Long Haul Fiber Workgroup Preliminary Report

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1 Project Introduction

The Next Generation Very Large Array (ngVLA) is a project of the National Radio Astronomy Observatory (NRAO) to design and build an astronomical observatory that will operate at centimeter wavelengths (25 to 0.26 centimeters, corresponding to a frequency range extending from 1.2 GHz to 116 GHz). The observatory will be a synthesis radio telescope constituted of approximately 244 reflector antennas each of 18 meters diameter, and 19 reflector antennas each of 6 meters diameter, operating in a phased or interferometric mode.

The facility will be operated as a proposal-driven instrument with the science program determined by Principal Investigator (PI)-led proposals. Data will generally be delivered to PIs and the broader scientific community as Science Ready Data Products; automated pipelines will calibrate raw data and create higher-level data products (typically image cubes). Data and quality assured data products will be available through an Observatory science archive. Data exploration tools will allow users to analyze the data directly from the archive, reducing the need for data transmission and reprocessing at user institutions.

The array signal processing center will reside at the Very Large Array site on the Plains of San Agustin, New Mexico. The array will include stations in other locations throughout New Mexico, west Texas, eastern Arizona, and northern Mexico. LBA stations will be located in Hawaii, Washington, California, Iowa, Massachusetts, New Hampshire, Puerto Rico, the US Virgin Islands, and Canada.

Array Operations will be conducted from both the VLA Site and the Array Operations and Repair Centers in Socorro, NM. A Science Operations Center and Data Center will likely be located in a large metropolitan area and will be the base for science operations and support staff, software operations, and related administration. Research and development activities will be split amongst these centers as appropriate.

1.1 Scope of this Document

The ngVLA Long-Haul Fiber Work Group (FWG) was charged with providing a Reference Design for the long-haul fiber and associated connectivity needs of the Mid-Baseline (MB) stations and the Long Baseline Array (LBA). The Mid-Baseline stations refer to all Main Array antennas outside the spiral arm structure on the Plains of San Agustin. This work intersects with several other work packages that are described in [AD02] through [AD09].

1.2 Applicable Documents

The following documents are applicable to this design report and are incorporated by reference. In the event of conflict, the applicable document supersedes the content of this report.

Ref. No.	Document Title	Rev / Doc. No.
AD01	ngVLA System Reference Design	020.10.20.00.00-0001-REP
AD02	Array Configuration: Preliminary Requirements	020.23.00.00.00-0001-REQ
AD03	Array Configuration: Reference Design Description	020.23.00.00.00-0002-DSN
AD04	Digital Back End & Data Transmission System: Preliminary Requirements	020.30.25.00.00-0001-REQ
AD05	Digital Back End & Data Transmission System: Reference Design	020.30.25.00.00-0002-DSN
AD06	LO Reference and Timing: Preliminary Requirements	020.35.00.00.00-0001-SPE
AD07	LO Reference and Timing: Reference Design	020.35.00.00.00-0002-DSN
AD08	Computing & Software Systems: Reference Design Architecture	020.50.00.00.01-0002-REP
AD09	Buildings & Array Infrastructure Reference Design Study	020.60.00.00.01-0002-REP

2 Fiber Workgroup Summary

The ngVLA Long-Haul Fiber Work Group (FWG) was charged with providing a Reference Design for the long-haul fiber and associated connectivity needs of the Mid-Baseline (MB) stations and Long Baseline Array (LBA). The current ngVLA design calls for 168 antennas within the core and spiral arms of the Main Array connected with trenched fiber, in addition to the 19 antennas of the Short Baseline Array (SBA). The Mid-Baseline stations are the 46 Main Array antennas beyond the spiral arms on the Plains of San Agustin. An additional 30 antennas will make up the Long Baseline Array, for a total of 263 ngVLA antennas.

The 46 antennas located at the MB stations will extend approximately 800 km from the core. The Working Group identified a 300 km radius from the core as being the maximum extent to which dark fiber would be practical for local oscillator (LO) and timing reference propagation (Figure 1, shown in green). To formulate a construction and operations model, it is proposed that stations within this radius be connected using a daisy-chain architecture for dark fiber connectivity (shown in red). This allows for LO and data signal regeneration since all station links within this radius are less than the 80 km maximum for unrepeated signal propagation.

