CASA INTERFEROMETRIC PIPELINE POLARIZATION CALIBRATION & IMAGING REQUIREMENT & DESIGN SPECIFICATIONS

Christopher A. Hales (NRAO Socorro)

Version: 2.1 (June 22, 2017)

CHANGE RECORD

Version	**Date**	**Affected Sections**	**Remarks**
0.0	2016-08-23	All	First draft, mostly VLA focus
0.1–0.3	2016-09-30	All	Added partial ALMA sections, general tidyup
1.0	2016-11-30	All	First complete version, solicit feedback
2.0	2016-12-16	6.1, 6.2.1, 6.2.2, 7	Minor clarifications, improved refant handling
2.1	2017-06-22	3, 4, remove App. A	Minor improvements, Appendix A not needed

SUMMARY

The CASA Interferometric Pipeline does not currently support polarimetry. This document outlines a 'phase 1' upgrade to support calibration and calibrator reference imaging for a subset of linear polarization observing modes with ALMA and the VLA. A framework is presented that is largely instrument agnostic, and upon which future upgrades or even new pipelines for different telescopes may be built. Required modifications to the pipeline, CASA, and wider infrastructure are described. A plan of work is outlined.

The document includes an overview of polarization theory. Equations are derived to explore the conditions under which a calibrator may be classified as unpolarized. Simulation results are presented to illustrate the role of calibrator signal to noise and parallactic angle coverage in limiting post-calibration spurious on-axis polarization and position angle errors. The simulations indicate that calibration schemes requiring parallactic angle coverage in the linear feed basis need only observe over 30°, beyond which no significant improvements in calibration accuracy are obtained. In the circular feed basis, 30° is also appropriate when the Stokes vector of the leakage calibrator is known a priori, but this rises to 90° when the Stokes vector is unknown.

This work is published as ALMA Memo 603 and EVLA Memo 201. Much of the material in Section 4, upon which the later sections are based, has been published separately in The Astronomical Journal; see Hales (2017).

Contents

1 Introduction

This document outlines a ‘phase 1’ upgrade to the CASA pipeline to facilitate calibration and imaging of polarimetric data observed using ALMA and the VLA.

ALMA observes with dual orthogonal linear feeds (X, Y) in all bands. The VLA observes with dual orthogonal feeds that are circular (R, L) in all bands above 1 GHz and linear at lower frequencies (P- and 4-bands). Pipeline capabilities for both feed bases will therefore be considered.

The broader philosophy of this document is to develop a general framework for pipeline polarization calibration that is interferometer agnostic. Additional functionality can then be added in the future (phase 2 and onwards) without needing to reinvent the scaffolding, whether that functionality is specific to ALMA or VLA or perhaps as part of a new pipeline for a different telescope.

The structure of this document is as follows. Section 2 presents a brief overview of the CASA integrated pipeline. Section 3 describes the scope of the phase 1 upgrade, listing assumptions that may be revisited for future upgrades. Section 4 presents a summary of polarization fundamentals including calibration degrees of freedom, predicted levels of spurious on-axis polarization leakage resulting from different calibration strategies, and atmospheric Faraday rotation. Section 5 describes calibrator classifications, scan intents, and practical calibration strategies suitable for the pipeline. Section 6 describes the proposed infrastructure for the phase 1 upgrade. Section 7 describes the plan of work. Section 8 looks ahead to possible requirements for future upgrades.

2 CASA Integrated Pipeline

The CASA integrated pipeline is a framework upon which 3 customized science pipelines have been built. These are designed to support automated processing of interferometric data from ALMA[1] and the VLA[2,3], and single dish data from ALMA. The pipelines are under continual development to provide end-to-end calibration and imaging for increasing observational parameter space. A fourth science pipeline is currently under development to support the VLA Sky Survey (VLASS). No formal functionality currently exists for polarimetry.

The pipelines are data-driven. Heuristics parse the characteristics of each dataset to drive a unique calibration and imaging strategy. During each pipeline run, the ‘context’ stores information such as which calibration tables are needed. The pipeline design philosophy is to use CASA tasks and their internal error checking mechanisms whenever possible.

There are 5 types of pipeline tasks, prefixed with the following:

h_	*Common tasks* – pipeline tasks suitable for both interferometry and single-dish datasets

---

[1] https://almascience.nrao.edu/documents-and-tools/

[2] https://science.nrao.edu/facilities/vla/data-processing/pipeline

[3] https://casaguides.nrao.edu/index.php/VLA_CASA_Pipeline

hif_	*Interferometry common tasks* – pipeline tasks used in the calibration and imaging of both ALMA and VLA interferometry datasets
hifa_	*Interferometry ALMA tasks* – pipeline tasks used in the calibration and imaging of ALMA interferometry datasets only
hifv_	*Interferometry VLA tasks* – pipeline tasks used in the calibration and imaging of VLA interferometry datasets only
hsd_	*Single-dish tasks* – pipeline tasks used in the calibration and imaging of single dish datasets only

Existing interferometric gain calibration tasks within the ALMA and VLA pipelines are customized by facility and prefixed accordingly. The pipeline imaging infrastructure is more general and is prefixed with `hif_`. The target prefix for polarization calibration and imaging tasks is `hif_`. The aim for polarization processing is to perform as much processing as possible in instrument-independent tasks.

Each of the pipeline tasks report quality assessment scores and associated information. These are presented to the user in a weblog interface. The scores can be used in formal quality assurance procedures. For ALMA, the zeroth stage of quality assurance (QA0) is associated with near-real-time monitoring of data quality thoughout an observation. The next stage, QA1, is associated with telescope performance parameters that are more slowly varying (timescales longer than a week). The QA2 stage is associated with the science products and supporting material produced by the pipeline with manual assessment provided by observatory personnel. For ALMA, the data are required to pass QA0–QA2 before being delivered to the PI, with raw data optionally included. An additional QA3 stage regards issues discovered after delivery and is handled though helpdesk tickets. As the pipeline is improved, the QA2 process will be increasingly driven by the automated pipeline scores, rather than manual assessment of pipeline products. Procedures for handling VLA data are similar. Raw data are made available to the PI immediately after observation. All VLA science observations are automatically processed by the pipeline (whether or not the observing setup conforms with supported pipeline functionality). The data undergo a basic manual check before being made available to the PI. If pipeline-processed VLA data fail the manual check, they are still made available but with a brief set of suggestions for PI followup.

For historical reference, the ALMA interferometric pipeline was first accepted for science operations in Sep 2014 (Cycle 2) followed by single dish pipeline acceptance in Sep 2015 (Cycle 3). The ALMA pipelines were first released to the public as version C2R1B in Oct 2014 within a dedicated CASA version (4.2.2-pipe). The calibration portion of the VLA pipeline originated as a set of stand-alone python scripts. These were first accepted for operational use in Feb 2013 (2013A D configuration) and publicly released at the same time as version 1.1.0 designed to operate within CASA 4.1.0. The VLA pipeline was subsequently integrated within the CASA pipeline infrastructure and released together with the ALMA pipelines in Aug 2015 within version C3R1B embedded within CASA 4.3.1. The C3R1B release was the first time that the pipelines were included in a standard release of CASA, rather than delivery within a custom CASA build.

3 Scope of Pipeline Polarimetry Upgrade Phase 1

The release schedules for CASA and the pipeline are as follows. CASA is released twice a year, in March and September. The next release is CASA 5.0 in March 2017, followed by 5.1 in September 2017. The latter will coincide with the start observations for ALMA Cycle 5 and VLASS. The pipeline will be released once a year, embedded within the September CASA release. The next pipeline release will therefore be in CASA 5.1. Internal releases of the pipeline will take place on a customized schedule. Planned internal pipeline releases on the path toward the 5.1 public release will be 5.1P1 in March 2017 and 5.1P2 in June 2017. This naming convention supersedes the C#R# nomenclature.

The phase 1 pipeline polarization upgrade described in this document is intended for implementation across the 5.1 (2017) and 5.3 (2018) CASA releases. Implementation of a subset of phase 1 functionality will be prioritized for public release in CASA 5.1, focusing on existing manual polarimetric calibration procedures for ALMA and planned procedures for the VLASS. Depending on resources, it is likely that implementation and validation of the full suite of capabilities described in this document will need to await delivery until the CASA 5.3 release in September 2018. A breakdown of priorities is provided in the plan of work described in Section 7.

The phase 1 upgrade will be designed to support the following standard observing modes:

ALMA Time division mode (TDM) and frequency division mode (FDM) correlation for 12-m Array observations of linear polarization. Currently only Bands 3, 6 and 7 are offered to observers for linear polarimetry. Bands 4 and 5 will be offered for linear polarimetry in Cycle 5.

VLA Interferometic observations of linear polarization at frequency bands between 1–50 GHz.

No explicit support will be provided for data where circular to linear (or vice versa) instrumental leakage effects are important, as these data require circular polarization calibration. The phase 1 upgrade will be designed to perform polarization calibration of science target data if corresponding observations are available for polarization calibrators using the same spectral setup(s); no support will be provided for transfer of polarization calibration solutions from one spectral setup to another, nor for polarization spectral window mapping. Functionality to support observing modes beyond those described above will be deferred to future upgrades (e.g. spectral line polarimetry, ALMA ACA, total power, circular polarimetry). Phase 1 pipeline polarimetric imaging will be limited to calibrators.

More generally, the phase 1 upgrade will only support polarimetric calibration of data from an interferometric array that meets the following requirements:

- All feeds are alt-az mounted, i.e. situated on alt-az antennas without dish rotators such as those used on ASKAP.
- There are at least 3 baselines; closure between $N \geq 3$ antennas is required to solve for of order N matrices from $N(N-1)/2$ baselines (Sault et al. 1996). The pipeline currently checks that $N \geq 2$.

- Parallactic angle is constant across the array; i.e. the array is small with $\psi_i = \psi$ for all i antennas[4]. CASA's polarimetric solvers are not currently designed to recover a calibrator's unknown polarization in the presence of differential parallactic angle over the array (note that this does not affect calibration strategies involving sources of known polarization).
- All antennas are fitted with dual orthogonal linear or circular feeds with the same nominal alignment, forming a homogeneous array. Mixed basis polarimetry is not yet considered, though this may become necessary in future upgrades to support phased ALMA for VLBI.

The phase 1 upgrade will assume that polarization calibrators are unresolved and located on-axis. In general, CASA polarimetric solvers are not currently designed to operate with spatially resolved calibrators[5], even if a model is supplied. The only exception is position angle calibration in the circular feed basis, provided a suitable model is supplied by the user. No such models are as yet embedded within CASA for known calibrators (e.g. 3C286). If CASA capabilities are upgraded in the future to fully support resolved polarization calibrators, the functionality of polarimetric calibration strategies outlined in this document will not be affected (indeed they should work better). The pipeline will however still require an upgrade to support any newly facilitated calibration strategies. CASA polarimetric calibration tasks are not currently designed to account for the off-axis polarimetric response of the system (furthermore, calibration tasks in general are not currently designed to account for the primary beam).

Finally, the proposed phase 1 upgrade aims to utilize as much of the existing CASA code base as possible (tools, tasks), minimizing the need to develop upgrades or new functionality. Section 7 describes a small number of improvements to CASA that are essential to support the proposed pipeline upgrade. A larger number of desired future upgrades to CASA are described in Section 8. Future versions of the pipeline can incorporate these future CASA improvements.

The assumptions above provide broad scope to the phase 1 upgrade. More specific assumptions will be presented throughout this document and highlighted in the proposed implementation.

4 Polarization Fundamentals

This section presents an overview of polarization theory and application. For simplicity, the assumptions from Section 3 will be incorporated implicitly. More detailed treatment is beyond the scope of this document. *Frequency dependence is implicitly assumed.*

CASA calibration is based on the measurement equation formalism (Hamaker et al. 1996; Sault et al. 1996; Noordam 1996; see also CASA Cookbook). The measurement equation

---

[4] It would be an interesting exercise to calculate a metric for this.

