A Notional Reference Observing Program

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Change Record

Version	Date	Reason
0.3	2019-02-14	Incorporated v0.3 ppt and weather conditions
1.0	2019-04-26	Mended English and pdf's missing equations, strange symbols
A	2019-05-20	Prepared document for release
A.1	2019-09-05	Addressed SAC RIDs
B	2019-10-15	Prepared PDF for approvals and release as v.B
B.1	2019-11-21	Fixed overhead error in 3.5.4. Mentioned plans re: SBA and re: Band 6
C	2019-11-21	Prepared PDF for approvals and release as v.C

Table of Contents

1 Charge and Approach

This document presents an analysis of whether or not the ngVLA Reference Design (Selina et al. 2018a) can reach the Key Science Goals (KSGs) in the array's first decade. The approach is to build a notional Reference Observing Program (ROP). This involves systematically quantifying the technical and observing needs of the driving use cases of the KSGs identified in the ngVLA Science Requirements (Murphy et al. 2018). This analysis also folds in the ancillary information needed to evaluate the ROP.

As emphasized in the document's title, this exercise is notional, intended only to gauge whether the ngVLA Reference Design can do what the community projects will be the highest priority science (Bolatto et al. 2017). The ROP should not be construed as dictating how science will play out during the array's first decade. As a proposal-driven facility, the ngVLA will be able to adapt to the evolving science landscape.

2 Assumptions

For context and simplicity, the analysis begins by casting the science time in Year 1 to Year 10 as wall-clock hours. A year holds 365.25 days x 24 h/day ~8770 h, where h denotes hours. The ngVLA aims to achieve a science efficiency of 95% (Selina et al. 2018b), implying ~8330 h of science observing per year. Realistically it may take a few years to reach such an efficiency. The VLA routinely achieves a science efficiency of ~70%, suggesting that value as a reasonable starting point for the ngVLA. Conservatively assuming that value for the ngVLA's first three years, referred to as the "learning" years, thus implies ~6000 h of science observing during each of those years.

Assuming a technical readiness to begin key science observing on 2034-01-01, Year 1 is thus CY2034. To accommodate weather conditions, the ROP adopts the preliminary estimates for the science time available per Local Sidereal Time (LST) per band (Butler 2019). These estimates will be conveyed in later figures.

The ngVLA is a single telescope, but it can logistically be divided into three primary subsets (McKinnon et al. 2019). These subsets are a Main Array (MA) and a Long Baseline Array (LBA), each involving reflector antennas of 18m diameter (Rosero 2019), and a Short Baseline Array (SBA) involving reflector antennas of 6m diameter (Mason et al. 2018).

The SBA subset will be sensitive to a portion of the larger angular scales poorly-sampled by the MA subset. Analyzing the role of the SBA subset is beyond the scope of the ROP, and will be addressed in a future document.

The MA and LBA subsets will drive the sensitivities and angular resolutions offered by the ngVLA. Analyzing the roles of those subsets is within the scope of the ROP. The MA subset itself can naturally be divided into subarrays (Rosero 2019). Table 1 and Figure 1 convey attributes of the subsets and subarrays adopted for the ROP. In Table 1, the minimum baseline of the LBA subset excludes the very short baselines within each of its 10 clusters.

For the subsets and subarrays in Table 1, the ROP assumes the performance metrics tabulated by Rosero (2019). To accommodate the quantized resolutions appearing in those performance tables, it will sometimes be necessary to modify the angular resolutions mentioned in the use cases.

To accommodate maintenance activities, the ROP assumes that a subset or subarray will observe with 95% of its 18m antennas (Selina et al. 2018b).

Band 6 is assumed to be viable from ~2 h after sunset until sunrise (Selena et al. 2018c).

Subset of ngVLA	Subarray of Main Array	# of 18m Antennas	Minimum Baseline (km)	Maximum Baseline (km)
Main Array (MA)		214	0.027	1005.4
	Core	94	0.027	1.3
	Plains + Core	168	0.027	36.5
	Mid-baseline	46	7.747	1005.4
Long Baseline Array (LBA)		30	32.6	8856.4

Table 1 – ngVLA subsets and subarrays of 18m antennas.

