ngVLA Calibration Concept

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1	2024-02-07		All	Initial draft.
A	2024-08-13	P. Kotzé, M. Archuleta	All	Update of document references. Formatting for Release.

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1 Reference Documents

ngVLA memos are available at: https://ngvla.nrao.edu/page/memos.

Ref. No.	Title	Document Number
RD01	ngVLA Conceptual Design Options and Trades	020.10.25.00.00-0005 REP
RD02	Calibration Requirements	020.22.00.00.00-0001 REQ
RD03	Water Vapor Radiometer: Design Description	020.45.00.00.00-0002 DSN
RD04	Fast Switching Phase Calibration at 3 mm at the VLA site	Carilli, C., ngVLA Memo #1
RD05	Candidate Phase Calibrators at 93 GHz in the ngVLA Sky	Wrobel, J. & Ho, A., ngVLA Memo #98
RD06	The Relationship between Image Dynamic Range and Antenna Based Gain Errors	Sridharan, T. K. et al 2023, ngVLA Memo #107
RD07	Feasibility of Self-cal for ngVLA Dynamic Range Requirements	Sridharan, T. K. & Bhatnagar, S., 2023, ngVLA Memo #108
RD08	ngVLA Observing Modes Framework	020.10.05.05.00-0005 PLA
RD09	ngVLA Observing Modes Calibration Strategy	020.10.05.05.00-0006 PLA
RD10	ngVLA System Conceptual Design Report	020.10.20.00.00-0005 REP
RD11	ngVLA System Requirements	020.10.15.10.00-0003 REQ
RD12	ngVLA Science Requirements	020.10.15.00.00-0001 REQ
RD13	ALMA Interferometric Pipeline Heuristics	PASP, 135, 074501
RD14	ngVLA Calibration Requirements Draft Update	Sridharan, T. K, et al Calibration Requirements draft update
RD15	ngVLA Data Processing Concept	020.50.55.00.00-0001 DSN
RD16	ngVLA Pointing and Primary Beam Requirements	Jagannathan, P, et al, ngVLA Memo (to be released)
RD17	ngVLA Telescope Operations Plan	Demorest et al., 2024
RD18	Size-of-Computing Estimates for ngVLA Synthesis Imaging	ngVLA Computing Memo #04
RD19	Pointing Self-Calibration Algorithm for Aperture Synthesis Telescopes	Bhatnagar, S. & Cornwell, T.J., 2017, AJ, 154, 197
RD20	VLBI Data Interchange Format Spec 1.1	https://vlbi.org/wp-content/uploads/2019/03/VDIF_specification_Release_1.1.1.pdf
RD21	VLA Holography	Perley, R., 2021 EVLA Memo. 212
RD22	Candidate Phase Calibrators at 93GHz in the ngVLASky: Developments Since 2022	Wrobel, Ho & Pesce, 2024, ngVLA Memo 123
RD23	ngVLA Observation Scheduling Concept	020.10.05.05.00-0012 PLA
RD24	ngVLA Observation Execution Concept	020.10.05.05.00-0013 PLA

2 Overview

This document provides a narrative description of the conceptual ngVLA calibration plan. It connects with the more quantitative material in the current draft version of the update to the calibration requirements (Calibration Requirements Draft Update) [RD14]. The document is intended to provide additional context to the requirements at their current level of development, describe the plan to meet them and, as an express purpose, inform the design of the ngVLA software and computational architecture and requirements. Pictorial representation of the calibration processes and decision flow are included wherever appropriate.

As noted in the ngVLA Telescope Operations Plan [RD17], it is anticipated that each calibration element will be owned by a Telescope Support Scientist who will be responsible for developing and maintaining the corresponding calibration observation and data analysis procedures, working with the telescope support, algorithms, data processing and the calibration groups to ensure functionality, adequacy and accuracy of the calibrations. A core set of these scientists will be part of the above groups during the design and development phase, gaining deep understanding of the processes by leading their development, and transition to the commissioning and science verification (CSV) team during the commissioning phase. These scientists will have interdisciplinary backgrounds and skills, spanning interferometric techniques, software and astrophysics and preferably also engineering.

3 Calibration Categories

The ngVLA intends to provide as much of the calibration information as possible, as observatory provided service. With this in mind, we define the following four calibration categories. This calibration classification structure, which includes both the parameters and the related processes required to obtain them, directly informs the computing architecture and interactions with the PI proposal, observation preparation, scheduling and execution, data processing, telescope operations and support, and monitoring and control components.

3.1 OBC: Observatory provided calibration

These are single dish and array calibration parameters maintained by the observatory through periodic measurements on a cadence appropriate for the individual parameters. This information will be provided to individual observations and used during their execution to ensure adequate calibration of the data obtained. The timescale for OBC parameters is long, expected to be few to several weeks with the final cadence being determined by field experience with the realized instrument. Much of this knowledge will be generated during the CSV and the initial science operations phases and will grow and mature with time as experience is gained. The parameters derived are maintained and updated by Telescope Support in corresponding databases which are identified in [RD14]. These databases provide the calibration data needed for processing the science data and for tracking trends in calibration parameters for diagnostic, and planning purposes.

3.2 SBC: Calibration included in the Scheduling Block

These are calibration data specific to individual observations and are obtained as part of the scheduling block to track parameters that change within an observation or are too specific and not generally applicable for the observatory to devote time to maintain under OBC. The observatory selects the calibrators used, consistent with the observing frequency, sub-array characteristics, observing conditions and the goals of the observation and includes them in the observing schedule, through observation preparation and scheduling processes [RD23, RD24]. An option for the PI to include specific choices shall be available when such non-standard calibration observations are adequately justified, through the TTAT process.

3.3 RNC: Realtime/Online Calibration

These are parameters whose values are needed for the on-going observations or for dynamic scheduling decisions. This category overlaps with the first two. Some of the elements in OBC and SBC will have to be handled on-line and in real time. Delay computations and antenna gain inputs to the phasing system have high time stringency and are needed in real time. Pointing solutions from reference pointing observations and elevation and weather dependent components of the pointing and feed position models are less time stringent but need to be handled on-line. Data flagging, formally not a calibration process, will include an initial online component. These functions are expected to be carried out by the *ngVLA TelCal* or an equivalent module.

3.4 IMC: Coupled Imaging/Calibration

Calibration and imaging are intimately coupled, in particular, in the calibration approach being adopted for the ngVLA for bands 1-3, and partly 4, that leverages the large array size of the ngVLA and its high sensitivity for self-calibration [RD06, RD14, RD16]. This category refers to the time dependent antenna based gain calibration for which the corrections are generated and applied as part of the coupled calibration-imaging loop. The calibration information is implicit in the science data and not obtained through separate calibration measurements. Some OBC and RNC calibration information are utilized in the IMC process.

Each of the calibration parameters would have an associated period of validity and an expected range of variation over that period. When an approved observation limits the allowable error to less than this range, the relevant parameters, including OBC, will need to be measured within a shorter period of time for that observation and may thus become SBC - e.g. high photometric accuracy flux calibration or high accuracy polarimetric calibration. When the last measurement of an OBC parameter crosses its validity time limit, new observations to update those parameters would be triggered for scheduling. Validity time periods applicable to such decisions will be set using operational experience during the commissioning phase and will continue to be updated to optimize observing efficiency, as more experience with the instrument is gained.

4 Generic Interferometric Observation Calibration

This section outlines the calibration elements and flow applicable to a generic interferometric observation. Many of its components will be common to specific specialized individual modes discussed later and previously documented in the Observing Modes Framework [RD09].

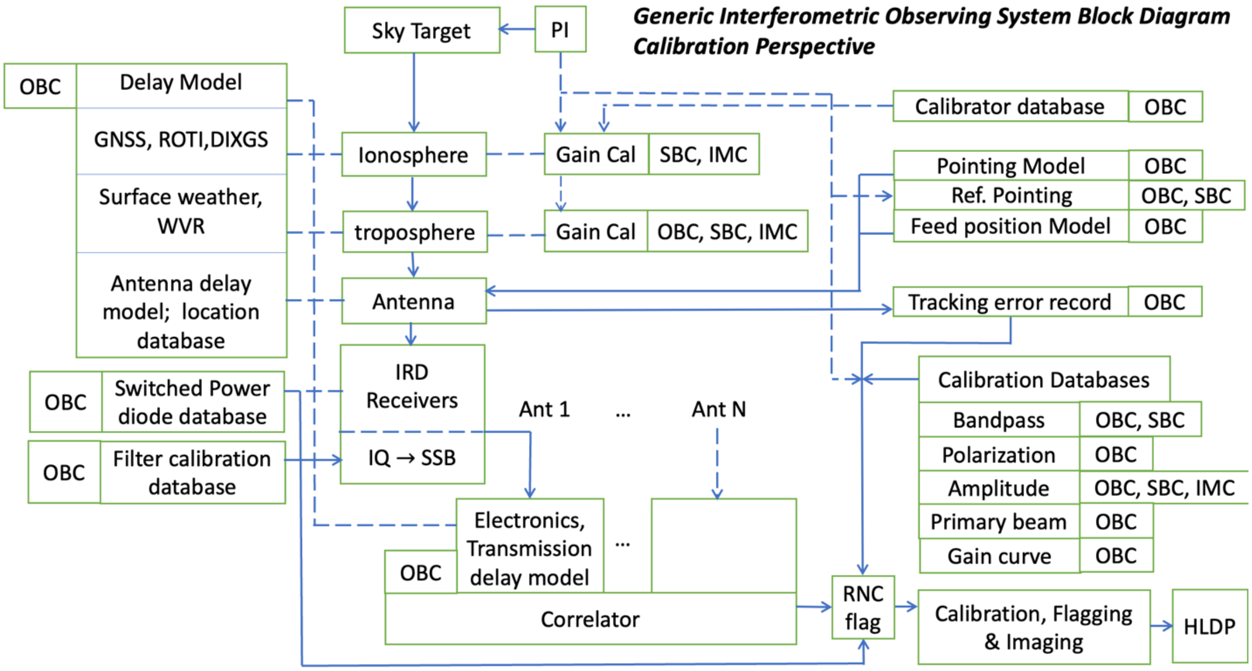

Figure 1. A high level observing system block diagram for generic interferometric observations from calibration perspective.

There are two paths one can trace through the observation process flow: (1) from a PI proposal and back to the PI delivering the proposed data obtained by the observations, provided in the high level data product (HLDP) processing level and format and (2) the signal flow path from the sky target, through the observing system, depositing data into the archive and delivering the HLDP to the PI. The two paths overlap in the observing system and the computing and software systems that generate the HLDP. The configuration and set up of the observing system, processes carried out by it and the processes in the HLDP system are informed by the goals and requirements presented in the PI proposal and circumscribed by the documented ngVLA science and system requirements [RD11, RD12]. The characteristics of the HLDP remain to be fully enunciated.

We follow the second path in the narrative below and indicate inputs from the first path wherever needed. Figure 1 presents a high level block diagram of the observing system from calibration perspective for generic interferometric observations and the generic calibration decision flow is shown in Figure 2.