[5] For example, the strategy suggested by Sault et al. (1996) to calibrate using a single observation of an extended polarized source that is at least 3 resolution cells in size with varying non-zero fractional polarization, à-la AIPS `LPCAL`.

relates observed visibilities to ideal model visibilities on a baseline as

$$\boldsymbol{V^{obs}} = \mathbf{B}\,\mathbf{G}\,\mathbf{D}\,\mathbf{P}\,\mathbf{F}\,\boldsymbol{V^{mod}} \tag{1}$$

where the corrupting Mueller matrix terms (frequency-dependent outer products of antenna-based Jones matrices) are associated with atmospheric Faraday rotation, parallactic angle, instrumental polarization leakage, combined electronic and atmospheric gains, and bandpass, respectively. Some terms are neglected above for clarity (e.g. phase delay associated with the ionosphere/plasmasphere, antenna elevation-dependence, non antenna-based terms). While the corrupting terms in the measurement equation are written as independent effects along the signal path, in general they are not. Care must therefore be taken to distinguish dominant terms from those that are coupled and thus depend on the results of terms yet to be calibrated. The former can be solved for independently and used in the bootstrap process to calibrate downstream terms, while the latter require iteration across multiple terms to converge on a global solution. The measurement equation is typically refactored to the relative phase frame of the bandpass/gain reference antenna (phase fixed to zero in both polarizations)

$$\boldsymbol{V^{obs}} = \mathbf{B_r}\,\mathbf{G_r}\,\mathbf{K_{crs}}\,\mathbf{D_r}\,\widetilde{\mathbf{X}}_\mathbf{r}\,\mathbf{P}\,\mathbf{F}\,\boldsymbol{V^{mod}} \tag{2}$$

where the reference antenna's crosshand bandpass phase $\mathbf{X_r} = \mathbf{K_{crs}}\,\widetilde{\mathbf{X}}_\mathbf{r}$ is separated into linear and non-linear parts given by the crosshand delay $\mathbf{K_{crs}}$ and crosshand phase $\widetilde{\mathbf{X}}_\mathbf{r}$ respectively, $\mathbf{X_r}$ remains unknown ($\mathbf{B}\,\mathbf{G} = \mathbf{B_r}\,\mathbf{G_r}\,\mathbf{X_r}$), and leakages $\mathbf{D_r} = \mathbf{X_r}\,\mathbf{D}\,\mathbf{X_r^{-1}}$ are measured in this crosshand phase frame. To compare leakages between different datasets, or to apply the leakages from one dataset to another, rotation back to the reference-antenna-independent alt-az instrument frame is required ($\mathbf{D} = \widetilde{\mathbf{X}}_\mathbf{r}^{\mathbf{-1}}\,\mathbf{K_{crs}^{-1}}\,\mathbf{D_r}\,\mathbf{K_{crs}}\,\widetilde{\mathbf{X}}_\mathbf{r}$). Critically, the same reference antenna must be used for all calibration solutions when polarization calibration will be performed. If this condition is not met, the crosshand phase frame will be ambiguous and polarization calibration will be corrupted (and possibly not in an immediately obvious way!). This is not a requirement when calibrating only parallel hand visibility data.

For an interferometer with dual linearly polarized feeds (ALMA, VLA < 1 GHz), $\boldsymbol{V^{mod}}$ is given by the 4-element vector

$$V_{XX} = \mathcal{I} + \mathcal{Q} \tag{3}$$
$$V_{XY} = \mathcal{U} + i\,\mathcal{V} \tag{4}$$
$$V_{YX} = \mathcal{U} - i\,\mathcal{V} \tag{5}$$
$$V_{YY} = \mathcal{I} - \mathcal{Q} \tag{6}$$

whereas for circular feeds (VLA > 1 GHz) the vector is

$$V_{RR} = \mathcal{I} + \mathcal{V} \tag{7}$$
$$V_{RL} = \mathcal{Q} + i\mathcal{U} \tag{8}$$
$$V_{LR} = \mathcal{Q} - i\mathcal{U} \tag{9}$$
$$V_{LL} = \mathcal{I} - \mathcal{V}\ . \tag{10}$$

The leakage terms ('dipole' terms or d-terms) describe imperfections in the polarimetric response of the system and quantify the degree to which each feed is sensitive to an orthogonally polarized signal. The imperfections arise from both telescope geometry (e.g. antenna illumination, feed horn, optics alignment) and electronic hardware (e.g. polarization splitter, hybrid coupler). Leakages are typically very stable over time, modulo known changes in instrument signal path (e.g. maintenance, elevation dependence due to dish deformation) and variance in observational approach (e.g. atmospheric elevation dependence). Notation for leakages in this document will follow

$$\mathbf{D}_i = \begin{bmatrix} 1 & d_{pi} \\ d_{qi} & 1 \end{bmatrix} \tag{11}$$

for antenna i where p is given by X (linear basis) or R (circular basis), d_{pi} is the fraction of the q polarization sensed by p, and on-diagonal effects are factored into $\mathbf{B}$ and $\mathbf{G}$ (Sault et al. 1996; though note sign difference in d-term notation). Antenna feeds are typically engineered with great care to be orthogonal such that $d_{pi} + d^*_{qi} = 0$. The model visibilities corrupted by parallactic angle, leakage, and crosshand phase terms ($\boldsymbol{V} = \mathbf{X_r}\,\mathbf{D}\,\mathbf{P}\,\boldsymbol{V^{mod}}$) are given in the linear basis by

$$\begin{aligned}
V_{XX} &= (\mathcal{I} + \mathcal{Q}_\psi) + \mathcal{U}_\psi\,(d_{Xi} + d^*_{Xj}) && (12)\\
V_{XY} &= \big[(\mathcal{U}_\psi + i\,\mathcal{V}) + \mathcal{I}\,(d_{Xi} + d^*_{Yj}) - \mathcal{Q}_\psi\,(d_{Xi} - d^*_{Yj})\big]\,e^{i\rho} && (13)\\
V_{YX} &= \big[(\mathcal{U}_\psi - i\,\mathcal{V}) + \mathcal{I}\,(d_{Yi} + d^*_{Xj}) + \mathcal{Q}_\psi\,(d_{Yi} - d^*_{Xj})\big]\,e^{-i\rho} && (14)\\
V_{YY} &= (\mathcal{I} - \mathcal{Q}_\psi) + \mathcal{U}_\psi\,(d_{Yi} + d^*_{Yj}) && (15)
\end{aligned}$$

where ψ is parallactic angle (more details about ψ provided below), ρ is crosshand phase, $\mathcal{Q}_\psi \equiv \mathcal{Q}\cos 2\psi + \mathcal{U}\sin 2\psi$, $\mathcal{U}_\psi \equiv \mathcal{U}\cos 2\psi - \mathcal{Q}\sin 2\psi$, and terms multiplied by second order leakages (e.g. $d_{Xi}\,d^*_{Xj}$) are neglected. The visibilities in the circular basis are given by

$$\begin{aligned}
V_{RR} &= (\mathcal{I} + \mathcal{V}) + d_{Ri}\,(\mathcal{Q} - i\mathcal{U})e^{+i2\psi} + d^*_{Rj}\,(\mathcal{Q} + i\mathcal{U})e^{-i2\psi} && (16)\\
V_{RL} &= \big[(\mathcal{Q} + i\mathcal{U})e^{-i2\psi} + \mathcal{I}\,(d_{Ri} + d^*_{Lj}) + \mathcal{V}\,(d^*_{Lj} - d_{Ri})\big]e^{i\rho} && (17)\\
V_{LR} &= \big[(\mathcal{Q} - i\mathcal{U})e^{+i2\psi} + \mathcal{I}\,(d_{Li} + d^*_{Rj}) + \mathcal{V}\,(d_{Li} - d^*_{Rj})\big]e^{-i\rho} && (18)\\
V_{LL} &= (\mathcal{I} - \mathcal{V}) + d_{Li}\,(\mathcal{Q} + i\mathcal{U})e^{-i2\psi} + d^*_{Lj}\,(\mathcal{Q} - i\mathcal{U})e^{+i2\psi}\quad . && (19)
\end{aligned}$$

Leakage moduli are typically a few percent: ALMA[6] $\lesssim 3\%$, VLA[7] $\lesssim 5\%$. CASA is currently designed to solve for linearized leakages, i.e. to first order in d-terms as presented above. To calibrate the leakages, CASA currently only examines the cross hand visibilities, with the additional assumption that Stokes $\mathcal{V}$ is zero unless a non-zero model is supplied. CASA performs crosshand phase calibration by taking the baseline average of cross hand visibilities,

$$\begin{aligned}
\langle V_{XY}\rangle + \langle V^*_{YX}\rangle &= e^{i\rho}\big[\mathcal{U}_\psi + \mathcal{I}\left\langle d_{Xi} + d^*_{Yi} + d_{Xj} + d^*_{Yj}\right\rangle - \\
&\qquad \mathcal{Q}_\psi\left\langle d_{Xi} - d^*_{Yi} + d_{Xj} - d^*_{Yj}\right\rangle\big] && (20)\\
\langle V_{RL}\rangle + \langle V^*_{LR}\rangle &= e^{i\rho}\big[\,(\mathcal{Q} + i\mathcal{U})\,e^{-i2\psi} + \mathcal{I}\left\langle d_{Ri} + d^*_{Li} + d_{Rj} + d^*_{Lj}\right\rangle\big]\quad . && (21)
\end{aligned}$$

In the circular basis, when leakages are known, crosshand phase calibration is synonymous with calibration of the absolute alignment of linear polarization[8] and requires an external

---

[6] Absolute leakage data from Cortes et al. (2015).

[7] Note that this value refers to absolute leakages, see EVLA memos 131, 141, 151, and 170. However, VLA users typically recover relative leakages, which are larger, typically $\lesssim 7\%$. The distinction between relative and absolute leakages is discussed later in Section 4.1.1.

[8] This is only strictly true for infinite signal to noise. In practice there will be a (likely) negligible yet non-zero bias between the recovered crosshand phase and the true overall position angle correction needed to correctly orient the crosshand phase frame.

source of known position angle. In the linear basis, an offset in the absolute alignment of the feeds (i.e. different observed $\mathcal{U}_\psi$ and $\mathcal{Q}_\psi$ in Equation 20) does not translate into a trivial change in crosshand phase. Thus, in the linear basis, crosshand phase and absolute position angle calibrations are not synonymous. However, unlike in the circular basis, if the linear antenna feeds are nominally aligned to the sky, an external source of known position angle is not formally required; variation in $\mathcal{U}_\psi$ over parallactic angle for a linearly polarized source with unknown $\mathcal{Q}$ and $\mathcal{U}$ is sufficient to solve for ρ. As a result, calibration strategies in the linear basis typically need to obtain a first-pass solution for $\mathbf{X_r}$, assuming zero leakages, prior to solving for $\mathbf{D_r}$. Subsequent iteration is technically required (though typically negligible in practice) to account for leakages in the $\mathbf{X_r}$ solve. In the circular basis, $\mathbf{X_r}$ is not needed to solve for the leakages (crosshand phase simply imparts an overall rotational ambiguity) while $\mathbf{D_r}$ is needed to optimally solve for $\mathbf{X_r}$. Thus circular basis calibration strategies typically solve for $\mathbf{D_r}$ prior to $\mathbf{X_r}$.

Parallactic angle describes the orientation of the sky as it rotates within the field of view of an alt-az telescope. It is defined as the angle between zenith and a line of constant RA at a given source, measured positive N through E,

$$\psi(t) = \frac{\cos b \ \sin H(t)}{\sin b \ \cos\delta - \cos b \ \sin\delta \ \cos H(t)} \tag{22}$$

where b is latitude, $H(t)$ is hour angle, and δ is declination. Absolute position angle calibration in the linear basis may be required to correct for a systematic offset between the mechanical antenna feed position angle and the meridian ($H = 0$) at $\psi = 0$. For reference, Figure 1 displays the parallactic angle coverage available for sources at different declinations as viewed from the VLA and ALMA. Figure 1 also displays the corresponding derivative of parallactic angle with respect to hour angle.