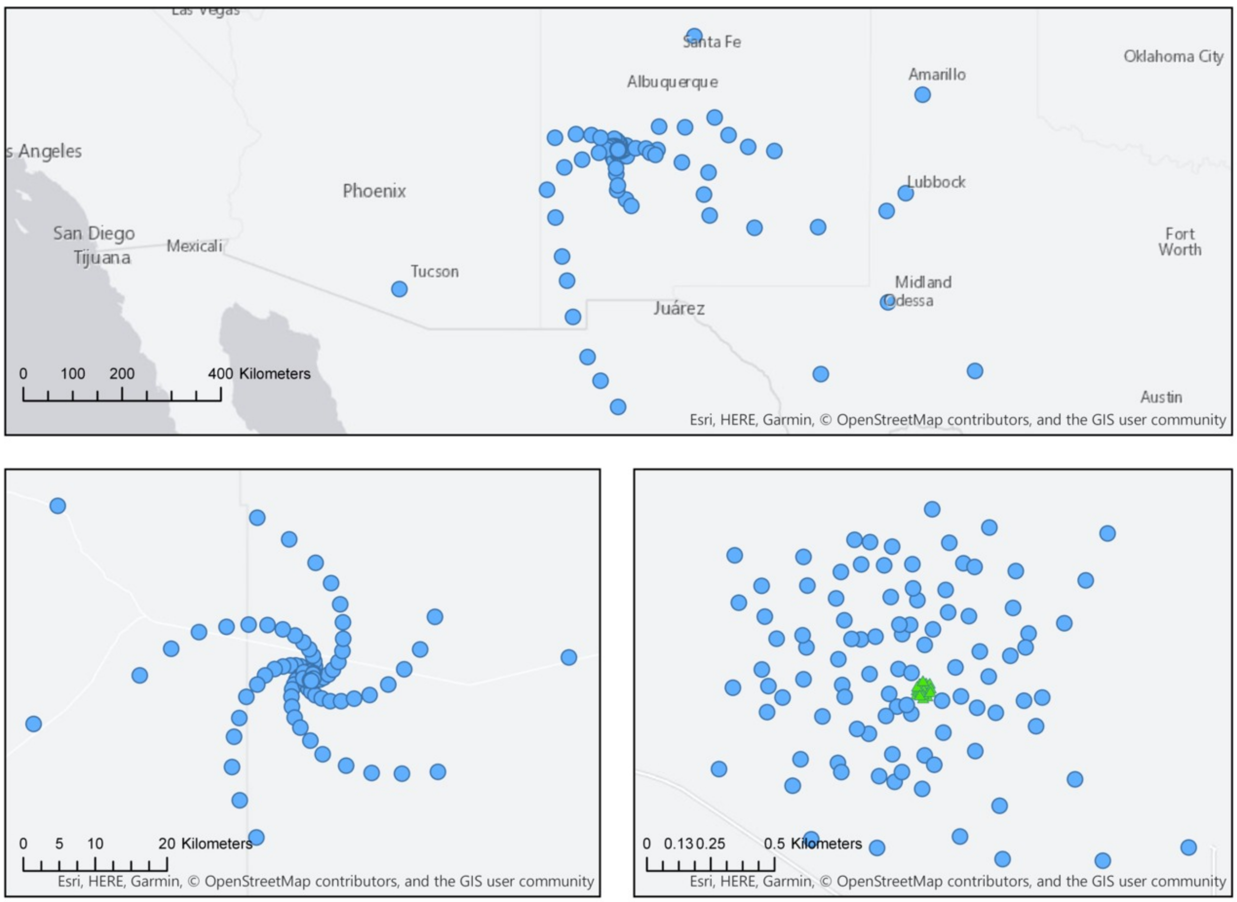

Figure 1 – Top: MA subset of 18m antennas from Configuration Rev. C (Spiral-214). Bottom left: Zoom view of the Plains subarray of 18m antennas. Bottom right: Zoom view of the Core subarray of 18m antennas. The Mid-baseline subarray is defined as the MA subset minus the Plains + Core subarray. The green symbol shows the SBA subset of 6m antennas.

Except for the LBA subset, Table 2 shows the preliminary and conservative estimates for the calibration overheads *(Ove)* as a function of the angular resolution *(Res)* from Selena et al. (2018b). For the LBA subset, phase referencing in the nodding style is assumed for Bands 1–5 and thus *Ove ~1.0* is adopted

(Wrobel et al. 2000). *Ove* is defined in the sense that $T_{sub} = T_{target} * (1+Ove)$, where T_{sub} is the time needed on a subset or subarray and T_{target} is the time needed on a science target.

Band 1		Band 2		Band 3		Band 4		Band 5		Band 6	
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 2 – Calibration overhead as a function of angular resolution, per ngVLA band.

For early releases, it is assumed this document should devise a methodology and conduct a preliminary evaluation of the ROP for the "learning" years, labelled Year 1, 2, and 3. To that end, this document attempts to assign key science pilots that make significant progress toward the KSGs. Some use cases were quite quantitative, making it easy to suggest reasonable pilots. Other use cases were more aspirational, making it harder, but not impossible, to suggest reasonable pilots. The ROP assumes ~2000 h per year of key science, likely involving many known users. This leaves the balance of ~4000 h per year for open science, signaling that all users and all ideas are welcomed by this new world-class facility.

3 Build the Reference Observing Program

The ROP is expressed in terms of the subset or subarray times needed by the driving use cases of the KSGs. This document first establishes the technical needs of the use cases. It then estimates the subset or subarray times needed, per LST and per band, by folding in performance metrics, maintenance activities, and calibration overheads.

Regarding technical needs, they were summarized in the Science Use Cases table in the Cost Model spreadsheet, with the latest update occurring on 2018-11-06. The technical needs are augmented with the sensitivity requirements quoted in submitted use cases or in later presentations or chapters of the ngVLA Science Book (Murphy 2018).

Regarding time needs, the first step is to assign a subset or subarray to a use case by matching the case's required band, angular resolution, bandwidth, and sensitivity to the entries in the performance tables. The tabulated sensitivity is then adjusted for antennas missing due to maintenance activities. Next, the adjusted sensitivity is used to estimate T_{target}. If more than one subset or subarray can meet the use case requirements, the one that will minimize T_{target} is generally picked. Then the calibration overhead *Ove* is applied to estimate T_{sub} and a suggestion is made regarding how to distribute that needed time over LSTs. Finally, the needed time is assigned to Year 1, 2, or 3, and added to Figure 2, Figure 3, or Figure 4, respectively.

After completing this exercise for each of the driving use cases of the KSGs, the time needed by the ROP will be captured in Figure 2, Figure 3, and Figure 4. These figures are not classic pressure plots because time needs that overlap in LST are not being stacked.

