A Notional Envelope Observing Program

020.10.15.05.10-0002-REP

Status: **RELEASED**

PREPARED BY	ORGANIZATION	DATE
J. M. Wrobel	NRAO	2020-08-17
B. S. Mason	NRAO	
E. Murphy	ngVLA/NM-Ops, NRAO	

APPROVALS	ORGANIZATION	SIGNATURES
E. Murphy, Project Scientist	ngVLA/NM-Operations, NRAO	Digitally signed by Eric J. Murphy Date: 2020.08.27 16:37:35 -04'00'
M. McKinnon, Project Director	Asst. Director for NM-Operations, NRAO	Mark McKinnon Digitally signed by Mark McKinnon Date: 2020.08.28 15:13:59 -06'00'

RELEASED BY	ORGANIZATION	SIGNATURE
M. McKinnon, Project Director	Asst. Director for NM-Operations, NRAO	Mark McKinnon Digitally signed by Mark McKinnon Date: 2020.08.28 15:14:13 -06'00'

Change Record

Version	Date	Author	Reason
0.1	2020-06-11	Wrobel	Initial draft
0.2	2020-06-23	Wrobel	Avoid oversubscribing suitable weather
0.3	2020-07-02	Mason	Added SBA/TP analysis and Table 5
0.4	2020-07-07	Wrobel	Tweaked formatting, added Table 6
0.5	2020-07-09	Murphy, Wrobel	Tweaked text and formatting
0.6	2020-08-12	Wrobel, Mason	Folded in feedback, tweaked a color in Figure 3, added LAS to Table 6, reformatted Table 6
1.0	2020-08-17	Wrobel, Mason, Murphy	Added [RD14] to improve Table 3, improved some figure and table captions, removed some TP discussion
2.0	2020-08-26	Lear	Formatting, minor copy edits; replaced Figures 2, 3, and 4 with amended versions per author's request
A	2020-08-26	Lear	Prepared PDF for signatures and approvals

Table of Contents

1 Introduction

1.1 Purpose

This document forms and analyzes a notional Envelope Observing Program (EOP) for a typical year during full science operations. The intent of this exercise is to make a reasonable prediction for how the community might use this PI-driven facility over a fully operational year. This prediction can help inform activities internal to the Project, such as gauging computational loads and guiding design decisions.

Wanting to take a conservative approach in such areas, the EOP adopts values for the availability of science time and of antennas that are more taxing than the Project's requirements and goals [AD03]. Specifically, the EOP assumes that science observing occurs 95% of the time and involves 95% of the antennas. The EOP thus represents an upper envelope on the resources demanded from the facility, making it more useful for informing the Project. It is not expected that the EOP will ever be executed in practice.

1.2 Scope

This document considers the use cases identified by the Science Advisory Council (SAC) as driving or supporting the Key Science Goals (KSGs) [AD01]. Those are augmented by late-arriving use cases, so labelled because they were submitted to the Project after the SAC had completed its use-case capture exercise. For context, the notional Reference Observing Program (ROP) considered only driving use cases and partially filled atypical years with pilot observations for those driving use cases [AD02]. The ROP and the EOP adopt identical values for the availability of science time and of antennas.

2 Related Documents

2.1 Applicable Documents

The following documents are applicable to the extent specified.

Ref. No.	Document Title	Doc. No.
AD01	Science Requirements	020.10.15.05.00-0001-REQ
AD02	A Notional Reference Observing Program	020.10.15.05.10-0001-REP
AD03	Stakeholder Requirements	020.10.15.01.00-0001-REQ
AD04	Array Configuration: Reference Design Description	020.23.00.00.00-0002-DSN
AD05	ngVLA: The Next Generation Very Large Array	020.05.55.10.00-0003-GEN
AD06	System Environmental Specifications	020.10.15.10.00-0001-SPE
AD07	Technical Parameters Spreadsheet	

Table 1 – Applicable documents.

2.2 Reference Documents

The following documents provide context or supporting material.

