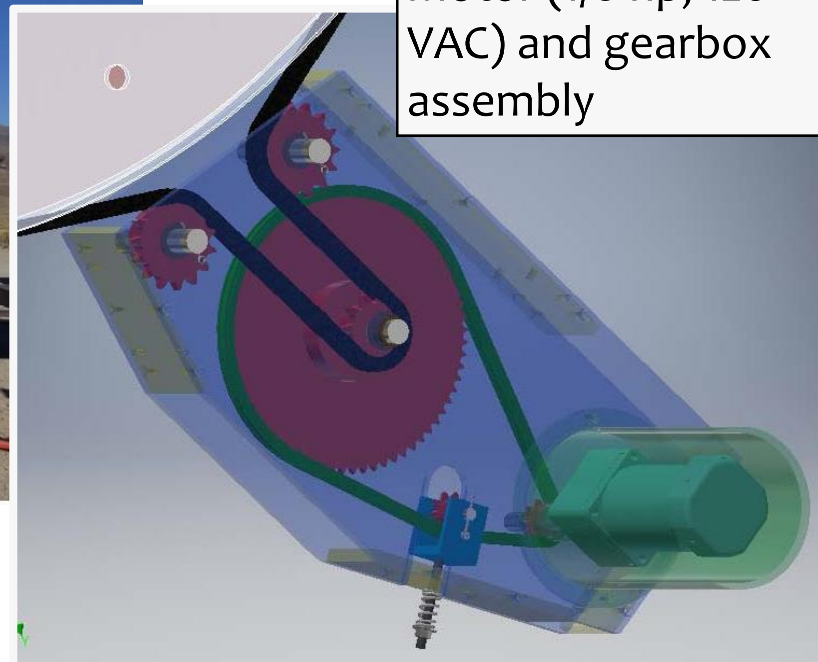
DSA-110 Progress: Antenna

D. Woody et al.

Mount alignment verified using observations of stars near NCP with 11x7 deg camera
<0.14 deg net rms pointing error.

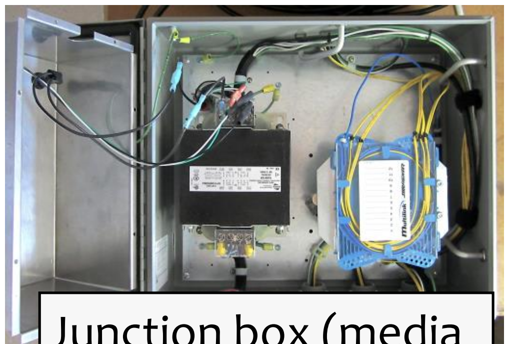
1.5” thick drive crescent provides counter weighting

Spun aluminium disk (DH Satellite)



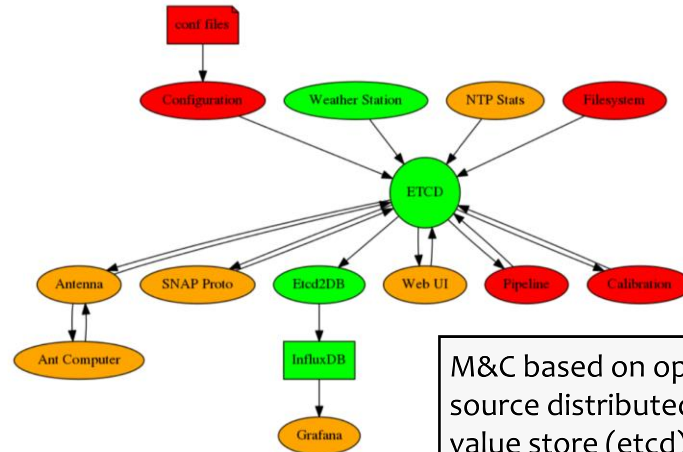
Motor (1/8 hp, 120 VAC) and gearbox assembly

DSA-110 progress: infrastructure, M&C, digital backend, software.

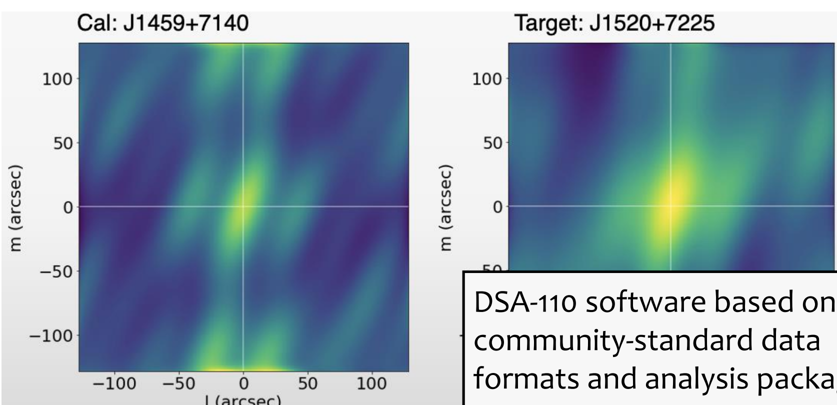


Antenna box (RFOF, LabJack)

Junction box (media converter, power/fiber splice)

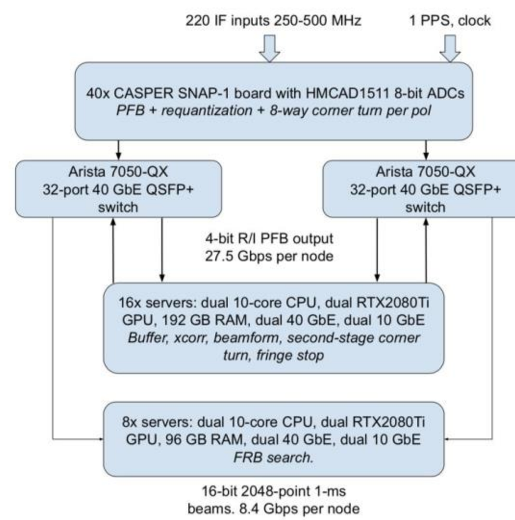


M&C based on open-source distributed key-value store (etcd).



DSA-110 software based on community-standard data formats and analysis packages.

FX architecture DBE, with 40x CASPER SNAP boards for F-engine, and 24 dual-GPU servers linked by 40 GbE for X-engine + FRB searching.

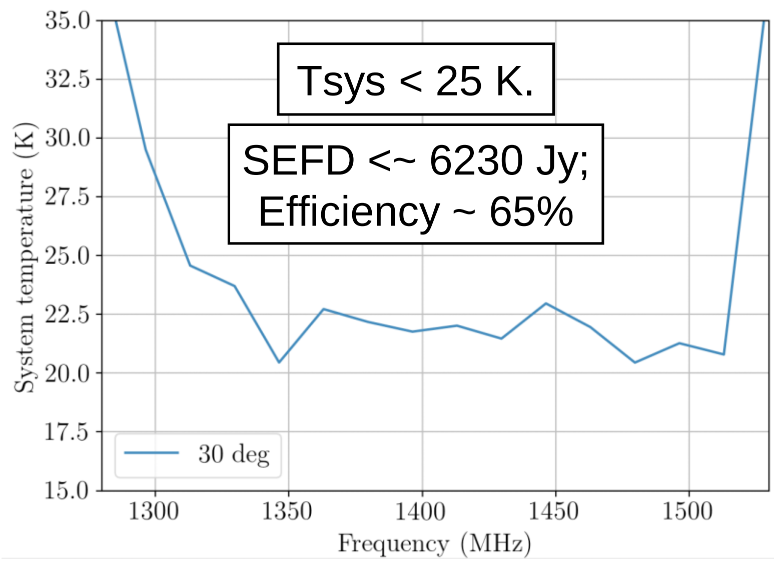


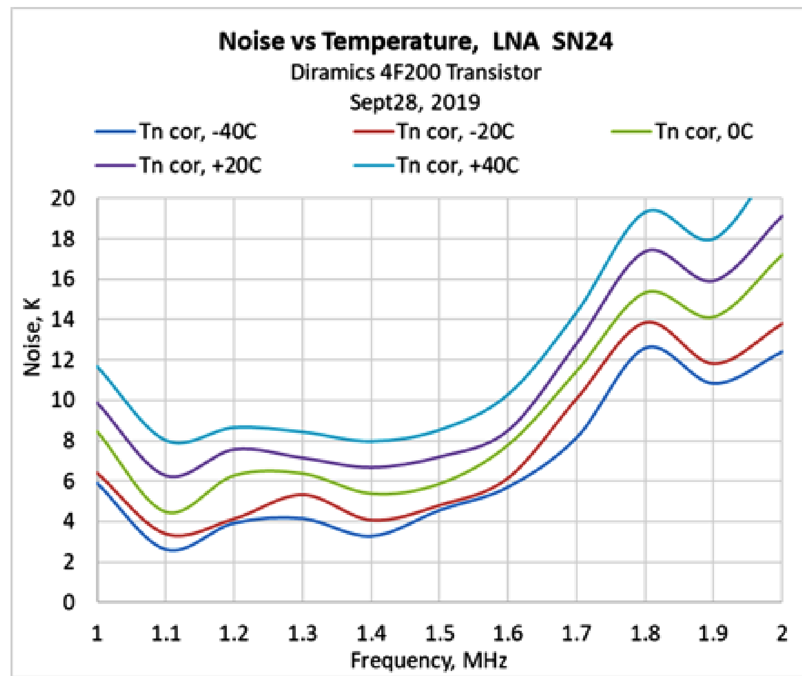
Lamb, Catha, Hobbs et al.
Ravi, Kocz, Law, Simard et al.

DSA-110 progress: receivers, sensitivity

A remarkably performant LNA design by S. Weinreb (~6K noise temp), combined with optimal optics (f=0.33) and transparent feed legs (fiberglass) result in Tsys < 25 K.

Scans of the dish across astronomical sources imply an SEFD of <~6230 Jy, 1.7x better than spec.



