Next Generation Very Large Array (ngVLA):
Long Haul Fiber Workgroup Preliminary Report

020.60.00.00.00-0002-REP
Version 03: 10/08/2018
Status: **DRAFT**

Authored by:
David Halstead, Derek Hart, Alan Erickson, Bill Shillue, Rob Selina

Approved By:		
Name	Role	Signature
R. Selina	ngVLA Project Engineer	
K. Cosper	ngVLA Project Manager	
Released By:		
Name	Role	Signature
M. McKinnon	ngVLA Project Director	

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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 made 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 the user’s institution.

The signal processing center of the array will be located at the Very Large Array site, on the plains of San Agustin, New Mexico. The array will include stations in other locations throughout the state of New Mexico, west Texas, eastern Arizona, and northern Mexico. Long baseline stations are 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 collocated 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 Long Baseline Array (LBA).

This work intersects with a number of 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.

Reference No.	Document Title	Rev / Doc. No.
AD 01	ngVLA System Reference Design	020.10.20.00.00-0001-REP
AD 02	Array Configuration: Preliminary Requirements	020.23.00.00.00-0001-REQ
AD 03	Array Configuration: Reference Design Description	020.23.00.00.00-0002-DSN
AD 04	Digital Back End & Data Transmission System: Preliminary Requirements	020.30.25.00.00-0001-REQ
AD 05	Digital Back End & Data Transmission System: Reference Design	020.30.25.00.00-0002-DSN
AD 06	LO Reference and Timing: Preliminary Requirements	020.35.00.00.00-0001-SPE
AD 07	LO Reference and Timing: Reference Design	020.35.00.00.00-0002-DSN
AD 08	Computing & Software Systems: Reference Design Architecture	020.50.00.00.01-0002-REP
AD 09	Buildings & Array Infrastructure Reference Design Study	020.60.00.00.01-0002-REP

1.3. Reference Documents

The following documents provide additional material or supporting context.

Reference No.	Document Title	Rev / Doc. No.

1.4. Acronyms and Abbreviations

Acronym	Description
AD	Applicable Document
EPSCoR	Established Program to Stimulate Competitive Research
FWG	Fiber Working Group

Acronym	Description
GIS	Geographic Information System
IP	Internet Protocol
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	

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).

46 antennas are located in the MB stations extending 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 LO timing propagation (Figure 1, shown in Green). In order to formulate a build and operations model, it was proposed that stations within this radius would be connected using a daisy-chain architecture for dark fiber connectivity (shown in Red). This allows for LO and data signal regeneration since all stations within this radius are less than the 80 km maximum for unrepeated signal propagation. Stations beyond this radius (currently 16), as well as the 30 antennas associated with the Long Baseline Array (LBA) will be

serviced via strategic partnership with an Internet Service Provider (ISP) see Figure 2. LO timing for these stations must be provided from a local time reference. [AD 07, 08]

A summary of the arrangement envisaged by the Working Group is shown in Table 1.

Table 1- Composition of ngVLA by number and type of antenna, type of connection to fiber networks, and distance from array center

Sub-Array	Number of Antennas	Antenna diameter	Trenched fiber	Commercial fiber - dark	Internet Service Provider	Distance from Array Center
MA - Core	94	18m	94	0	0	0-1km
MA - Spiral Arms	74	18m	74	0	0	1-30km
Mid-Baseline	46	18m	0	30	16	30-1000km
Main Array Total	*214*		*168*	*30*	*16*	
Small Baseline Array (SBA)	19	6m	19	0	0	0.1km
Long Baseline array (LBA)	30	18m	0	0	30	1050-5300 km
ngVLA Total	*263*		*187*	*30*	*46*	

The ngVLA data rates are large, 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 scaling with Moore's Law that can be expected from today to the start of early science operations in 2028, and full operations by 2035.

The roles and responsibilities of the ngVLA FWG are summarized below.

3. Fiber Workgroup Membership

The membership of the ngVLA FWG will be selected to provide a breadth of 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 will be overseen by a chair, who will be responsible for coordinating the group's activities.