Evaluating the viability of the ROP involves comparing its time needed per LST per band to the time available per LST per band. Estimates for the times available are provided by Butler (2019) for the months of Jan-Feb-Mar (Q1), Apr-May-Jun (Q2), Jul-Aug-Sep (Q3), and Oct-Nov-Dec (Q4). To accommodate a gradient in suitable weather conditions within Band 6, Butler (2019) provided separate availability estimates for frequencies below and above 95 GHz, notionally labeled as Band 6a and 6b, respectively. The times needed during Years 1, 2, and 3 are thus separated into those four quarters and seven effective bands. Also, for each quarter, times available are adjusted by the science efficiency assumed for the "learning" years before adding those times to Figure 2, Figure 3, and Figure 4.

Two weather and sky bottlenecks are anticipated, namely KSG1 and KSG3 each need Band 6b, and KSG2, KSG4, and KSG5 each need Galactic Center LSTs. Staggering their pilots quarterly could help to mitigate these bottlenecks. Some degradation of weather conditions beyond the Plains subarray is also anticipated. To adapt, the ROP will be on the lookout for use cases that involve point-like targets and low frequencies, and will consider forcing such cases onto the Mid-baseline subarray.

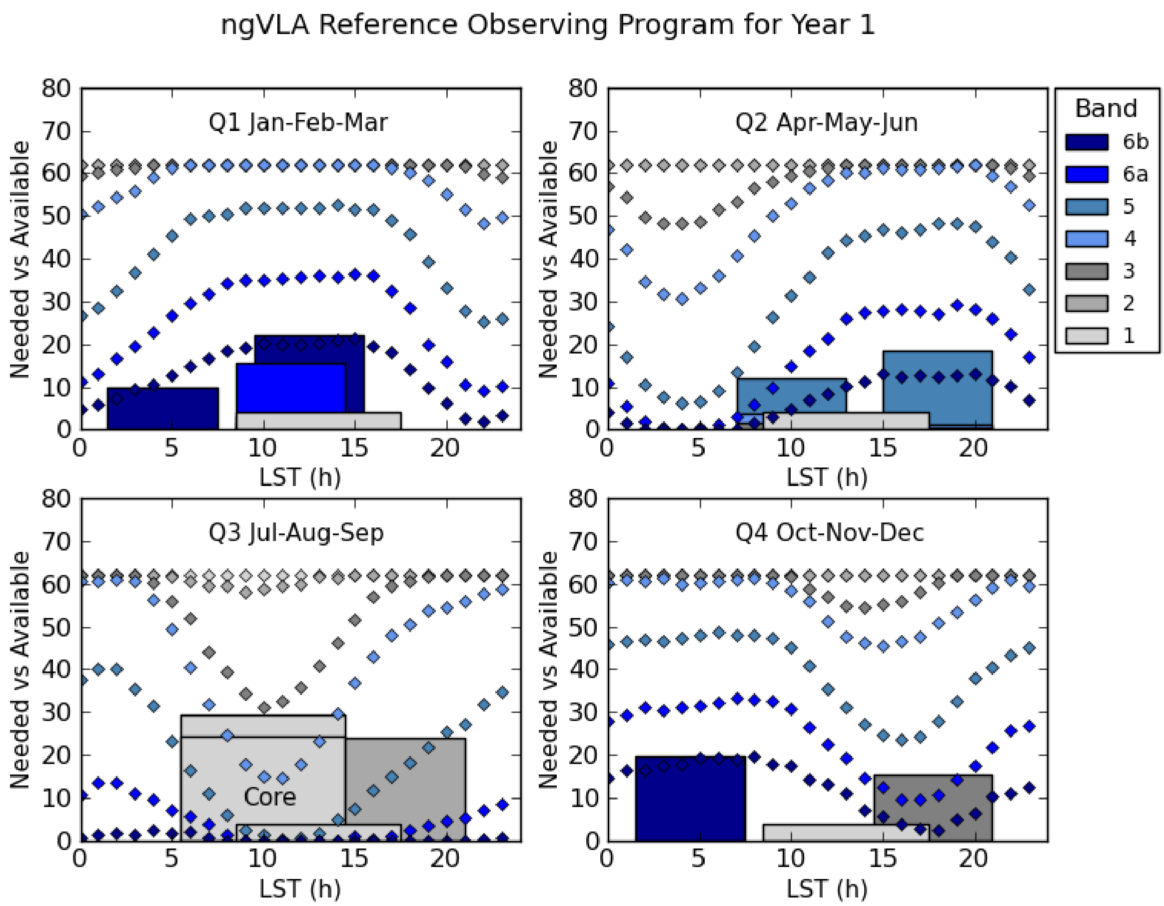

Figure 2 – Comparing the times needed (histograms) to the times available (lines) in Year 1 of the Reference Observing Program. The colors encode the bands and apply to both histograms and lines. The abscissa is the Local Sidereal Time for the Core subarray. The ordinate is the number of LST passes needed vs available. Three months offer no more than *6000 h / (4*24 h)* passes, thus ~62 passes.