Practical strategies for calibrating the equations above will be presented in Section 5. To motivate these strategies, Section 4.1 will examine some important aspects regarding degrees of freedom in polarimetric calibration, Section 4.2 will examine spurious on-axis polarization leakage resulting from different calibration strategies, and Section 4.3 will examine atmospheric Faraday rotation. The connection between crosshand phase and absolute position angle calibrations within CASA will be discussed further in Section 5.2.

4.1 Degrees of freedom

Polarimetric calibration involves solving for the crosshand phase, leakage d-terms, and absolute alignment of linear polarization. External calibration is required to determine the absolute position angle in the same way that an interferometer cannot self-calibrate the absolute flux density level. Theoretically, to solve for all degrees of freedom in any basis that uses dual orthogonally polarized feeds, at least 3 distinct observations of calibrators with linearly independent Stokes vectors are required (Sault et al. 1996). This implies that at least 2 observations need to be on a polarized calibrator, at least 1 needs to be linearly polarized, and a circularly polarized calibrator is not essential. Observation of a linearly polarized calibrator over a range of parallactic angles can provide the necessary 3 distinct observations; rotation of the sky within the alt-az instrument frame enables the leakages and source polarization to be jointly solved. In practice, for circular polarization science in the linear feed basis, external

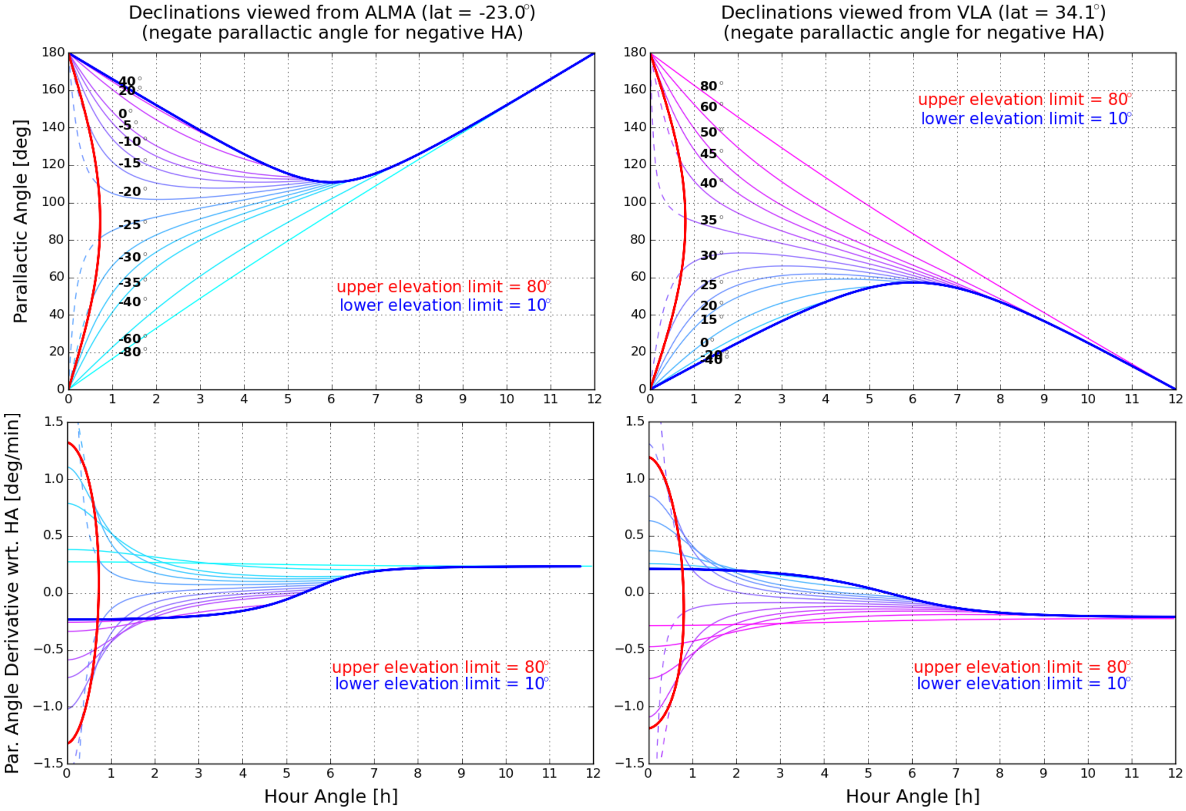

Figure 1 *Upper panels:* Parallactic angle coverage for sources at varying declinations viewed from ALMA (left) and the VLA (right), accounting for telescope elevation limits. Sources rise at negative HA. *Lower panels:* Rate of parallactic angle change with respect to hour angle, with curves corresponding to those displayed in the upper panels. The code used to produce these plots is available at https://github.com/chrishales/plotparang .

(absolute) calibration of Stokes $\mathcal{V}$ is also required[9] (e.g. Rayner et al. 2000) due to leakages being small (as a result of good engineering).

In general, the aim of calibration is to obtain well calibrated data rather than full instrumental characterization. It is possible to relax the theoretical requirements above and yet still deliver calibrated data of sufficient quality to satisfy many scientific objectives. Sault et al. (1996) consider the implications of degeneracies resulting from various calibration strategies in detail. Leakage and position angle calibrations are of particular interest, as explored below.

---

[9] To avoid the need for a circularly polarized calibrator in accord with the theoretical requirements presented above, second-order d-terms must be taken into account to break the imaginary-axis degeneracy otherwise present in the linearized $\mathbf{D}\,\mathbf{P}\,\boldsymbol{V}^{\boldsymbol{mod}}$ equations. However, even if these terms are included, non-singular solutions are likely to be produced in practice (small leakages, thermal noise, gain stability), in turn requiring absolute circular polarization calibration in the linear basis. To intuit why a similar issue does not arise in the circular basis, note that in the limit of large leakages there is no difference between observations in either basis, i.e. circular feeds can be thought of as linear feeds with high leakages (or leakages that act with crosshand phase to effectively operate as a quadrature hybrid coupler). In this case, the additional constraints available through the linear basis second-order terms become accessible. CASA is not designed to operate within such a generalized basis formalism.

4.1.1 Absolute vs. relative leakages

Not all scientific objectives require solving for the d-terms unambiguously. For example, an unpolarized calibrator will yield solutions that are degenerate in the sum of leakage pairs (e.g. $d_{Ri} + d_{Lj}^*$). This corresponds to an undetermined Jones matrix which, in the small angle approximation, corresponds to a complex offset (β) that can be added to one polarization and subtracted with conjugation from the other (e.g. $d'_{pi} = d_{pi} + \beta$ and $d'_{qj} = d_{qj} - \beta^*$ for all antennas). Thus the equations cannot be used to solve for absolute d-terms. When solving for degenerate leakages in CASA, the real and imaginary components of the X or R feed leakages will be (arbitrarily) set to zero on the gain reference antenna, effectively setting β to the negative of the true d-term on this antenna (e.g. $\beta = -d_{p\,ref}$). Leakage solutions degenerate in this manner are known as relative leakages, denoted here by $\widetilde{\mathbf{D}}$ or $\widetilde{\mathbf{D}}_{\mathbf{r}}$. Relative leakages cannot substitute absolute leakages in the measurement equation without incurring errors. For calibration strategies that recover relative leakages (e.g. using an unpolarized calibrator), the degenerate nature of the solutions will manifest in the linear basis as an error in the position angle of linear polarization and an unknown degree of leakage between linearly and circularly polarized components. In the circular basis there will be an unknown degree of leakage between linearly and circularly polarized components. (These effects can be gleaned from the leakage-corrupted equations above.) Note that careful consideration of error propagation is required if relative leakages are to be measured from one dataset and applied to another; only absolute leakages in the instrument frame ($\mathbf{D}$) are stable over time (modulo the issues mentioned earlier). Ideally, only $\mathbf{D}$ should ever be accepted into a calibration database. Note that, at present, CASA is not capable of solving for absolute leakages in the circular basis; polarization is ignored in the parallel hand visibilities at solve (and apply) time resulting in relative leakages. In the linear basis, CASA again ignores parallel hand visibilities when solving for leakages, but here it can still solve for absolute leakages because the d-term sum degeneracy can be broken purely in the cross hands by $\mathcal{Q}_\psi$.

For completeness, it is worth noting that even 'absolute' leakages will in reality be quasi-absolute[10], for the following two reasons. First, the CASA task `POLCAL` currently solves for linearized leakages, i.e. second order d-terms are not considered in the solver. This necessarily introduces a degeneracy. And second, the measurement equation formalism adopted by CASA assumes that the full signal path can be characterized by a specific and limited set of effects. That there are known missing factors that charaterize details such as telescope analogue components (Price & Smirnov 2015) and direction dependent effects (Smirnov 2011) demonstrates that recovered leakages will necessarily be quasi-absolute in the best case and likely relative in general. To quote Smirnov (2011), 'We must therefore take care that our thinking about calibration does not fall into a rut marked out by a specific series of Jones terms.' In practice, absolute leakages are non-singular solutions within the assumed framework.

4.1.2 Position angle calibration

Similar to leakages, not all scientific objectives require absolute position angle calibration. In the linear basis, calibration strategies must recover $\mathrm{Re}(d_{X\,ref})$, the real part of the d-term on the X feed of the gain reference antenna, in order to provide self-consistent alignment to

---

[10] By this I mean systematically non-absolute, rather than variance introduced by thermal noise.

the assumed sky frame. If relative leakages are used, a systematic contribution to position angle errors will be imposed, given in the worst-case by the magnitude of $\mathrm{Re}(d_{X\,ref})$. For example, $\mathrm{Re}(d_{X\,ref}) \sim 2\%$ implies a systematic position angle error contribution of $\sim 1°$. This relationship can be derived by considering how the unaccounted degree of freedom associated with the true value of $d_{X\,ref}$ will be absorbed by $\mathcal{Q}_\psi$ and $\mathcal{U}_\psi$ in Equations 12–15 when relative leakages (r) are utilized, compared with their original values calculated in the presence of absolute leakages (a). The differences are $\mathcal{Q}_{\psi_r} - \mathcal{Q}_{\psi_a} = -2\,\mathrm{Re}(d_{X\,ref})\,\mathcal{U}_{\psi_a}$ and $\mathcal{U}_{\psi_r} - \mathcal{U}_{\psi_a} = 2\,\mathrm{Re}(d_{X\,ref})\,\mathcal{Q}_{\psi_a}$. The position angle difference is then $\mathrm{Re}(d_{X\,ref})$ in the small angle approximation. This calculation can also be used to consider position angle errors resulting from d-term statistical measurement errors. It is possible that even when $\mathrm{Re}(d_{X\,ref})$ is recovered, an additional systematic offset may exist due to systematic misalignment of the mechanical antenna feeds over the array. This will will lead to an offset between the assumed and true sky frames. External position angle calibration is required to account for this offset. However, in practice, mechanical offsets are be engineered to be small. As a result, the systematic position angle uncertainty associated with feed offsets may be within an acceptable limit (e.g. ALMA $\lesssim 2°/\sqrt{N_a} \approx 0.3°$ for $N_a = 40$).

Thus, total position angle uncertainties in the linear basis are the quadrature sum of up to 4 terms: statistical error (from signal to noise of source detection), systematic error from d-term measurement errors, systematic feed-offset error, and an additional systematic error given by the magnitude of the true $\mathrm{Re}(d_{X\,ref})$ when relative leakages are recovered (i.e. when complex $d_{X\,ref}$ is set to zero). CASA cannot currently perform absolute position angle calibration in the linear basis, though future implementation of this functionality is planned. In the circular basis, absolute position angle calibration is tied to crosshand phase calibration. If absolute position angles are not calibrated in either the linear or circular basis, scientifically useful data may still result, for example if the spectrum of fractional polarization is of interest.