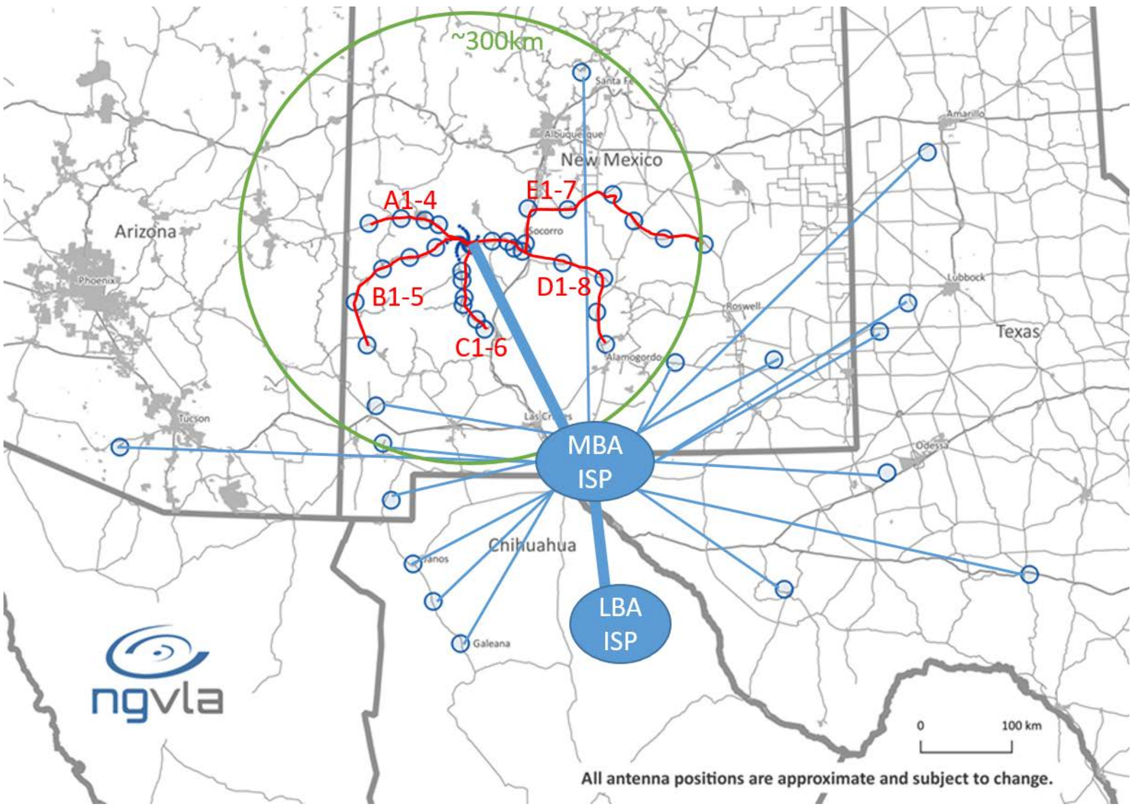

Figure 1 - ngVLA Main Array [AD03]. Approximately 168 antennas are located on the Plains of San Agustin, and 46 antennas are outside the five-spiral-arm configuration.

As Figure 1 shows, stations beyond this radius (currently 16), as well as the 30 antennas associated with the Long Baseline Array (LBA), will be serviced via a strategic partnership with an Internet Service Provider (ISP). LO and timing references for these stations must be provided by local references [AD06, AD07].