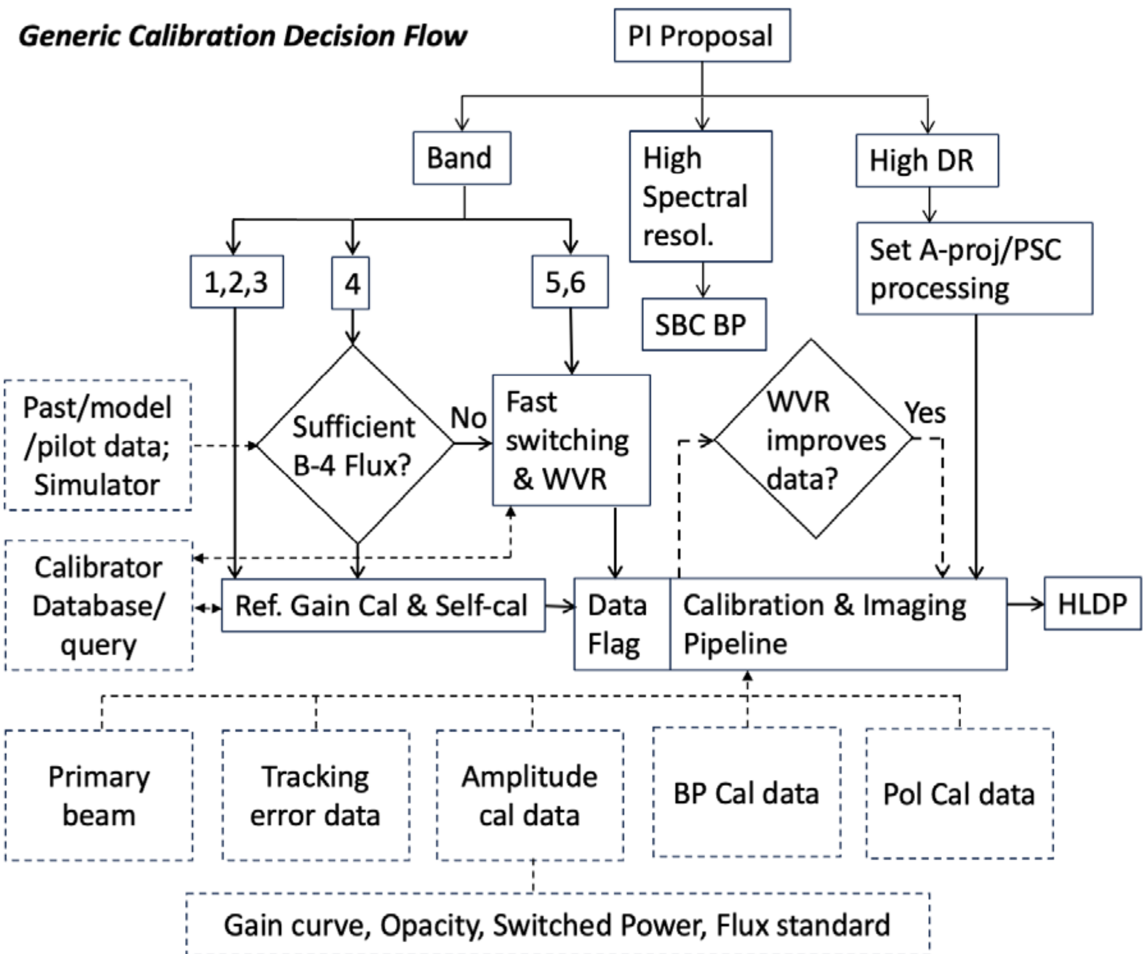

Figure 2. High level generic interferometric calibration decision and processing flow.

It is recommended that the association of specific calibrator identification and calibrator data with a specific science target for which the calibration is intended be explicitly recorded as metadata in the SDM for all calibration categories and not be left to the data processing pipeline to determine later. This includes OBC data or pointers to such data from the past and from the calibrator observations scheduled to be carried out in future. Careful book-keeping is recommended priority so that all corrections applied along the signal path are tracked and recorded as they are applied, resulting in the data arriving at the pipeline for processing having an exact and unambiguous account of what has been done to the data.

5 Sky Target

The following points are not calibration topics but included here for completeness. They are handled by TTAT.

Source position is obtained from the PI proposal and shall be in the ICRF3 frame (TBD). Source position types are sidereal target and non-sidereal target - Solar system, planetary orbit, earth orbit (and possibly, sub-orbital). For non-sidereal targets an indicative position during the scheduling period is needed for planning purposes and exact specifications of the position will be used at the time of observation.

Velocity - types are topocentric, heliocentric, barycentric and LSR. This information is used to compute Doppler correction to frequencies (Doppler setting) at the start of an SB. ngVLA does not support dynamically changing Doppler corrections during an observation (i.e. Doppler tracking) and such corrections are made offline, post-facto.

Proper motion, parallax and distance - option to include these parameters may be provided to ensure more accurate positions at the time of observation.

Tasks/processes: computing exact coordinates, realization of non-sidereal tracking, computing Doppler setting.

6 Atmospheric phase and delay

The atmospheric phase and delay variations consist of systematic components tied to the observing geometry and a fluctuating component related to changing conditions in the atmosphere. The calibration measurements and computations needed to determine the corrections also account for errors arising in the electronics and transmission systems.

6.1 Delay Model (OBC, RNC)

The delay model would include an atmospheric component which in turn is composed of ionospheric and tropospheric components. GNSS data shall be used to compute ionospheric delays. The tropospheric delay is estimated from surface weather parameters and may possibly include information from water vapor radiometer (WVR) data. Other components of the delay model are antenna positions, electronics and transmission. The delay model, applicable to all antennas, is addressed under long baseline/VLBI (section 14), where the impact is the most constraining from the perspective of astrometry as a fraction of the synthesized beam. Any ngVLA antenna can be part of a VLBI/Long baseline project and no distinction is made between different antennas from the delay model and antenna position calibration perspectives.

The computation and application of the delays will be an RNC component of OBC. The model generated data are provided to the Central Signal Processor (CSP; or computed in the CSP) and are used to set delays before correlation.

The Rate of Total Electron Content (TEC) Index (ROTI) and the Disturbance Ionospheric Index Spatial Gradient (DIXSG) data characterize ionospheric stability conditions and will be inputs for dynamic scheduling, and including the Crustal Dynamics Data Information System (CDDIS) data, to provide Faraday rotation corrections for low frequency polarimetric observations (section 9). Similarly, WVR data will be an input on tropospheric fluctuation conditions for dynamic scheduling of higher frequency band (4, 5 & 6) observations and for low overhead tropospheric delay correction (section 15). Accordingly, they are part of RNC. In addition, the phase RMS of the ngVLA interferometric phase data from the on-going observations, during calibrator visits, and science target scans if strong enough, will also provide real time assessment of phase fluctuations conditions. These RMS computations are categorized as RNC although they inform scheduling adjustments rather than calibration (section 15) and are carried out by the *ngVLA TelCal* module.

6.2 Reference Complex Gain Calibration (SBC)

Periodic observations of an appropriate nearby calibrator is included in the scheduling block which will be used for producing the initial sky model for the combined self-calibration and imaging loop in pipeline data processing. The choice of this calibrator, its observing cadence and integration time are determined by the observatory and will accommodate evolving prevailing phase stability conditions. For the higher frequency bands (5 & 6), and for some band 4 targets this calibration will constitute the primary gain calibration in the fast switching mode, addressed in more detail in Section 15.

Calibrator selection shall follow a three-tier process and is informed by the dynamic range and astrometric requirements set out in the PI proposal. An allowable calibration solution error is first computed from the proposal specified dynamic range and astrometric accuracy. The ngVLA Simulator (Section 19 below) will be utilized for this purpose. Then (1) a calibrator which can meet this requirement is sought from the calibrator catalog maintained by the observatory, failing which (2) nearby sources are observed and characterized for use as calibrators e.g. identified from the VLASS source catalog, current wide-area survey from the Atacama Cosmology Telescope and planned surveys from the Simons Observatory and the CMB-S4 [RD04, RD05, RD22] failing which (3) a region around the target is mapped to find a new calibrator (cone search). The calibrator database is updated with results from (2) and (3) as applicable. These steps are carried out in advance of the observations, during the observation preparation, scheduling and queuing process. In the case of a triggered transient observation with a previously unknown target location, the steps are executed at the time of the observation (on-the-fly calibrator selection). This process shall be fully automated with interface to scheduling, execution and support staff work flow through a *"waiting for calibrator"* state. An outline of this process flow is presented in Figure 3.

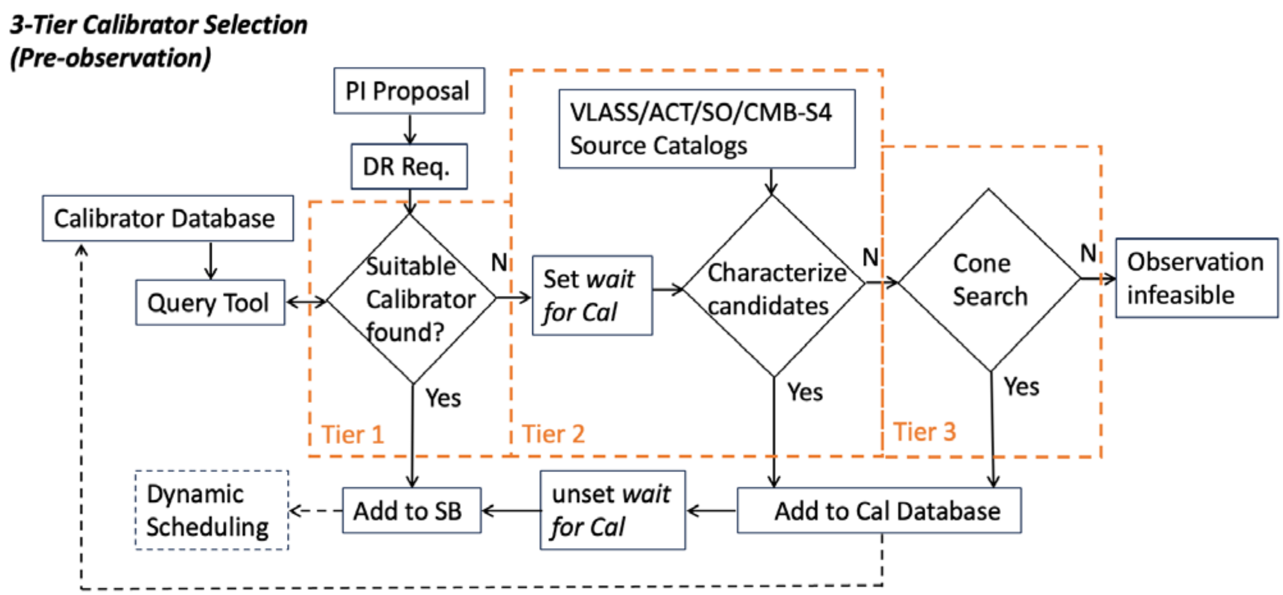

Figure 3. High level 3-Tier Calibrator Selection flow.

The compilation of the full ngVLA calibrator database is envisaged to be an ongoing process as part of science operations, without dedicated calibrator campaigns. Tiers 2 and 3 will be the core of this process, necessary and executed often during the commissioning and initial operations phases of the ngVLA when the calibrator database is being built. These tiers will largely drop off as the calibrator catalog matures. During routine operations, calibrators for most observations would be found in Tier 1.

In the case of high frequency observations, the reference gain calibration is the primary strategy and needs to be carried out with short cycling times of ~ 30 seconds. This approach, with a short switching cycle, is called fast switching. More details of reference gain calibration in general and in particular as it applies to fast switching, are presented in Section 15.

Tasks/processes: compute allowed calibration solution error; calibrator selection, cadence and integration time determination, inclusion in the SBC; cadence and integration time are determined from known calibrator model, distance to calibrator, selected sub-array, current stability conditions (Section 15), frequency of observation and a phase structure function model, using an algorithm to predict expected gain solution errors (to be developed). For triggered observations these tasks will be accomplished on-the-fly. The ngVLA Simulator (section 19) is a helpful tool for efficient and reliable decision making. This process is outlined in Figure 8 in section 15.

6.3 Self-Calibration (IMC)

For bands 1-3 self-calibration is the baseline complex gain calibration strategy, supported by reference gain calibration observations to create starting source models. The wide bandwidths of the ngVLA bands dictate the use of multiple sub-bands or the multi-frequency multi-term (MTMF) algorithm to derive self-cal solutions, with both being available. The MTMF approach provides optimal use of the available full bandwidth SNR for computing self-cal solutions by adding a small number of additional parameters. The A-projection algorithm will be available and will be used along with primary beam models when demanded by the proposed image dynamic range.