4.2 Strategies to limit spurious on-axis polarization

Leakage calibration strategies typically involve a single observation of an unpolarized calibrator or multiple observations of a polarized calibrator spanning a range of parallactic angles. This section will examine requirements on calibrator signal to noise and parallactic angle coverage so that subsequent observation of an unpolarized science target will exhibit spurious on-axis polarization below a nominated threshold. For example, ALMA specifications require spurious on-axis polarization to be below 0.1% of total intensity after calibration. Distinction between relative and absolute d-terms is not required here.

Throughout this section and the remainder of this document, an observation of a calibrator at a particular parallactic angle will be termed a *slice*. A slice may comprise one or more scans, but it will be assumed that parallactic angle is approximately constant throughout the slice and that the quoted signal to noise represents all combined scans within the slice. Note that, in practice, these concepts are linked: the ability to define the timespan over which parallactic angle can be considered constant is a function of signal to noise. Separation of these concepts is useful for framing the simulations. As a guide to the results presented below, be sure to check that the time required to obtain a requisite signal to noise does not become comparable to the parallactic angle range over which significant changes occur in predicted spurious leakage.

A requirement for maximum spurious on-axis polarization translates to a calibration requirement for d-term accuracy. Taking σ_d as the characteristic d-term modulus error[11] and N_a as the number of antennas in the array, the approximate level of spurious on-axis linear or circular polarization produced when observing an unpolarized source in the linear basis is $\mathcal{I}\sigma_d/\sqrt{N_a}$; spurious elliptical polarization is $\mathcal{I}\sigma_d\sqrt{\pi/(2N_a)}$. In the circular basis, the level of spurious linear polarization is approximately $\mathcal{I}\sigma_d\sqrt{\pi/(2N_a)}$; no spurious circular polarization will be produced. Derivations of these equations are presented in the Appendix. These equations assume a worst-case scenario where the science target is observed within a single parallactic angle slice. For wider parallactic angle coverage the spurious leakage will be smaller due to depolarization. For reference, a requirement of 0.1% spurious on-axis linear polarization translates to $\sigma_d \lesssim 0.6\%$ for ALMA ($N_a = 40$) and $\sigma_d \lesssim 0.4\%$ for the VLA ($N_a = 27$). The equations above can now be used to translate σ_d into limits on anticipated spurious on-axis polarization for various calibration strategies.

4.2.1 Unpolarized calibrators

A calibrator that is classified as unpolarized may in fact exhibit a low level of polarization, to be denoted below by $\mathcal{L}_{\text{true}}$ (linear polarization), $\mathcal{U}_{\psi,\text{true}}$, and $\mathcal{V}_{\text{true}}$ (other terms not needed). Taking this into account, if leakage calibration is performed using an assumed unpolarized calibrator, the resulting d-term modulus error σ_d will be approximately $\sqrt{([\mathcal{U}_{\psi,\text{true}}/\mathcal{I}]^2 + [\mathcal{V}_{\text{true}}/\mathcal{I}]^2 + N_a/A^2)/2}$ in the linear basis and $\sqrt{([\mathcal{L}_{\text{true}}/\mathcal{I}]^2 + N_a/A^2)/2}$ in the circular basis, where A is the full-array dual-polarization total intensity signal to noise of the calibrator within the single spectral channel of interest. Derivations for these equations are presented in the Appendix. Note that the level of fractional polarization at which a source may be classified as 'unpolarized' depends on the telescope being used and the science goals of the observation. For telescopes such as ALMA that place a requirement on the acceptable level of spurious on-axis polarization resulting from calibration, the equations above provide a mechanism for classifying calibrators as unpolarized.

Leakage calibration using an unpolarized calibrator can be performed using a single slice (or single scan) observation. In the circular basis, taking the example of an assumed unpolarized leakage calibrator with true linear polarization $\sim 1\%$ observed with the VLA at high signal to noise, we find $\sigma_d \sim 0.7\%$. The resulting spurious on-axis fractional polarization for an unpolarized target will then be $\sim 0.2\%$. Position angle calibration in the circular basis requires a polarized calibrator; this is described at the end of the next section.

For an unpolarized (or negligibly polarized) calibrator observed in the linear basis, using σ_d from above, the predicted spurious fractional linear polarization for an unpolarized target is $1/\sqrt{2A^2}$. In the linear basis, σ_d from above also provides an estimate for the worst-case systematic position angle error arising from d-term measurement errors (i.e. if all d-terms were made relative to an offset of magnitude σ_d). For an unpolarized calibrator, relative leakages will be recovered, so the total position angle error is calculated by combining this statistical error in quadrature with the systematic errors described in Section 4.1.2. The predicted total position angle error, when including systematics from relative leakage calculation and from a mechanical feed alignment uncertainty ξ per antenna, is then given by $\sqrt{N_a/(2A^2) + \text{Re}(d_{X\,ref})^2 + \xi^2/N_a}$. These relationships are displayed in Figure 2. This figure also characterizes errors when using

---

[11] If characteristic errors in either the real or imaginary d-term components are σ, then under Rayleigh statistics $\sigma_d = \sqrt{\pi/2}\,\sigma$.

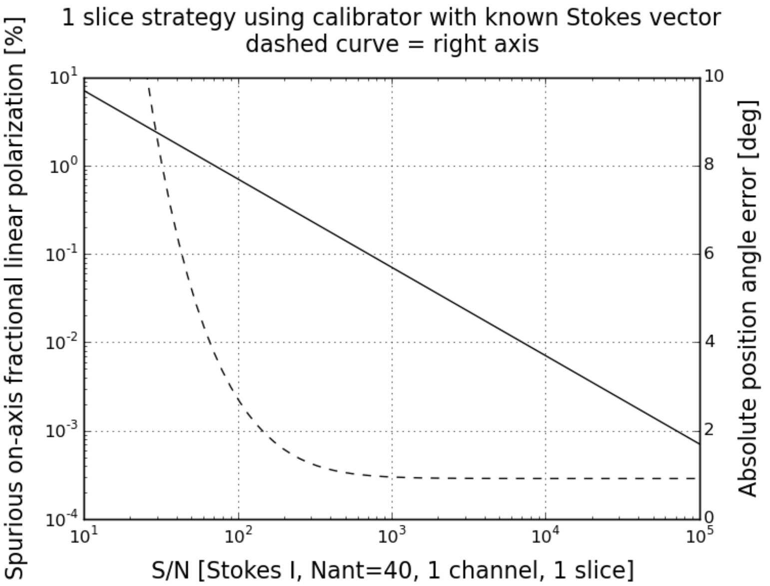

Figure 2 Predicted spurious on-axis fractional linear polarization (percent) and absolute position angle error within 1 spectral channel when using a linear basis telescope to calibrate relative leakages with a single slice observation of a calibrator with known Stokes vector (unpolarized or polarized). This assumes an array with 40 antennas, $\mathrm{Re}(d_{X\,ref}) = 1.5\%$, and a mechanical feed alignment uncertainty of 2° per antenna. The indicated position angle error must be added in quadrature with a target source's statistical error to obtain its total position angle error.

a polarized calibrator with known Stokes vector within a single slice calibration scheme, as described in the next section.

4.2.2 Polarized calibrators

Linear basis

To calibrate leakages in the linear basis using a polarized source, observations are required over at least 3 parallactic angle slices if the Stokes vector is unknown a priori, or as little as a single slice if the Stokes vector is known. When unknown a priori, the Stokes vector needs to be solved for in addition to the d-terms and crosshand phase. Simulations were performed to predict the level of spurious on-axis polarization and absolute position angle error resulting from a 1 (Stokes known), 2 (Stokes known), 3 (Stokes unknown), and 10 (Stokes unknown) slice strategy. For full details including a web link to the simulation code, see the Appendix. The simulations approximate the behaviour of the generalized solvers within CASA by examining the accuracy with which the d-terms, crosshand phase, and calibrator polarization (when relevant) can be measured from the cross hand visibilities when a source is subjected to parallactic angle rotation in the presence of thermal noise. The simulations assume a typical d-term modulus of 1.5%, a mechanical feed alignment uncertainty of 2° per antenna, and that the first slice is observed at maximum $|\mathcal{U}_\psi|$. Monte Carlo sampling was used to recover the distributions of spurious linear polarization and absolute position angle error, from which the 95^{th} percentiles were recovered for each. Two scenarios were examined, the first for a calibrator exhibiting 3% fractional linear polarization and the second with fraction 10%.

Results for the 1 slice strategy are practically indistinguishable from the analytic unpolarized calibrator results and will not be repeated here; see Figure 2. The reason is because d-term errors arising from crosshand phase errors, drawn from data where all baselines are combined for the solve, always remain practically negligible compared to thermal noise in the subset of baselines from which individual d-terms are effectively solved. The fractional polarization of the calibrator does not practically affect this finding.

Spurious polarization results for the 2, 3, and 10 slice strategies are displayed in Figures 3, while those for absolute position angle errors are displayed in 4. The results in Figure 3 enable the following question to be answered: for a calibrator with given signal to noise, what is the parallactic angle coverage required (or vice versa) to ensure that spurious on-axis linear polarization will remain below a nominated threshold when viewing calibrated data for an unpolarized target. Similarly, Figure 4 enables absolute position angle error to be related with specifics of calibration strategy.

The plots demonstrate that, in general for a given calibrator, total parallactic angle coverage of approximately 30° is sufficient to maximize calibration accuracy. Beyond 30°, additional parallactic angle coverage only delivers minor improvements. As far as I am aware, no similar plots are available in the literature from which to draw such a finding.

Note that the slightly unusual features seen for very small or very large parallactic angle coverages are artifacts that can be safely ignored; they are the result of simplifications in the simulations which do not affect the results throughout the remainder of the figures.

Circular basis

To calibrate leakages in the circular basis using a polarized source, observations are required over at least 2 or 3 parallactic angle slices depending on whether the Stokes vector is known a priori or not, respectively. When unknown a priori, the Stokes vector needs to be solved for in addition to the d-terms. Simulations were performed to predict the level of spurious on-axis polarization resulting from a 2 (Stokes known), 3 (Stokes unknown), and 10 (Stokes unknown) slice strategy. For full details including a web link to the simulation code, see the Appendix. The simulations approximate the behaviour of the generalized solvers within CASA by examining the accuracy with which d-terms can be measured from the cross hand visibilities when a source is subjected to parallactic angle rotation in the presence of thermal noise. Monte Carlo sampling was used to recover the distribution of spurious linear polarization, from which the 95^{th} percentile was recovered. Two scenarios were examined, the first for a calibrator exhibiting 3% fractional linear polarization and the second with fraction 10%. The results are displayed in Figure 5. As with the linear basis simulations, the results here enable the following question to be answered: for a calibrator with given signal to noise, what is the parallactic angle coverage required (or vice versa) to ensure that spurious on-axis linear polarization will remain below a nominated threshold when viewing calibrated data for an unpolarized target.