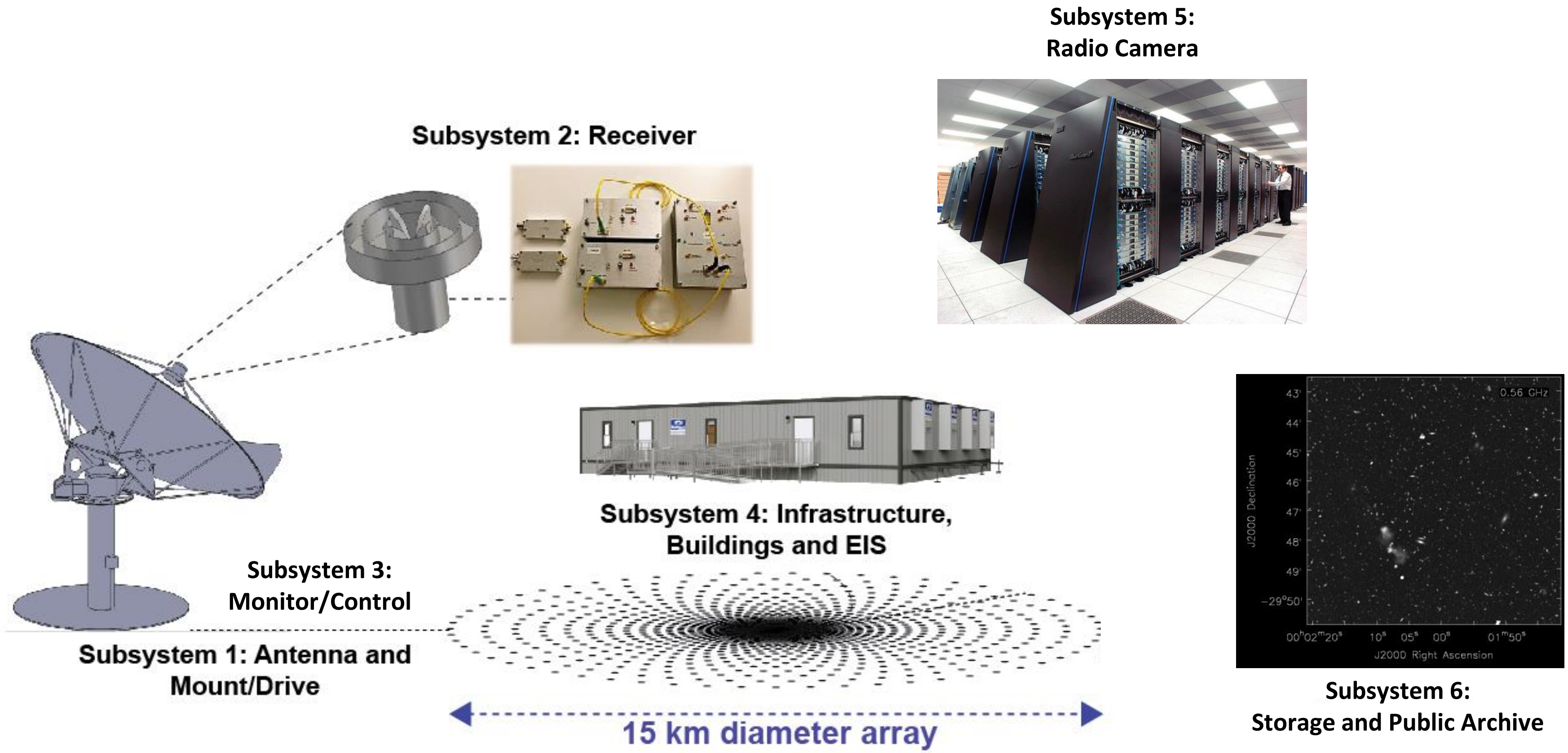


S. Weinreb et al.

DSA-2000 Reference Design

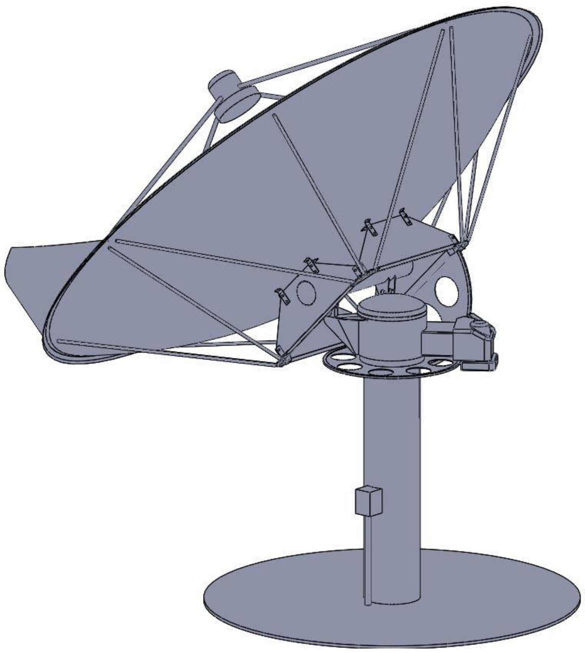
- DSA-2000 is in the early conceptual design phase
- Reference design to demonstrate feasibility and enable assessment of overall architecture for cost and risk
- Cost estimates:
  - Conservative bottom-up cost estimates where possible
  - Extrapolation from DSA-110
  - Expert judgement used where direct data are unavailable

- ***The design can (and will) be modified significantly during the preliminary design phase based on planned trade studies and subsequent optimization***

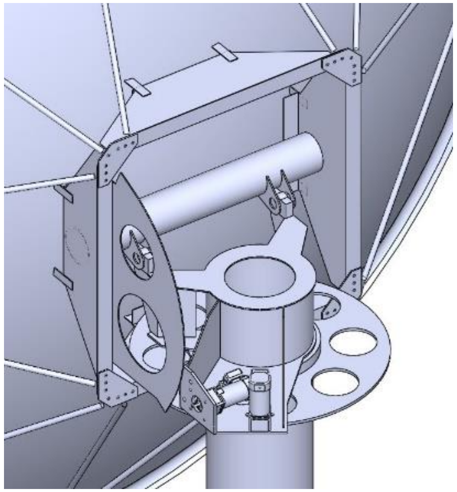


- Subsystem structure largely preserved from DSA-110
- A more detailed WBS will be made available to the Panel

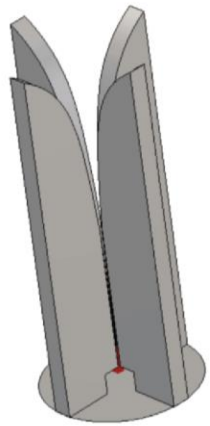
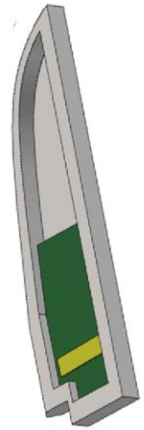
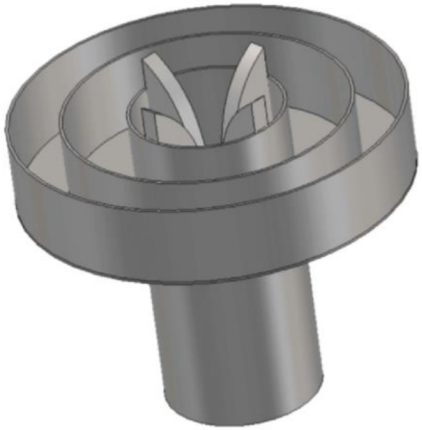
Antenna, Mount and Drive



- Conceptual design by Matt Fleming (Minex)
- Reflector will be 5 m solid spun aluminum antenna (f/D ~ 0.33), with prime focus optics
- Fabricated on site
- Addition of support struts greatly improves stiffness
- Addition of spillover shield inproves T_{sys}
- Both azimuth and elevation drive systems are envisioned as roller chain type mechanisms
- Azimuth range of 370° and elevation range of 15 - 90°
- **Reference Design: $33.9 million + 20% contingency = $40.6 million**



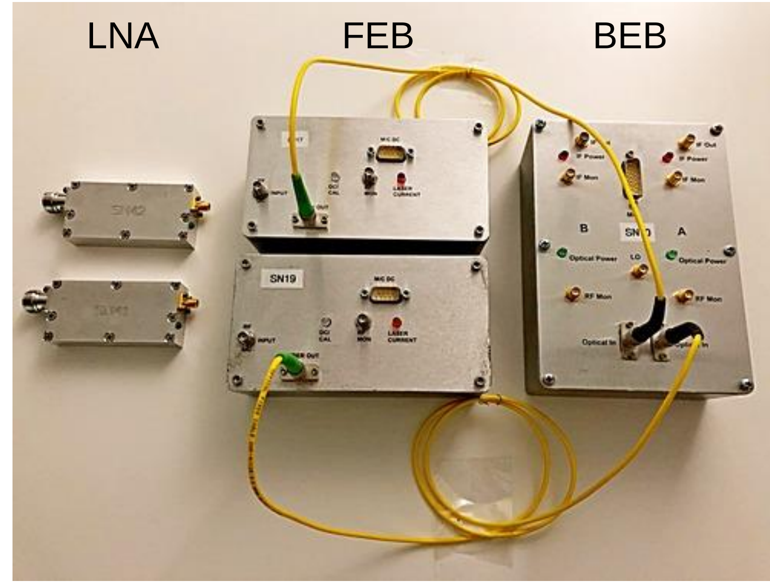
Receiver - Feed

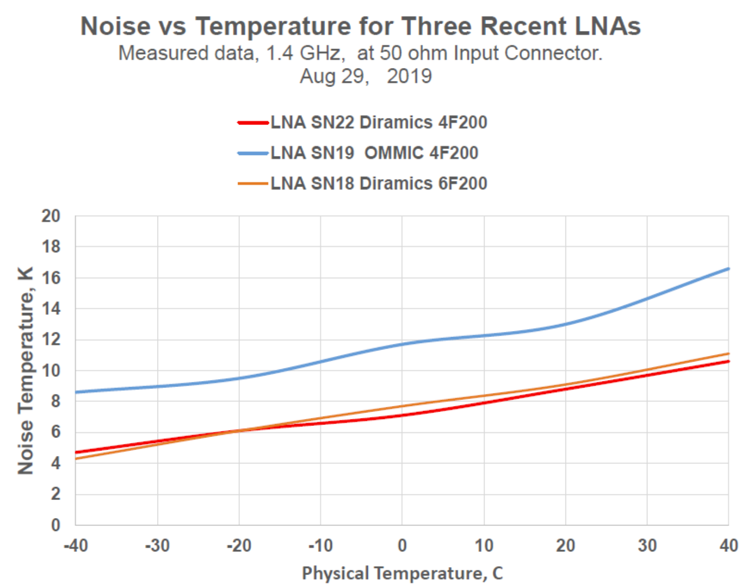





- Wide-band evolution of DSA-110 “cakepan” feed
- Quad-ridge cakepan feed
- Conceptual design by Jonas Flygare (with Sandy Weinreb)
- LNA embedded in the ridges

Receiver - Electronics

- **FEB & BEB**
- Front-End Box (FEB) and Back-End Box (BEB) will be iterations of DSA-110
- Requires a much different design for filters, frequency conversion, and dynamic range for the fiber link
- **LNA**
- Design of wideband LNA in preliminary stages
- Initial transistor modeling completed via contract with Modelithics
- Temperature-stabilized noise calibration source to be included
- Use of solid-state Peltier micro-cooler (8 mW) to cool transistor chip (0.5 mm square)
- **Reference Design: $6.18 million + 40% contingency = $8.65 million**