Bands 5 & 6 use fast switching calibration and WVR based corrections by default and will apply self-calibration to improve image dynamic range on time scales allowed by detected source flux, to be determined in the self-calibration and imaging pipeline. While fast switching and WVR are also the default strategies for Band 4, many targets will likely allow self-calibration (e.g., the KSG-3 mosaic science case requiring 35 dB dynamic range). This will depend on the source flux and can be determined on a case-by-case basis using expected source flux and possible short duration pilot observations. This choice and the pilot observation, when needed, will be made in advance of the observations during the observation preparation, scheduling and queuing process. The filler observations category provides a path for obtaining such pilot data.

We have estimated the compute requirements for self-calibration to be 500 MFLOP per solution interval for two polarizations, 214 antennas and 100 spectral channels. With sub-second solution intervals, the requirement is ~ few GFLOPS which is very small compared to the much larger requirement for imaging. Use of selfcal, including pointing-selfcal, to improve imaging performance requires re-imaging with the latest calibration solutions applied to the data. The spectral dependence of the sky brightness is handled as part of the imaging and its cost is included in the imaging compute cost. For projects that require selfcal/pointing-selfcal, we expect a few selfcal-imaging iterations. The additional computing cost will be close to the number of such iterations multiplied by the cost of imaging, for the fraction of projects requiring high dynamic range. Additional details about pointing-selfcal are included in the primary beam and pointing selfcal section below (section 8).

The need for self-calibration, A-projection and pointing self-cal are determined during the observation preparation stage for which the ngVLA simulation tool and/or decision heuristics developed using the tool, provide appropriate methods. The choices made at this stage are recorded suitably and carried in the SDM, so that appropriate recipes can be invoked in the data processing pipeline.

7 Pointing model and reference pointing (OBC/SBC)

Pointing corrections are computed and applied on multiple time scales - the all-sky pointing model on the longest, progressively followed to shorter time scales by SBC reference offset pointing, and pointing self-cal and tracking error record based corrections (discussed in Section 8), if required to satisfy PI proposal requested dynamic range. The term pointing here denotes where the antenna is pointing for a given data sample, including tracking error. The pointing model and reference pointing based corrections are applied by mechanical means, through the antenna control, tracking and monitoring system. Interferometric pointing is the operational baseline method for pointing error measurements with single dish pointing available for single antenna test purposes during commissioning or when integrating an antenna back into the array after maintenance, without requiring availability of other antennas.

Interferometric pointing measurements are comprised of:

- Absolute (All-Sky) Pointing: Pointing measurements carried out and used to derive and update the pointing models for each individual antenna (OBC); derived parameters maintained in the pointing model database.
- Antenna-dependent pointing model terms tracked within the monitor and control (OBC) database. Desirable properties for this system and database include:
    - Pointing model term coefficients tracked as a function of time
    - All-sky pointing measurement results should be provided in a form that is decoupled from the pointing model used to make the measurements with each antenna. This will allow for tracking and analysis of pointing model changes independent of the specific pointing model used at any given time.
    - Band-dependent offsets referenced to a common "reference band" that are tracked with pointing model coefficients for each antenna.
- Coefficients for optimal feed positioning in X (lateral; feed selection) and Z (axial) as a function of elevation (ngVLA feed indexer does not allow feed positioning in Y). Elevation dependent antenna gain curve measurements are addressed under amplitude calibration (section 13).
- Referenced (Offset) Pointing: Pointing measurements which are used to correct for small spatial and time scale variations of the antenna pointing which are not included in the all -sky pointing model for each antenna (SBC).
- Data acquisition time scales:
    - Absolute: >1 month (ideal, to minimize impact on operations)
    - Referenced: Included with each SB. For observations at frequencies >~ 20 GHz it might be necessary to apply measurements made at a lower frequency (<~ 20 GHz) if appropriate pointing calibrators are not available at higher frequencies (>~ 20 GHz).
- Compile SB-based referenced pointing measurements to track band-dependent offsets for each antenna (tracked relative to principal pointing model frequency band) (OBC)
- On-line refraction correction (RNC)
- Pointing self-cal (see Pointing Self-Cal, section 8) (IMC)
- Correction in data processing through A-projection using tracking error record (RNC, IMC; section 8)

8 Primary Beam & Pointing Self-calibration (OBC, SBC, IMC)

Meeting the high ngVLA dynamic range requirements necessitate corrections for direction dependent effects (DDE) [RD14, RD16]. These corrections fall under two separate categories. The first are the primary beam (PB) corrections which are the known per antenna elevation dependent beams (particularly at frequencies higher than 30GHz). These primary beams are OBC. The complex primary beams in each frequency band for each antenna would be measured and maintained in a database with updates as necessary. While the required measurement cadence is to be determined by observed change of the beams over time on the prototype antenna system, the VLA experience points to many years of stability [RD21]. The measurements will be dual polarization and include co-polar and cross-polar beams, although the ngVLA polarimetry requirements are explicitly on-axis. These beams will be applied to remove DDE effects at the time of gridding using the aperture illumination derived from these measured beams (Fourier transform of the measured PB). The imaging cost and KSGs for which they are required have been covered in detail in RD18(Table #1 of the computing memo). The known pointing offsets, such as the interpolated pointing offset from the known reference pointing offsets (section 7), from the tracking error record (a priori) or the continuous pointing table during an OTF scan are present in the pointing table as OBC and are taken into account at the time of gridding as a phase gradient. These pointing errors are limited by the engineering specifications of the antenna to ~3" or smaller. Corrections for residual pointing errors are required to meet ngVLA dynamic range requirements [RD14, RD16] which in turn require the use of the pointing self-calibration algorithm.

Given a priori knowledge of the PB and antenna pointing the AW-Projection framework can be used to determine the unknown residual pointing offset via the pointing self-calibration algorithm (PSC) [RD19]. PSC is triggered for observations requiring high dynamic range, DR > 10000 at 8 GHz for a single pointing or DR > 1000 for a mosaic at 27 GHz. This covers the two KSGs that require these algorithms and have been discussed in detail in the calibration requirements (sec 5.3 of RD14 & RD16). Pointing self-calibration introduces one additional major cycle along with a calibration cycle that determines the per antenna per time interval pointing offset which updates the pointing column of the data. This increases the compute requirements for these high DR cases by a factor of two over the estimates in the ngVLA computing memo [RD18] (Table #4 would increase to 1.0e13 FLOPs). At the end of one pointing self-calibration loop we would have sub-arcsec pointing accuracy on the source of consideration [RD16]. Pointing Self-cal is a unique case which is an IMC utilizing a priori OBC namely per antenna elevation dependent PB models providing corrections over and above a priori mechanical pointing offsets in the tracking error record which is an SBC, and interpolated reference offset pointing which is an OBC.

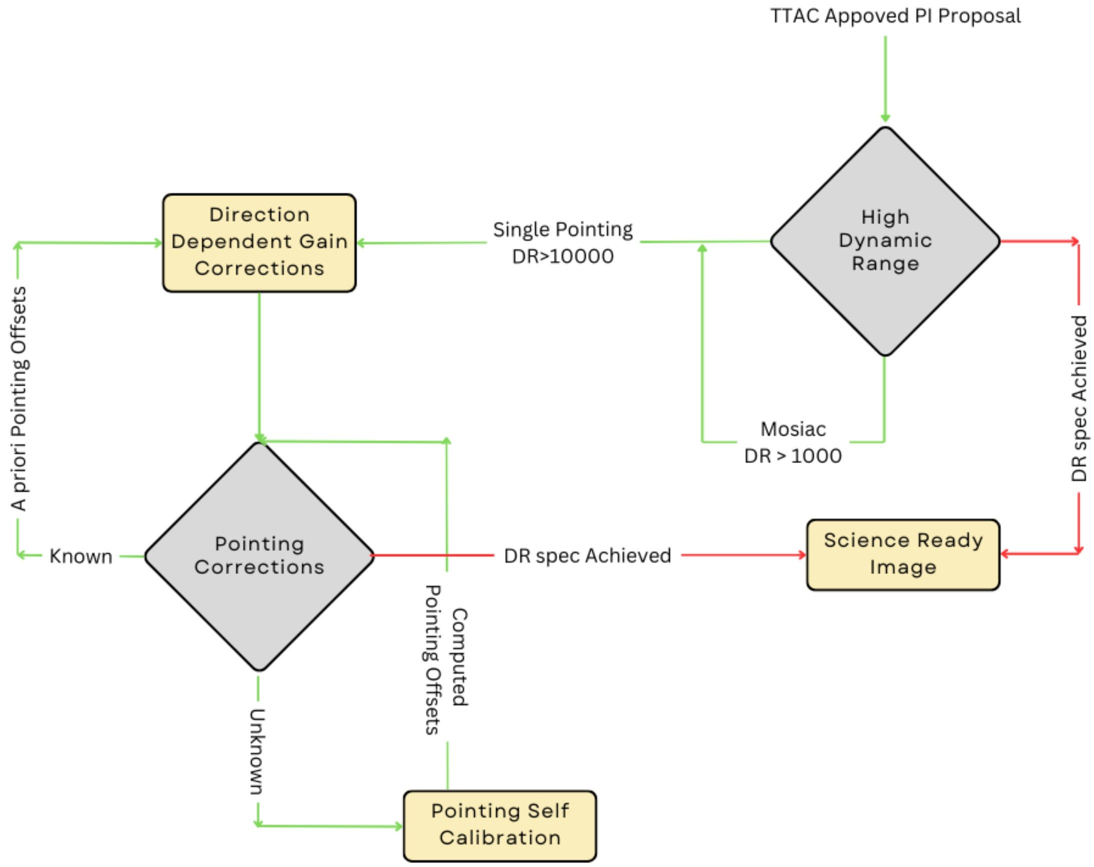

Figure 4. Pointing Self-calibration and a priori pointing correction flow.

The timescale of the PSC pointing solution is determined by the targeted dynamic range and the minimum time scale over which it is achievable given the SNR of the solution determined by the number of point sources in the beam (many) or the nature of the extended source (coverage over the PB at the observing frequency). This requires simulations for the use cases not covered by the KSGs. Such simulations capabilities can be part of the ngVLA simulation tool (Section 19).

9 Polarimetry

This section describes on-axis instrumental polarization calibration, i.e., the component of polarimetric impurity common to all directions within the sensitivity pattern of the antennas (primary beam). The direction-dependent polarization is included above in "Primary Beam" (section 8) and will be determined relative to the on-axis term. We note, however, that the ngVLA polarization science and system requirements are restricted to on-axis performance.

The complex instrumental polarization spectrum describes the degree to which each of the nominally-orthogonal pairs of linearly-polarized feeds on each antenna are spuriously sensitive to the other polarization. For well-designed front-ends, this polarization impurity should be less than a few percent (in voltage). These offsets are referred to the local meridian frame of the antenna. The large relative feed orientations originating in the wide geographical distribution of the array are *not* a component of the instrumental polarization, and will be described by the local parallactic angle at each antenna, calculated analytically. Effectively, the local parallactic angle for each antenna sets the nominal feed position angle relative to the rest of the array; instrumental polarization is a perturbation on this nominal, and results from finite errors in component manufacture and mounting registration. For small impurities, the real part of the instrumental polarization represents a small offset in feed orientation (from the local nominal); the imag part represents a small offset (from zero) in ellipticity. Instrumental polarization residuals limit cross-hand visibility accuracy in proportion to total intensity, and so its calibration is required for polarimetry, since (for linear feeds) ~half of the source linear polarization information occurs in the cross-hands. In general, polarimetry calibration will also be desirable even for total-intensity observing, since instrumental polarization residuals are an important dynamic range-limiting error.

The instrumental polarization spectrum, ***D***, is strictly OBC, since it is a property of the forward optics and front-end components inside the dewar and thus should be stable on timescales of at least months (barring cryogenic cycles or other maintenance events affecting the front-end and optics), and would be relatively expensive (and largely redundant) to solve for as SBC. For high-precision polarimetry observations requiring polarimetric accuracy not guaranteed by the OBC solutions, the instrumental polarization (and related) calibration solving scenarios described below could be included as SBC, for either absolute or incremental (to current OBC) solutions.