Ref. No.	Document Title	Doc. No.
RD01	Imaging Winds from Massive and Evolved Stars	Use Case SF9
RD02	Intermediate-Mass Black Holes in Globular Cluster Systems	Use Case NGA15
RD03	Measuring Galaxy Dynamics and Evolution: Stellar SiO Maser Astrometry in the Galactic Bulge	Use Case NGA16
RD04	Galaxy Proper Motions	Use Case NGA17
RD05	Blazar Imaging: From Parsec to Kiloparsec Scales	Use Case TDCP16

Ref. No.	Document Title	Doc. No.
RD06	X-Ray Binary Astrometry	Use Case TDCP17
RD07	Ejected Black Holes	Use Case TDCP18
RD08	Science with a Next-Generation Very Large Array	ASP Conf. Series, 517
RD09	Taperability Study for the ngVLA and Performance Estimates	ngVLA Memo #55
RD10	Strategies for Phase Referencing with the VLBA	VLBA Sci Memo #24
RD11	The ngVLA Short Baseline Array	ngVLA Memo #43
RD12	Preliminary ngVLA Observing Band Availability Estimate	ngVLA Memo #73
RD13	The Effect of Weather on MUSTANG Data Quality	GBT Memo #269
RD14	Subarray Selection for the Reference Observing Program	ngVLA Memo #76

Table 2 – Reference documents.

3 Assumptions and Approach

A year holds 365.25 days x 24 hours/day, or about 8770 hours. If science observing occurs 95% of the time (see Section 1.1), about 8330 hours will be available for science per year. To gauge how the community might reasonably be expected to fill those science hours, the use cases tagged by the SAC as driving or supporting the KSGs were considered. Those types of use cases are identified in [AD01].

Use cases [RD01, RD02, RD03, RD04, RD05, RD06, RD07] were submitted to the Project after the SAC had completed its tagging exercise. This type of use case is referred to as late-arriving. Each was assigned to a KSG and also considered. As in [AD02], some use case requirements were updated based on later presentations or chapters in [RD08].

The following steps were taken for each driving, supporting, and late-arriving use case:

- Identify the required frequency, angular resolution, largest angular scale, and rms sensitivity. If multiple frequencies are involved and require multiple bands, record the requirements for each.
- Assign a subset or subarray with some number of 18m antennas. See Table 3 and Figure 1. There has been some evolution in minimum-baseline values; those shown in Table 3 are from [RD14].
- Use the ngVLA Sensitivity Calculator (https://gitlab.nrao.edu/vrosero/ngvla-sensitivity-calculator) to estimate the time-on-target to achieve the required rms sensitivity.
- To accommodate maintenance and similar activities, a subset or subarray will observe with 95% of its 18m antennas (see Section 1.1). For this reason, the time-on-target is scaled up by a factor of 1.1.
- To accommodate calibration overheads, assign a calibration overhead factor, Ove, of 1.0 for the Long Baseline Array subset [RD10] and as shown in Table 4 for the Main Array subset and its subarrays.
- Multiply the scaled time-on-target by 1+Ove to estimate the time-on-sub, where sub stands for either subset or subarray.
- Assign multiple targets and/or multiple looks at a target, thereby increasing the time-on-sub. For the driving use cases this step was strongly guided by [AD02].
- Check for sky-location, weather and/or time-of-day imperatives (e.g., Sgr A*, winter LSTs, nighttime). Band 6 is assumed to be viable from about 2 hours after sunset until sunrise [AD06].
- Capture the needs of the use case as the number of 18m antennas times the time-on-sub.
- Use the required largest angular scale to estimate the times needed, if any, on the SBA subset of 6m antennas and/or the antennas equipped for total power measurements [RD11].

In total, 63 use cases were examined.

Subset or Subarray	# of Antennas	Minimum Baseline (m)	Maximum Baseline (km)
Long Baseline Array (LBA)	30 x 18m	32.6	8856.4
Main Array + LBA	244 x 18m	30.6	8856.4
Main Array (MA)	214 x 18m	30.6	1005.4
Mid	46 x 18m	7857.7	1005.4
Mid + LBA	76 x 18m	32.6	8856.4
Plains + Mid	120 x 18m	275.1	1005.4
Plains	74 x 18m	275.1	36.7
Plains + Core	168 x 18m	30.6	36.7
Core	94 x 18m	30.6	1.3
Short Baseline Array (SBA)	19 x 6m	11	

Table 3 – ngVLA subsets and subarrays from Configuration Rev. C. [AD04, AD05, RD09, RD14].