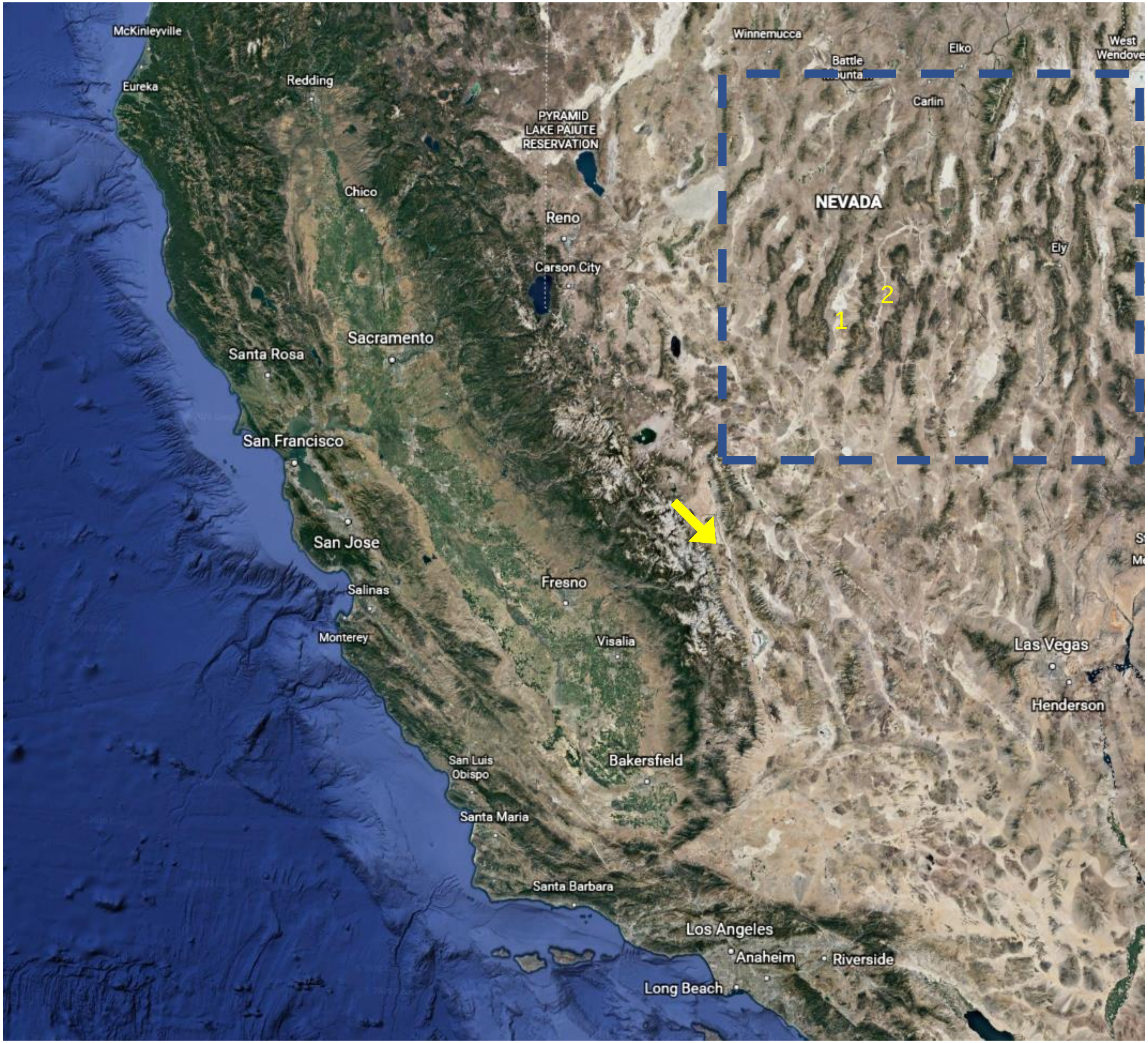


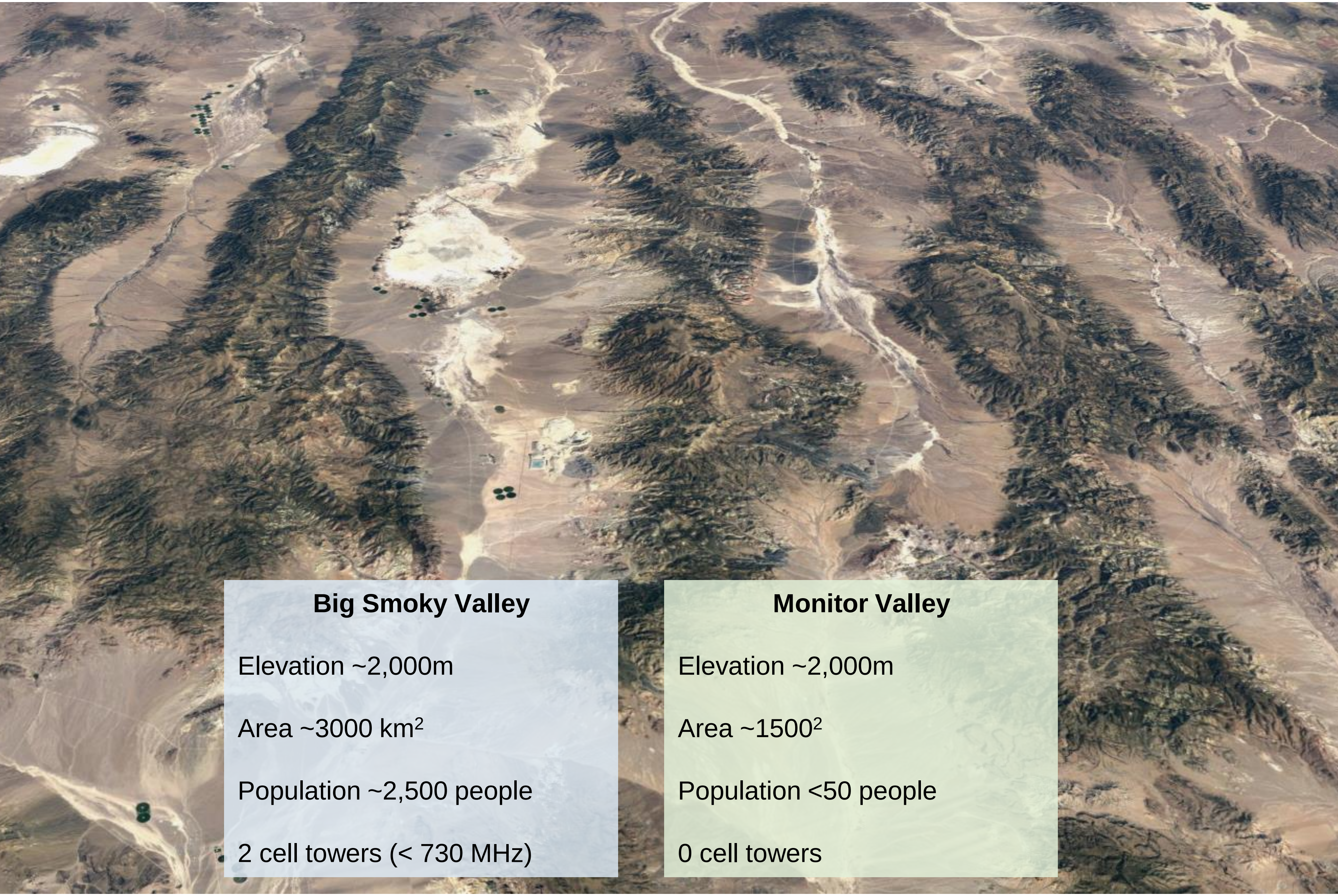
Infrastructure, Buildings and EIS

- Site selection criteria
    - 15 km diameter flat area
    - Access to power and fiber
    - Low levels of RFI
    - Manageable lease and EIS process

Owens Valley and Deep Spring Valley are too small for DSA-2000

Low population valleys can provide comparable isolation to best sites in the world


McKinleyville
Eureka
Redding
Chico
PYRAMID LAKE PAIUTE RESERVATION
Reno
Carson City
Winnemucca
Battle Mountain
Elko
West Wendover
Carlin
NEVADA
Ely
1
2
Sacramento
Santa Rosa
San Francisco
San Jose
Salinas
Monterey
Fresno
Visalia
Las Vegas
Henderson
San Luis Obispo
Bakersfield
Santa Maria
Santa Barbara
Los Angeles
Anaheim
Riverside
Long Beach



Big Smoky Valley

Elevation ~2,000m

Area ~3000 km^2

Population ~2,500 people

2 cell towers (< 730 MHz)