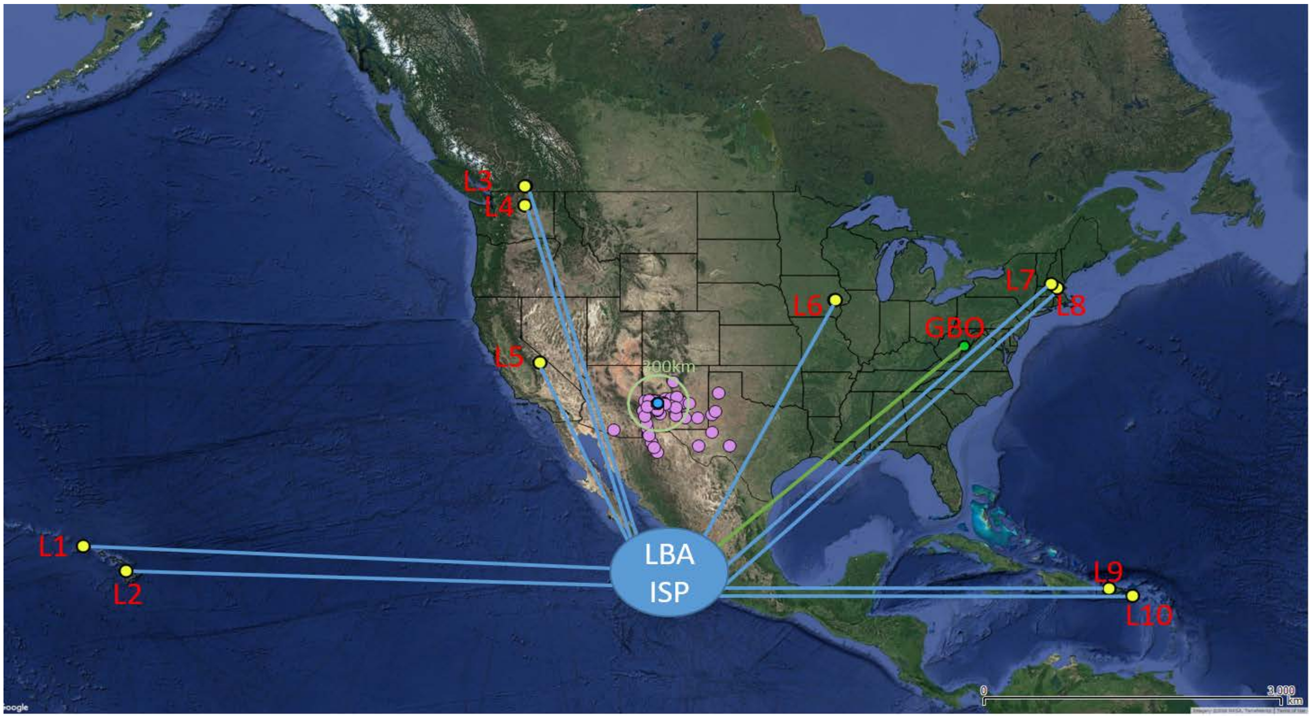

Figure 2 - ngVLA LBA sites are shown in yellow, GBT site in green, and ngVLA SBA and Main Array in blue and purple respectively. The configuration includes 30 LBA antennas, distributed per the table below [AD03].

# of Antennas	Location	Possible Sites
3	Puerto Rico	Arecibo Observatory.
3	St. Croix	Existing VLBA site.
3	Kauai, Hawaii	Kokee Park Geophysical Observatory.
3	Hawaii, Hawaii	New site.
2	Hancock, NH	Existing VLBA site.
3	Westford, MA	Haystack Observatory.
2	Brewster, WA	Existing VLBA site.
3	Penticton, BC	Dominion Radio Astrophysical Observatory.
4	North Liberty, IA	Existing VLBA site.
4	Owens Valley, CA	Existing VLBA site.

Table 1 summarizes the connectivity arrangement envisaged by the Working Group.

Sub-Array	# of Antennas	Antenna Diameter	Trenched Fiber	Commercial Fiber—Dark	ISP	Distance from Array Center
MA: Core	94	18m	94	0	0	0–1 km
MA: Spiral Arms	74	18m	74	0	0	1–30 km
Mid-Baseline	46	18m	0	30	16	30–1000 km
Main Array Total	**214**		**168**	**30**	**16**	
SBA	19	6m	19	0	0	0.1 km
LBA	30	18m	0	0	30	1050–5300 km
ngVLA Total	**263**		**187**	**30**	**46**	

Table 1 - ngVLA configuration by antenna number and type, fiber network connection, and distance from array center.

The ngVLA data rates are substantial, with individual antennas outputting 320 Gbps each. However, *these data rates can be accommodated with present technology*, even over the ISP links. The technical risk associated with this approach is low, with the uncertainty being in the cost estimate and the likely cost scaling that can be expected from today to the start of early science operations in 2028, and full operations by 2035.

3 Fiber Workgroup Membership

The ngVLA FWG membership is selected to provide broad expertise and representation of interests in ngVLA network infrastructure, utility system construction, data transmission, and frequency reference transmission. The number of people serving on the FWG is not set. The FWG is overseen by a chair who is responsible for coordinating the group's activities.

FWG members currently include:

- David Halstead (Chair)
- Viviana Rosero (Array Configuration)
- Alan Erickson (GIS Database)
- Jim Jackson (Data Transmission System)
- Bill Shillue (Time & Frequency Distribution)
- Christophe Jacques (Time & Frequency Distribution)
- Omar Ojeda (Central Signal Processor)
- Kevin Baker (Array Infrastructure)
- Chris Langley (Array Infrastructure)
- Jody Bolyard (Land Acquisition & Reg. Compliance)
- Derek Hart (Lead Network Administrator)

Additional members will be added based on suggestions from the Project Director or the Chair.