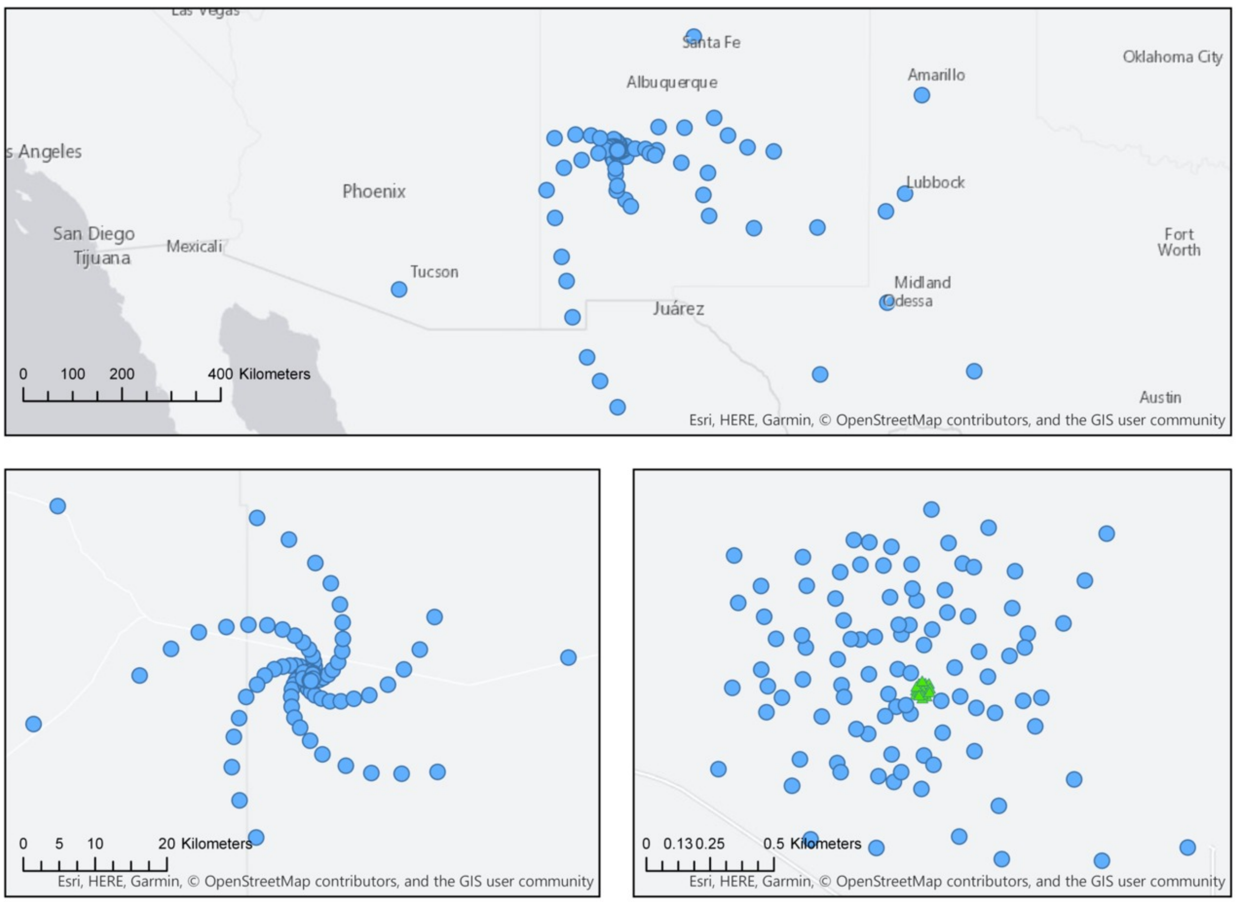

Figure 1 – Top: Main Array subset of 18m antennas from Configuration Rev. C (Spiral-214). Bottom left: Zoom view of the Plains subarray of 18m antennas. Bottom right: Zoom view of the Core subarray of 18m antennas. The green symbol shows the SBA subset of 6m antennas. Adapted from [AD04, AD05, RD09, RD14].

Band 1 f_c = 2.4 GHz		Band 2 f_c = 8 GHz		Band 3 f_c = 16 GHz		Band 4 f_c = 27 GHz		Band 5 f_c = 41 GHz		Band 6 f_c = 93 GHz	
Res (mas)	Ove	*Res* (mas)	Ove	*Res* (mas)	Ove	*Res* (mas)	Ove	*Res* (mas)	Ove	*Res* (mas)	Ove
26000	0.20	7700	0.25	3800	0.50	2300	0.75	1500	0.75	700	1.00
2600	0.20	770	0.25	380	0.50	230	1.00	150	1.00	70	1.50
260	0.20	77	0.35	38	0.75	23	1.50	15	1.50	7	2.00

Table 4 – Calibration overhead factor, Ove, for the Main Array subset and its subarrays [AD02, AD03], assuming the same length for scheduling block for all bands and that some calibrations are performed as service calibrations outside scheduling blocks.