Monitor Valley

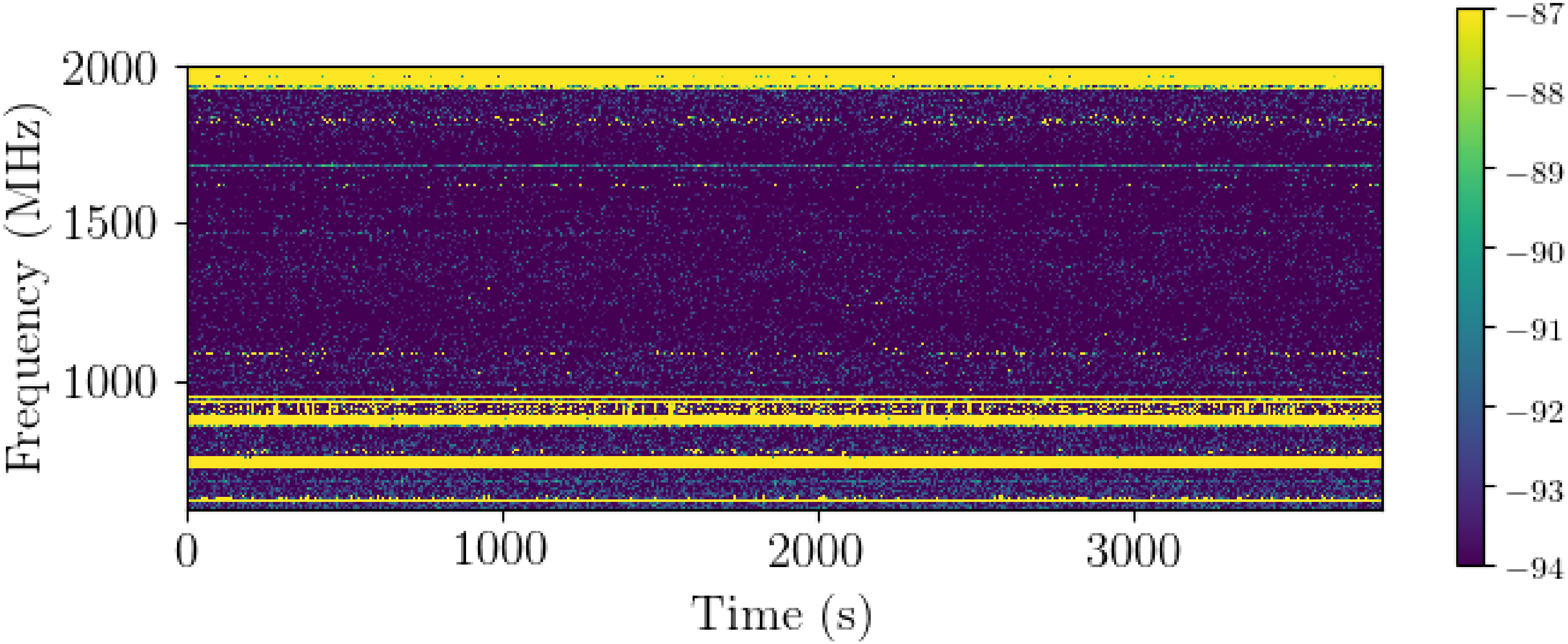
Elevation ~2,000m

Area ~1500^2

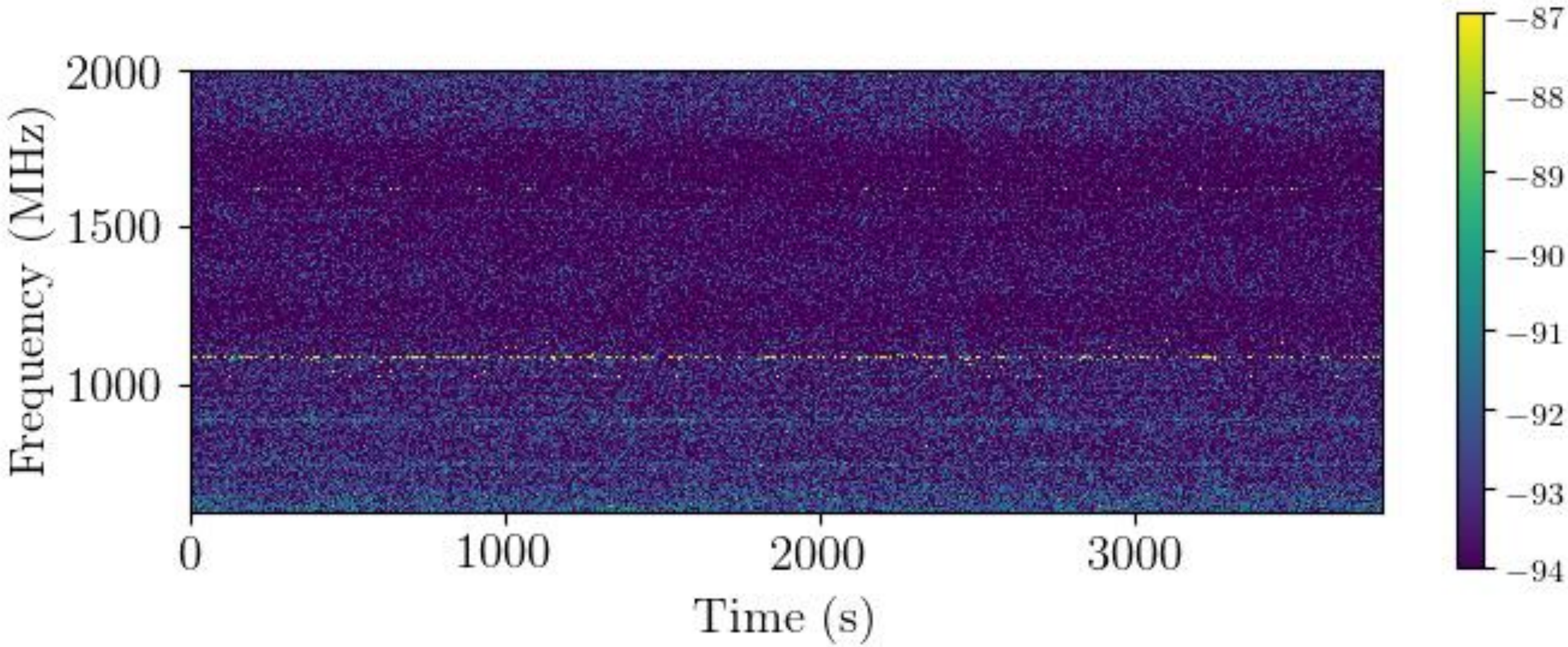
Population <50 people

0 cell towers

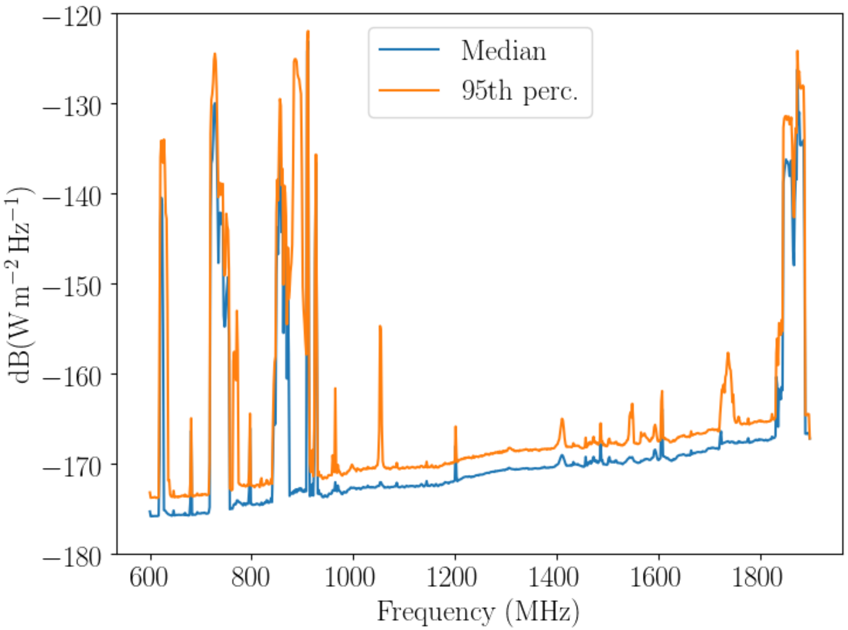
OVRO


Frequency (MHz)
2000
1500
1000
0
1000
2000
3000
Time (s)
−87
−88
−89
−90
−91
−92
−93
−94