Ex-Officio members include:

- Rob Selina (ngVLA Project Engineer)
- Rafael Hiriart (ngVLA Software & Computing IPT Lead)

4 Design Assumptions

The following assumptions are inherent in the proposed design.

- Data will be transmitted over 100 Gbps IPv6 streams employing standard protocols such as UPD (no guarantee of delivery) or TCP (re-transmit of lost packets) depending on data profiles.
- Packet size will be maximized (~64 KB).
- Data streams will be multiplexed via wavelength separation to improve fiber utilization: 800 Gbps is the current norm for an individual long-haul single mode fiber.
- The maximum unrepeated fiber distance for LO timing and 100 Gbps Ethernet is 80 km.
- Dark fiber will be provisioned over 24-strand single-mode fiber using ZX (or equivalent) optics.
- Fiber is trenched for the main array central cluster and spiral arms, and for the small baseline array. For commercial fiber in the mid-baseline array, existing commercial fiber infrastructure will be used where available, either buried or pole strung (usually in place for power distribution).
- Current costs for 10 Gbps network technology will approximate to 100 Gbps technology in eight to ten years (a conservative Moore's Law projection).
- The model assumes that each single-mode fiber strand can carry 800 Gbps of data.
- No replacement funds are allocated beyond warranty maintenance for addressing hardware failure during construction.
- Maximum data rate from any single antenna is 320 Gbps, requiring four 100-Gbps circuits.
- LO reference signals require dark fiber reserved in each bundle for "home-run" strands to the central time source (using passive signal regeneration at every 80 km or less). This requires bidirectional transmission.
- The model includes no LO components other than the fiber.
- Post-correlation data will flow to a national data center for processing and archiving with a maximum data rate of 800 Gbps.
- The correlator has ~250 ms of delay tolerance from station send to receive, which implies that lost or out-of-sequence packets will not be viable.
- The MB station fiber network topology is not provisioned as fiber loops, meaning only a single path exists for any given source. This has the advantage of simplifying the network hardware (no IP routing) but will impact availability (see risks).
- Each of the 30 LBA stations (distributed between 10 sites) will require 320 Gbps of bandwidth per antenna.
- At each step along each chain, the hardware required for repeating the signals from downstream stations will be co-located with that station's network hardware. For some chains, this will result in a substantial footprint of repeating equipment; e.g., Station D1 will be servicing 14 downstream stations. A fiber build path factor was added to the inter-site fiber lengths obtained from GIS data to reflect the actual installed length vs. point-to-point distance available.
- This model does not include correlator network switch hardware costs, as these will be included in the CSP budget.

5 Recommendations

A clear differentiation exists between the stations to which the project can run dark fiber and those for which ISPs providing lit service must be engaged. It is strongly recommended that the dark fiber be owned and managed by a local service provider (for installation and fiber repair) but that the ngVLA provide the lit service electronics to these stations. Typically, stations with dark fiber will have a higher construction cost but lower recurrent operations cost. ISP-serviced stations will require last-mile fiber provisioning, and the monthly recurrent cost (MRC) will be high with unpredictable variability per location depending on installed infrastructure and upstream service partner(s).

It is important that the ngVLA project identify a National Research serving partner for coordinating the provisioning and operations management of infrastructure of this scale; current candidates would, for example, include Internet 2 and ESNet. The current model predicts a total fiber length of ~1,100 km to service the 30 MB stations being provisioned with dark fiber.

The LBA station costs will be weighted toward operations since service providers are reluctant to give access to dark fiber and tend to charge by capacity. Provisioning a low "committed" rate (tens of Gbps) with a much higher "burstable" rate (320 Gbps) may be possible with quality of service and priority of service definitions being useful to align service expectations. The project should define these to be recognizable by ISPs.

ISP contracts based around IRUs (e.g., 10+ year indefeasible right of use) are essential for amortizing the initial cost but will result in higher operating costs. Partnering with ISPs to access NTIA and Federal communications grants should be explored especially for EPSCoR locations (e.g., NM, Hawaii, US Virgin Islands). ISP contracts should assume no access to commodity Internet services. This will simplify the infrastructure and reduce the security overhead at the sites. A separate commodity service (e.g., 10 Mbps) should be provisioned for basic network needs such as M&C connectivity, visiting service technicians, security cameras, and alerts.