The plots demonstrate that, as expected, a floor is reached at low signal to noise where no amount of parallactic angle coverage can make up for the dominant randomizing influence

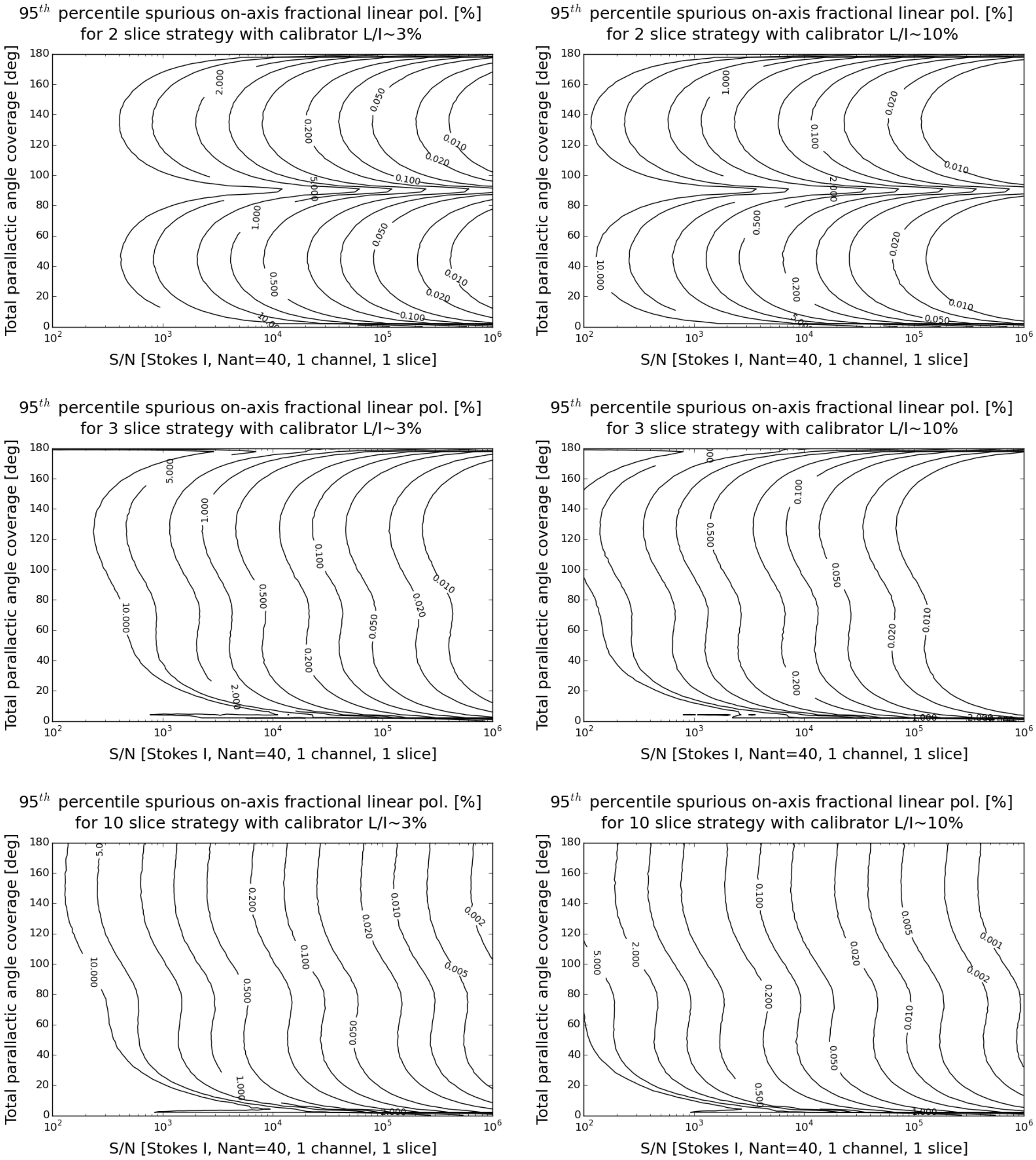

Figure 3 Simulated spurious on-axis fractional linear polarization (percent) in the linear basis for an unpolarized target following application of leakage solutions obtained using different calibration strategies. The simulation assumes an array with 40 antennas and the first slice observed at maximum $|\mathcal{U}_\psi|$. Top row: 2 slice strategy with polarization known a priori. Middle row: 3 slice strategy with unknown polarization. Bottom row: 10 slice strategy with unknown polarization. Panels in the left and right columns show results obtained using a calibrator with 3% or 10% fractional linear polarization, respectively. Abscissa: Full-array dual-polarization total intensity signal to noise within 1 spectral channel and 1 slice. Ordinate: Total parallactic angle coverage; divide by 1 less than the number of slices to get the inter-slice separation.

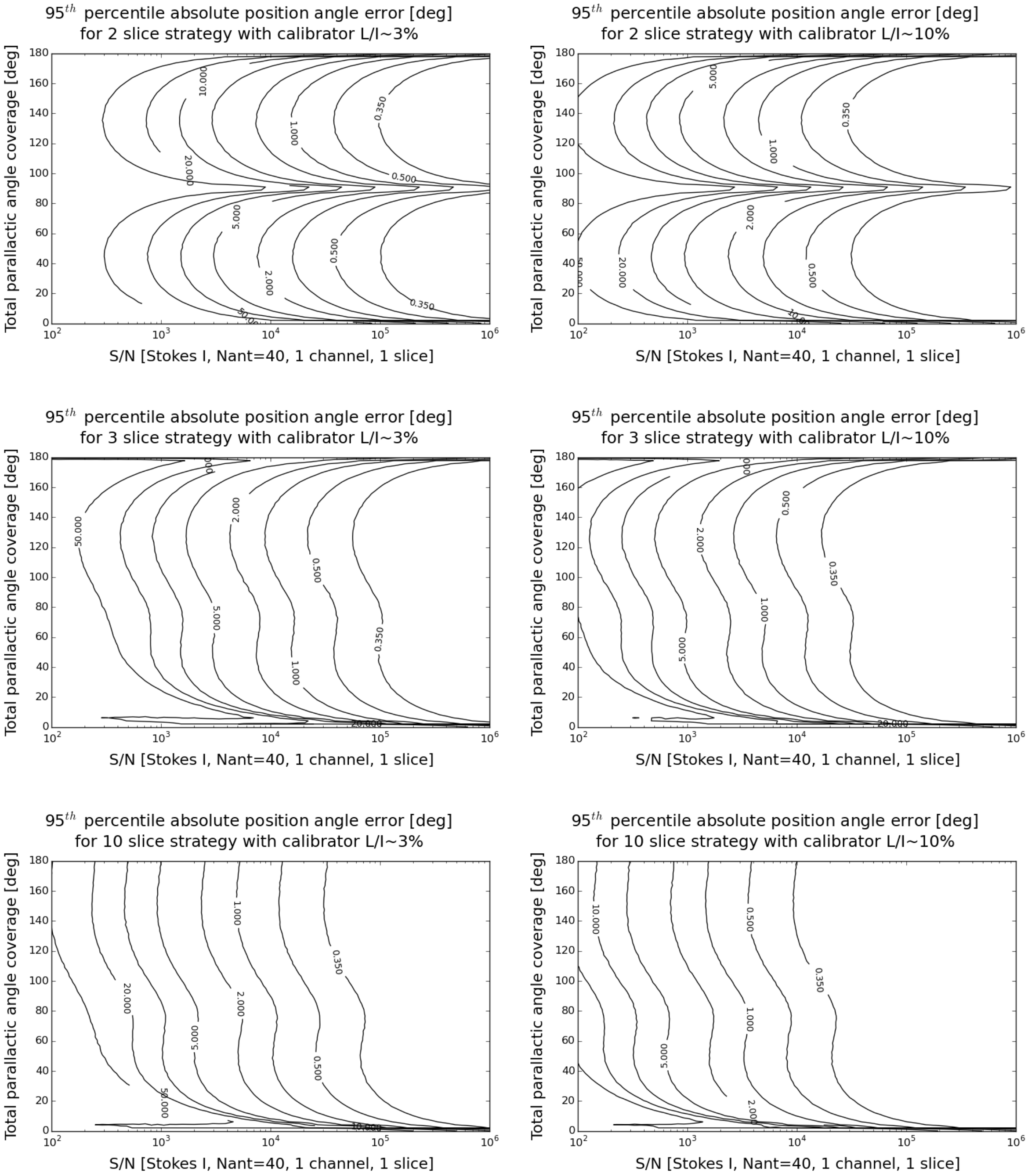

Figure 4 Simulated absolute position angle error (degrees) in the linear basis correponding to the calibration strategies displayed in Figure 3. The simulations assume a typical d-term modulus of 1.5% and a mechanical feed alignment uncertainty of 2° per antenna. The indicated error must be added in quadrature with a target source's statistical error to obtain its total position angle error.

of thermal noise[12]. The slightly unusual features seen for small parallactic angle coverage in the multi-scan strategies are artifacts that can be safely ignored; they are the result of simplifications in the simulations which do not affect the results throughout the remainder of the figures.

The 2 slice strategy reveals the counter-intuitive result that a calibrator with larger fractional polarization will, at low signal to noise, result in higher spurious polarization than a calibrator with low fractional polarization. This is because the fractional polarization is a fixed known quantity when signal to noise is defined for total intensity; solving for the origin of a circle with fixed radius in the presence of thermal noise leads to larger fractional errors when the radius is larger. Indeed, this trend continues to the case of unpolarized calibrators; spurious polarization limits are even better when observing an unpolarized calibrator at the equivalent signal to noise. For the 3 and 10 slice strategies, the Stokes vector is not known a-priori, so calibrators with higher fractional polarization deliver better quality solutions than lower ones, as expected.

The results presented here indicate that, in general for a given calibrator, when the Stokes vector of the leakage calibrator is known a priori, total parallactic angle coverage of approximately 30° is sufficient to maximize calibration accuracy. Additional coverage is not found to deliver significant improvements. This matches the finding in the linear basis presented in the previous section. However, when the Stokes vector is unknown in the circular basis, this minimum coverage value increases to approximately 90°.

Finally, for completness regarding circular basis calibration strategies that require observation of a position angle calibrator, Figure 6 presents position angle errors from a simulation based on Equation 21.

4.3 Atmospheric Faraday rotation

The Earth's upper atmosphere consists of the ionosphere from about 60–1000 km and the plasmasphere which extends to the plasmapause at approximately geosynchronous altitude. Linearly polarized radiation traversing this ionized path through the Earth's magnetic field will experience Faraday rotation. Typical line-of-sight rotation measures for facilities worldwide are ~ 1 rad/m^2 and a factor 10 higher under active solar conditions (the 11 year solar cycle peaked most recently in ~ 2013 and is currently heading toward a minimum). Corrections for atmospheric Faraday rotation are typically only required at observing frequencies $\lesssim 4$ GHz.

CASA stable versions 4.7.38+ are designed to account and correct for on-axis atmospheric Faraday rotation for all calibration strategies except those that require solving for source polarization (as opposed to being supplied calibrators of known polarization). The `tec_maps`[13] helper function from the CASA recipes repository will retrieve GPS-derived total electron content (TEC) maps from the internet. These data can be imported to a standard caltable using `gencal` and used in the calibration process. Internally, CASA models the atmospheric Faraday rotation along the line of sight as a function of time by combining TEC data with a model of the Earth's magnetic field (IGRF). The nominal repository from which the TEC

---

[12] Note that this is not seen in the linear basis results because the method of solving for d-terms is different. Note also that the plotted signal to noise range is different between the linear and circular basis plots.