Accurate characterization of the instrumental polarization requires standard gain and bandpass calibration priors, as well as accurate estimates of the cross-hand phase and delay (which otherwise confuses the real and imaginary parts of the impurity) and calibrator polarization (which provides a near-absolute reference for the nominal polarization).

Cross-hand delay, $\boldsymbol{\tau}_x$, is effectively implicit within the electronic path components of the general delay model described in section 6.1, and thus is stored OBC, and real-time applied RNC. It should be periodically estimated alongside the general per-polarization electronic path delay estimation, by leveraging cross-hand correlations from observations of a strongly linearly-polarized calibrator. Note that the cross-hand delays of all but one antenna (the reference antenna) are implicit within any traditional (parallel-hand-only) per-polarization delay solution[1]. As such, the required specific cross-hand delay solution describes a residual net delay between the X and Y delay references of the whole array. Therefore, it is redundant to store per-polarization *and* cross-hand delays for each antenna from the astronomical calibration; instead, it is sufficient to store the per-polarization delays with one hand corrected for the cross-hand delay.

[1] Traditional parallel-hand-only astronomical electronic delay estimation ignoring the cross-hands yields an essentially arbitrary residual cross-hand delay.

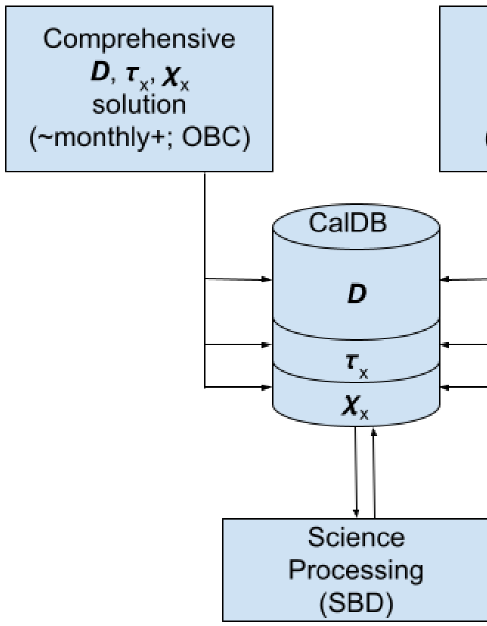

Figure 5. Polarization Calibration Block Diagram.

It is expected that a noise source common to both polarizations ("phase-coherent in both polarizations") will be available to supplement cross-hand delay calibration on individual antennas; this may be useful to track any electronic instability that occurs on timescales shorter than is practical to monitor with astronomical calibrators. However, it should be noted that this calibration signal will not traverse the entire signal path and may not be sufficient on its own to track all possible instabilities. Also, cross-hand auto-correlations (the XY correlation on a single antenna, within which the noise source is to be detected) are subject to RFI contributions that will not be dampened by differential (among antennas) geometric delay/phase compensation, and which may distort cross-hand delay estimation using a noise source. If determined to be sufficiently robust, this noise-source cross-hand delay calibration could be included on-the-fly within the delay model (as RNC), but there is probably no compelling scientific rationale for doing so; in any case, it should be recorded on an appropriate timescale for diagnostic purposes and/or offline application (OBC). Note that this cross-hand delay calibration is distinct from and relative to the astronomical cross-hand delay calibration described above. Care will be required to maintain the veracity of their combination, and of their combination with ordinary bandpass and the cross-hand phase bandpass described below.

The cross-hand phase spectrum, χ_x, describes the non-linear phase residual to the cross-hand delay phase (but possibly including any residual cross-hand delay not accurately accounted for in the available RNC delay solutions). It will be OBC insofar as bandpasses are also OBC; else it will need to be SBC. Like the cross-hand delay, it is implicit in all ordinary ("parallel-hand") phase bandpasses in all but one antenna (the net gain and bandpass reference antenna), and the solution will effectively describe the residual net bandpass between the X and Y phase references of the whole array. And so one hand of the OBC phase bandpass spectra on all antennas should be offset by the cross-hand phase spectrum solution. Use of an internal noise source common to the two polarizations on each antenna for cross-hand phase monitoring will be subject to the same limited signal path and RFI contribution limitations described for the cross-hand delay described above.

Absolute global cross-hand delay and phase solutions will be obtained astronomically alongside the comprehensive instrumental polarization spectra solution described below (nominally using parallactic angle coverage on a strong, polarized calibrator). With a good OBC instrumental polarization calibration solution in hand, routine monitoring of the cross-hand phase spectrum (or SBC solutions) may be achieved through short observations of a strongly polarized calibrator at an hour angle where its linearly polarized emission is not nearly parallel to either linear feed for the bulk of the array near the center. Such instantaneous measurements, as well as any short-timescale monitoring performed via a noise source, will be relative to the absolute solution.

The best-constrained global instrumental polarization spectrum solution, ***D***, will be obtained via a strong linearly-polarized point-like calibrator observed over a sufficiently broad range (>60 deg?) of parallactic angle (cf the traditional preference for circular feeds for a single scan on an unpolarized calibrator which can only yield a relative solution where the instrumental polarization on one feed of one antenna must be set (incorrectly) to zero, and then separately calibrated). The intrinsic polarization of the calibrator need not be known a priori, as long as it has non-zero linear polarization, and will be determined as part of the solution; most point-like calibrators will vary with time, and so prior knowledge will not be guaranteed. These observations also provide a well-constrained independent estimate of the cross-hand phase spectrum (including any residual cross-hand delay). In general, this will require an observation covering several hours centered on transit of the calibrator, and serially covering the full ngVLA frequency range (or a standardized subset?) at spectral resolution adequate to sample instrumental polarization variation (~ few MHz?) at adequate SNR.

This solution will yield instrumental polarization orientation spectra with an accuracy equivalent to the mean absolute feed orientation error across the whole array, which may be subsequently calibrated (if necessary) by observing a calibrator with precisely known linear polarization position angle (and offsetting the stored instrumental polarization calibration solution accordingly). Accuracy in ellipticity will be more elusive, and limited by scant (at best!) prior knowledge of calibrator circular polarization (typically at the few 0.1% level or less); constraints derived from a modest survey of calibrators, assuming mean intrinsic circular polarization of zero, may be necessary to constrain the circular polarization zero point.

There are several options for reducing the observing cost for the global instrumental polarization spectrum solution, including leveraging the wide geographical distribution of antennas to provide near-instantaneous estimation of calibrator polarization, or optimizing the parallactic angle range required (ongoing investigation; Ching et al) for a well-constrained solution. In general, the formally required parallactic angle range will scale inversely with the available SNR at the spectral resolution required to describe the instrumental polarization spectra. For long baselines, algorithms appropriate for handling resolved calibrators will likely be necessary to optimize this approach.

It is expected that a subset of individual antennas will cycle through maintenance events, and upon returning to the array require updates to cross-hand delay and phase and instrumental polarization. Note that this requires a mechanism within the OBC database of indicating the deprecation of the "current" solutions for such antennas. With a good OBC instrumental calibration solution available for the bulk of the array, it should be possible to bootstrap the polarization calibration parameters for returning antennas with mere single-scan observation, with the required observing time determined only by achieving adequate SNR at adequate spectral resolution for the required ngVLA frequency range (full, or standardized subsets). A single scan intended for astronomical cross-hand delay/phase calibration will likely be adequate for this additional purpose. The detailed algorithms for this bootstrapped incremental calibration, which should also permit identification and correction of nominal antennas which may be diverging from their current OBC solutions, are currently under study.

At low frequencies (< ~5 GHz, depending upon required sensitivity), the ionosphere will limit polarimetry due to Faraday rotation. Correction of this effect (which also includes a dispersive time- and direction-dependent delay that will limit total intensity bandpass phase accuracy) will be implemented using total-electron-content (TEC) estimates provided (at least initially) by 3rd-party services (e.g., CDDIS). These 3rd-party TEC surface maps are typically available within a few days of an observation, and should be provided to offline processing as if OBC.

All OBC polarimetry calibrations should be used as priors for SBC calibration solving activities, and included within the final calibration applied before imaging.

Instrumental polarization calibration (and related) solving will not require remarkable computing capacity, especially if the expected stability is achieved. Aggregation of time-distributed calibrator observations per-band/sub-band (i.e., over parallactic angle variation) must be supported, but otherwise, data/solution volumes and compute processing demands will be similar to bandpass calibration at similar SNR.

10 Interferometric On-the-Fly (I-OTF) mapping

On-the-Fly (OTF) observations are used to scan the sky rapidly in order to map out large areas efficiently, avoiding overheads incurred by moving disjointly between different pointing and phase centers. In interferometric OTF (I-OTF), this means that the phase and pointing centers during a "scan" are decoupled, with the antennas moving with respect to the target coordinates while the delay centers are kept stationary in the target frame (although occasionally stepped if desired) in order not to smear the point-spread-function (PSF) during imaging. Single-dish observations can employ OTF techniques without having to worry about this issue (non-interferometric OTF is discussed below).

The primary scientific use of OTF observing is to cover much larger areas of sky faster (e.g. higher survey speeds in deg^2/hr) and shallower (in "depth" or sensitivity, e.g. image rms in Jy/beam). Most often, these areas span many (100+) primary beam areas. Moderately large or very large area sky surveys can be done in this manner. This technique can also allow more rapid observing to carry out synoptic surveys. OTF observing has also proved useful to scan the whole sky very quickly to find RFI affected regions in the visibilities (no imaging was done).

The OTF observations themselves are carried out by specifying a non-sidereal antenna trajectory, moving the antenna Primary Beams (PB) continuously with respect to the celestial (or other) target sources. A given continuous track is designated as a "scan". At the same time, for interferometric I-OTF observations, the delay centers are fixed for some length of time (integration time, or a sub-scan) on a given Celestial, Ephemerides, or Terrestrial coordinates (e.g. RFI scans). On a longer time scale, this delay center can then be shifted periodically, usually along the trajectory. If these delay centers are within a given OTF scan, then these are designated as "sub-scans". Individual visibilities are taken at much smaller intervals within a scan or sub-scan, with a duration set by the OTF scanning rate and the antenna PB angular size so as not to smear the resulting effective PB for that integration too much. In theory, one would like if possible to have a motion of less than 0.1xFWHM during an integration, in practice we have had reasonable results with coarser sampling. For VLASS, this was restricted to 0.45 s visibility integrations although more like 0.2 s would have been better and ngVLA might use ~ 0.1 s or faster integrations in some cases. Thus, raw data rates and storage and data access volumes are significantly higher for I-OTF observations and processing (there are no quantitative estimates here but they can be scaled from standard estimates using a factor of 3 or more depending on how fast the visibilities are sampled).

During the imaging process, the OTF data is combined using the technique of "mosaicking" (OTFM) to account for the moving PB and the stepped delay centers (for I-OTFM). This is carried out by application of a "smeared" PB, if needed, during the imaging process (e.g. with AW projection as is done in CASA). For slow enough scanning rates or fast enough integrations or sub-scans this smearing might even be ignored, as is the case with VLASS. In this case, standard imaging algorithms can be used without any additional OTFM considerations. Self-calibration, primarily phase or delay self-calibration, can be carried out as normal, using the pointings in which a bright source is near the center of the PB. Since the goal of self-calibration is to solve for and apply a time sequence of (phase) corrections, there is no significant difference in the case of I-OTF observations other than the lower signal-to-noise due to shorter integration times per field.

Given the above considerations, OTF observing is used when the overhead from doing standard stepped pointed observations would lead to impractical inefficiencies, such as when very short integration times are desirable for the use case. For example, for the current VLA, there is usually (for a small slew) a 6-10 second "startup" cost at the start of pointed scan to allow move and settle. This can be somewhat shorter for antennas with new ACUs. Thus, if you want to observe very large areas, with a few seconds or less integration time at any location, then OTF observing is the technique of choice. By definition, the goal in these cases is for less sensitivity (by thermal noise measures) but larger area coverage, and often involves lower dynamic range or fidelity requirements (with respect to those of an equivalent significantly longer pointed integration), again based on the specific use case.