Engaging a support partner for operating and supporting the fiber (e.g., American Tower, Crown Castle, or SBA Communications) may prove beneficial since their business model permits distributed communications technology infrastructure support. The project would also benefit from their insight into current wireless communications infrastructure placement.

Identification of "anchor" institutes within individual stations' geographic regions could prove useful in coordinating fiber construction and sponsoring network access operations. VLBA experience has shown that this model works well, but does increase the management overhead overall due to distributed ownership.

6 Budget Model

The model identifies four main costing items:

- dark fiber installation and operation (based on a distance scaling),
- network switch gear purchase and maintenance (in units of 100 Gbps),
- equipment needed for network signal regeneration (LO signal regeneration requirements are tracked elsewhere), and
- ISP lit service costs (in units of 100 Gbps/year)

The current working model (Appendix 8.1) is populated with order of magnitude dollar amounts for proof of concept purposes. The model intends to allow for a defensible Basis of Estimate parameterization.

7 Identified Risks

- Any assumption of "Moore's Law" value scaling is an approximation and may not apply to each technology equally.
- The daisy-chain model assumes a risk from fiber damage and single-path availability that would result in multiple stations being taken off-line in the event of a localized fault along the fiber chain. In the worst case, 15 of the Mid-Baseline stations could be impacted by a single failure.
- The power and cooling needed for signal regeneration (LO and data) must be factored into station design.
- The use of aerial strung fiber may not be appropriate for LO signal distribution over long distances due to thermal fluctuations, but the cost of trenched fiber will be two to three times higher.
- Stations in areas of low population density have the associated challenge that local broadband providers will not have exposure of infrastructure to support a Peta-scale communications initiative.
- The aggregation of ISP data flowing from the 16 MB stations and 30 LBA antennas will be massive and will need a co-location demarcation point.
- The four MB Stations outside of the US (three in Mexico and one in Canada) and Island sites will present unique issues for bandwidth provisioning.
- The ISP-supported stations will often have a local service provider for last-mile access from the site to the backbone infrastructure managed by a national carrier (e.g. Level3/Century Link, Verizon, AT&T). This can result in accountability gaps especially for ownership of intermittent throughput performance issues.

8 Appendix

8.1 ngVLA Long Haul Fiber Costing Model

ngVLA Long Haul Fiber costing model for 46 Mid Baseline Stations and 10 Long Baseline Array sites
October 2018

Parameters						
Build				Operations		
Fiber Build/km	400G Router/ Switch	100Gbps repeater	Fiber Build Path factor (GIS vs. actual)	Fiber strand/km/year	Operating per 100Gbps/year	Annual Maintenance % of purchase
$20,400	$50,000	$2,000	1.20	$500	$72,000	10%

	MBA	LBA	Total
Construction cost:	$26,540,592	$3,224,400	$29,764,992
Annual Operating cost:	$6,809,490	$8,940,000	$15,749,490