4 Analysis and Visualizations

4.1 Subsets and Subarrays of 18m Antennas

The information assembled for each of the 63 use cases was entered into a spreadsheet. A python script was developed to form a candidate EOP by aggregating the needs of all use cases. The script also generated visualizations to help verify that the candidate EOP:

- Suitably emphasized the driving use cases [AD03].
- Adhered to estimates for the time available per band per year [RD12]. To avoid oversubscribing available band-dependent time, the number of needed versus available hours was monitored for the "building blocks" with 94 (Core), 74 (Plains), 46 (Mid), and 30 (LBA) antennas.
- Had an antenna-hours-total that did not exceed the overall cap of 244 antennas x 8330 hours ~ 2 million antenna-hours.

A satisfactory notional EOP was reached by folding in driving, then supporting, then late-arriving use cases. Adjustments were also made to try to approach the band-dependent caps on the available time [RD12], folding in Band 6up, then 6lo, then 5, then 4, etc. While Band 6 involves one physical receiver, it is divided conceptually into a Band 6lo for frequencies below 90 GHz and a Band 6up for frequencies above 90 GHz [RD12]. Key traits of the notional EOP are highlighted in Figure 2, Figure 3, and Figure 4.

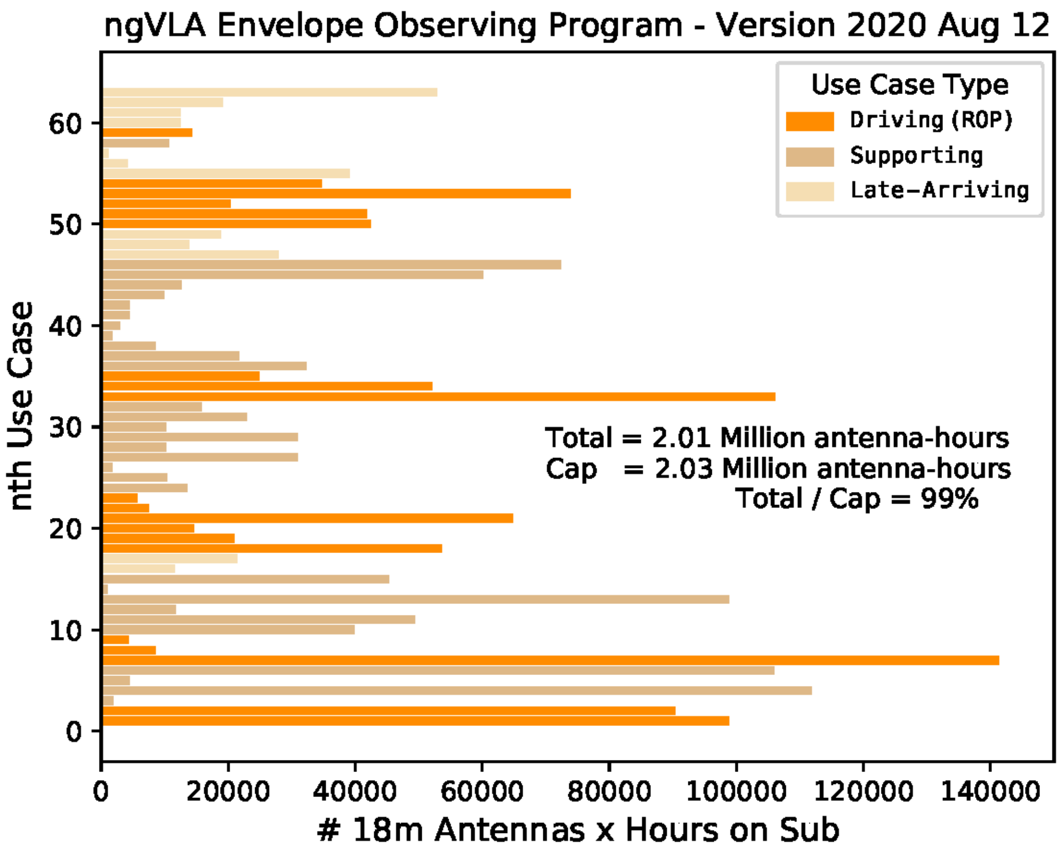

Figure 2 – A notional EOP. The types of use cases are highlighted. The driving, supporting, and late-arriving use cases account for 45%, 42%, and 12%, respectively, of the overall cap on antenna-hours.