[13] See code for details and references, see also CASA Cookbook Section 4.3.9:
https://casa.nrao.edu/docs/UserMan/casa_cookbook005.html#section:cal.prior.ionosphere

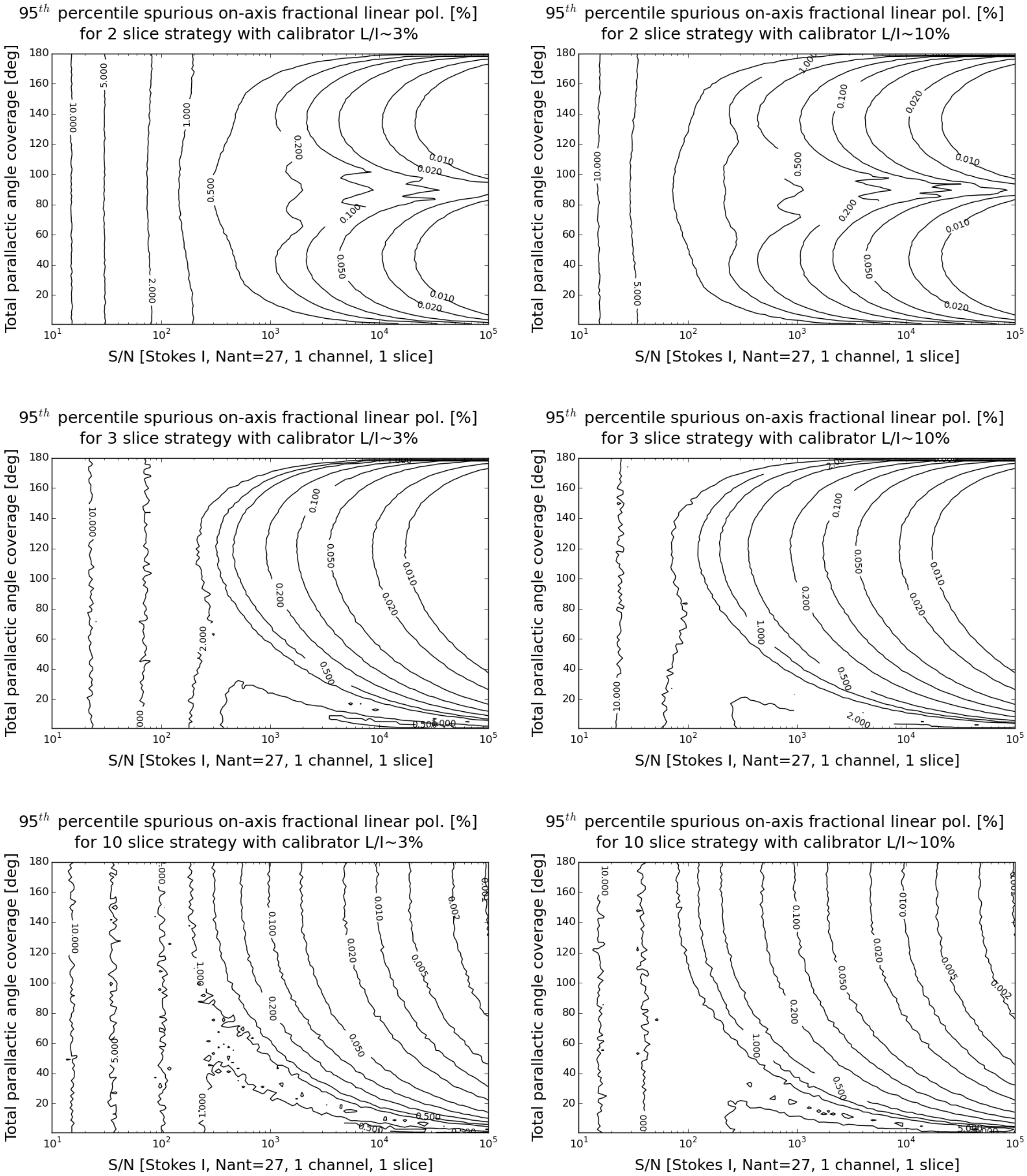

Figure 5 Simulated spurious on-axis fractional linear polarization (percent) in the circular basis for an unpolarized target following application of leakage solutions obtained using different calibration strategies. The simulation assumes an array with 27 antennas. Panel layout and axes are the same as Figure 3.

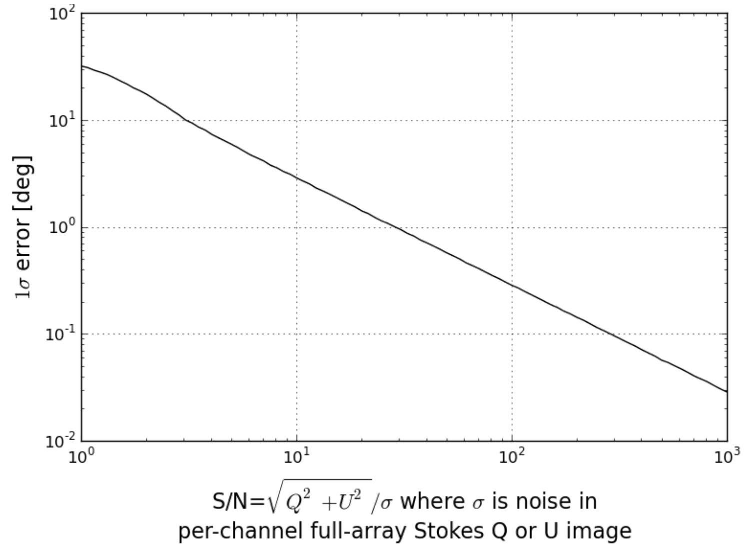

Figure 6 Error in recovered position angle due to thermal noise when using a circular basis telescope to observe a calibrator with specified linear polarization signal to noise, where noise is defined as above. For example, consider position angle calibration with the VLA within a 2 MHz channel at 3 GHz using 3C48 ($\sim$ 10 Jy, $\sim$ 2% fractional linear polarization). To limit position angle uncertainty to within 0.1° requires S/N>300, which translates to an on-source time approaching 4 min (ECT V17A). For 0.3° uncertainty, the required on-source time is $\sim$ 30 sec.

maps are retrieved is the IGS (housed on CDDIS servers), which provide data sampled with a common formal resolution of 2 hours, 5 degrees, and 2.5 degrees in UT, longitude, and latitude, respectively. The IGS Final products are available within about 2 weeks after an observation, whereas the IGS Rapid Products are typically available within 1-2 days. Differences between these two products are typically minimal. JPL Rapid Products may also be available on short timescales. `tec_maps` will search for these products in the order listed above and report if no valid data could be found. Automated pipeline polarimetric reduction at low frequencies should ideally be delayed to enable the TEC data to become available. CASA does not use the TEC data to perform dispersive delay corrections; TEC map quality is not considered sufficient for this purpose[14].

For reference, the resolution in Faraday depth space (e.g. following rotation measure synthesis) is $\sim 2\sqrt{3}/\Delta\lambda^2$ rad/m^2, where $\Delta\lambda^2 = \lambda^2_{\rm max} - \lambda^2_{\rm min}$ (λ in meters) spans the total observing bandwidth (Brentjens & de Bruyn 2005). The rotation measure uncertainty for a source with linearly polarized signal to noise A is then $\sim \sqrt{3}/(A\,\Delta\lambda^2)$ rad/m^2. If the mean observed atmospheric Faraday rotation is of order this uncertainty or less throughout an observation, it may be left uncorrected in the data without significant impact as statistical errors will dominate the systematic one. Note however that this estimate is only applicable to science cases where no further improvements in rotation measure signal to noise will be made. For example, this would not be appropriate for a study in which a statistical analysis of all rotation measures in a field of view will be performed, as the atmospheric contribution

---

[14] The raw data is in fact better suited for this, though errors incurred from ignoring dispersive delay will likely be negligible, even at L-band with the VLA, due to being soaked up by per-spw gain calibration.

may no longer remain buried in the aggregated noise, possibly leading to incorrect scientific conclusions.

Finally, the following scaling relationship is provided for reference, suitable for Faraday rotation of any origin (atmospheric, astrophysical). The effective signal to noise in visibility amplitudes following averaging over phase rotation $\Delta\theta$ across a contiguous and otherwise coherent bandwidth is given by $\mathrm{sinc}(\Delta\theta/2)$. The Faraday rotation measure required to cause a 50% reduction in visibility amplitude signal to noise over a contiguous bandwidth $\Delta\lambda^2$ is thus $\sim 3.8/\Delta\lambda^2$ rad/m^2.

5 Practical Calibration Strategies

Section 5.1 outlines the different types of calibrators available for polarimetry. Section 5.2 discusses scan intents within CASA. Using the identified calibrator classes, scan intents, and the slice definition from Section 4.2, Sections 5.3 and 5.4 consider pipeline calibration strategies in the linear and circular bases. Not all of the strategies identified are suitable for phase 1, nor are the lists comprehensive. However, the most common strategies are described with details for implementation provided.

5.1 Calibrator classifications

There are 6 general types of polarization calibrators:

EPOL	An elliptically polarized source with frequency-dependent Stokes $\mathcal{I}$, $\mathcal{Q}$, $\mathcal{U}$ & $\mathcal{V}$ known a priori (i.e. complete elliptical polarization known).
LPOL	A linearly polarized source with frequency-dependent Stokes $\mathcal{I}$, $\mathcal{Q}$ & $\mathcal{U}$ known a priori (i.e. fractional linear polarization and position angle known). Circular polarization properties are not known.
CPOL	A circularly polarized source with frequency-dependent Stokes $\mathcal{I}$ & $\mathcal{V}$ known a priori. Linear polarization properties are not known.
UNPOL	A source that is known a priori or assumed to be elliptically unpolarized. This captures special cases of LPOL, CPOL, and EPOL where Stokes $\mathcal{Q}$, $\mathcal{U}$ & $\mathcal{V}$ are known to be zero or this is assumed. Section 4.2 examined errors resulting from assuming a calibrator is unpolarized when in fact it is not.
POL	A source known a priori to be linearly polarized, but lacking definitive Stokes $\mathcal{Q}$ & $\mathcal{U}$ information. For example, such sources could be identified in ALMA calibrator monitoring data (snapshot observations calibrated in total intensity only) as those exhibiting significant variability in gain amplitude polarization ratio when observed at different parallactic angles over multiple epochs. While regular variability over the time baseline between snapshots may preclude accurate reconstruction of source polarization, the data should be sufficient to identify sources that will

exhibit polarization in future observations (and will therefore be suitable for some of the calibration strategies described below). For low frequency observations with the VLA, POL sources (also UNPOL) could be identified from the NVSS.

UNKWN A source with unknown polarization (may be unpolarized or polarized).

5.2 Scan intents

CASA contains a master list of officially recognized scan intents. Currently available intents for polarimetry are `CALIBRATE_POL_LEAKAGE`, `CALIBRATE_POL_ANGLE`, and a generic option `CALIBRATE_POLARIZATION`. To date, all polarization calibrator scans with ALMA have been identified using only the last of these options. While the intents above can be mapped to a customized set of polarimetric calibration functions, the lack of a specific intent for crosshand phase calibration can impart ambiguity regarding the exact purpose of a calibrator scan. For this reason it is recommended that CASA adopt an additional scan intent `CALIBRATE_CROSSHAND_PHASE`. Furthermore, operational use of the intent `CALIBRATE_POLARIZATION` should be deprecated (removal from the CASA master list is not appropriate due to complications with backward compatilibity and reordering of other valid intents). This proposed upgrade will enable flexible pipeline automation for a range of calibration strategies and, more generally and perhaps importantly, provide greater clarity to the user when considering scan intents for calibrators and the true nature of the calibration solution to be obtained.

Offline documentation should be made available informing users to specify `CALIBRATE_CROSSHAND_PHASE` unless they really intend to perform position angle calibration. `CALIBRATE_POL_ANGLE` should only be specified for a source with known position angle. CASA is not currently capable of performing absolute position angle calibration in the linear basis. For many scientific objectives, calibration of crosshand phase alone will deliver sufficient absolute position angle accuracy. In the circular basis, distinction between crosshand phase and position angle calibration is not required. Calibrators with known position may be specified as `CALIBRATE_CROSSHAND_PHASE` and/or `CALIBRATE_POL_ANGLE`, to be utilized in a single calibration step.

5.3 Linear feed basis

There are 5 typical strategies for calibrating polarization when observing with an interferometer with linear feeds such as ALMA, subject to the assumptions outlined earlier in this document. The order of calibration is typically crosshand delay, crosshand phase, leakage, then optionally absolute position angle. Iteration may be required to account for initially unknown source polarization in parallel-hand visibilities for gain calibration. The strategies are defined below using the slice definition from Section 4.2, and using the calibrator classifications from Section 5.1 matched to the scan intents from Section 5.2. The minimum number of slices is indicated for each calibrator type. Implementation summaries are provided. It is assumed that previous calibrations are applied at each step. More detailed implementation information is provided later in Section 6.2. The strategies are labelled L# to indicate linear basis; the numbering is arbitrary.