Site	Inbound Neighbor	Inbound fiber (km)	100Gbps circuits	Network Hardware	Fiber Build	Operating
A1 (m105)	Core (via m059)	30.0	16	$82,000	$612,000	$38,200
A2 (m78)	A1 (m105)	19.1	12	$74,000	$389,232	$21,710
A3 (m107)	A2 (m78)	31.2	8	$66,000	$636,480	$22,200
A4 (m082)	A3 (m107)	43.0	4	$58,000	$876,384	$16,540
B1 (m107)	Core (via m074)	36.0	20	$90,000	$734,400	$54,000
B2 (m080)	B1 (m106)	36.7	16	$82,000	$749,088	$44,920
B3 (m111)	B2 (m80)	38.8	12	$74,000	$790,704	$36,470
B4 (m81)	B3 (m111)	56.9	8	$66,000	$1,160,352	$35,040
B5 (m108)	B4 (m81)	58.8	4	$58,000	$1,199,520	$20,500
C1 (m109)	Core (via m015)	30.0	24	$98,000	$612,000	$54,800
C2 (m79)	C1 (m109)	11.9	20	$90,000	$242,352	$23,850
C3 (m110)	C2 (m79)	23.3	16	$82,000	$474,912	$31,480
C4 (m092)	C3 (m110)	9.5	12	$74,000	$193,392	$14,510
C5 (m084)	C4 (m092)	26.3	8	$66,000	$536,112	$19,740
C6 (m087)	C5 (m084)	16.8	4	$58,000	$342,720	$10,000
D1 (m093)	Core (via m044)	42.0	60	$170,000	$856,800	$174,500
D2 (m102)	D1 (m093)	20.3	56	$162,000	$413,712	$87,180
D3 (m103)	D2 (m102)	12.2	52	$154,000	$249,696	$55,180
D4 (m104)	D3 (m103)	11.5	48	$146,000	$235,008	$49,160
D5 (m099)	D4 (m104)	55.3	16	$82,000	$1,128,528	$63,520
D6 (m100)	D5 (m099)	57.7	12	$74,000	$1,177,488	$50,690
D7 (m089)	D6 (m100)	45.6	8	$66,000	$930,240	$29,400
D8 (m090)	D7 (m089)	44.3	4	$58,000	$903,312	$16,870
E1 (m094)	D4 (m104)	12.0	28	$106,000	$244,800	$31,600
E2 (m096)	E1 (m094)	46.6	24	$98,000	$949,824	$79,640
E3 (m097)	E2 (m096)	52.3	20	$90,000	$1,067,328	$74,400
E4 (m098)	E3 (m097)	62.5	16	$82,000	$1,275,408	$70,720
E5 (m085)	E4 (m098)	44.6	12	$74,000	$910,656	$40,880
E6 (m091)	E5 (m085)	46.2	8	$66,000	$942,480	$29,700
E7 (m113)	E6 (m091)	53.2	4	$58,000	$1,084,464	$19,090
ISP1		1.0	4	$50,000	$20,400	$293,000
ISP2		1.0	4	$50,000	$20,400	$293,000
ISP3		1.0	4	$50,000	$20,400	$293,000
ISP4		1.0	4	$50,000	$20,400	$293,000
ISP5		1.0	4	$50,000	$20,400	$293,000
ISP6		1.0	4	$50,000	$20,400	$293,000
ISP7		1.0	4	$50,000	$20,400	$293,000
ISP8		1.0	4	$50,000	$20,400	$293,000
ISP9		1.0	4	$50,000	$20,400	$293,000
ISP10		1.0	4	$50,000	$20,400	$293,000
ISP11		1.0	4	$50,000	$20,400	$293,000
ISP12		1.0	4	$50,000	$20,400	$293,000
ISP13		1.0	4	$50,000	$20,400	$293,000
ISP14		1.0	4	$50,000	$20,400	$293,000
ISP15		1.0	4	$50,000	$20,400	$293,000
ISP16		1.0	4	$50,000	$20,400	$293,000
ISP Core (MBA)		1.0	64	$800,000	$20,400	$80,000
LBA1		1.0	8	$100,000	$20,400	$586,000
LBA2		1.0	8	$100,000	$20,400	$586,000
LBA3		1.0	12	$150,000	$20,400	$879,000
LBA4		1.0	12	$150,000	$20,400	$879,000
LBA5		1.0	12	$150,000	$20,400	$879,000
LBA6		1.0	12	$150,000	$20,400	$879,000
LBA7		1.0	12	$150,000	$20,400	$879,000
LBA8		1.0	12	$150,000	$20,400	$879,000
LBA9		1.0	16	$200,000	$20,400	$1,172,000
LBA10		1.0	16	$200,000	$20,400	$1,172,000
ISP Core (LBA)		1.0	120	$1,500,000	$20,400	$150,000
Archive Data Center link		1	10	$50,000	$20,400	$725,000

8.2 *Acronyms and Abbreviations*

Acronym	Description
AD	Applicable Document
CSP	Central Signal Processor
DB	Data Base
DBE	Digital Back End
DTS	Data Transmission System
EPSCoR	Established Program to Stimulate Competitive Research
FWG	Fiber Working Group
Gbps	Giga-bits per second
GIS	Geographic Information System
IP	Internet Protocol
IPT	Data Transmission System
IRU	Indefeasible Right of Use
ISP	Internet Service Provider
ITU	International Telecommunication Union
LBA	Long Baseline Array
LO	Local Oscillator
MA	Main Array
MB	Mid-Baseline
MRC	Monthly Recurrent Cost
ngVLA	Next Generation Very Large Array
NTIA	National Telecommunications and Information Administration
PI	Principal Investigator
RD	Reference Document
SBA	Short Baseline Array
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
VLBA	Very Long Baseline Array
ZX	1000BASE-ZX, a nonstandard but multivendor term, refers to Gigabit Ethernet using a 1550 nm wavelength to transmit data 70+ km over single-mode fiber.