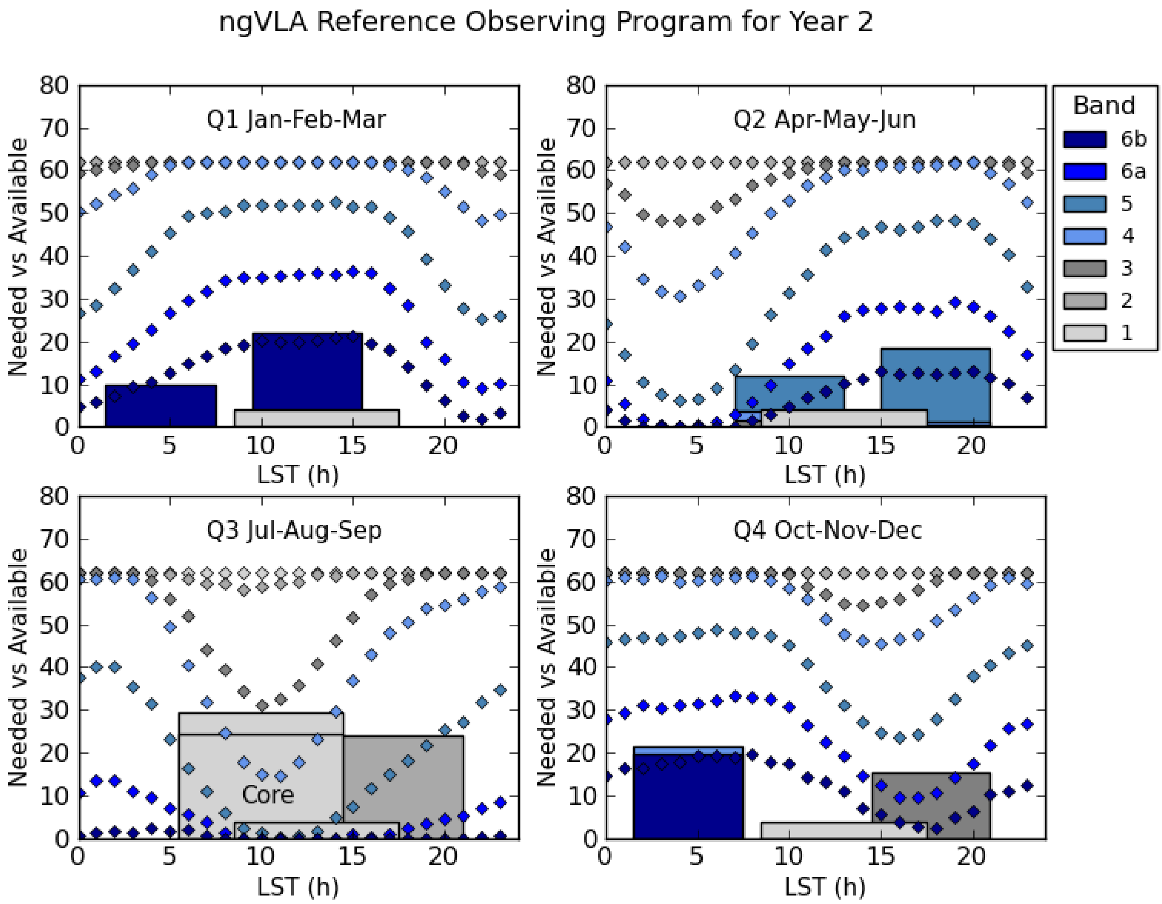

Figure 3 – Comparing the times needed (histograms) to the times available (lines) in Year 2 of the Reference Observing Program. The colors encode the bands and apply to both histograms and lines. The abscissa is the Local Sidereal Time for the Core subarray. The ordinate is the number of LST passes needed vs available. Three months offer no more than *6000 h / (4*24 h)* passes, thus ~62 passes.