FWG Members:

1. David Halstead (Chair)

2. Viviana Rosero (Array Config)
3. Alan Erickson (GIS DB)
4. Jim Jackson (DBE/DTS)
5. Bill Shillue (Time & Freq Distrib)
6. Christophe Jacques (Time & Freq Distrib)
7. Omar Ojeda (CSP)
8. Kevin Baker (Array Infrastructure)
9. Chris Langley (Array Infrastructure)
10. Jody Bolyard (Land Acquisition & Reg. Compliance)
11. Derek Hart (Lead Network Administrator)

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

Ex-Officio members:

1. Rob Selina (ngVLA Project Engineer)
2. Cristina Simon (ngVLA Systems Engineer)
3. Rafael Hiriart (ngVLA Software & Computing IPT Lead)

4. Design Assumptions

The following assumptions are inherent in the design proposed:

- Data will be transmitted over 100Gbps IP V6 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 (~64k Bytes)
- It is expected that these 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 the small baseline array. For commercial fiber in the mid-baseline array existing commercial fiber infrastructure will be used; 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 8-10 years (conservative Moore’s Law projection).
- It is assumed that each single-mode fiber strand can carry 800 Gbps of data.

- No replacement funds are allocated beyond warranty maintenance for addressing hardware failure.
- Maximum data rate from any single antennae is 320 Gbps, requiring four 100 Gbps circuits.
- LO timing signals will require dark fiber reserved in each bundle for “home-run” strands to the central time source (using passive signal regeneration at a maximum of every 80 km). Note: Bidirectional transmission is needed.
- No LO components, other than fiber, are included in the model.
- Post-correlation data will flow to a national data center for processing and archival 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 fiber network topology for the MB stations is not provisioned as fiber loops, meaning that there is only a single path 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.
- At each step along each of the chains, the hardware required for repeating the signals from down-stream stations will be co-located with the network hardware for that station. For some of the chains, this will result in a substantial footprint of repeating equipment; e.g. Station D1 will be servicing 14 down-stream 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.
- No cost of correlator network switch hardware is included in this cost model.

5. Recommendations

There is a clear differentiation between the stations to which dark fiber can be run by the project, and those for which an ISP providing lit service are to 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 operations recurrent cost. ISP services stations will require “last-mile” fiber provisioning, but the monthly recurrent cost (MRC) will be high with unpredictable variability per location depending on installed infrastructure and up-stream service partner(s).

It is important that the ngVLA project identify a National Research serving partner for coordinating the provisioning and operations management of an 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 cost of the LBA stations will be weighted toward operations since service providers are reluctant to give access to dark fiber and tend to charge by capacity. The opportunity of provisioning a low “committed” rate (10s of Gbps) with a much higher “burstable” rate (320 Gbps) may be possible with definitions around quality of service and priority of service being useful to align service expectations. These should be defined by the project in a way that is recognizable by ISPs.

ISP contracts based around IRUs (e.g. 10+ year indefeasible right of use) will be essential for amortizing the initial cost, but will result in higher operating costs. The possibility of partnering with ISPs to access NTIA and federal communications grants should be explored especially for EPSCoR locations (e.g. NM, Hawaii, U.S. Virgin Islands).

ISP contracts should be conducted with the expectation of 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 connectivity needs for M&C, visiting service technicians, security cameras, and alerts.

There is an opportunity to engage a support partner for operating and supporting the fiber (e.g. American Tower, Crown Castle or SBA Communications) since their business model allows for support of a distributed communications technology infrastructure. The project would also benefit from their insight into placement of current wireless communications infrastructure.

Identification of “anchor” institutes within the geographic region of individual stations is a key enabler in coordinating fiber construction and sponsoring network access operations. Experience from the VLBA has shown that this model works well, but does increase the management overhead overall due to distributed ownership.