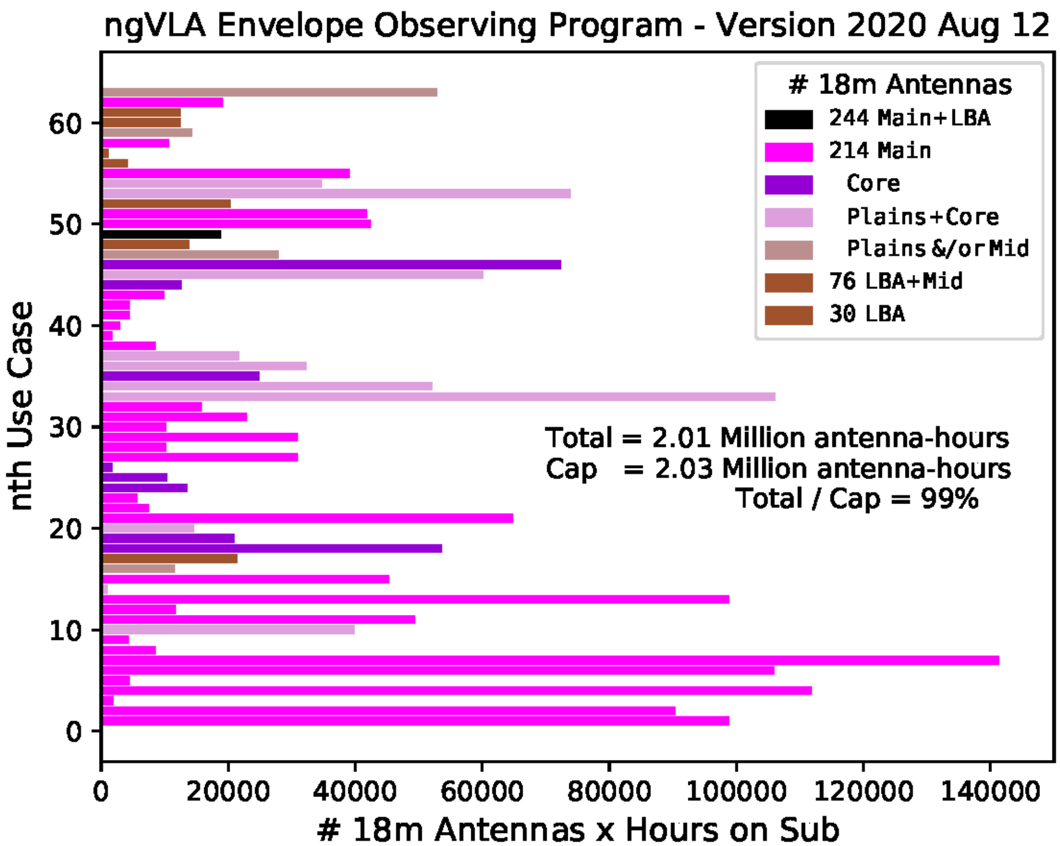

Figure 3 – A notional EOP. The numbers of 18m antennas are highlighted. Note the dominant use of the Main Array subset, as well as co-observing opportunities involving subarrays of the Main Array subset. The dominant use of the Main Array subset potentially offers many co-observing opportunities with the Long Baseline Array (LBA) subset. At present only a few of those opportunities could be utilized because of the small number of use cases involving just the LBA subset. However, it is anticipated that more use cases involving just the LBA subset will arrive in the near future.