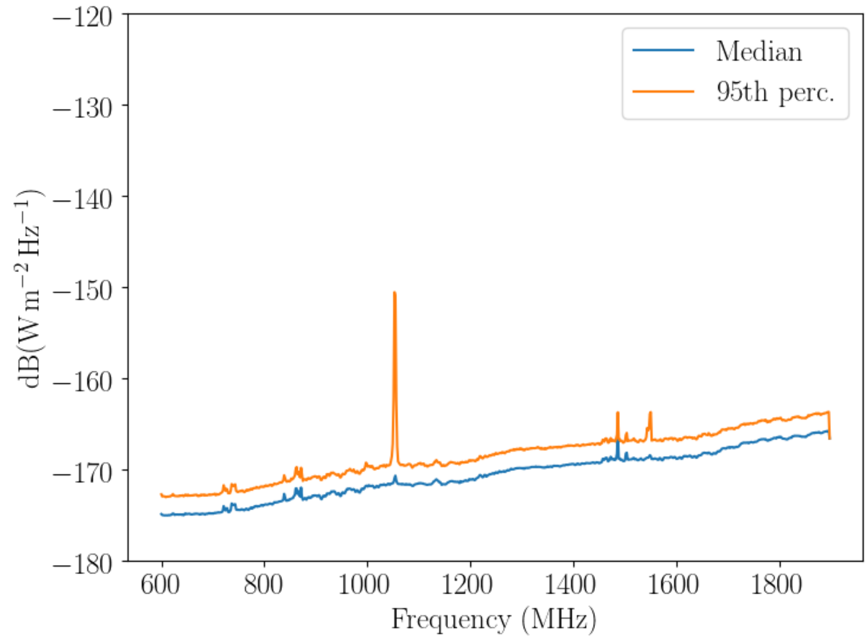
Monitor Valley



OVRO

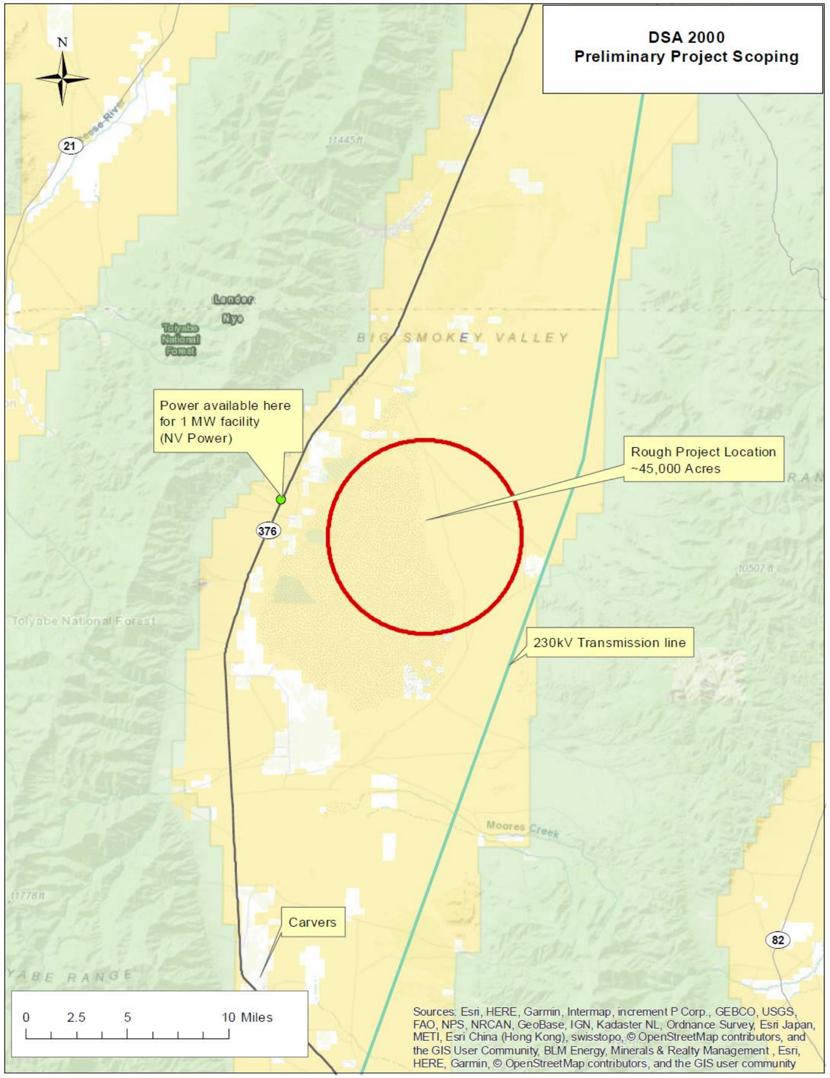


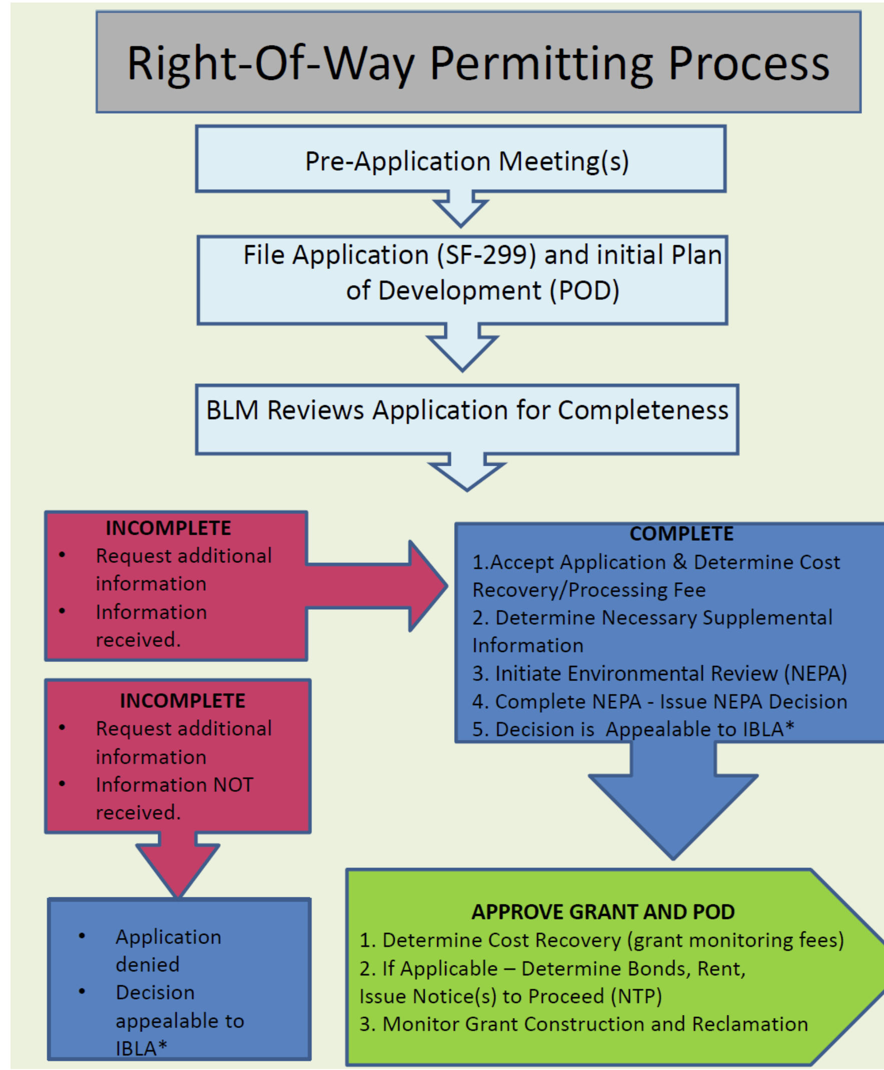
Monitor Valley



- **Big Smoky Valley survey planned**

Environmental Impact Statement

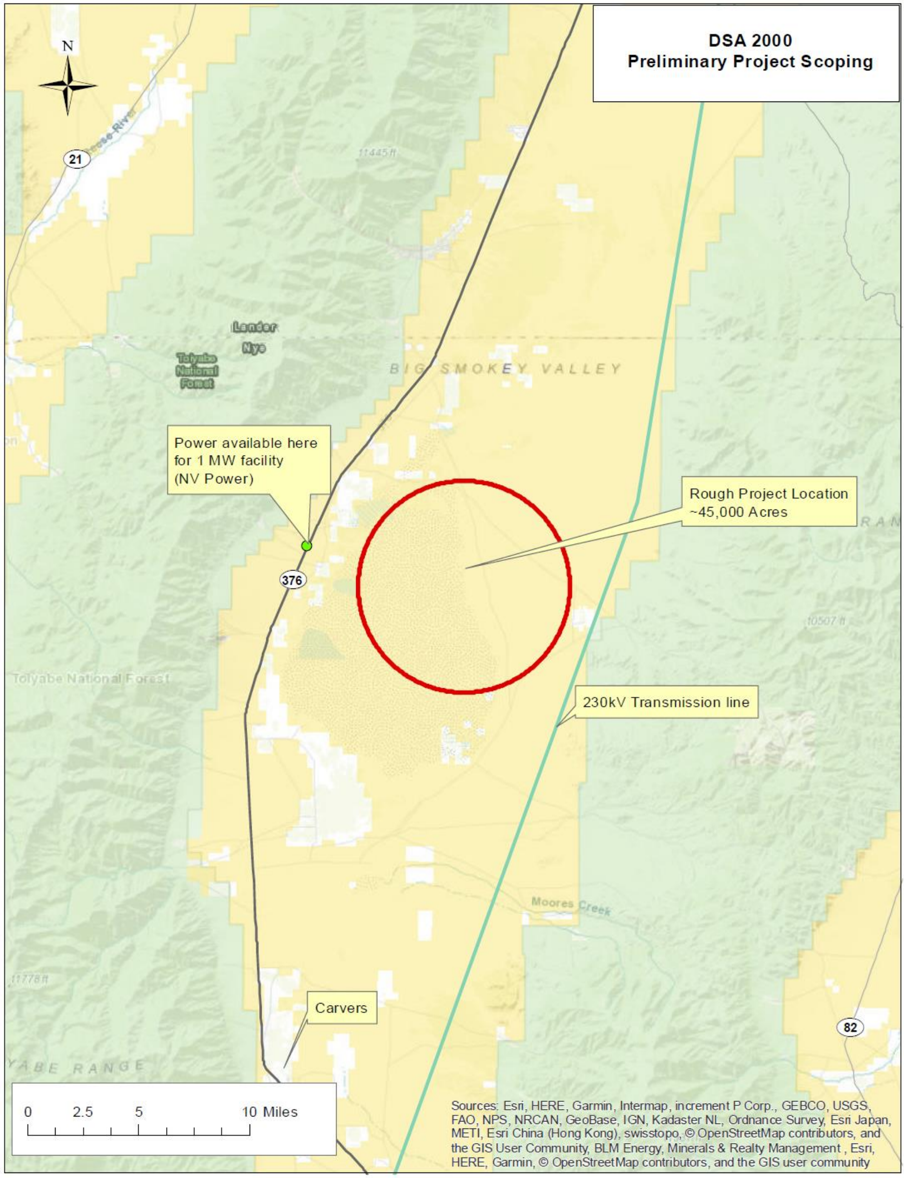




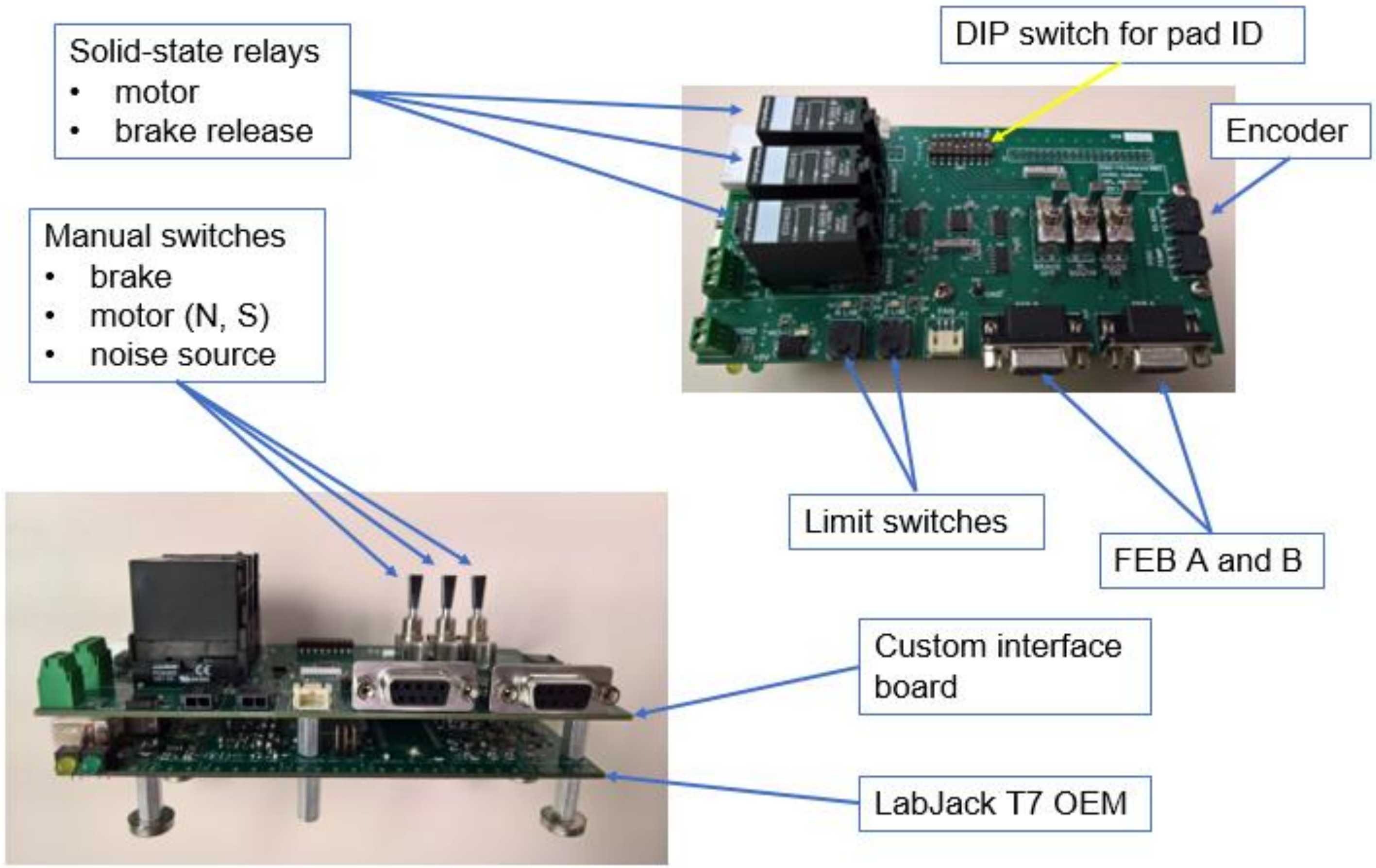
- Sage Grouse, existing grazing allotments, existing mineral leases, DOD airspace consultation area.
- Local residents are mostly in the mining industry and supportive of development.
- **Environmental Impact Statement: $1 million + 50% contingency = $1.5 million**

Infrastructure and Buildings

- **Reference design costs assume Big Smoky Valley**
- Buildings, vehicles, test equipment:
  $6.9 million + ~50% contingency = $10.6 million
- Mains power and fiber to central processing building:
  $3.7 million + ~50% contingency = $5.6 million
- Antenna solar power (including 48-hr batteries):
  $5.65 million + 20% contingency = $6.75 million
- **Total: 16.3 million + 41% contingency = $23 million**
- Mod 1: Replace solar with mains power for antenna:
  $27.5 million total
- Mod 2: Bring fiber/power into Monitor Valley:
  $40 million total