In summary:

1. OTF observing decouples the antenna scanning and delay center trajectories. Delay centers can be in Celestial, Ephemerides (e.g. moving sources), or Terrestrial (e.g. for RFI mapping) frames dependent on use case.
2. System requirements involve maintaining accurate super-sidereal tracking, handling very short dump times in the correlator and correlator back-end, and handling larger data rates in the real time system and the ingestion and retrieval of higher data volumes in archive.
3. Standard visibility calibration is unchanged from non-OTF cases.
4. Mosaicked imaging of I-OTF data also uses mostly the same software and algorithms as the non-OTF cases, although it will need to handle higher data volumes and more densely sampled mosaics.
5. Imaging using a smeared PB might be needed (given rate and desired DR and fidelity) but can be constructed from the normal antenna PB.
6. Self-cal is also mostly carried out as normal, except any pointing self-cal may need to use the smeared PB. Tracking may be worse for OTF than pointed so may want Pointing Self-Cal more often (but will

have higher sampling so this will be possible). Self-calibration will need to work with large datasets, but with less data per pointing.

7. OTF is usually for cases where wide areas are mapped with lower sensitivity, with lower S/N or fidelity requirements (usually). So requirements are generally less stringent. Main cost is using short integration times and high data rates.
8. Impact on post-processing computing is substantial, with a significant cost. This is best done further into the operational lifetime of the ngVLA. For example, the primary I-OTF science driver identified in the current ngVLA Science Case is for the search of LISA localization regions in Band 4, which appears to require 3.6sec integrations per pointing and is on the edge of requiring I-OTF to carry out. LISA is planned for launch in 2035.
9. Note that I-OTF observing is also useful for observatory operations and non-science applications, such as rapid surveying of the sky for sources of RFI. This was successfully done at S-Band with the VLA for VLASS preparation.

11 Data Flagging

The goal of automated visibility flagging is to remove all data affected by instrumental problems that cannot be well calibrated, meaning that it would remain as an outlier after full pipeline calibration. As developed and implemented in the ALMA pipeline [RD13], achieving this goal requires multiple steps, some of which involve selecting data, in many cases across scan boundaries, computing temporary calibration tables, examining the solutions or applying them, and comparing the corrected data to the model.

Flags generated by the online system (including the correlator) in response to out-of-range hardware conditions on a per-antenna/spw/time range basis should be applied to the affected data.

1. Deterministic flags should be applied, including for antenna shadowing and edge channel heuristics and any known self-generated RFI.
2. If any unflagged visibilities have retained only a subset of their polarization products, these flags should be extended to all polarization products because all of them are typically affected by the same problem at some level.
3. Solve for antenna-based gains on (at least) one scan of the brightest calibrator. Detect and flag antenna/spw combinations with persistently highly discrepant (>50%) amplitude gains. These flags are applied to all sources. Such data typically remains as obvious outliers after calibration, so the best course is to flag it early so that it does not compromise the subsequent calibration solutions, nor reduce the sensitivity of the more sophisticated visibility flagging heuristics. In some bands, this stage may need to be preceded by an RFI flagging stage to avoid spoiling the channel-averaged data.
4. Solve again for antenna-based gains on the calibrator(s) and apply them to the calibrators. For each calibrator field individually, compute the vector-channel-averaged corrected amplitude and take the scalar difference between that and the model amplitude on a per-spw basis. This value should concentrate around zero. Compute the median and MAD and identify outliers from the median beyond specific threshold factors of the MAD. For ALMA these thresholds begin at 3.3 sigma and extend to 12 sigma. Intermediate levels are used to identify persistent baseline-based outliers, antenna-based outliers, or integration-based outliers. The highest threshold is used to

catch any remaining outliers that do not correspond to such groupings. Because care needs to be taken to avoid flagging low points simply due to natural decorrelation at long baselines, the lowest threshold is doubled if very low amplitude outliers are found (<6.5 sigma) and they originate from more than a few antennas.

5. For flagging science targets, use the same method as (5) but use only the largest threshold factor and perform the statistics in individual bins of uv distance. In order to adapt to arbitrary uv structure and not flag good data, overlap the bins by 50% and require that a visibility must appear as an outlier in both bins in order to be flagged.

A related use case for flagging is in the real-time phasing solution for beam-forming modes. In general, poorly performing or even broken antennas will be noted in the scheduling system and not be included in an EB. However, there may be cases where a failure occurs just before or just after the start of a beam-forming EB and will need to be detected as an outlier in the gain solutions computed by TelCal and subsequently discarded from the online summation.

12 Total Power (TP) & TP- On-the-Fly (OTF) mapping

Some of the TP calibration activities are the same as for the individual antennas of the interferometric array and are collected together in the beginning below.

1. Antenna pointing calibration (follows section 7) can probably use existing system infrastructure (it should be interferometric anyway), but will happen on a cadence determined by TPA observations since it depends on where in the sky you are looking. The interferometric pointing here will be within the complement of TP antennas.
2. Optimal feed positioning offsets as a function of elevation ("focus check")
3. Polarization calibration can be OBC by the same mechanisms as other antennas, likely from the same observations. These should also be derived from interferometric observations.
4. Antenna gains (K/Jy) can be OBC but should be monitored, checked and updated. These gains are amplitude only. The switched power relative amplitude calibration and tracking using noise diodes (section 13) is applicable, but may need higher stability levels.
   4.1. Consideration should be given to including celestial SBC calibration checks to validate the OBC provided calibration (e.g., to identify antennas impacted by inadequately cleared snow accumulation).
   4.2. Main beam areas, near sidelobes, and relevant antenna efficiencies will need to be characterized and possibly tracked (forward coupling efficiency, etc.).

The following elements are specific to the TP antennas

5. Each TP map will require an OFF position which is free of spectral line emission in (at a minimum) the critical spectral region of interest.
6. These will need to be identified ahead of time. Observations will sometimes be required to check; the observing / data reduction workflow for these checks will need to be largely automated
7. The resulting spectra, for both "good" and "bad" candidate OFFs, should be tracked in a system database (ALMA does this in the source catalog). "Good" and "bad" here are labels that mean "usable as an OFF for a specific observation"

8. The allowable distance to an OFF is a function of system stability/linearity, atmospheric stability, and science goals (broad lines vs narrow lines - former is usually harder w.r.t. Residual spectral baseline ripple). The ALMA experience, perhaps specific to ALMA hardware and situation generally, is that up to a few degrees is ok. More than that (say 6 degrees), you get a lot of spectral baseline ripple. In the Galactic plane this requirement is commonly problematic.
9. Identifying, confirming and the maintaining OFF position database can adopt a similar approach as gain calibrators for interferometric observations.
10. Alternative "reference-less" calibration methods to (ON-OFF)/OFF need to be investigated such as Least squares frequency switching (Heiles+2007; Winkel & Kerp 2007) and LO modulation (Taniguchi+ 2021).

13 Relative and Absolute Amplitude and Flux Calibration

Amplitude calibration can be divided into two stages:

- Relative (Switched Power) Amplitude Calibration uses measurements derived from a switched power diode noise injection device to convert total power amplitude measurements (in Volts) to an antenna-based temperature scale (in Kelvin or flux with a known antenna SEFD) and to correct for gain (amplitude) fluctuations. These switched power measurements can include corrections for opacity (from tipping scans) and antenna gain curves.
- Absolute Amplitude Calibration extends the relative (switched power) calibration measurements to an absolute astrophysical flux scale using a set of known flux density calibrators. The fluxes of these absolute amplitude calibrators are regularly monitored and maintained in a database by the observatory.

Relative (Switched Power) Amplitude Calibration Requirements:

- [OBC] T_{Cal} values for the noise diodes should be measured in the lab, in the field or through celestial standard measurements (Figure 6) and maintained in a database.
- [SBC/RNC] Switched power diode device ("noise diode") measurements processed and included in the science data model that is subsequently applied in the calibration and imaging pipeline.
- [SBC/RNC] Switched power measurements with a recommended switching frequency of ~ 10 Hz allows correction for the amplitude part of the antenna based gain fluctuations.
- [IMC] Self-calibration also provides relative amplitude calibration, with respect to a reference antenna. In general, adequate S/N will be available only for bands 1-3.
- [RNC] Switched power derived amplitude gains provided to the phasing system for scaling antenna voltages before summing.
- [OBC/SBC] Opacity measurements from tipping scans performed as needed (interval TBD and based on science goals). Measurement results tracked and maintained in an observatory database.
- Required time scale for all contributions to the relative amplitude calibration requirement, which includes antenna gain curve, atmospheric opacity, and noise diode calibration, will need to be derived on the ngVLA. The noise diode stability requirements are set by the ngVLA dynamic range requirements [RD 14].

Diode Absolute Amplitude Calibration Flow

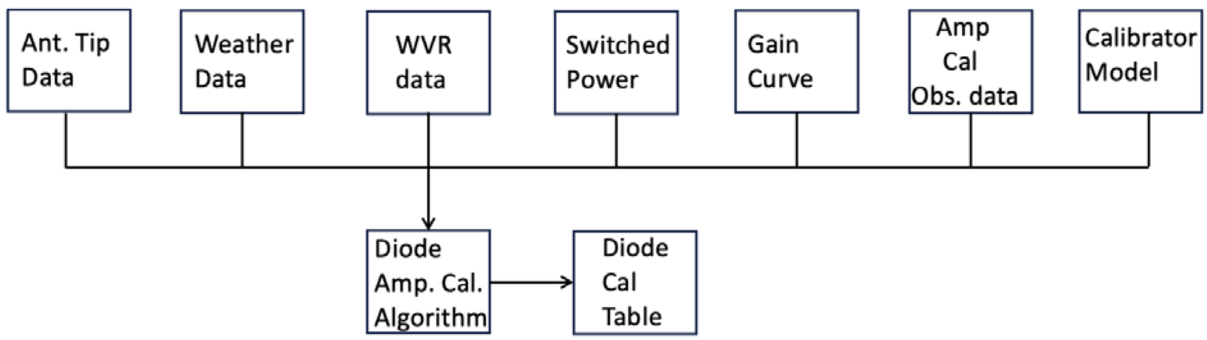

Figure 6. Calibration flow for the switched power diodes.

Absolute Amplitude (Flux) Calibration Requirements:

- [SBC] All relative (switched power) amplitude calibration requirements satisfied.
- [OBC] Amplitude calibration measurements on celestial calibrators, primary and secondary, that are regularly measured and stored in an observatory database.
- [OBC] Elevation dependent antenna gain (gain curve) for each band is measured through celestial observations and maintained in an observatory database. Opacity measurements and signal peak up by application of local pointing corrections and feed focus positioning at the time of each observation are necessary for accurate gain curve determination.
- [OBC] Periodic calibration of the noise diode power levels using observations of celestial references along with measurements of additional parameters that impact amplitude levels combined with sufficient stability of noise diode power levels would allow the use of the noise diodes for absolute flux calibration. Given the wide geographic distribution of the ngVLA, this approach (Figure 6) allows remote noise diode calibration without staff visits to individual antennas.

When the approved science proposal goals require better than 5% amplitude calibration accuracy for the observing system (excluding the error in the celestial flux standard; SYS6101 requires 1%), additional measurements will be required. This situation is summarized in Figure 7. This may also need bracketing the science observations with celestial flux reference measurements and the flexibility to include them in the SB should be available.