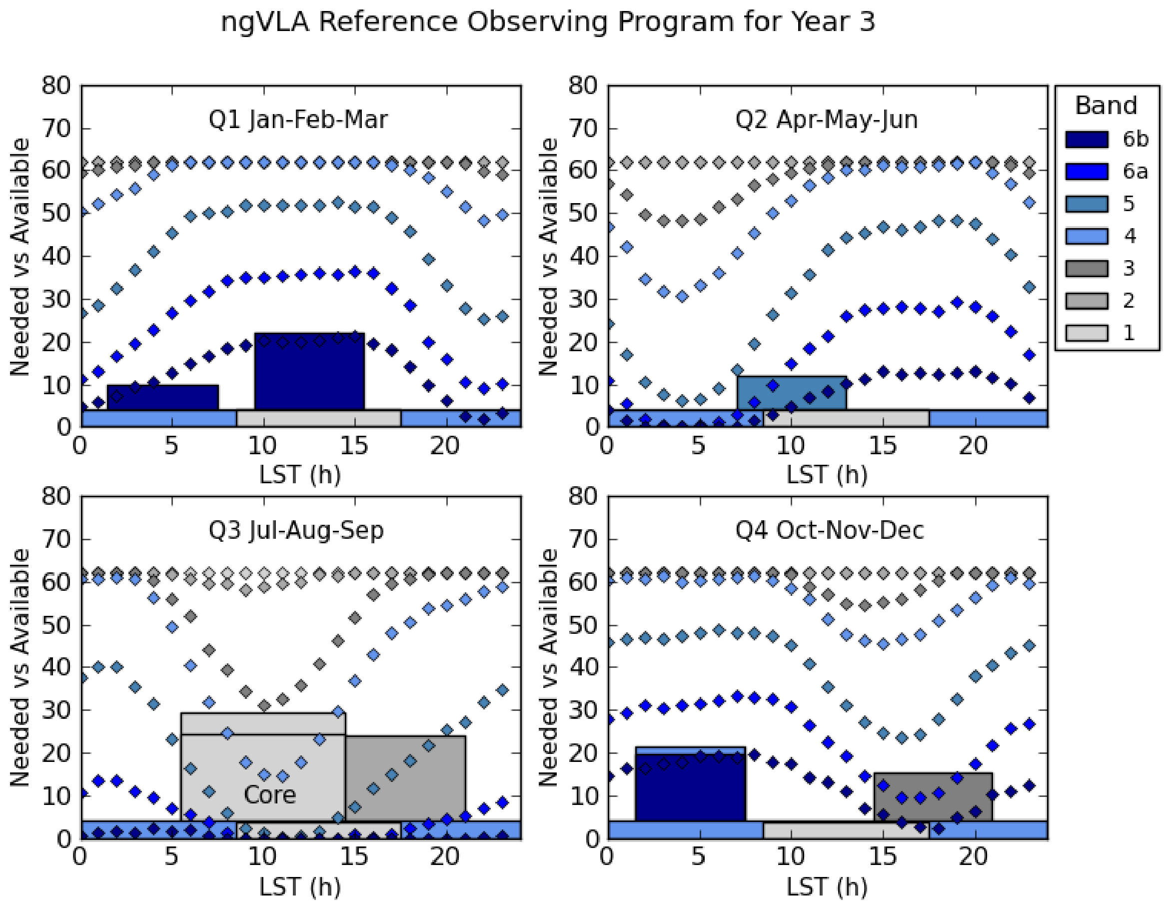

Figure 4 – Comparing the times needed (histograms) to the times available (lines) in Year 3 of the Reference Observing Program. The colors encode the bands and apply to both histograms and lines. The abscissa is the Local Sidereal Time for the Core subarray. The ordinate is the number of LST passes needed vs available. Three months offer no more than *6000 h / (4*24 h)* passes, thus ~62 passes.

3.1 KSG1: Unveiling the Formation of Solar System Analogs on Terrestrial Scales

The PF3 use cases, as updated by Ricci et al. (2018), require continuum observations at full bandwidths in Bands 6b and 4, plus a matched angular resolution of about 5 mas. Because the imaging performance tables are quantized in terms of tapered and robustly weighted resolutions (Rosero 2019), the ROP adopts 10 mas for the MA subset. The science targets are individual protoplanetary disks. Ricci et al. (2018) suggest starting in Taurus at a distance of 140 pc, with ~100 disks in Band 6b and the brighter disks in Band 4. For such disks, the required rms sensitivities are 0.5 microJy/beam in Band 6b and 0.07 microJy/beam in Band 4. A pilot is assigned in Taurus, implying right ascension *RA ~4.5 h*, declination *Dec ~+18 degrees (d)*, and a midnight transit near December 1st.

For Year 1, 15 looks in Band 6b are suggested to pursue demographics and movies. The time per look on a science target is T_{target} *~3.9 h*. The observing time needed is T_{sub} *~15 * 3.9 h * (1+2.0) ~176 h*, preferably discharged within ± 3 h near transit at night. Both Q1 and Q4 offer nighttime transits. The suggestion, then, is to conduct ten looks that need T_{sub} *~117 h* in Q4 and five looks that need T_{sub} *~59 h* in Q1, as conveyed in Figure 2.

It is suggested that Year 2 be like Year 1 in Band 6b and also explore four disks in Band 4. In Band 4, the time per disk on a science target is T_{target} *~12.9 h,* and the net observing time needed is T_{sub} *~4 * 12.9 h * (1+1.5) ~129 h.* The bands' needs should be discharged within ± 3 h near transit at night, with Band 6b split between Q1 and Q4 as for Year 1 and with Band 4 placed fully in Q4. See Figure 3.

Year 3 should be like Year 2. See Figure 4.

3.2 KSG2: Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry

The AC5 use cases involve a blind search across Bands 5, 4, and 3 for molecular gas in the hot cores Sgr B2(N) at *RA ~18 h* and *Dec ~–28 d*, and IRAS 16293 at *RA ~16.5 h* and *Dec ~–24 d*. The requested spectral resolution is 0.1 km/s, meaning that the search is limited to only 4 GHz per frequency setting. Spanning Bands 5, 4, and 3 thus requires five, three, and two frequency settings. Each band requires the same tapered and robustly weighted angular resolution of 100 mas. The rms sensitivity required for each band is said to be 30 microJy/beam in a 0.1 km/s channel. But the predictions invoke spectral resolutions of 0.3 or 0.6 km/s and times per frequency setting of ~10 h in Band 5, 1 h in Band 4, and 1 h in Band 3 (AC5, McGuire et al. 2018).

The MA subset is assigned and these per-setting times are adjusted for missing antennas. Band 5 requires five settings, takes T_{target} *~55 h*, and needs T_{sub} *~55 h * (1+1.0) ~110 h*. Band 4 requires three settings, takes T_{target} *~3.3 h*, and needs T_{sub} *~3.3 h * (1+1.0) ~6.6 h*. Band 3 requires two settings, takes T_{target} *~2.2 h*, and needs T_{sub} *~2.2 h * (1+0.5) ~3.3 h*. These needs total ~120 h and should be discharged within ± 3 h near transit during nights in Q2.

Year 1 should involve observing Sgr B2(N). The times needed are conveyed in Figure 2.

Year 2 should involve observing IRAS 16293. The times needed are conveyed in Figure 3.

This completes KSG2. The times needed for Bands 3 and 4 seem especially modest. But keep in mind that only the ngVLA will offer the essential combination of angular and spectral resolutions.