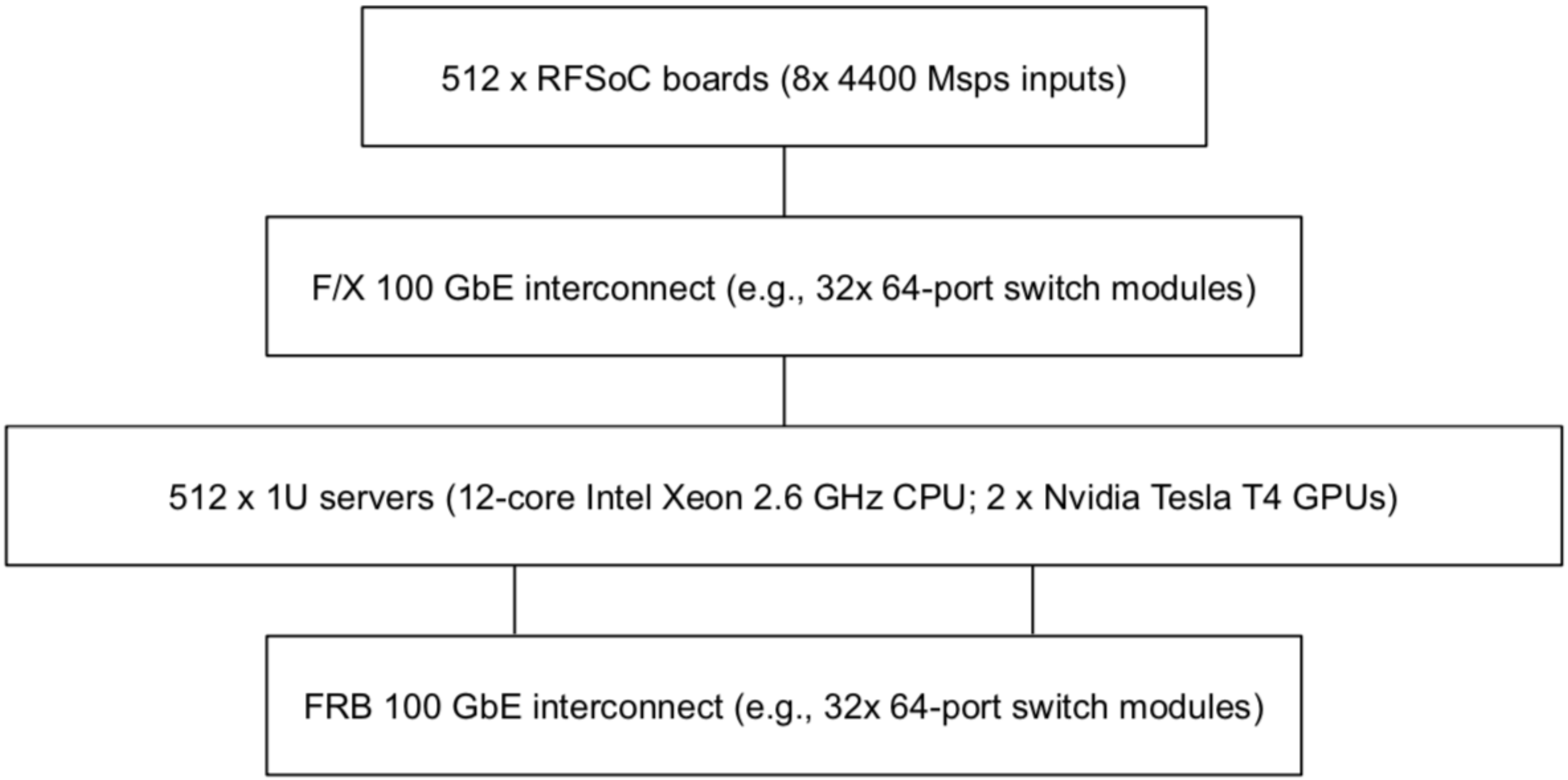
Monitor/Control



- Hardware costs assumed to be 50% larger due to additional complexity of az/el drive (two servo loops)
- Etcd-based approach has been benchmarked for DSA-2000 antenna M/C software
- **Total: 2.6 million + 25% contingency = $3.2 million**

The Radio Camera

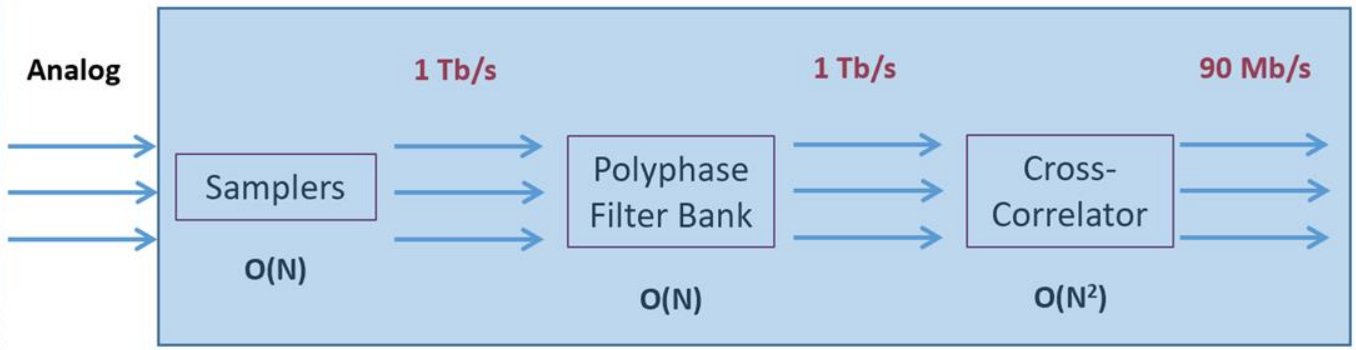
Digital Hardware Costs



- **Total: 20.7 million + 0% contingency = $20.7 million (excluding storage)**
- Detailed design breakdown in document submitted to Decadal Panel

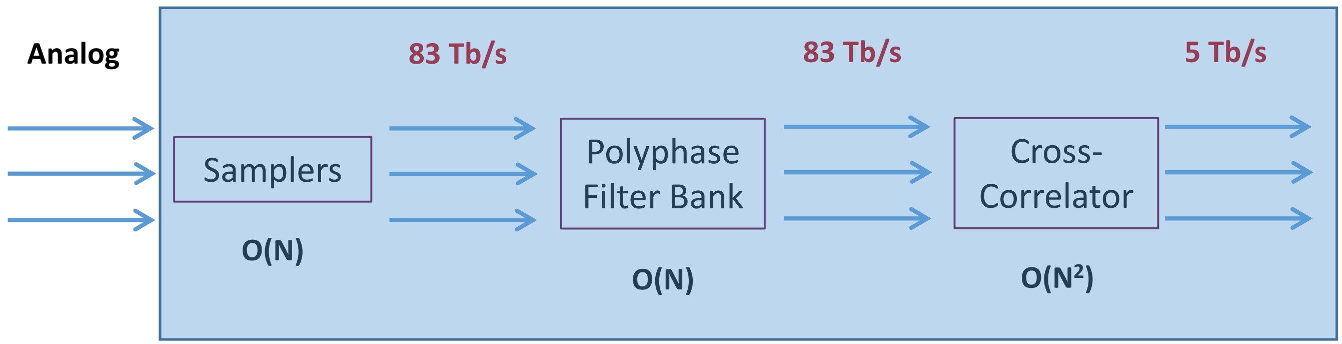
Data Deluge in Radio Astronomy

Correlator



N = 27

Correlator



N = 2000

- **Flagging, calibration, gridding+imaging (and deconvolution) done on local machines**
- **Software requires large degree of flexibility and compatibility with many platforms – makes optimization very difficult**
- **Model does not scale for next-gen facilities**

The DSA-2000

Radio Camera

ADCs

83 Tb/s

FPGAs

83 Tb/s

100 Mb/s

Samplers

Polyphase Filter Bank

Cross-Correlator

Flagging

Calibration

Gridding / Imaging

O(N)

O(N)

10 PTOPS **6.7 GFLOPS** **400 TFLOPS** **28 TFLOPS**

@80% efficiency

512 servers
PCIe 3 @200 Mbps
= 100 Tb/s

512 x Nvidia Tesla T4 Tensor Core GPU
= 100 PTOPS (4-bit)
4.2 PFLOPS (FP32)

Real-time flagging, calibration, gridding/imaging

- **Flagging (statistical and machine learning approaches**

  - Existing flagging methods based on statistical approaches (e.g. kurtosis)
  - Baseline design assumes a GPU-based implementation (e.g. AOFlagger)
  - machine learning based approaches being explored

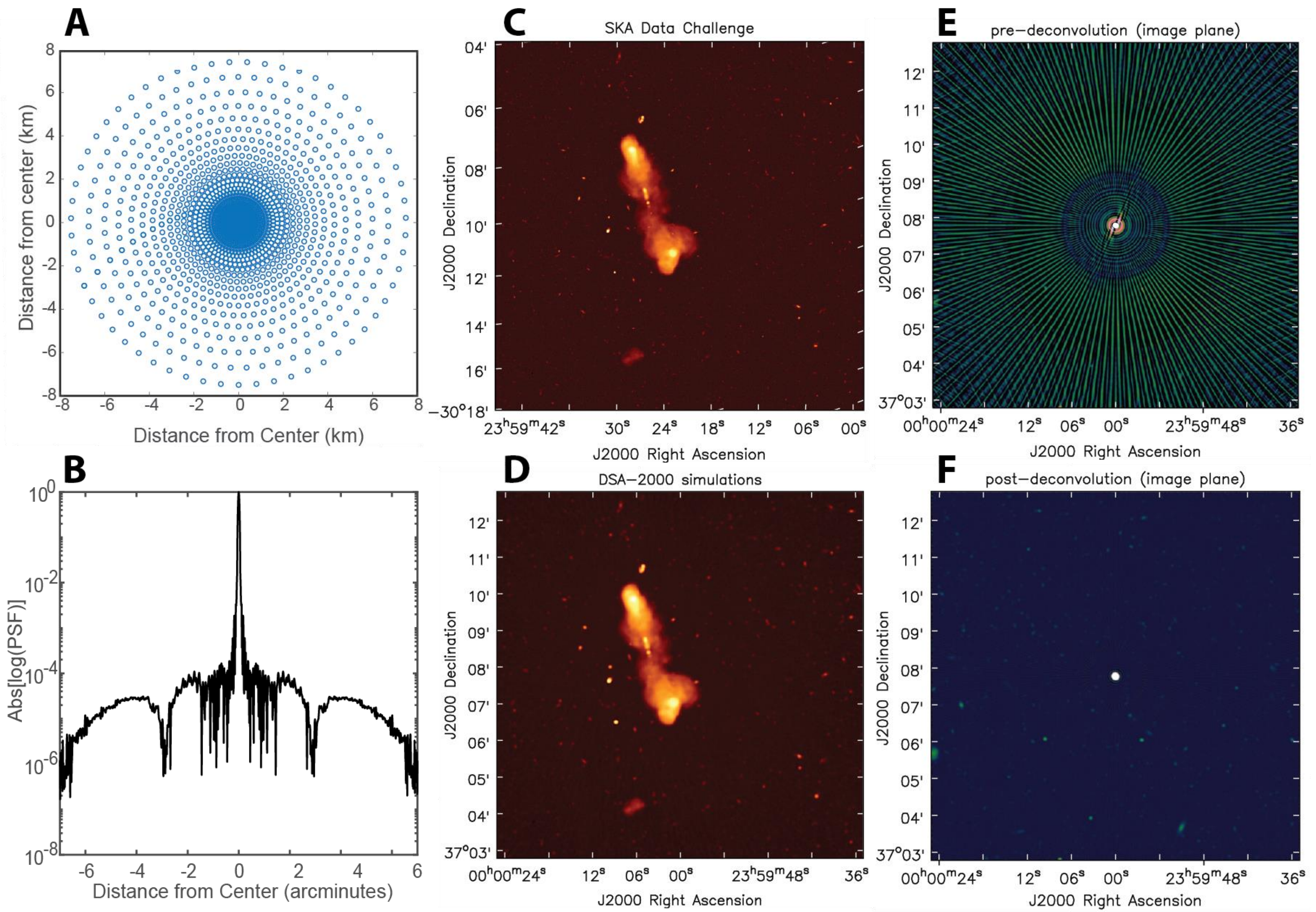
- **Calibration progresses in two stages**