6. Budget Model

The model identifies 4 main areas items for costing:

- 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 timing regeneration requirements tracked elsewhere)
- ISP lit service costs (in units of 100 Gbps/year)

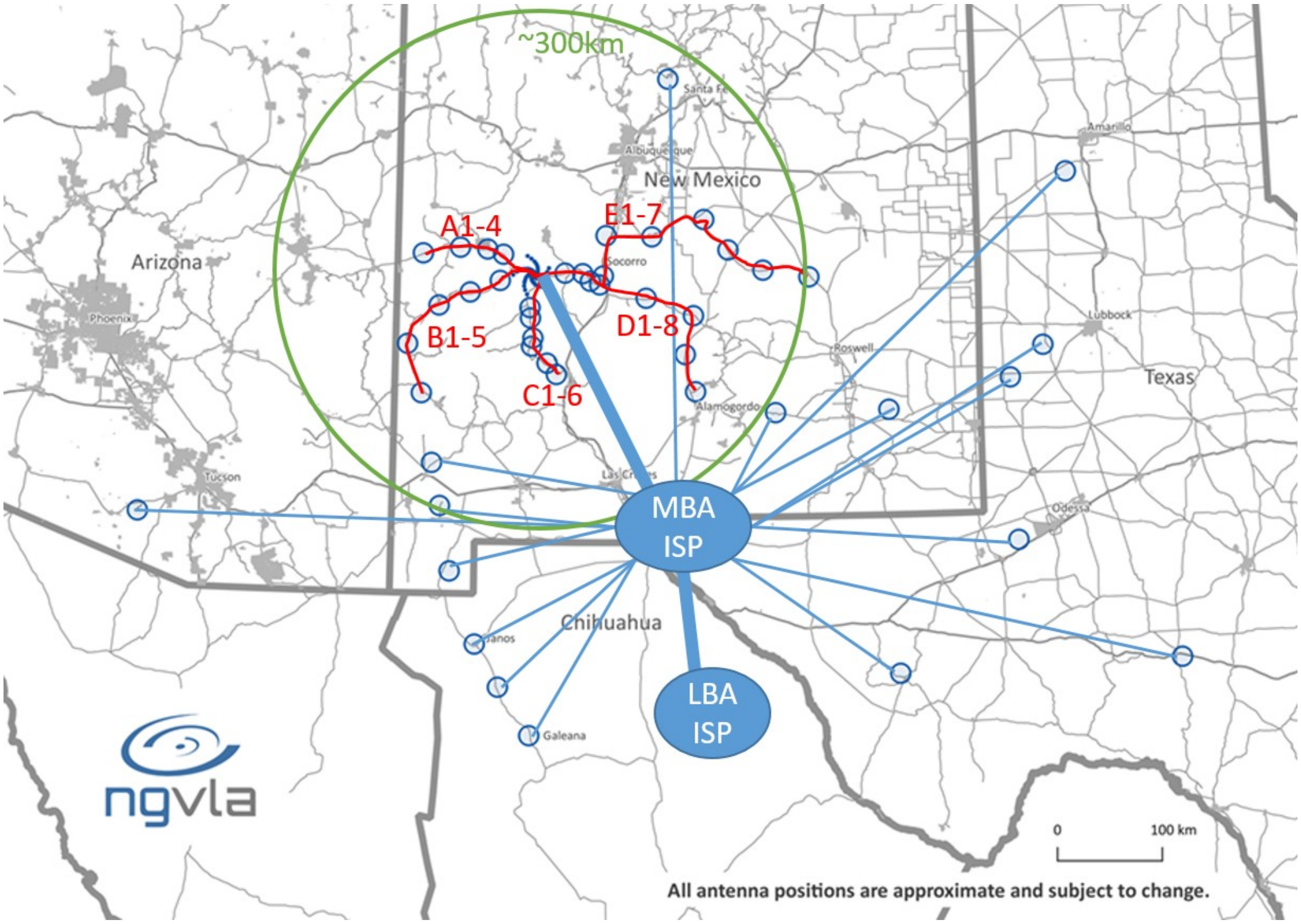
Current working model (Appendix A) is populated with order of magnitude $ amounts, but only for proof of concept purposes. The intent of this model is to allow for a defensible Basis of Estimate parameterization.

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.
- The power and cooling needed for signal regeneration (LO and data) needs to be factored into the 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 2-3 time higher.
- Stations are in areas of low population density with 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 antennae will be massive and will need a co-location demarcation point.
- The 4 MB Stations outside of the US (3 in Mexico and 1 in Canada) and Island sites will present unique issues for bandwidth provisioning.
- For the ISP supported stations, there will often be 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) and this can result in accountability gaps especially for ownership of intermittent throughput performance issues.

8. Figures

Figure 1 - ngVLA Main Array. [AD03] Approx 168 antennas are located on the plains of San Agustin. 46 antennas are outside the 5-spiral arm configuration.