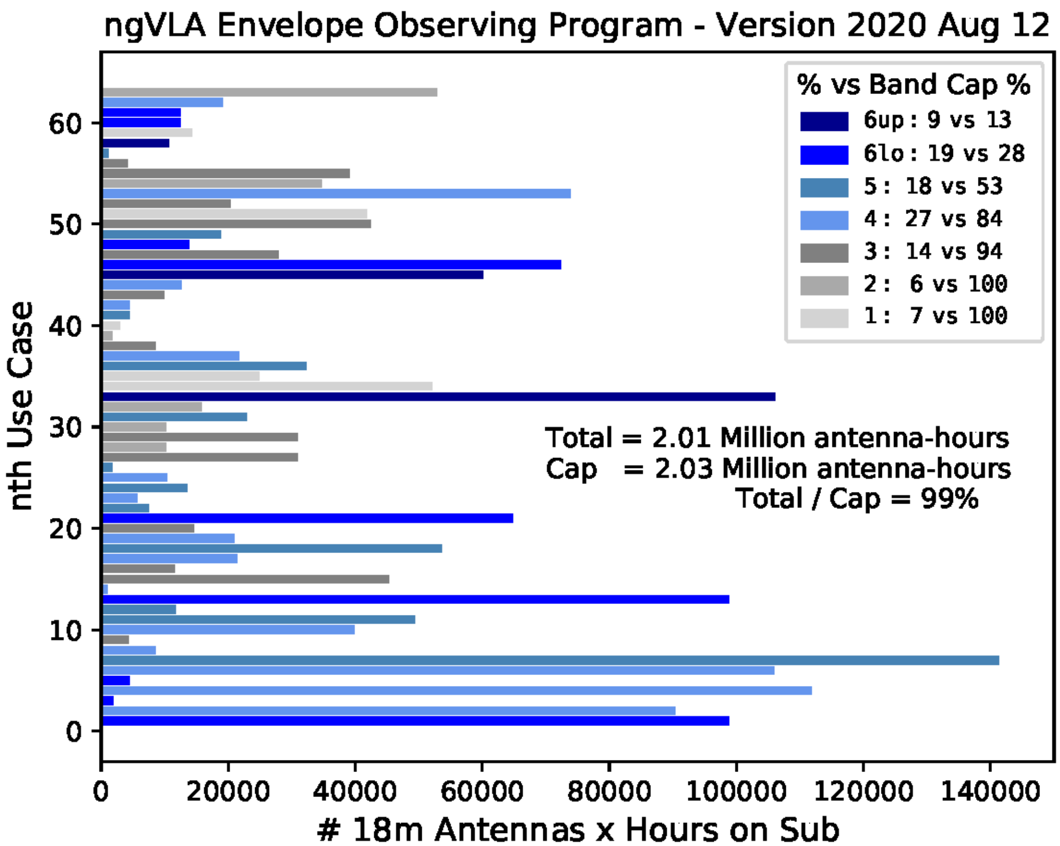

Figure 4 – A notional EOP. The observing bands are highlighted. A dynamic scheduler would consider snippets of each of the horizontal bars.

4.2 The Short Baseline and Total Power Arrays

The ngVLA reference design includes a Short Baseline Array (SBA) comprising 19 6m antennas to provide information down to ~11m baselines, and four 18m total power antennas (the Total Power Array or TPA) to provide even larger spatial scale information [RD11]. Use cases in the notional EOP requiring SBA or TPA observations were identified on the basis of the largest-angular-scale requirement given in the corresponding use case.

The needed SBA observing time for a given ngVLA main interferometric subarray observation was calculated using the methodology described in [RD11], updated to the current (Rev. C) 18m array configuration; TPA observing times were calculated in a similar manner. Both calculations assume the same observing and calibration overheads. We find an SBA to ngVLA observing time ratio 1.03, and a TPA to SBA observing time ratio of 1.75. We further restrict the set of use cases supported by the TPA to those which are primarily spectroscopic in nature, since high sensitivity total power continuum observations require special purpose receivers and backend electronics which are not currently within the scope of the ngVLA reference design.

The amount of time available for SBA and TPA observing was determined based on 9 years of precipitable water vapor (PWV) statistics (B. Butler, private communication). Observations with the 100m Green Bank Telescope (GBT) have demonstrated that excellent 3mm single dish data can reliably be obtained with

PWV as high as 10mm ([RD13] and D. Frayer, private communication). We conservatively assume that Bands 4–6 SBA and TP observing will require PWV < 7mm (met 61% of the time); Band 3 will require PWV < 10mm (met 74% of the time); and longer wavelengths are unconstrained with respect to PWV. We also require that Band 6 observations occur at night (50% of the time when averaged over the year).

The SBA and TPA observing times required by the EOP are summarized in Table 5. The SBA EOP comfortably fits within total and per band time availability constraints. The TPA EOP is heavily skewed toward short wavelengths where there is a ~1.4x oversubscription, allowing for the fact that Band 6up and 6lo conditions are highly correlated.

Band	SBA Observing Time [hours]	TPA Observing Time [hours]
1	272 (3%)	476 (6%)
2	-	-
3	218 (4%)	-
4	133 (3%)	-
5	198 (4%)	-
6lo	793 (31%)	1387 (55%)
6up	1278 (50%)	2238 (88%)

Table 5 – SBA and TPA observing times required by the notional EOP. Parenthesized quantities show the time required as a fraction of the time available.

4.3 Key Attributes of the Use Cases

Key attributes of the 63 use cases of the notional EOP are captured in Table 6 (next two pages). For each case, computing-related information will be added to the spreadsheet. A python script will be developed to extract this information and deliver it to the Computing IPT [AD07].

5 Acknowledgments

The authors thank Viviana Rosero for providing early access to the ngVLA Sensitivity Calculator and Bryan Butler for providing VLA site PWV statistics.