L1: 1 slice UNPOL + 1 slice LPOL/EPOL

- UNPOL = `CALIBRATE_POL_LEAKAGE`
- LPOL/EPOL = `CALIBRATE_CROSSHAND_PHASE` with possible addition of `CALIBRATE_POL_ANGLE`
- `POLCAL 'Dflls' smodel=unpolarized refant=required` →
  `GAINCAL 'KCROSS' smodel=provided` → `POLCAL 'Xf' smodel=provided`
- No iteration required
- Without position angle calibration, recovers $\widetilde{\mathbf{D}}_{\mathbf{r}}$ (i.e. relative leakages in the crosshand phase frame of the gain reference antenna) and $\mathbf{X}_{\mathbf{r}}$. Position angles will be referenced to the mechanical alignment of the feeds.
- If position angle calibration requested, if CASA functionality available, and if LPOL observed, leakages will be instead recovered as $\breve{\mathbf{D}}_{\mathbf{r}}$, where this terminology denotes 'incomplete absolute' leakages in the crosshand phase frame of the gain reference antenna. The incompleteness arises from lack of explicit circular polarization calibration, where the imaginary d-term components will remain unconstrained (i.e. relative). If EPOL is instead observed, $\mathbf{D}_{\mathbf{r}}$ (absolute) will be recovered (again, pending implementation of the necessary CASA functionality; a new scan intent specifically for circular polarization calibration may be of interest for CASA in the future.). In both cases, position angles are now referenced to the true sky frame. Note that $\breve{\mathbf{D}}_{\mathbf{r}}$ cannot be treated like $\mathbf{D}_{\mathbf{r}}$ and used for conversion to the reference-antenna-independent instrument frame $\mathbf{D}$ for storage in a calibration database.

L2: 1 slice LPOL/EPOL

- LPOL/EPOL = `CALIBRATE_POL_LEAKAGE` and `CALIBRATE_CROSSHAND_PHASE`, with possible addition of `CALIBRATE_POL_ANGLE`
- `GAINCAL 'KCROSS' smodel=provided` → `POLCAL 'Xf' smodel=provided` →
  `POLCAL 'Dflls' smodel=provided refant=required` (→ iterate)
- Without position angle calibration, recovers $\widetilde{\mathbf{D}}_{\mathbf{r}}$ and $\mathbf{X}_{\mathbf{r}}$, with position angles referenced to the mechanical alignment of the feeds.
- If position angle calibration requested, if CASA functionality available, leakages will instead be recovered as $\breve{\mathbf{D}}_{\mathbf{r}}$ (LPOL) or $\mathbf{D}_{\mathbf{r}}$ (EPOL). In both cases, position angles are now referenced to the true sky frame.

L3: 2 slices LPOL/EPOL

- LPOL/EPOL = `CALIBRATE_POL_LEAKAGE` and `CALIBRATE_CROSSHAND_PHASE` with possible addition of `CALIBRATE_POL_ANGLE`
- `GAINCAL 'KCROSS' smodel=provided` → `POLCAL 'Xf' smodel=provided` →
  `POLCAL 'Dflls' smodel=provided refant=none` (→ iterate)
- Without position angle calibration, and if LPOL observed, recovers $\breve{\mathbf{D}}_{\mathbf{r}}$ (lack of circular polarization calibration results in unconstrained imaginary d-term components, even though these components were never made explicitly 'relative' by setting any of them to zero) and $\mathbf{X}_{\mathbf{r}}$, with position angles aligned to mechnical feeds. If EPOL observed, leakages instead recovered as $\mathbf{D}_{\mathbf{r}}$.

- If position angle calibration requested, and if CASA functionality is available, position angles now aligned to true sky frame

L4: 3 slices POL/CPOL/UNKWN

- POL/CPOL/UNKWN = `CALIBRATE_POL_LEAKAGE` and `CALIBRATE_CROSSHAND_PHASE`
- Alternative to provide backward compatibility with pre Cycle 5 observations: POL/CPOL/UNKWN = `CALIBRATE_POLARIZATION`
- `GAINCAL 'KCROSS'` → `GAINCAL 'XYf+QU'` → `POLCAL 'Dflls'` (→ iterate)
- Recovers $\breve{\mathbf{D}}_\mathbf{r}$ (POL/UNKWN) or $\mathbf{D_r}$ (CPOL). Recovers $\mathbf{X_r}$. Position angles will be aligned to the mechnical feeds. Leakage calibrator `QU` recovered and used in leakage solve.
- If using CPOL or UNKWN, must exhibit linearly polarized emission, otherwise calibration will fail
- Ideally the polarization solve should be channelized, rather than spectral window dependent as currently implemented in CASA. If a channelized `QU` solve is not available, provide a warning noting that if the calibrator has a large rotation measure, this will depolarize in the solve (Section 4.3) and corrupt the results.

L5: 3 slices POL/CPOL/UNKWN + 1 slice LPOL/EPOL

- POL/CPOL/UNKWN = `CALIBRATE_POL_LEAKAGE` and `CALIBRATE_CROSSHAND_PHASE`
- LPOL/EPOL = `CALIBRATE_POL_ANGLE`
- Same as L4 but with addition of position angle calibration, pending functionality upgrade within CASA
- Recovers $\breve{\mathbf{D}}_\mathbf{r}$ (does not include CPOL or EPOL) or $\mathbf{D_r}$ (includes CPOL and/or EPOL). Recovers $\mathbf{X_r}$. Position angles will be aligned to the true sky frame.

The default linear polarization calibration strategy for ALMA is currently L4. It is anticipated that this will be the only approved method of polarization calibration for Cycle 5. Commissioning of the L2 strategy is currently underway, though it is unlikely to be ready for Cycle 5 (SCIREQ-808).

5.4 Circular feed basis

There are 6 typical strategies for calibrating polarization when observing with an interferometer with circular feeds such as the VLA, subject to the assumptions outlined earlier in this document. The order of calibration is nominally crosshand delay, leakage, then crosshand phase (effectively absolute position angle) without the need for iteration. These steps are typically carried out after standard total intensity calibration, and without using rescaled gains from `FLUXSCALE`. The strategies are defined below using the slice definition from Section 4.2, and using the calibrator classifications from Section 5.1 matched to the scan intents from Section 5.2. The minimum number of slices is indicated for each calibrator type. Implementation summaries are provided. It is assumed that previous calibrations are applied at each step. More detailed implementation information is provided later in Section 6.2. The strategies are labelled C# to indicate circular basis; the numbering is arbitrary.

C1: 1 slice UNPOL + 1 slice LPOL/EPOL

- UNPOL = `CALIBRATE_POL_LEAKAGE`
- LPOL/EPOL = `CALIBRATE_CROSSHAND_PHASE` and/or `CALIBRATE_POL_ANGLE`
- `GAINCAL 'KCROSS'` → `POLCAL 'Df'` → `POLCAL 'Xf'`
- Recovers $\widetilde{\mathbf{D}}_\mathbf{r}$ (i.e. relative leakages in the crosshand phase frame of the gain reference antenna) and $\mathbf{X}_\mathbf{r}$

C2: 2 slices LPOL/EPOL

- LPOL/EPOL = `CALIBRATE_POL_LEAKAGE` and `CALIBRATE_CROSSHAND_PHASE` and/or `CALIBRATE_POL_ANGLE`
- `GAINCAL 'KCROSS'` → `POLCAL 'Df+X'` → `POLCAL 'Xf'`
- Recovers $\widetilde{\mathbf{D}}_\mathbf{r}$ and $\mathbf{X}_\mathbf{r}$
- Ideally the position angle solve in `Df+X` should be channelized, rather than spectral window dependent as currently implemented in CASA. If a channelized version is not available, provide a warning noting that if the calibrator has a large rotation measure or if the spectral windows exhibit significant structure in crosshand phases, the leakages will be corrupted.

C3: 3 slices POL/CPOL/UNKWN

- POL/CPOL/UNKWN = `CALIBRATE_POL_LEAKAGE`
- `POLCAL 'Df+QU'` (ideally requires `Df+QUf`; this is not currently available in CASA)
- Recovers $\widetilde{\mathbf{D}}_\mathbf{r}$. Leakage calibrator `QU` also recovered, though this is not needed as input for any subsequent calibration steps. The `QU` solve could return zero polarization for CPOL/UNKWN (this is ok).
- Warn that only partial polarization calibration is possible; $\mathbf{X}_\mathbf{r}$ cannot be recovered and thus absolute position angle calibration cannot be performed due to lack of a suitable calibrator. This calibration strategy is unlikely to be useful unless the user is only interested in channelized fractional polarization spectra for science targets.
- Ideally the polarization solve should be channelized, rather than spectral window dependent as currently implemented in CASA. If a channelized `QU` solve is not available (i.e. `Df+QUf`), provide a warning noting that if the calibrator has true non-zero polarization (POL and possibly CPOL/UNKWN) then it is practically guaranteed that the lack of crosshand delay calibration will lead to depolarization in the solve and corrupt the results. If the calibrator has a large rotation measure, this will cause additional depolarization in the solve (Section 4.3).

- CASA does not yet suitably account for atmospheric Faraday rotation in the polarization solve. If observing at low frequencies (< 4 GHz) and TEC data is available, do not include the TEC caltable, and warn that the data will be uncorrected for atmospheric Faraday rotation.

C4: 3 slices POL/CPOL/UNKWN + 1 slice LPOL/EPOL

- POL/CPOL/UNKWN = `CALIBRATE_POL_LEAKAGE`
- LPOL/EPOL = `CALIBRATE_CROSSHAND_PHASE` and/or `CALIBRATE_POL_ANGLE`
- `GAINCAL ‘KCROSS’` → `POLCAL ‘Df+QU’` → `POLCAL ‘Xf’`
- Recovers $\widetilde{\mathbf{D}}_{\mathbf{r}}$ and $\mathbf{X}_{\mathbf{r}}$. Leakage calibrator `QU` also recovered, though this is not needed as input for any subsequent calibration steps. The `QU` solve could return zero polarization for CPOL/UNKWN (this is ok).
- Ideally the polarization solve should be channelized[15] rather than spectral window dependent as currently available in CASA. If a channelized `QU` solve is not available (`Df+QU` vs. `Df+QUf`), provide a warning noting that if the calibrator has a large rotation measure (Section 4.3), or if the crosshand phase solutions span a large range in phase (see below), this will depolarize in the solve and corrupt the results. The presently nominated C4 workflow is not ideal because there will be a residual `Xf` across each spectral window that will artificially depolarize the `QU` solve. However, as `KCROSS` is solved per spectral window, this should leave `Xf` spanning only a modest range in phase (hopefully < 90°, or else the behavior should have been accommodated in the delay). In practice, this should provide a largely coherent frame for the `QU` solve to operate within. See CAS-9388 for more details.
- CASA does not yet suitably account for atmospheric Faraday rotation in the polarization solve. If observing at low frequencies (< 4 GHz) and TEC data is available, do not include the TEC caltable, and warn that the data will be uncorrected for atmospheric Faraday rotation.

C5: 1 slice UNPOL

- UNPOL = `CALIBRATE_POL_LEAKAGE`
- `POLCAL ‘Df’`
- Recovers $\widetilde{\mathbf{D}}_{\mathbf{r}}$
- Warn that only partial polarization calibration is possible; $\mathbf{X}_{\mathbf{r}}$ cannot be recovered and thus absolute position angle calibration cannot be performed due to lack of a suitable calibrator. This calibration strategy is unlikely to be useful unless the user is only interested in channelized fractional polarization spectra for science targets.

---

[15] The calibration workflow should then proceed as `POLCAL ‘Df+QUf’` → `GAINCAL ‘KCROSS’` → `POLCAL ‘Xf’`.

C6: UNPOL (`GAINCAL` only) + 2 slices LPOL/EPOL or 3 slices POL

- Strategy not currently provisioned in CASA. Requires solving for gains using an unpolarized calibrator then solving for parallactic angle dependence of polarized source in both cross and parallel hands. See demonstration by Sault & Perley (2013).
- Recovers $\mathbf{D_r}$ (i.e. absolute leakages) and $\mathbf{X_r}$. Suitable for high dynamic range total intensity or situations where both linear and circular polarization are of interest. Suitable for converting to reference-antenna-independent instrument frame $\mathbf{D}$ for storage in calibration database.
- Included here to indicate alternate strategy, *not intended for phase 1*

The VLASS is planning to use strategies C1 and C4 for polarization calibration.