3.3 KSG3: Charting the Assembly, Structure, and Evolution of Galaxies from the First Billion Years to the Present

3.3.1 Blind Search for CO Galaxies at High Redshift

The HiZ1 use cases require pointed mosaics for a blind search for CO across Bands 5, 4 and 3. Each band requires the same tapered and robustly weighted angular resolution of 1000 mas and rms sensitivity of 10 microJy/beam/(2 MHz). The science targets are CO galaxies at high redshift. The use case suggests reaching ~100 galaxies per pointing and eventually reaching ~1000 galaxies for the completed mosaic. The Plains + Core subarray is assigned, as is a pilot in COSMOS, implying *RA ~10 h, Dec ~0 d*, and a midnight transit near March 1st. One pointing per band per year is suggested.

For Year 1, the times on science targets are T_{target} *~41.9 h* in Band 5, T_{target} *~12.8 h* in Band 4, and T_{target} *~6.2 h* in Band 3. The observing times needed are T_{sub} *~41.9 h * (1+0.75) ~73.3 h* in Band 5, T_{sub} *~12.8 h * (1+0.75) ~22.4 h* in Band 4, and T_{sub} *~6.2 h * (1+0.5) ~9.3 h* in Band 3. These needs total ~105 h and should be discharged within ± 3 h near transit during Q2 nights, as shown in Figure 2.

Year 2 should be like Year 1. See Figure 3.

Year 3 should be like Year 1. See Figure 4.

3.3.2 Imaging Molecular Gas in CO Galaxies at High Redshift

The HiZ5 use cases require imaging CO, HCO+, and HCN in galaxies at high redshift *(z)*. Each transition requires the same tapered and robustly-weighted angular resolution of 100 mas and rms sensitivity of 10 microJy/beam/(30 km/s). The science targets are two CO-discovered galaxies at *z ~2.5*. The MA subset is assigned, as is a pilot on the Spiderweb Galaxy (Emonts et al. 2016), implying *RA ~11.5 h, Dec ~–26 d*, and a midnight transit near April 1st. The Spiderweb Galaxy is at z *~2.2* so its transitions CO(2-1), CO(1-0), HCO+(1-0), and HCN(1-0) appear in Bands 6a, 5, 4, and 4. (The use cases do not mention seeking higher-J transitions like 3-2 or 4-3.)

For Year 1, the times on the science target are T_{target} *~37.6 h* in Band 6a, T_{target} *~9.5 h* in Band 5, and T_{target} *~4.8 h* in Band 4. The observing times needed are T_{sub} *~37.6 h * (1+1.5) ~94 h* in Band 6a, T_{sub} *~9.5 h * (1+1.0) ~19 h* in Band 5, and T_{sub} *~4.8 h * (1+1.0) ~9.6 h* in Band 4. These needs total ~123 h and should be discharged within ± 3 h near transit during Q1 nights, as shown in Figure 2.

The second science target could eventually be identified from the COSMOS pilot.

3.3.3 Imaging Molecular Gas in Nearby Galaxies

The NGA8 use case requires imaging molecular gas in nearby galaxies in Band 6b at a tapered and robustly weighted angular resolution of 100 mas. Ideally, each galaxy would be mosaicked with tens to hundreds of pointings. A. Leroy (2018, private communication) suggests starting with the CO-brightest galaxies, an ALMA-like spectral resolution of 2 km/s, and a rms sensitivity of 0.75 K. The Plains + Core subarray is assigned, as is a pilot on a Virgo Cluster galaxy, implying *RA ~12.5 h, Dec ~+12 d*, and a midnight transit near April 15th. Three pointings per year are suggested.

For Year 1, the time per pointing on a science target is T_{target} *~17.6 h*. The observing time needed is T_{sub} *~3 * 17.6 h * (1+1.5) ~132 h* and should be discharged within ± 3 h near transit during Q1 nights, as conveyed in Figure 2.

Year 2 should be like Year 1. See Figure 3.

Year 3 should be like Year 1. See Figure 4.

Notably, only one galaxy will have been partly done by the end of the pilot. This key science will thus experience slow progress.

3.3.4 HI Emission from Nearby Galaxies

This NGA2 use case requires imaging HI emission from nearby galaxies in Band 1 at a tapered and robustly-weighted angular resolution of 1000 mas and rms sensitivity of 50 microJy/beam/(1 km/s). The Plains + Core subarray is assigned, as is a pilot in the circumpolar M81 Group. Two pointings per year are suggested.

For Year 1, the time per pointing on a science target is T_{target} *~88.6 h*. The observing time needed is T_{sub} *~2 * 88.6 h * (1+0.2) ~213 h* and it could be discharged within ± 4.5 h near transit during Q3, as conveyed in Figure 2.

Year 2 should be like Year 1. See Figure 3.

Year 3 should be like Year 1. See Figure 4.

3.3.5 HI Emission Around Nearby Galaxies

This NGA2 use case requires pointed mosaics of HI emission around nearby galaxies in Band 1 at a tapered and robustly-weighted angular resolution of 60,000 mas. Pisano et al. (2018) state a required column density of 10^{17} cm^{-2} and a spectral resolution of 10 km/s, and say these measurements correspond to using the Core subarray for 600 h. After adjusting for missing antennas, the time on the science target becomes T_{target} *~660 h*. One pointing in the M81 Group is assigned as a pilot.