~300km
Santa Fe
Albuquerque
New Mexico
Amarillo
Arizona
A1-4
E1-7
Socorro
Phoenix
B1-5
D1-8
Lubbock
Roswell
Texas
C1-6
Alamogordo
Tucson
Las Cruces
MBA
ISP
Odessa
Chihuahua
LBA
ISP
Galeana
ngvla
0
100 km
All antenna positions are approximate and subject to change.

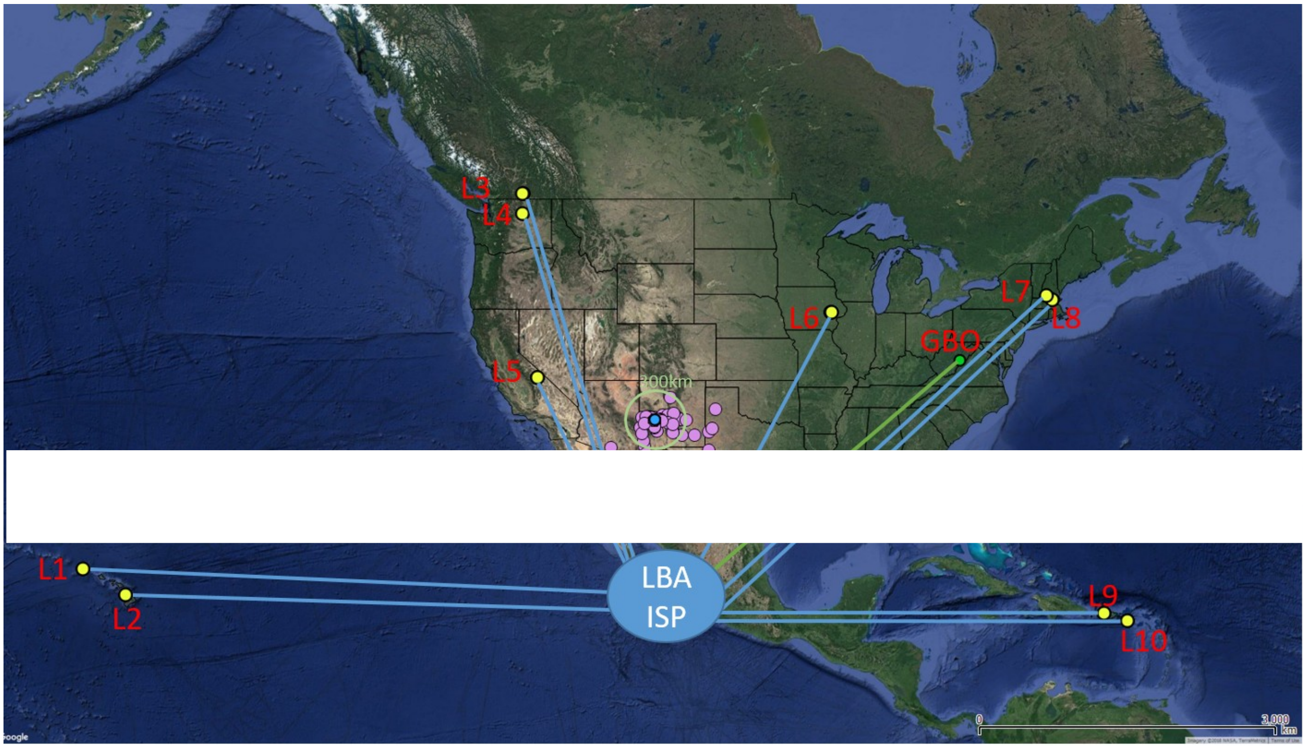


Figure 2 - ngVLA LBA Sites shown in yellow. GBT site shown in green. ngVLA core and main array in blue and purple respectively. 30 antennas are included in the LBA configuration, distributed per the table below. [AD03]

Antenna Qty	Location	Possible Site Notes
3	Puerto Rico	Arecibo Observatory.
3	St. Croix	Existing VLBA site.
3	Kauai, Hawaii	Kokee Park Geophysical Observatory.
3	Hawaii, Hawaii	NOT on MK. 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.

Appendix A

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