  - An initial sky model is created from VLASS+NVSS data
  - First stage calibration/imaging involves aw-projection with a-priori primary beams
  - Additional phase-only self-cal solves for antenna pointing offsets and ionospheric phase screens

- **Gridding /Imaging**
  - Existing GPU-based gridder/imager implementations will be tested and optimized for the DSA-2000 data stream

- **Source extraction and cataloging done on image data by 6,000 x CPU cores**

The Radio Camera



Data Storage and Archive

- Public archive will serve CASS data 30,000 deg^2, 10 sub-bands, 16 epochs
  5-year data volume of 500 TB
  160-billion data points

- Data storage facility consists of 102 PiB available storage (BeeGFS backed by ZFS)
  - tape back-up

- Accommodates ~70 PB of final data products

- **Reference Design (Public Archive): $2.2 million + 50% contingency = $3.3 million**

- **Reference Design (Storage Facility): $7 million + 0% contingency = $7 million**

- With thanks to Adam Brazier (Cornell Center for Advanced Computing)

Operations Model

- OVRO maintained as base for design and advanced technology effort

- Maintenance and operations staff on-site

Senior Scientist / Management : 2 FTE
Ground, building and road maintenance: 3 FTE
Mechanical Engineer: 1 FTE
,Power management: 1 FTE,
Machine work: 1 FTE,
Technicians: 10 FTEs,
Cluster admin: 2 FTEs,
Networking: 1 FTE,
Software Engineer: 1 FTE
Digital Engineer: 1 FTE
Admin: 2 FTE
Canteen: 1 FTE
Public Archive: 2.5 FTEs

Total: 28.5 FTEs/yr + benefits + overhead = $4.1 million/yr
Power: 2000 * 100 Watts (average) per antenna + <300kW (building) = <$1 million
Equipment/parts/misc: $200k/year

Total:$5.3 million/year + 25% contingency = $6.6 million (~6% construction costs)

Risk

- **In July 2019: largest risk was receiver performance – now demonstrated**

- **In February 2020: largest perceived risk – the radio camera concept**

- Additional risk:
    - Complex and evolving RFI environment
    - Schedule risk due to drawn out EIS process
    - A-priori primary beam knowledge
    - Delay in design funding
    - MTBF poorly constrained for operations

Proposed Design Effort

- **Early conceptual design efforts ongoing**
  - i) Antenna package (Fleming and Woody)
  - ii) Wideband feed (Flygare, Weinreb)
  - iii) Transistor Modeling (Weinreb)
  - iv) Antenna size/optics trade study (De Villiers)

- Full design proposed to commence in September 2020

- Unlikely to be funded via MSIP process in Decadal Review year

- **Three independent design threads initiated**
  - i) Hardware proposal to build 6-antenna prototype array (NSF ATI: $2 million)
  - ii) Initial project management funding via Caltech – hiring of Project Manager and Project Engineer underway; initial site investigations
  - iii) Radio Camera Initiative – private funding sought

- **If endorsed by Decadal Review NSF funding will be sought in early 2021 to fund the project management and design review process, as well as EIS**

University deployment of Prototype Array

Figure 10: Locations of proposed community college and university sites for five DSA-2000 prototype dishes.

Schmidt Futures Funding

- **Discussions have been ongoing with Stu Feldman (Chief Scientist) and Eric Schmidt**

- **Year 1 funding award made in late January ($629k). The design process to commence immediately, with a particular focus on demonstrating the feasibility of the architecture proposed.**

- **Year 1 activities:**

- Optimization of our reference design configuration to further suppress imaging sidelobes, together with simultaneous investigation of alternative imaging techniques and associated array configurations.

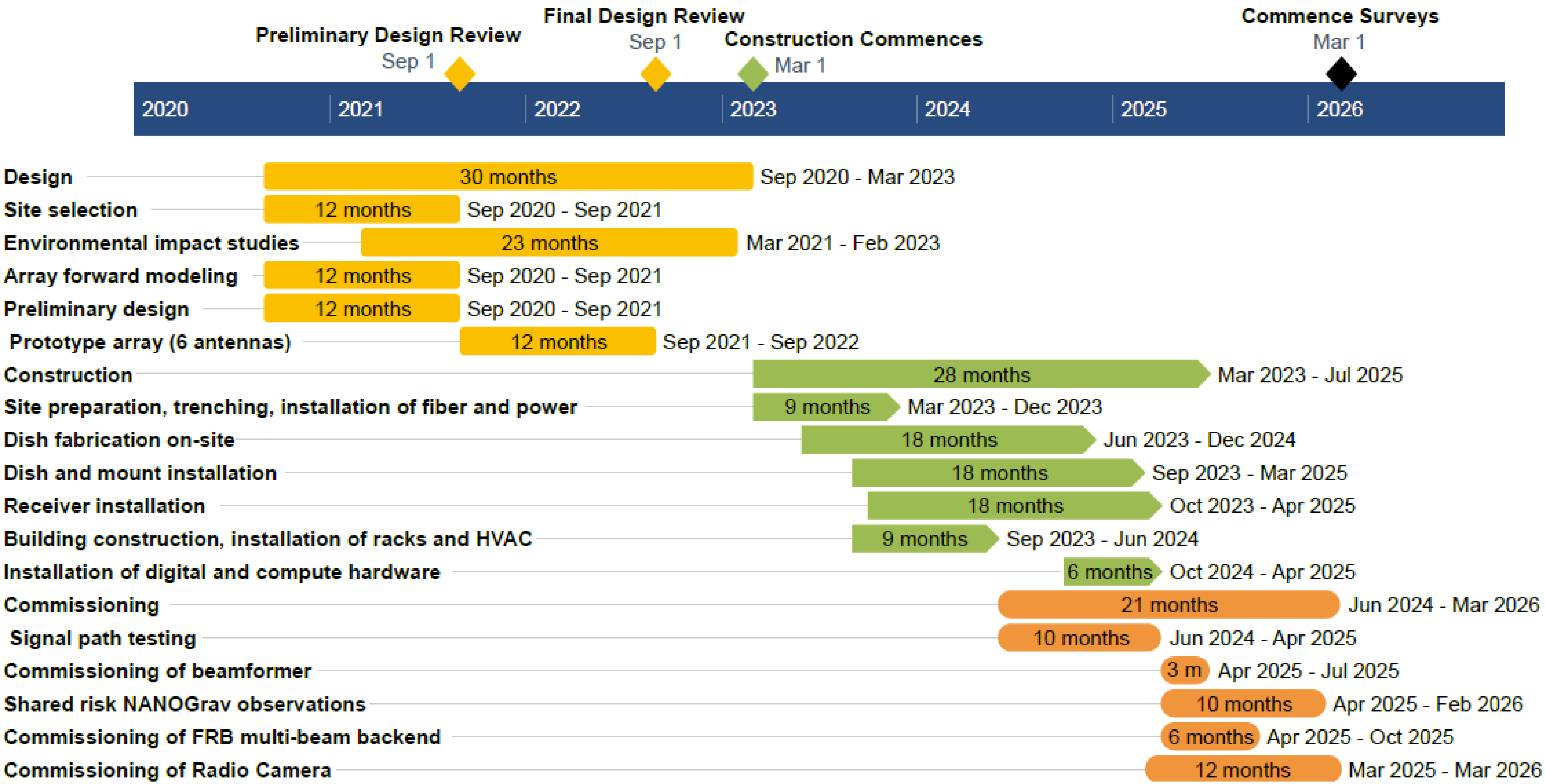
- Forward modeling of our reference design, with full inclusion of all (known) sources of possible errors, including gain variations of antenna electronics, variation of the antenna beam pattern, pointing errors, ionospheric phase screens, RFI and the impact of antenna down-time.

- Production of a model dataset for our baseline configuration for a range of representative sky pointings for the DSA-2000

- Benchmarking of existing GPU-based software for flagging, calibration and gridding/imaging with the model data set produced via forward modeling.

- Software engineering of the architecture of the overall pipeline to determine restrictions in memory, processing and I/O that must be incorporated into the algorithm choices for flagging, calibration and gridding/imaging, and the overall hardware design of the radio camera.

Proposed Timeline



Reference Design Budget

Table 2 DSA-2000 Reference Design Costs

	Estimated Cost	Contingency	Total
Design/Development	**$5 million**	**25%**	**$6.25 million**
Antennas, Mounts and Drives	$33.4 million	20%	$40.6 million
Receivers	$6.2 million	40%	$8.6 million
Infrastructure, Buildings	$17.3 million	41%	$23 million
Environmental Impact Statement	$1 million	50%	$1.5 million
Monitor/Control Hardware	$2.65 million	20%	$3.2 million
Radio Camera and Storage	$27.1 million	0%	$27.1 million
Public Archive	$2.3 million	50%	$3.5 million
Total Construction	**$88.9 million**	**20%**	**$107.5 million**
Operations/yr	**$5.3 million**	**25%**	**$6.6 million**

- Difference from APC White Paper budget (primarily in the Antennas and Receiver subsystems) due to presentation of a Reference Design
-

Proposed Funding Model

- **Construction funds via public/private partnership**

- Public funding to be requested via MSRI-R2 ($70 million)
    - i) provides rapid access to CASS data products
    - ii) 6-month cadence data release of pulsar timing data (via NANOGrav)
    - iii) rapid trigger alerts for FRBs also likely
    - iv) public alerts for GW events

- **Discussions with possible private partners in preliminary stages**
    - i) Deep field data (with public release after proprietary period)
    - ii) Polarization data (with public release catalog after proprietary period?)
    - iii) Spectral line data (with public release catalog after proprietary period?)

- **Partnership to be formally structured after PDR (includes bottom up costing)**

NGVLA

SKA

RMS Panel Questions

- **Q1: What is the project team’s plan for securing funds to serve data to the community, and is there a contingency plan (or partnership) being explored if that funding cannot be secured?**

- Public archive data are funded via the planned construction and operations funding request

RMS Panel Questions

- **Q2: How unique are the planned Hi and OH spectral line data products compared with those for other current and planned line surveys?**

- Addressed on HI science slide

RMS Panel Questions

- **Q3: Can the project team provide a more detailed Basis of Estimate for the costs of developing and operating the science software pipeline and archive?**

- Document shared with the Panel

RMS Panel Questions

- **Q4: What is the project team's proposed approach for staffing, developing, and validating an on-site fabrication facility for spun aluminum reflectors?**

- The efficient fabrication of 2,000 x 5 m dia reflectors requires construction of new a fabrication and assembly line. The existing commercial facilities are not set up for this large quantity production. Building this new facility on site avoids the cost and complications of shipping and handling. An inexpensive 10,000 sq-ft steel prefabricated steel agricultural building will handle all of the fabrication, storage and work space for this project. Labs, repair shops and offices will have heating and air conditioning and will be built interior to this building. The rest of the building will use barn heaters and swamp coolers when needed.