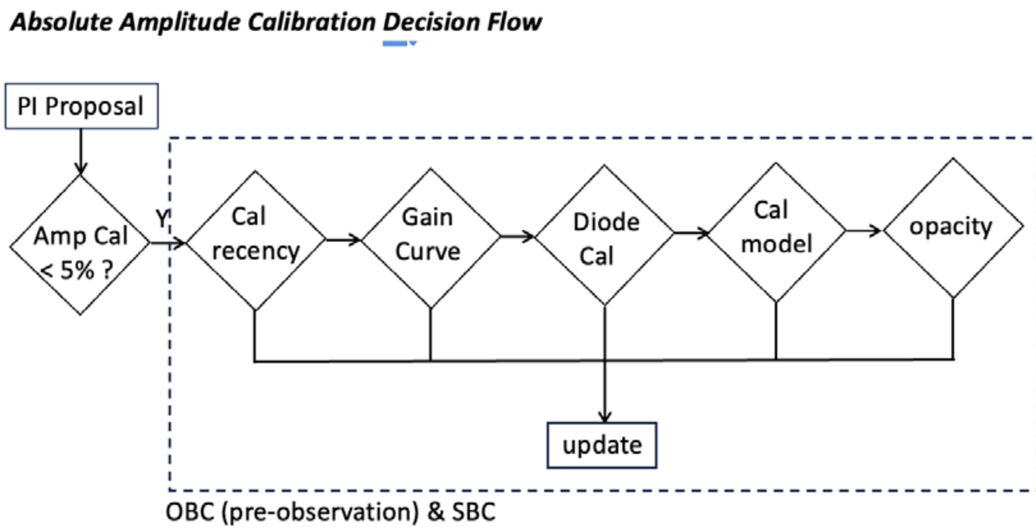

Figure 7. Decision flow for absolute amplitude calibration.

14 Long baseline/VLBI

The ngVLA operates as a connected element interferometer even on its longest baselines and any antenna can be part of a VLBI observation or an ngVLA project that uses the long baseline antennas. Accordingly, there is no distinction made between different antennas with respect to topics discussed here, in particular, antenna position measurements, gain curves and delay and clock model computations, and the discussions here apply to all antennas. The details of the operations model for LONG and VLBI observations need further thought and definition.

VLBI relies heavily on accurate timekeeping and on an accurate delay model. The VLBA currently uses the delay model from the Calc 11 software developed by the NASA Goddard Space Flight Center. The ngVLA should continue to use the state-of-the-art model developed by the Geodetic community, as currently implemented in Calc 11. The VLBA currently records data using the VLBI Data Interchange Format (VDIF) [RD20], with a 5 MHz timing reference signal and 1 pulse per second reference both tied to GPS time. The ngVLA has selected its own format for recording baseband data from the digital backend. Data output from the correlator will be formatted in VDIF, and it will be possible to convert data from individual antennas to VDIF as it passes through the ngVLA correlator. This method will allow us to correlate observations taken with external antennas using some form of digital correlator (e.g. ngVLA observations in coordination with other telescopes to form something like the Event Horizon Telescope or the Global Millimeter VLBI Array).

The VLBA currently maintains a database that holds observatory provided information, similar to data that would fall under observatory provided calibrations (OBC). This includes parameters like receiver calibration temperature, antenna gain curves (antenna gain vs. elevation and feed positions vs elevation), instrumental delay and pointing. Table 1 below outlines data maintained by the VLBA that is relevant to the ngVLA and which we adopt for the ngVLA. Currently the expectation is that the NRAO will choose calibrators for the required observations.

Table 1. Data currently stored for the VLBA that is relevant for long baselines on ngVLA.

Name	Calibration Element	Data Source	Notes
Calibration Temperature (T_{cal})	Amplitude	NRAO	T_{cal} values are measured in the lab for each receiver, and updated when receivers go through maintenance/upgrades. This is discussed in Section 13 above
Switched Power	Amplitude	NRAO	A noise diode injects known power into the front end. The "on" and "off" power values are measured by the backend and recorded. This is mentioned in Section 13 Above.
System Temperature	Amplitude	NRAO	Calibration temperature and switched power values are used to generate System Temperature
Gain Curve	Amplitude	NRAO	Determined through regular gain curve measurement datasets. Currently gains measurements are made after major changes to an antenna, typically many months of data used to make the calculations. Mentioned in Sections 7 and, more thoroughly, in Section 13
Single Dish/Interferometer pointing	Pointing	NRAO	Single Dish used to measure pointing offsets and update gains; Interferometric Pointing measurements are used to construct the pointing model. This is thoroughly discussed in section 7.
Horizon Data	Pointing	NRAO	Determined shortly after deployment. Kept in Sched to help with scheduling
Clock Model	Delay	NRAO	Offset and rate for the Hydrogen Masers are maintained by NRAO. More information on how timing is tied to GPS below
Antenna Positions	Delay	NASA Goddard	NASA Goddard Space Flight Center maintains antenna positions for VLBA. Kept in Sched, updated with new releases (approximately every 1.25 years). More

Name	Calibration Element	Data Source	Notes
			discussion below on suggestions for ngVLA
Earth Orientation Parameters (EOPs)	Delay	United States Naval Observatory	EOPs are critical to transformation between the Celestial Reference Frame and the Terrestrial Reference Frame. USNO Generates EOP Predictions, and updates them. Data comes from global VLBI experiments
Ephemeris Data	Delay	NASA Jet Propulsion Laboratory	Information is downloaded from NASA as needed. Information goes into scheduling.
Site Weather Data	Delay	NRAO	Temperature, barometric pressure, dew point, wind speed, gust and direction, and precipitation.
Atmospheric Mapping Function	Delay	NRAO/Vienna	Currently, NRAO uses a simple model to estimate the delay contribution from the Atmosphere (Troposphere). It is possible to request the Vienna Mapping Function, calculated by the geodesy group at TU Wien, which uses a Numerical Weather Model of actual weather conditions to determine the delay contribution from the atmosphere.

Name	Calibration Element	Data Source	Notes
Ionosphere TEC	Delay	NASA	Currently, NRAO uses global TEC maps developed by NASA to estimate the delay contribution from the Ionosphere. The data comes from GPS satellites/receivers, and has relatively poor spatial and temporal resolution. The VLBA is currently installing high quality GPS receivers and as part of that, will look at using the collocated GPS receivers to get a better TEC product. More discussion on GPS below. Note: Ionosphere corrections are useful for astronomical observations, but critical for astrometric observations. Current TEC maps are insufficient for high quality astrometry, so the main reason the astrometric community observes with two frequencies simultaneously is to remove this effect. The optimal bandwidth for removing ionospheric effects is approximate ν_{high}=4 x ν_{low}. Only band 2 spans this frequency range. This information will be critical for station positions, and finding a good way to remove the effect will be important.

Antenna position information is critical to operation of long baselines. This is done through a series of astrometric observations, which is then used to solve for antenna position. Currently, NRAO does not carry out this task internally. Instead, data is taken from the NASA Crustal Dynamics Data Information System (CDDIS). New station positions are included in updates to the VLBA scheduling software Sched, roughly once every 1.25 years. This information is made up of data that has been taken over many years, with many different telescopes to make up a global VLBI network.

The Geodetic VLBI community currently monitors station positions. They schedule 24-hour observations targeting as many bright quasars as possible covering the entire sky. The sky coverage allows them to determine a number of effects including atmosphere, clock offsets, and changes in cable lengths. After correcting errors, the information is stored in databases. Typically, every 3 months or so, a global solution is done which takes the data from all collected sessions and simultaneously solves for all parameters, which include station positions, source positions, Earth Orientation Parameters, atmosphere, and clock parameters.

To determine antenna positions, the NRAO should continue to work with the geodetic community. We should start by using collocated GPS receivers to get good estimates of station positions. A new technique to do this is being developed wherein the astronomical antenna and GPS receiver will simultaneously observe the same very bright AGN, the data correlated, and delays used to determine station position relative to the GPS monument. This allows the antenna to be seated in the GPS terrestrial reference frame. Once that initial site position determination is done, the LONG stations of the ngVLA should participate in Geodetic VLBI observations to bring it into the VLBI Terrestrial Reference Frame. This will involve a number of geodetic VLBI observation sessions that will have to be properly processed. After the antenna positions are determined, ngVLA LONG should continue to participate in 24-hr sessions at least once per month.

The main array can be properly seated in the ICRF/ITRF through observations with the long baselines. In the early phases, when the LONG stations may not yet be available, core/ mid/ spiral antennas could be part of the geodetic campaigns. The length and frequency required for these observations will be determined in the future, but they should include sources with well determined positions and cover all declinations.

Currently, source positions are determined at S-band (2.3 GHz), X-band (8.6 GHz), K-band (24 GHz), and Ka-band (32 GHz). The expectation is that for the near future this work will continue at all frequencies listed. The dual band set-ups (S/X and X/Ka) are used to remove the effects of the Ionosphere, and currently the ngVLA will not be able to observe these frequencies simultaneously (though band 2 covers a similar frequency range to S/X). The ngVLA will likely have a few options for correcting this, including GNSS data or observing with two antennas tuned to different frequencies. The International Celestial Reference Frame is the current standard for high quality astrometric sources. It is currently maintained at 2.3, 8.6, 24, and 32 GHz. The 8.6 GHz catalog is currently large, but the 24 GHz and 32 GHz catalog are growing every year. The ICRF is maintained by the International Earth Rotation and Reference Systems Service (IERS). The ngVLA should continue working with the IERS to expand the number of known calibrators, and expand the number of known high frequency reference sources through collaboration and telescope time allocations as part of OBC campaigns.

Earth Orientation Parameters (EOP), the values that tie the Celestial Reference Frame to the Terrestrial Reference Frame, are critical to operation of the VLBA, and will be critical to the ngVLA. Earth Orientation Parameters are downloaded from USNO, with predictions used for initial observations and correlation, and final values downloaded after correlation for correction during post-processing. It's likely the predicted values will be good enough for some projects, but for many projects, the final EOP release will be required to correct in post-correlation analysis, especially on the longest baselines.

For syncing time, the ngVLA should have a 1 Pulse Per Second reference tied to GPS time. When we are ready, the Hydrogen Maser(s) should generate its own 1PPS and reference timing signal. The GPS 1PPS and Maser 1PPS should be compared. This information is used to generate a clock model that has an offset and rate for each maser, which is applied at correlation. When the difference between the GPS and Maser gets too large, the drift rate of the Maser should be adjusted to bring it back to normal. With the VLBA, it takes more than 24 hours to generate a clock model. Higher quality GPS receivers being installed at the

VLBA now (and which should be installed at ngVLA sites) will provide higher quality data and should need less time to generate a clock model.

15 Tropospheric Calibration - Fast Switching/WVR

For high frequency observations, self-calibration shall not be the primary strategy for interferometric amplitude and phase correction. In order to calibrate random phase errors due mainly to atmospheric phase fluctuations, which occur on short time scales, fast switching would be mandatory. This calibration will also correct for slower electronics and other system fluctuations, including residual error due to antenna position uncertainties. Current analyses [RD04, RD05 & RD14] indicate that adequate calibration to achieve ngVLA imaging dynamic range goals is feasible with 30-40 s fast switching cycling time, which entails a ~ 50% calibration overhead efficiency. Water vapor radiometry (WVR) is being developed as an approach to improve this efficiency.

For fast switching, nearby phase calibrators, usually bright and compact quasars, have to be selected for each observation. For all high frequency observations, the observatory will maintain a catalog of phase calibrators available in Bands 4, 5 and 6 compiled through the 3-tier approach presented in Section 6.2. Previous work has established the availability of such calibrators in close proximity of ~ 2 deg, statistically, to any location on the sky in Band 6 [RD04, RD05, RD22] (easier in Bands 4 & 5). The observatory will validate the flux densities and structure of these calibrators through confirmatory OBC service observations, as many of these calibrators may not have previous interferometric observations of adequate quality. Assuming that a majority of high frequency observations are scheduled in the winter season (for example, December to March), the relevant OBC high frequency confirmatory observations applicable to the upcoming observations may be conducted only before the start of the observation season in one combined OBC run. For observations scheduled at other times, separate OBC observations will be necessary. These short confirmatory calibrator observations, nominally one calibrator for each science target, will be no longer than a minute. As noted earlier, the ngVLA approach is to build and maintain calibrator catalogs and databases progressively as part of science operations, rather than through dedicated calibrator campaigns. After the initial phases of catalog compilation, confirmatory observations will generally not be necessary (tiers 2 & 3 in Section 6.2, Figure 2).