For Year 1, the time on the science target is T_{target} *~220 h*. The observing time needed is T_{sub} *~220 h * (1+0.2) ~264 h* and it could be discharged within ± 4.5 h near transit during Q3, as conveyed in Figure 2. This need is labeled "Core" to signal significant opportunities for co-observing with other subarrays.

Year 2 should be like Year 1. See Figure 3.

Year 3 should be like Year 1. See Figure 4.

3.4 KSG4: Using Pulsars in the Galactic Center as Fundamental Tests of Gravity

One TDCP1 use case requires continuum observations in Band 3 at full bandwidth to search for pulsars within 500 mas around Sgr A* at *RA ~18 h* and *Dec ~–29 d*. Ten phased-array beams are required simultaneously. The phasing-up facilitates signal conditioning for pulsars. As updated by Ransom & Demorest (2018), each phased-array beam will offer a tapered, robustly-weighted resolution near 20 mas. The total number of such phased-array beams needed is $(pi * 500^2 \, mas^2)/(1.1331 * 20^2 \, mas^2) \sim 1730$. To ease data handling, the team will settle for the rms sensitivity delivered by the MA subset after a 6-h track. A 26% pilot of 450 phased-array beams is assigned. The calibration overhead is a modest *Ove ~0.1*, because every 300 s the phasing can be touched up with a 30-s observation on Sgr A* (cf. Ku Band in the A configuration of the VLA).

For Year 1, 150 phased-array beams need T_{sub} *~15 * 6 h * (1+0.1) ~99 h*. This should be discharged in Q4 in the LST range 14.5 h to 21 h, as conveyed in Figure 2.

Year 2 should be like Year 1. See Figure 3.

Year 3 should be like Year 1. See Figure 4.

If any pulsars are found, timing them is required. Such follow-up needs cannot yet be estimated.

Another TDCP1 use case involves a pulsar search on degree scales in the inner Galaxy. Data from a black hole search, described below, could be shared for a use case for KSG5.

3.5 KSG5: Understanding the Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy

3.5.1 Localize a LIGO Event

The TDCP2 use case requires full-bandwidth continuum observations in Band 1 to localize a LIGO event at a tapered and robustly weighted angular resolution of 1000 mas, and rms sensitivity of ~1 microJy/beam. Two looks are required to localize the LIGO transient. Completing each look in ~10 h is desirable. Each look involves on-the-fly mosaicking over an area of ~7 square degrees (Nissanke et al. 2013). The total number of primary beams to be covered is thus *~7 square degrees /* $(0.5665 * 0.41^2)$ *square degrees ~74*. Assigning the MA subset for an effective T_{target} *~0.1 h* per primary beam, the mosaic will be completed in ~10 h to a rms sensitivity of ~1.8 microJy/beam. Corsi et al. (2018) suggest eventually triggering on ≳10 events per year. A pilot of eight events per year is assigned.

For Year 1, its eight events need T_{sub} *~8 * 2 * 7.4 h * (1+0.2) ~142 h*. Two events per quarter are suggested. The areal density of known galaxies that might host LIGO events is generally higher toward the northern Galactic cap than the southern one (Dalya et al. 2018). Figure 2 thus notionally centers each 8.9-h track at an LST of 13 h, the *RA* of the North Galactic Pole.

Year 2 should be like Year 1. See Figure 3.

Year 3 should be like Year 1. See Figure 4.

3.5.2 Proper Motion of a LIGO Event

Once a LIGO event has been localized, some follow-up will ensue. For example, it may be desirable to constrain the event's proper motion. This TDCP8-inspired use case was quantified by T. Maccarone (2018, private communication). It requires full-bandwidth continuum observations with the LBA subset near 10 GHz with an angular resolution of 0.6mas and rms sensitivity of ~0.23 microJy/beam. At least two looks are required to constrain a proper motion. Band 3 and natural weighting leads to T_{target} *~58.7 h* per look. For phase referencing in the nodding style, *Ove ~1.0* is adopted (Wrobel et al. 2000). A pilot is assigned to follow two events per year.

For Year 1, following up two events needs T_{sub} *~2 * 2 * 58.7 h * (1+1.0) ~470 h*. Co-observing can occur with any of the time needs plotted in Figure 2.

Year 2 should be like Year 1; co-observing can occur with any of the time needs plotted in Figure 3.

Year 3 should be like Year 1; co-observing can occur with any of the time needs plotted in Figure 4.

3.5.3 Localize a LISA Event

This TDCP5-inspired use case was roughly quantified in Bolatto et al. (2017). It requires full-bandwidth continuum observations in Band 4 to localize a LISA event at a tapered and robustly-weighted angular resolution of 1000 mas, and rms sensitivity of ~10 microJy/beam. Two looks are required to identify the LISA transient. Completing each look in ~10 h is desirable. Each look involves on-the-fly mosaicking over an area of ~10 square degrees (Lang & Hughes 2008). The total number of primary beams to be covered is thus *~10 square degrees/(0.5665 * 0.037*^{2}*) square degrees ~10*^{4}. Assigning the Plains + Core subarray for an effective T_{target} *~0.0001 h* per primary beam, the mosaic will be completed in ~10 h to a rms sensitivity of ~14 microJy/beam. Bolatto et al. (2017) mention that LISA will detect tens to hundreds of events per year. A pilot of eight events per year is assigned. LISA is expected to begin issuing event alerts in 2036, hence Year 3. LISA plans to be issuing alerts for at least four years; however, alerts could possibly occur for up to ten years (Amaro-Seoane et al. 2017).