Index [1]	Label [2]	Center Frequency [3]	Point Spread Function [4]	Largest Angular Scale [5]	Subset or Subarray [6]	# of 18m Antennas [7]	Time on Subset or Subarray [8]	Overall Cap Fraction [9]	Terse Observation Descriptor [10]
1	PF3	80.00	5.0	2.0	Main	214	462.0	4.86	Protoplanetary disks (100 looks)
2		27.25	5.0	2.0	Main	214	422.5	4.45	8 protoplanetary disks
3	PF1	80.00	15.0	2.0	Main	214	9.0	0.09	2 protoplanetary disks (substructures)
4		27.25	15.0	2.0	Main	214	522.5	5.50	
5	PF5	80.00	5.0	5.0	Main	214	21.0	0.22	2 protoplanetary disks (circumplanets)
6		27.25	5.0	5.0	Main	214	495.0	5.21	
7	AC5	40.50	100.0	10.0	Main	214	660.0	6.95	6 hot cores (5 frequency settings)
8		27.25	100.0	10.0	Main	214	39.6	0.42	6 hot cores (3 frequency settings)
9		16.40	100.0	10.0	Main	214	19.8	0.21	6 hot cores (2 frequency settings)
10	AC1	24.00	400.0	2.0	Plains+Core	168	237.6	1.96	3 protoplanetary disks (NH3 snowlines)
11	AC2	37.00	200.0	2.0	Main	214	231.0	2.43	Protoplanetary disk (organic lines)
12	AC3	45.00	35.0	2.0	Main	214	55.0	0.58	Hot core (organic lines)
13	AC4	70.00	200.0	2.0	Main	214	462.0	4.86	Protostellar cores (deuterated lines)
14	AC6	24.00	1000.0	5.0	Plains+Core	168	6.3	0.05	Comet (NH3)
15	SS06	16.40	20.0	90.0	Main	214	211.8	2.23	Uranus (bright polar regions)
16	SF9	16.40	8.0	0.1	Plains+Mid	120	96.2	0.57	500 massive stars (wind clumping)
17		27.25	1.5	1.5	LBA	30	715.0	1.06	50 red giant stars (2D velocities in globular clusters)
18	HiZ1	40.50	2000.0	5.0	Core	94	569.8	2.64	CO galaxy search (8 pointings)
19		27.25	2000.0	5.0	Core	94	223.3	1.03	
20		16.40	2000.0	5.0	Plains+Core	168	87.2	0.72	
21	HiZ5	72.00	100.0	5.0	Main	214	302.5	3.18	4 CO galaxies (lines z~2)
22		36.00	100.0	5.0	Main	214	35.2	0.37	
23		28.00	100.0	5.0	Main	214	26.4	0.28	
24	HiZ2	38.40	2000.0	4.0	Core	94	144.4	0.67	50 dusty galaxy redshifts (CO z~2)
25	HiZ3	29.00	2000.0	3.0	Core	94	109.7	0.51	3 galaxies' dense gas (HCN z~2)
26	HiZ6	36.00	1500.0	30.0	Core	94	19.2	0.09	CO galaxy environs (lines)
27	HiZ7	16.40	190.0	10.0	Main	214	144.4	1.52	2 JWST deep fields
28		7.90	150.0	10.0	Main	214	47.5	0.50	
29		16.40	190.0	10.0	Main	214	144.4	1.52	
30		7.90	150.0	10.0	Main	214	47.5	0.50	
31	HiZ8	38.00	50.0	1.0	Main	214	107.2	1.13	3 AGN outflows (CO z~0.5-2)
32	HiZ10	7.90	100.0	10.0	Main	214	73.7	0.78	Obscured AGN in 1 deg^2 (62 pointings)

Table 6 – Key attributes of the use cases in the notional EOP. Column contents:
[1] index corresponding to the vertical axes in Figure 2, Figure 3, and Figure 4,
[2] label,
[3] center frequency (GHz),
[4] point spread function at full-width-half-maximum (mas),
[5] largest angular scale (arcsec),
[6] subset or subarray,
[7] # of 18m antennas,
[8] time on subset or subarray (hours),
[9] fraction of overall cap on antenna-hours (%), and
[10] terse observation descriptor.