Adequately justified PI requests to use specific phase calibrator(s) and strategies for their science goals shall be accommodated, for example, precise astrometry using multiple phase calibrators surrounding the target source. Similarly, check observations of an additional weak calibrator may be included in the SB if warranted by science justification.

The residual phase error Φ_{err} after fast switching phase referencing is expressed as follows:

$$\Phi_{err} \sim \left[(kT_{sys}/AS)^2/2B\tau + 2 \times (2\pi)^2 \times (\theta_{sep} \times \Delta b/\lambda)^2 + (2\pi/\lambda)^2 C_s (vt/2 + h\theta_{sep})^{5/3} \right]^{1/2}$$

where the first term is double the Gaussian random phase noise (k is Boltzmann constant, T_{sys} is the system noise temperature, A is the effective antenna aperture, S is the phase calibrator flux density, B is the cross-correlated bandwidth, τ is the phase calibrator scan length), the second is baseline vector phase error (θ_{sep} is the angular separation between the calibrator and the target, Δb is the antenna position error at the edge of the configuration, λ is the observing wavelength), and the third is the residual atmospheric phase fluctuation after phase referencing (C_s is the structure coefficient of the atmospheric excess path length (EPL) fluctuations at that moment, v is wind velocity, t is cycle time, $h\theta_{sep}$ is the horizontal distance between the target and phase calibrator at the altitude of the water vapor scale height of h). Based on the above phase error, the following considerations apply to fast switching calibrator selection:

(1) *Separation angle* of the calibrator to the target source. Inputs are observing frequency, array configuration (maximum baseline length), the antenna position accuracy achieved in baseline measurements, and nominal values of phase structure function parameters (OBC).

(2) *Calibrator S/N* for a single scan. Inputs are scan length, observing bandwidth, calibrator flux density, and system noise temperature (OBC). The ability to change the bandwidth between science target and the calibrator observations will be necessary to attain high calibrator S/N for otherwise narrow bandwidth spectral line science observations.

(3) *Calibrator cycle time*. Inputs are observing frequency, current atmospheric Excess Path Length (EPL) fluctuation RMS (RNC) and fluctuation time scale and phase structure function parameters.

(4) *Calibrator structure*. Inputs are calibrator database entries uvmax and uvmin (OBC).

The ngVLA Simulator will be useful in these considerations and allow determination of the applicable parameters. Heuristics derived from simulator experiments and accumulating ngVLA operational experience may be used, rather than running the simulator itself in each instance.

Below, we focus on observatory tasks to provide a nominal fast switching strategy, that is, using a single gain calibrator as close to the target source as possible. The process flow envisioned is shown in Figure 8, and described in the following sub-sections.

15.1 Pre-selection of gain calibrator candidates for pre-observation confirmation (OBC)

For approved proposals for high frequency observations, the observatory will make a list of gain calibrator candidates for the set of the upcoming target sources. The input parameters to make the candidate lists are (1) target source position, (2) observing frequency, (3) array size (maximum baseline length), and (4) PI requested dynamic range, astrometric accuracy, and amplitude calibration accuracy. Based on the above inputs, the observatory estimates (through algorithms to be developed and the ngVLA simulator) (i) the maximum separation angle, and (ii) the minimum flux density needed to meet the PI requests. Then the observatory automatically generates a scheduling plan for a combined OBC calibrator confirmatory observation run for the list of calibrators. This list will exclude calibrators for which such confirmation is not necessary based on existing information in the calibrator database. This process will be carried out whenever there are approved high frequency observing proposals.

15.2 Confirmatory Calibrator flux and structure check (IMC/OBC)

It is required to confirm the flux density and source structure of the gain calibrator candidates because many quasars show time variations in structure and cm/mm wavelength flux. While the combination of a mature calibrator database and accumulated operational experience will eliminate the necessity of this confirmatory step for most observations, the process flow and software architecture should allow for it, as it is especially needed in the initial phases. The required high observing frequency, if the weather allows. The flux, uvmin and uvmax information will be updated in the calibrator database using the results. If the observatory is unable to accomplish observations at the high frequency because of the weather and/or instrument maintenance, observations will be arranged at a lower dual frequency (for example, in Bands 3 and 4) to infer the flux density at the observing high frequency from the measured spectral index. If a second component whose peak flux density exceeds a pre-set fraction (TBD) of the main component is found, the candidate must be flagged as "No-Phase-Cal-Use (Structure)". If suitable calibrators are not identified for some targets a second run will be necessary with a smaller subset until calibrators are found for all targets. This process is known as the "*cone search*" at ALMA.

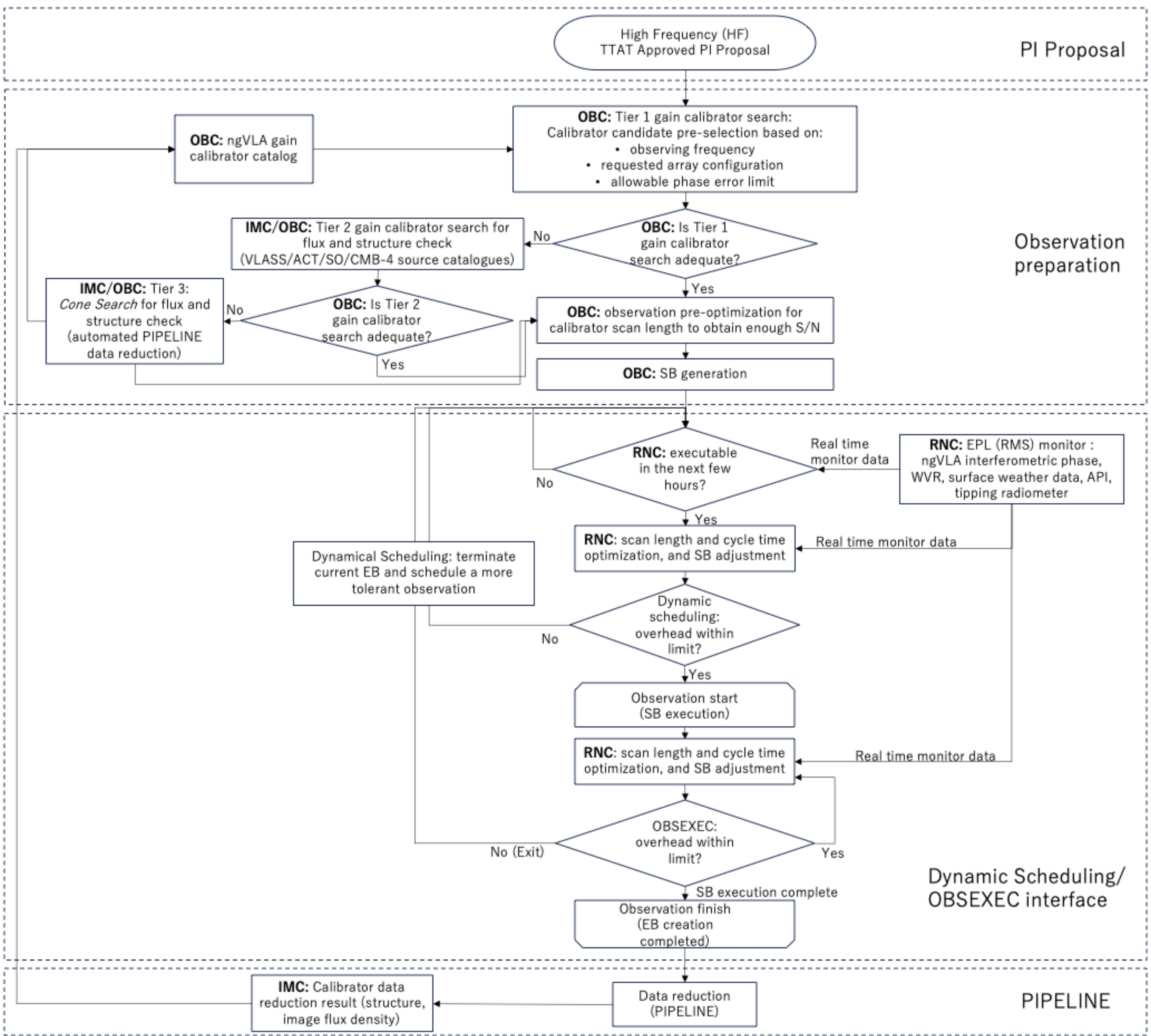

Figure 8. Fast Switching calibration process flow.

The possibility of using calibrators with known structure determined through self-calibration will be investigated and implemented in future. This will be essential for the ngVLA as many calibrators in current use at other observatories will likely show structure, both due to the high resolution and sensitivity of the ngVLA. In this approach, the calibrator database will include the actual imaged calibrator models.

Since gain calibrator candidates must be brighter than a certain threshold and have compact structure, they can be self-calibrated, and the data reduction of the confirmatory calibrator observations can be pipeline processed.

A confirmed gain calibrator for each target source is determined as a result of the above calibrator check process. At this stage, the calibrator scan length can be pre-optimized using the Eq (1) to obtain enough S/N assuming an expected system noise temperature, up-to-date flux density at the observing frequency and nominal values for C_S, v and t.

15.3 Real-time monitoring of atmospheric EPL RMS and PWV and cycle time optimization (RNC)

It is necessary to monitor the atmospheric EPL RMS derived from the real-time ngVLA interferometric phase RMS divided by the observing frequency to be used as an input to determine allowable combinations of the observing frequency and maximum baseline length in real time: for example, SBA and Core up to Band 6, Spiral up to Band 5, and so on. In parallel, surface weather parameters and PWV sensed with WVR shall be monitored to determine if current conditions allow high frequency observations from system noise temperature and phase stability points of view. A real time estimate for the C_S may be developed from the combination of WVR data, weather data, current observed interferometric phase fluctuations over the array, and the less geographically representative atmospheric phase interferometer (API) and tipping radiometer data, through algorithms to be developed.

Using this combination of real time assessments, if a high frequency observation is feasible as the next observation in the dynamic scheduling process, array operations conduct the following two checks. One consideration is to select the optimum cycle time because the atmospheric phase fluctuation is dynamically changing. Expected residual phase errors are calculated for two to three cycle time values (for example, 120, 60, and 30 s) and compared with allowable errors to meet proposal goals. Another consideration is to check the fast switching observation feasibility. If the calibration overhead, determined from the separation angle, observing elevation, the corresponding slew and settling times, cycle time and scan lengths, is excessive, the observations will have to be returned to the queue for a better opportunity. This includes source passage near the zenith, when small switching cycle time will not be feasible due to the large azimuth rotation required with the alt-azimuth mount antennas.

The ability to dynamically modify the parameters involved should be possible during an executing observation, to adjust the cycle time and scan length to respond to changing conditions within limits and the effect of airmass on thermal noise. Outside some to-be-specified limits, scheduling a different observation will be warranted, which is included in this dynamic behavior as a boundary.

These functions belong to obsexec and dynamic scheduling processes and the general concept is outlined here as the driving factor for these decisions is the evolving calibration overhead along with system noise. The overall ideas presented here are meant to draw attention to these elements and their connection to calibration and not intended to dictate a particular implementation. The specific approach can be further refined and developed leading up to FDR and during the construction phase.

15.4 PIPELINE data reduction feedback (IMC/OBC)

If a suitable phase calibrator is selected according to the above procedure, PIPELINE data reduction would be straightforward and the appropriate recipe will be invoked in data processing [RD15]. The phase calibrator's flux density and structure information obtained in the PIPELINE data reduction can be fed back to the observatory calibrator database updating it with newly derived parameters. This process is applicable to all reference gain calibrator observations.

15.5. Water Vapor Radiometry (WVR) OBC/RNC

As previously noted, in order to improve observing efficiency, 22 GHz WVR is being developed to provide tropospheric delay fluctuation corrections without fast switching. Delay predictions from WVR shall be applied off-line until sufficient operational experience has been gained with a well proven algorithm to derive tropospheric delays from WVR data. The time rate for this correction is yet to be determined and is expected to be in seconds and therefore the observatory provided WVR OBC correction is also categorized as RNC. The delay correction process shall compute coherence measures during calibrator observations and on the science target field, if sufficiently strong emission is present, with and without WVR correction to determine if WVR correction is beneficial. Correction is applied if it results in improvement. Once WVR is well understood, the predictions may also be applied to the phased array mode to improve short time scale phasing efficiency, in particular, for higher frequencies.