- The large production run will require building a more automated and robust spin-forming lathe. The plan is to contract with our existing DSA-110 reflector supplier to consult on designing and building the new spin-forming lathe. The design of the facilities and specialized machines will take 2 engineers ~6 months followed by the building, testing and verifying the fabrication process with 2 engineers and 4 mechanics/machinists over next year. The fabrication crew will consist of 2 engineers plus a crew of 10 laborers and mechanics/machinists. This crew should be able to produce 20 reflectors a week with the full production of 2,000 reflectors taking 2 years.

- Most of the people building and working on this project will reside during the work week in nearby mining communities that are ~20 miles away or in the town of Tonopah which is ~60 miles away. The town of Bishop is ~2 ½ hour drive from the site. It should only be necessary to staff the site for construction and maintenance during a 40-hour work week of 4 x 10 hour days. Workers could live elsewhere and have temporary lodging near the sire during the work week. Ideally there would be a full site manager living full-time near the site. The design and advanced technology staff will do most of their work from OVRO, which is a 3 hour drive away, or from their home institution. (Note that commercial air service to Bishop is expected to start at the end of 2020 or early 2021.)

RMS Panel Questions

- **Q5: Will the dishes for the 6-antenna prototype array be spun on site, or will commercial segmented dishes be used? If the latter, how useful will tests of the prototype array be in assessing the performance of the final antennas?**
- The ATI budget includes the cost of an escorted shipment of 6x uncut prototype antennas

RMS Panel Questions

- **Q6: Is the Owens Valley site, which appears simplest in terms of environmental impact, large enough to accommodate the proposed 15 km array? Has RFI been a problem for DSA-110 or other Owens Valley facilities (e.g., EOVSA)?**

- The Owens Valley site is too small. EIS in the Owens Valley is also much higher risk than in Nevada.

- DSA-110 makes use of a 256 MHz relatively clean band. EOVSA required divergence from the original design with aggressive filtering of RFI below 1.9 MHz

- OVRO-LWA makes use of a relatively clean band below 100 MHz

RMS Panel Questions

- **Q7: Has RFI monitoring already been done at sites other than OVRO and Deep Springs? Are such sites within 10 km of an existing power line that could handle the electrical load of DSA-2000?**

- Presented earlier in the talk.

RMS Panel Questions

- **Q8: Will forward modeling of the array performance include possible effects of RFI? What dynamic range is required of the receivers and fiber links so that RFI in a narrow frequency band does not subtly corrupt images in other frequency channels? Has the project team taken a critical look at the impacts of 5G RFI on the data products, assuming both conservative and worst-case scenarios, to determine if any design modifications are needed to meet the science goals?**

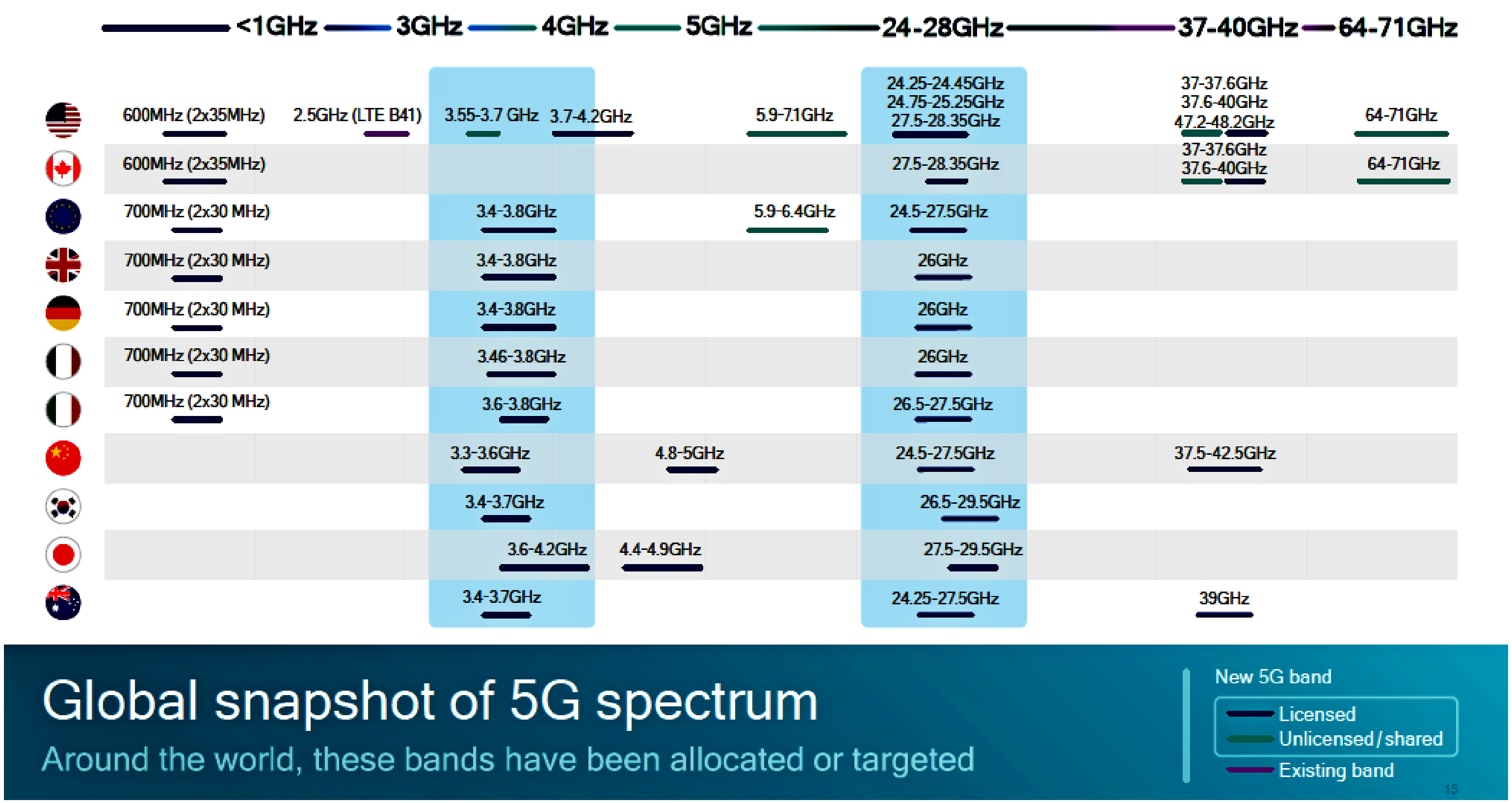
- RFI will be included in the forward modeling – e.g., impact of RFI sidelobes in the PFB on visibility data.

- The current very low noise LNA baselined for DSA2000 has a measured input 1dB gain compression power of -29dBm. RFI input power levels lower that -50 dBm with have negligible effect on the LNA gain. Taking OVRO as a worst case, the peak RFI power at peak frequency of 1950 MHz is -70dBm into the -30 dB sidelobe level of a 5m paraboloid and less into the feed spillover. The levels in the candidate sites are much lower.

- Taking OVRO as a worst case, the peak RFI power at peak frequency of 1950 MHz is -70dBm into the -30 dB sidelobe level of a 5m paraboloid and less into the feed spillover. The levels in the candidate sites are much lower.

RMS Panel Questions

- Most of the 5G communications is at frequencies above, 24.25 GHz, see the spectrum snapshot below.. There are bands for 600 MHz, 2.5 GHz, and 3.6 GHz assigned in the US – all out of the 700 MHz to 2GHz planned for DSA2000. The 600 MHz and 2.5 GHz bands are close to the LNA operating frequency but the level is too low to be a problem (see next point). The millimeter wave frequencies can easily be filtered in the DSA2000 feeds and LNAs.



RMS Panel Questions

- **Q10: When are science operations with DSA-110 expected to commence? Will there be time to fold lessons from DSA-110 into the design for DSA-2000?**

- Commissioning scheduled for September 2020, with full science operations in March 2021

- Data will be available (e.g. MTBF) for input to the DSA-2000 design

RMS Panel Questions

- **Q9: Can the project team provide proof-of-concept evidence from existing facilities for the successful excision of RFI in real-time processing.**

- LOFAR and SKA are exploring real-time data flagging

- E.g. An AOFlagger-based implementation is discussed in van Nieuwpoort (1701.08197)

RMS Panel Questions

- **Q11: What are the current prospects for securing $26M (of a total $96M cost) from non-federal partners?**

- Discussed in earlier slide.

RMS Panel Questions

- **Q12: What assumptions about mean time between failures (MTBF) and rate of repair inform the project's maintenance plan?**

- Antennas are being designed for low maintenance operations but true MTBF data will not be available until late in the design stage

- Current estimate is that it will take a staff of 10-20 people to maintain a 95% (1,900 antennas) uptime given the huge quantity of antenna drives, antenna electronics, power systems, digital electronics and AC that we will have.

- Estimates are based on staff experience ranging from OVRO-LWA (very low maintenance) through to DSA-10 and CARMA (high maintenance)

RMS Panel Questions

- **Q13: What is the minimum number of antennas that must be on line simultaneously in order to enable the proposed approach of eliminating visibility-based deconvolution? (If the answer depends on whether antennas are unavailable because they are down for maintenance, or were never built due to a project descope, please specify.)**

- Eliminating visibility-based deconvolution requires low far sidelobes, which scale as 1/N. 100 antennas down for maintenance at a time will not affect the far sidelobes much (5%). Correlated failure modes can increase this impact and should be accounted for in the design effort. On-the-fly PSFs will be generated for each planned image-plane deconvolution direction.

RMS Panel Questions

- **Q14: The sensitivity calculations presented in the RFI response assume 100% beam-forming efficiency. Has a more realistic efficiency been estimated that takes into account various losses (phase noise, quantization, etc.)?**

- Quantization losses are less than 2%. Phase noise losses are negligible due to calibration data from radio camera.

RMS Panel Questions

- **Q15: Cost estimates for data storage and backup have been derived by scaling from DSA-110, but can those approaches be realistically scaled to meet expected needs? Are there new disk or tape technologies coming on line that could reduce these costs?**

- Cost estimates for storage and back-up are based on 2019 data (BeeGFS with ZFS) and include options for managed maintenance.

RMS Panel Questions

- **Q16: Can the project team describe in more detail the envisioned VLBI mode of operation? For example, how will the data stream be formatted, time stamped, and recorded for correlation with other VLBI sites? How and where will the VLBI correlation be performed?**

- Reference design does not include costs for VLBI recorder but include the possibility of subsequent upgrade.

- VLBI option is perceived as a vehicle for community engagement and can involve universities and existing VLBI facilities. Certain science cases do not need VLBI-specialized hardware (FRBs).

RMS Panel Questions

- **Q17: Would eliminating the spectral line component of the survey significantly impact cost, e.g., by simplifying RFI mitigation and/or significantly decreasing the required spectral resolution (and thus the total data volume)?**

- It would reduce the requirements for storage, but not the spectral resolution (outside the zoom-in bands for HI and OH), as this is driven by bandwidth smearing requirements (<1% reduction in peak response).