Index [1]	Label [2]	Center Frequency [3]	Point Spread Function [4]	Largest Angular Scale [5]	Subset or Subarray [6]	# of 18m Antennas [7]	Time on Subset or Subarray [8]	Overall Cap Fraction [9]	Terse Observation Descriptor [10]
33	NGA8	115.00	100.0	120.0	Plains+Core	168	631.0	5.22	CO in nearby galaxies (17 pointings)
34	NGA2	1.42	1000.0	60.0	Plains+Core	168	310.2	2.56	HI in 5 group galaxies
35	NGA2	1.42	60000.0	6000.0	Core	94	264.0	1.22	HI around group galaxies
36	NGA3	40.50	1000.0	60.0	Plains+Core	168	192.5	1.59	2 nearby galaxies (5 pointings each)
37		27.25	1000.0	60.0	Plains+Core	168	129.3	1.07	2 nearby galaxies (7 pointings each)
38		16.40	1000.0	60.0	Main	214	39.6	0.42	2 nearby galaxies (3 pointings each)
39		7.90	1000.0	60.0	Main	214	8.2	0.09	2 nearby galaxies (1 pointing each)
40		2.35	1000.0	60.0	Main	214	13.7	0.14	2 nearby galaxies (1 pointing each)
41	NGA6	40.50	6.0	10.0	Main	214	20.5	0.22	Massive SF in local galaxy
42		27.25	6.0	10.0	Main	214	20.5	0.22	
43		16.40	6.0	10.0	Main	214	46.2	0.49	
44	NGA7	23.00	2500.0	60.0	Core	94	135.0	0.62	NH3 in local galaxy (10 pointings)
45	NGA9	115.00	200.0	200.0	Plains+Core	168	357.5	2.95	CO in 2 local group galaxies (1 pointing each)
46	NGA10	88.00	1000.0	200.0	Core	94	770.0	3.56	HCN in nearby galaxy (10 pointings)
47	NGA15	16.40	100.0	0.1	Plains+Mid	120	232.6	1.37	Globular star clusters in 3 nearby galaxies
48	NGA16	86.00	0.15	1e-3	LBA	30	462.0	0.68	Parallaxes of 50 SiO masers in Galactic bulge
49	NGA17	40.50	1.0	5e-3	Main+LBA	244	77.0	0.92	Proper motions of 50 galaxies in Virgo Cluster
50	TDCP1	16.40	20.0	1e-6	Main	214	198.0	2.08	Pulsar search near Sgr A* (30 looks)
51	TDCP2	2.40	1000.0	1e-6	Main	214	195.4	2.06	Localize 10 LIGO events (2 looks each)
52	TDCP8	16.40	0.6	6e-3	LBA	30	679.8	1.00	Proper motions of 3 LIGO events (2 looks each)
53	TDCP5	27.25	1000.0	1.0	Plains+Core	168	440.0	3.64	Localize 10 LISA events (2 looks each)
54	Prepare	7.90	1000.0	1.0	Plains+Core	168	206.2	1.70	Find candidate BHs and pulsars in inner Galaxy
55	TDCP17	16.40	10.0	5e-3	Main	214	182.9	1.93	Astrometry of 50 BH candidates
56		16.40	1.0	5e-3	LBA+Mid	76	55.0	0.21	Parallax of a BH (5 looks)
57		40.50	0.17	1e-3	LBA	30	40.0	0.06	Orbital wobble of Cyg X-1 (20 looks)
58	NGA12	115.00	50.0	2.0	Main	214	49.5	0.52	SMBH masses in 12 nearby galaxies (CO)
59	TDCP7	2.35	100.0	1e-6	Mid	46	312.0	0.71	Time 10 pulsars (52 looks each)
60	TDCP16	80.00	0.1	1e-3	LBA+Mid	76	164.5	0.62	Jet of EHT primary (2 looks)
61		80.00	0.1	1e-3	LBA+Mid	76	164.5	0.62	Jet of EHT primary (2 looks)
62		27.25	1000.0	30.0	Main	214	89.2	0.94	2 primaries plus 4 others (52 looks each)
63	TDCP18	7.90	15.0	1e-6	Plains+Mid	120	440.0	2.60	Find ejected SMBHs

Table 6 (continued) – Key attributes of the use cases in the notional EOP. Column contents:
[1] index corresponding to the vertical axes in Figure 2, Figure 3, and Figure 4,
[2] label,
[3] center frequency (GHz),
[4] point spread function at full-width-half-maximum (mas),
[5] largest angular scale (arcsec),
[6] subset or subarray,
[7] # of 18m antennas,
[8] time on subset or subarray (hours),
[9] fraction of overall cap on antenna-hours (%), and
[10] terse observation descriptor.

6 Appendix

6.1 Acronyms and Abbreviations

Acronym	Description
AD	Applicable Document
EOP	Envelope Observing Program
GBT	Green Bank Telescope
IPT	Integrated Product Team
KSG	Key Science Goals
LBA	Long Baseline Array
MA	Main Array
ngVLA	Next Generation Very Large Array
PI	Principal Investigator
PWV	Precipitable Water Vapor
RD	Reference Document
ROP	Reference Observing Program
SAC	Science Advisory Council
SBA	Short Baseline Array
TP	Total Power
TPA	Total Power Array
VLA	Jansky Very Large Array