WVR is also useful for higher frequency observations to monitor precipitable water vapor (PWV) to avoid high Tsys conditions on a per station basis, in addition to the coarser definition of precision observing condition.

16 Phased Array

In addition to antenna cross-correlation, the ngVLA will also support phased-array observing modes (also sometimes referred to as summed-array or tied-array). In this case, the voltage data streams from all antennas are summed after appropriate calibration factors have been applied. The voltage data are then either recorded as-is, or detected and recorded as power versus time and frequency. The primary use cases for this mode are:

- Observations where an ngVLA subarray is intended to be used as a single element in a VLBI experiment. The voltage data are recorded, and the data are correlated offline with the other participating antennas.
- Observations that aim to acquire high time resolution (typically µs to ms; these timescales are impractical for visibility data) on a small number of individual pixels within the field of view. The most common targets are expected to be pulsars. In this case the data are detected, and recorded as power versus time, frequency, and polarization.

The fundamental principles of phased-array calibration are identical to those of other interferometric calibration described elsewhere in this document. The only significant difference is that per-antenna corrections need to be applied to the data in real-time, before summing the antenna data streams. It may be conceptually useful to split phased-array calibration into two parts:

1. Individual antenna calibrations that are applied prior to summing. The primary goal of this calibration step is to remove variation between antennas, therefore *maximizing the signal-to-noise ratio in the phased sum*.
2. Calibrations that can be applied after the sum. These might include additional amplitude scaling to put data in correct flux density units, clock corrections needed for VLBI correlation or pulsar timing, or further polarization correction ("absolute D-terms"). While it may be possible to handle these in real-time along with the per-antenna calibrations, this is not strictly required.

The standard observing pattern expected to be used for phased-array is switching between a gain/phase calibrator (observed in interferometric/cross-correlation mode) and a target source (observed in phased-array mode) similarly as described in Sections 6.2 and 15. The necessary switching cadences will be similar and can be determined by the level of decoherence as a function of time since the calibration solution. The switching cadence is a function of observing frequency, maximum baseline length, and weather conditions; typical values will range from ~tens of minutes or longer at the lowest frequencies and shortest baselines, to ~30s at 100 GHz as noted in Sec. 15. Similarly, WVR data as described in Sec. 15.5 may potentially be used to supplement calibrator switching and lengthen the cycle times at the higher frequencies.

At lower frequencies there may in some cases be enough flux in the target field of view to calibrate without having to switch to a phase calibrator. This could be from the target source itself and/or from nearby unrelated background sources. In this case solutions could be continuously computed and applied, likely on ~minute timescales. While this would increase observing efficiency it may also require an *a priori* image of the field be provided, rather than the usual case of a point-like calibrator. This approach has not been demonstrated on the VLA. It should be investigated further, and ideally not ruled out in any ngVLA software/system design, but the standard approach for now should assume calibrator switching.

The per-antenna calibration terms that must be applied to the data in real-time (prior to antenna summation; all RNC) are:

1. Bandpass (gain amplitude and phase versus frequency) – applied based on previously measured, observatory-maintained tabulated values (OBC).
2. Polarization (***D*** from Sec. 9) – also OBC.
3. Gain phase and delay determined from the phase calibrator and possibly WVR data (SBC).
4. Amplitude weighting to maximize S/N ratio; may make use of SBC data such as switched power. If all antenna gains and system temperatures agree to within ~20%, a simple scaling to normalize power levels may suffice.

With the potential exception of WVR data, all these calibration terms can be assumed to be held constant for the on-target portion of the observing cycle. A "bracketing" observation of the phase calibrator should generally be made at the end of the cycle in order to assess the amount of decorrelation across the target scan. This can also be used to determine updated calibration coefficients for the next iteration on the same target.

The most unique aspect of phased-array observing is the requirement to solve for and apply phase and delay calibrations in near-real time. These are determined via interferometric observations of a point-like calibrator near the target field. Solutions are calculated using standard methods as in offline interferometric calibration. The frequency scale over which the solution needs to be calculated is an open question. If the OBC bandpass solutions are accurate and stable enough, a single phase and delay may potentially be solved for the entire observed band. This allows fainter calibrator sources to be used and should be the preferred approach. Alternatively, separate solutions could be computed per 200-MHz sub-band, this is more consistent with current VLA practice. In either case, RFI flagging should be applied to avoid bad channels corrupting the solution; this becomes more critical for wider-band solutions. In order to support calibration cycles of ~30s without loss of observing efficiency, calibration solving should take at most ~10% of the cycle time. Therefore, all calibrations should be computed and applied within ~3s of the end of the calibrator scan.

The primary calibration that must be done after summation is rescaling the data to calibrated flux density units. This can be done using the same basic procedures as described in Section 13. The main phased-array-specific consideration is that all pre-summation calibration and data scale/weight factors as listed above *must* be recorded so that the sum can be re-scaled appropriately. In other words there should be no automatic power-leveling, bit selection, etc, where the relevant scale factor is lost. If needed, the flux scale can be corrected for loss of phasing efficiency based on bracketing phase calibrator observations and/or self-calibration solutions on the target field using simultaneously-recorded interferometric data.

17 Pulsar

For pulsar timing observations, the only additional calibration consideration beyond those described in Sec. 16 is the requirement to tie the time of observation to a standard absolute time scale such as GPS time (to 10 ns, as set in the system requirements). This is also required for VLBI and the scheme of monitoring a local clock (maser) versus GPS described in Sec. 14 should work for pulsar data as well, provided the system requirement is satisfied. This clock correction is not required to be known in real time, it can be tabulated and applied to the data after observation.

18 Bandpass

Correcting the instrumental response of each antenna in frequency is a critical step in calibrating interferometric data. This is not only applicable to spectral-line science data, but also to continuum-science data which are obtained in multiple frequency chunks (basebands and/or sub-bands) and numerous spectral channels over the wide instantaneous bandwidths of the instrument.

The bandpass calibration outlined below assumes the following for the ngVLA system:

- I-Q filter bandpasses are stored and applied/corrected on-the-fly during the acquisition of the data. This is necessary to enable sub-band selection at the antenna.

- Antenna f-shifts are removed before the application of the default 218.75 MHz sub-band filters and the subsequent forming of the visibilities [020.30.25.00.00-0003 DSN, Section 4.2.1.1.5.8]. This is critical to avoid introducing baseline-dependent artifacts, as has been the case with the EVLA, which in turn lead to having undesirable spectral ripples when using very narrow sub-bands (e.g., EVLA memo 171).

With these two assumptions in place, bandpass calibration will then be needed to correct for:

1. The analog band shape, i.e., of the front end and RF post-amplification stages,
2. The digital filter shape of the sub-bands with both being antenna based.

The ngVLA system, as noted earlier, will deliver 218.75 MHz sub-bands by default, but can also be configured to deliver narrower sub-bands when necessary to generate finer channelization. Both the default 218.75 MHz sub-band filter shape and the narrower ones have known responses in frequency, and their polynomial representations should at least be recorded and made available for data processing. Alternatively, if the ngVLA resources allow, having them applied on-the-fly may be considered.

With the antenna-based nature of bandpass calibration, this correction can then be performed by observing a dedicated calibrator source, which should be adequate for most observations. How or when such a calibrator may be observed in practice is noted in point (I) below. However, there are exceptions to this, where a suitable bandpass calibrator may not be available, and this case is expanded in point (II) below.

I. *Bandpass calibration using a calibrator:* Here, we note two scenarios
   A. For standard data, which we define as 218.75 MHz wide sub-bands and native 15.625 kHz wide spectral channels: The observatory carries out OBC service observing on strong calibrators that can be adequate for bandpass calibration purposes, and the bandpass solutions obtained from such service observations are applied to science observations during post-processing.
   B. For non-standard data, which we define as any data set with channels narrower than the native 15.625 kHz, the science observations themselves include scans on the bandpass calibrator, as SBC. The bandpass solutions are derived from these scans that are included in the science observations and applied during post-processing. These SBC based corrections are currently considered to be incremental, i.e. relative to the OBC bandpass correction, pending further discussion and clarification of the pros and cons.

   The boundary between OBC and SBC is yet to be clearly determined and will be based on the expected overheads for these observations.

II. *Bandpass calibration when the traditional approach of observing a celestial calibrator does not work:* This will be the case for spectral-line observations that include very strong target sources that make finding a suitable bandpass calibrator impossible (e.g., very strong maser lines, or very strong continuum sources that are the background for spectral-line science). Because appropriate celestial bandpass calibrators may not be found for such cases, it becomes critical to remove the bandpass response of the digital filters by knowing and applying their shapes using their stored polynomial representations. Hence, the need to record/store them and then provide them during data processing. What is left in this scenario is the frequency response of the front-end. However, the science cases that fall under this are typically for narrow spectral lines. If the ngVLA front end response is similar to the EVLA (and more likely better), then the response of the front end over such narrow ranges of frequency should be fairly flat and therefore a non-issue for this case.

19 ngVLA Simulator

A software package that generates simulated ngVLA data is a desirable nice-to-have tool. Such a tool can serve multiple purposes, primarily heuristics development for decision making during observation preparation and to test and secure proposed calibration strategies. Its utilities were indicated throughout the discussions in the previous sections. Individual pieces of the simulator may exist, and it will be valuable to add missing functionalities and assemble them into an ngVLA focused package. The full-fledged simulator is envisioned as an integrated tool, incorporating sky model input, realistic phase/delay fluctuations based on phase structure functions, amplitude and opacity fluctuations, configurable subarrays, pointing errors with partial correlations across the array, elevation dependent primary beam model and polarization parameters, IRD electronics stability, calibrator model, distance to the calibrator, antenna position error and fast-switching antenna mechanical performance. A preliminary implementation may simply be a collection of independent tools. A barebones initial simulator realization built with a modular approach can accommodate upgrades and additions as resources permit. While decision heuristics development is the goal, simulation of individual observations may be considered in demanding cases where observational parameter optimization may be an enabler. The tools, and the studies employing the tools, can be developed as part of the construction phase. The simulation results can be distilled into decision criteria in combination with on-sky data and instrument knowledge during the commissioning phase. The decision criteria and heuristics developed will transition into the operational phase and continuously revised, providing up to date operational guidance.

20 Appendix

20.1 Acronyms and Abbreviations

Acronym	Description
ACT	Atacama Cosmology Telescope
API	Atmospheric Phase Interferometer
CDDIS	Crustal Dynamics Data Information System (NASA)
CMB	S4 Cosmic Microwave Background Stage 4
CSP	Central Signal Processor
CSV	Commissioning and Science Verification
DDE	Direction Dependent Effects
DIXSG	Disturbance Ionospheric Index Spatial Gradient
DR	Dynamic range
EPL	Excess Path Length
GNSS	Global Navigation Satellite System
HLDP	High Level Data Product
IMC	Calibration coupled with imaging
I-OTF	OTF-Interferometric OTF
I-Q	Q- In-phase and Quadrature
IRD	Integrated Receiver Digitizer
KSG	Key science goal
MAD	Median Absolute Deviation
OBC	Observatory provided service calibration
OTF	On-The-Fly
PB	Primary beam
PSC	Pointing self
PWV	Precipitable Water Vapor
RFI	Radio Frequency Interference
RNC	Realtime and on
ROTI	Rate of TEC index
SBC	Calibration included in Scheduling Block

SO	Simon Observatory
SSB	Single Side Band
SDM	Science Data Model
SEFD	System Equivalent Flux Density
TEC	Total Electron Content
TP	Total Power
TP-OTF	Total Power OTF
TTAT	Telescope Time Allocation Tool
VLASS	Very Large Array Sky Survey
WVR	Water Vapor Radiometer/Radiometry

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