For Year 3, its eight events need T_{sub} *~8 * 2 * 10 h * (1+1.5) ~400 h*. Two events per quarter are suggested. Radio counterparts to LISA events will be at cosmological distances, implying a uniform areal density. For want of a better approach, the needed times are spread across all LSTs in Figure 4.

3.5.4 Search for Black Holes and Pulsars in the Galactic Center

This search is in preparation for follow-up use cases for KSG4 and KSG5 in the Galactic Center.

Focusing on KSG5, the use case is mentioned in Bolatto et al. (2017) and quantified in Maccarone et al. (2018). The latter authors assume that recording media will be available, enabling a first correlation to refine positions of candidate black holes and a second correlation at those refined positions to initiate a proper motion study. However, such a dual-correlation mode is not planned. The lead author was consulted and agreed to revise their search approach as outlined below. This revised approach for KSG5 could also accommodate the search for KSG4 that was roughly quantified in the use case TDCP1.

The search requires full-bandwidth continuum observations in Band 2 to localize persistent sources with a tapered and robustly-weighted angular resolution of 1000 mas, and rms sensitivity of ~1 microJy/beam. Flat-spectrum sources found over an area of ~10 square degrees will become follow-up candidates for black hole proper motions for KSG5. Steep-spectrum sources found over a smaller area, ~4 square degrees defined by the Central Molecular Zone, will become follow-up candidates for pulsar timing for KSG4. The search will employ on-the-fly mosaicking.

A substantial pilot covering ~12 square degrees would help jumpstart the follow-up for KSG5. The total number of primary beams to be covered is thus *~12 square degrees/(0.5665 * 0.12²) square degrees ~1500*. The Plains + Core subarray is assigned for an effective T_{target} *~0.25 h* per primary beam to achieve the required sensitivity.

For Year 1, to cover ~4 square degrees or ~500 primary beams T_{sub} *~500 * 0.25 h * (1+0.25) ~156 h* is needed. This should be discharged in the LST range 14.5 h to 21 h in Q3, as conveyed in Figure 2. This would formally complete the pulsar search on degree scales for KSG4.

Year 2 should be like Year 1. See Figure 3.

Year 3 should be like Year 1. See Figure 4.

3.5.5 Time Pulsars for the Pulsar Timing Array

This TDCP7-inspired use case was further quantified by Chatterjee et al. (2018). It involves Band 1 or 2, and can involve as little as one-fifth of the MA subset. Each subarray will be phased up to facilitate signal conditioning for pulsars. There are ~200 pulsars currently known north of *Dec ~–40 d,* and the team would be willing to observe each of them for ~0.5 h per week in a one-fifth subarray. This case is assigned the Mid-baseline subarray: its 46 antennas comprise a one-fifth subarray and it is a good match to the point-like pulsars. A pilot of 10 northern pulsars is assigned. The tapered and robustly-weighted angular resolution could be 100 mas in Band 1 or 2, but it will be finer in real time because the subarray will be phased up.

For Year 1, these ten pulsars need T_{sub} *~52 * 10 * 0.5 h * (1+0.2) ~312 h*. This Mid-baseline subarray can co-observe with a use case involving a Plains + Core subarray in Figure 2.

Year 2 should be like Year 1; co-observing can occur with a Plains + Core subarray in Figure 3.

Year 3 should be like Year 1; co-observing can occur with a Plains + Core subarray in Figure 4.

4 Evaluation of the Reference Observing Program

This document developed a notional observing program of three-year pilots for the driving use cases of KSG1 through KSG5. It was found that the driving use cases for KSG2 could be completed after only two years. It was also found that significant progress could be made discharging all but one of the many driving use cases for KSG1, KSG3, KSG4 and KSG5. As noted in KSG3's Section 3.3.3, that single exception occurs because only one galaxy will have been partially completed during its pilot, whereas the aspiration is to observe many galaxies eventually. The driving use case in Section 3.3.3 would thus experience slow science progress.

For optimal efficiency, a driving use case involving the Mid-baseline subarray can co-observe with a driving use case involving the Plains + Core subarray. Similarly, a driving use case involving the LBA subset can co-observe with a driving use case involving, for example, the MA subset. Skipping over use cases assigned to the Mid-baseline subarray or the LBA subset, the T_{sub} totals for key science are 1549 h in Year 1, 1556 h in Year 2, and 1836 h in Year 3. These values approach the ~2000 h per year mentioned in Section 2. The desired balance of ≥4000 h per year would thus be available for open science. But if key science is discharged first, a worry is that not many hours would be left for open science in Bands 6a or 6b.

5 Next Steps

Only preliminary estimates for calibration overheads were available. It would be desirable to gain access to study-based estimates applicable to the subsets and subarrays in Table 1.

The preliminary estimates for the available science time per LST per band involve only phase stability data on the Plains of San Agustin. It would be desirable to gain access to estimates that fold in wind and opacity data on the Plains, and also to fold in phase-stability, wind, and opacity data beyond the Plains. Related, to make optimal use of the available science time per LST in Bands 6a and 6b, it would be desirable to investigate pushing continuum work to Band 6a thereby increasing opportunities for line work in Band 6b.

It would be desirable to analyze the role of the SBA subset.

The authors should re-read the ngVLA Science Book (Murphy 2018) cover to cover to ensure that this document has captured updates, if any, to the sensitivity requirements quoted in the driving use cases.

6 Appendix

6.1 *Acknowledgments*

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6.2 *Reference Documents*

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