6 Proposed Infrastructure

The phase 1 upgrade requires modification to 7 key areas of the pipeline. These are described in the following sections in order of pipeline workflow. Section 6.1 focuses on pipeline initialization. Section 6.2 describes new polarization calibration tasks for the linear and circular feed bases that include automated selection of calibration strategy, diagnostics, and optimization. Section 6.4 details modifications to the pipeline imaging tasks. Section 6.5 describes QA2 scoring for polarimetric calibration and imaging tasks. Section 6.6 focuses on the weblog. Section 6.7 identifies data products to be exported to the `products` subdirectory.

This document will assume that wider pipeline infrastructure to support combined handling of multiple scheduling blocks, each potentially containing multiple execution blocks, will be available (to date this is only partially implemented). For example, this is relevant for the ALMA observing scheme known as ‘sessions’, used for polarimetry, where not all scheduling blocks contain all necessary calibration scans and combined analysis must be performed. Sessions will be used in Cycle 5 (SCIREQ-603, SCIREQ-811, CAS-5709). Note that session-type analysis is only appropriate if it can be safely assumed that instrumental parameters such as crosshand phase will remain stable over all combined data.

6.1 Initialization

The ALMA pipeline is initialized by `hifa_importdata`. The VLA pipeline is initialized by `hifv_importdata`. These tasks and others described below need to be modified so they can accept and suitably parse polarimetric data in preparation for calibration and imaging. New steps to be performed within the ALMA and VLA `importdata` tasks are:

1. Disable polarization processing if the polarization calibration task in the pipeline workflow is disabled or commented out, i.e. if this is the case, do not consider any of the following initialization steps, including the VLA-only steps described at the end of this section. This enables a user to turn off polarization calibration and force total intensity calibration only when running the pipeline, even if the data meets all requirements for polarization processing.

2. Examine the scan intents associated with each correlator setup in the data. Turn on a switch (boolean per correlator setup) to enable polarization processing if any of the following appear:

    - `CALIBRATE_POL_LEAKAGE`
    - `CALIBRATE_CROSSHAND_PHASE`
    - `CALIBRATE_POL_ANGLE`
    - `CALIBRATE_POLARIZATION`

    Note that modification of `state.py` (in domain) is required. If any of the steps below result in a decision to disable polarization processing, turn off the relevant switch and inform the user. Switch status should be considered before operating any polarization task in the pipeline. *For simplicitly, the remainder of Section 6 will only focus on a single correlator setup, and will implicitly assume independent polarization processing per setup including independent calibration tables.*

3. Disable polarization processing if less than 4 polarization products were recorded. Note that modification of `measurementset.py` (in domain) is required.

4. Disable polarization processing if the spectral setup is only used to observe science targets, i.e. if corresponding observations on polarization calibrators are missing. Note that this step will not affect the possible intended use of spectral window mapping for aspects of total intensity calibration.

5. If any of the polarization calibrators are not also specified as a bandpass, flux, or gain calibrator, modify the context to ensure they will be treated as if they were also a gain calibrator, i.e. perform flagging and gain calibration (amplitude & phase). Of course, do not use these calibrators for intents other than their original specification.

6. Set `parang=True` for all tasks[16].

A new task needs to be included in the pipeline workflow to ensure that one consistent reference antenna will be maintained throughout all bandpass and 'long'-timescale[17] post-bandpass gain phase calibration tables (in all sessions). This new pipeline task, provisionally named `hif_checkrefantflag`, should be placed in the pipeline workflow after the last possible alteration to the reference antenna list nominated by `hif_refant`, but before any delay, bandpass, or gain calibration tables have been created. This requires placement immediately prior to `hif_bandpass` in the ALMA pipeline and `hifv_testBPdcals` in the VLA pipeline. `hif_checkrefantflag` should include the following functionality:

- If polarization processing is enabled, then all integrations for the delay, bandpass, gain, and polarization calibrators need to be checked to ensure that the reference antenna

---

[16] `parang=True` could be set as the default option everywhere, even for non polarimetric data, because the pipeline is I/O limited and additional compute time will be negligible.

[17] Pipeline gain phase solutions are produced on 2 timescales: (i) 'short' solutions obtained per-integration are used for `inf` amplitude gain calibration, and (ii) 'long' solutions are applied with interpolation to target fields, where the averaging duration is selected to ensure that any consecutive scans on a gain calibrator will be combined to form a solution at a single timestamp. Only reference antenna changes in the latter are of concern here, as the former are never applied to data using the full measurement equation.

is available. If polarization processing is not enabled, then `hif_checkrefantflag` can simply exit immediately. If the reference antenna is found to be flagged for a given integration, then all data for that integration should be flagged. This will prevent calibration tasks from ever needing to perform an internal reference antenna change due to a missing nominated reference antenna. If such flagging is not performed, then it will be possible for internal reference antenna changes to exist within calibration tables, in turn preventing a consistent crosshand phase frame from being established and thus leading to corrupted polarization calibration.

A custom CASA task to demonstrate this flagging is currently available: `antintflag`[18] (Hales 2016). However, full incorporation into CASA is required, ideally through a new mode in `flagdata`; the current coding of `antintflag` is not optimized for speed or robust data selection.

Note that the alternative is to require all calibration tables to undergo a check for phase changes on the reference antenna, and if found, flag the affected integrations prior to caltable recalculation. This approach has the potential to become very time consuming, as well as overly complex to implement, and is therefore discouraged.

Finally, the following steps are only relevant for VLA data. Modify `hifv_priorcals` as follows:

- If the data are at frequencies < 4 GHz (S band or lower), download TEC data from the internet using `tec_map,tec_map_rms = tec_maps.create(vis)` (see Section 4.3). Use `gencal` with `infile=tec_map` and `caltype='tecim'` to read the data into a calibration table with extension `.tec`. Add this table to the context for application to all calibration tasks. Continue with regular pipeline polarization processing if no valid TEC data are available. The pipeline should not include functionality to delay processing while waiting for TEC data to become available; if desired, this should be provisioned externally.

  To complicate matters, corrupted TEC data are likely to be encountered often, in which case `tec_maps` will *appear* to fail and it will not be possible to successfully run `gaincal`. However, it should be possible to remedy most of these cases by repairing the downloaded TEC data and then re-running `tec_maps`. This procedure is tenable because `tec_maps` will search for existing TEC data in the local directory prior to looking on the internet. Raw TEC data are downloaded in IONEX[19] format (`#.i` text file) spanning 24 h, in which groups of rows bracketed by `START OF TEC MAP`/`END OF TEC MAP` and `START OF RMS MAP`/`END OF RMS MAP` correspond to global data for an individual timestamp. If the astronomical observations traverse 0 UT, then 2 files will be downloaded (or N files for N crossings). Corrupted IONEX data can be identified when the text `END OF FILE` is missing from the last line. Fortunately, when data are corrupted, this typically only affects the RMS data rather than the primary TEC data. The RMS data are located toward the end of the file and are not used nor required by CASA. If the missing bracket before `END OF FILE` is `END OF RMS MAP`, repair the file by removing all lines up to and including the last `START OF RMS MAP`, then insert a final line reading `END OF FILE`. If the missing bracket is `END OF TEC MAP`, then check the timestamp recorded on the line immediately following `START OF TEC MAP` (format `ymdhms` in UT). If this timestamp is

---

[18] https://github.com/chrishales/antintflag

[19] ftp://igscb.jpl.nasa.gov/igscb/data/format/ionex1.pdf

later than the last timestamp in the astronomical data, then remove all lines up to and including the last `START OF TEC MAP` and insert a final line reading `END OF FILE`. If the timestamp does not provide coverage over the full astronomical data, then continue with regular polarization processing as if no TEC data were available, and report to the user than an unsuccessful attempt was made to salvage TEC data. Note that, ideally, the error checking described above should instead be incorporated within `tec_maps`.

Modify `hifv_targetflag`[20] as follows:

- Perform this task as currently defined, operating on all calibrators and science targets. If polarization processing is enabled, save the flagging state and repeat, this time including cross hand visibilities when running `rflag` (i.e. `ABS_ALL`).

6.2 New polarization calibration tasks

This section describes two new pipeline tasks, `hif_linfeedpolcal` and `hif_circfeedpolcal`. These tasks are designed to perform polarimetric calibration in the linear and circular feed bases, respectively, including strategy selection, diagnostics, and optimization. Two tasks are recommended rather than a single master polarization calibration task so as to ease code readability and maintenance[21]. The tasks contain generic (instrument-independent) calibration procedures that facilitate customized implementation of the strategies from Sections 5.3 and 5.4, taking into account results from the initialization steps described in the previous section.

The overall pipeline workflow needs to be adjusted as follows when polarization processing is enabled:

- In the ALMA pipeline, `hif_linfeedpolcal` should be run prior to `hif_applycal`.
- In the VLA pipeline, `hif_circfeedpolcal` should be run after `hifv_targetflag` so as to access additional calibrator flagging that takes place following `hifv_applycals`.

The following initialization steps should be performed at the start of both `hif_linfeedpolcal` and `hif_circfeedpolcal`:

1. Save the flagging state. This will ensure that the pipeline can be restored to its pre-polarization-processing state should polarization calibration fail.
2. *Include a placeholder for this step, but do not activate until defined in more detail for a future pipeline upgrade:* Search prior-calibration database for appropriate leakage calibration table. If available, take this into account when selecting the appropriate calibration strategy in the next step.

---

[20] This document does not recommend an equivalent flagging step for calibrator data in the ALMA pipeline, though this could be included in the future if use cases are identified. Note that the ALMA pipeline does not currently include science target non-deterministic flagging (e.g. `rflag`), even in the parallel hand visibilities, though this may change in the future (SCIREQ-707).

[21] Additionally, this allows easy separation of possible future tasks such as `hif_mixedfeedpolcal`.

3. Identify the appropriate calibration strategy. There is currently no mechanism to recover this directly from the user. However, in most cases this is not required as the intended strategy can be reconstructed from the calibrator scan intents, the number of scans, and their span in parallactic angle. A requirement for users is that their chosen strategy conforms to one of the supported options described in Section 5 (all common strategies are supported). If not, the pipeline may not necessarily fail, though the calibrated data could be corrupted. Limited logic is included below to accommodate unsupported or poorly implemented calibration strategies, though this is far from comprehensive[22]. Note that this step should not be performed earlier in the pipeline workflow; if relevant calibrator scans are flagged, the pipeline may still be able to select a different yet suitable calibration strategy.

   Flowcharts to automatically identify the appropriate calibration strategy are provided in Figure 7 for the linear basis and Figure 8 for the circular basis. The flowcharts account for the possibility that additional scans or slices may have been observed, beyond the minimum requirements identified in Section 5. Note that some steps require querying a polarization calibrator database to determine if a suitable Stokes model is available; this database is described in more detail below. If the scan intents do not enable a unique calibrator to be identified for a particular calibration task (e.g multiple leakage calibrators are identified), choose the first suitable source and use the flowchart to deduce the intended calibration strategy. If the flowchart leads to a strategy involving a warning, repeat using the next suitable source. If, for example, multiple leakage and crosshand phase calibrators are available, examine all possible combinations until either a calibration strategy without a warning is identified, or all options have been examined. If the latter, use the first identified strategy and provide a message to the user explaining that strategy selection was based on the nominated calibrator.

   The flowcharts indicate where theoretical requirements for parallactic angle coverage have been translated into practical requirements (see keyword 'formally'). In most cases it is not appropriate for the pipeline to enforce theoretical requirements, as this responsibility falls on the relevant CASA tasks to calculate solutions and deliver error messages if they are degenerate. An exception to this rule is required in the circular basis when selecting between strategies C1 and C4, or similarly between C5 and C3. An issue can arise here if a user selects a calibrator that they assume is unpolarized, but where an a priori source model is unavailable to definitively specify zero polarization. If the user observes the assumed unpolarized leakage calibrator over a range in parallactic angle (e.g. if this is also a gain calibrator), there is no way for the pipeline to discriminate the intended C1 (or C5) strategy from the apparent need to perform C4 (or C3) and solve for source polarization. While the C4 (or C3) strategy is capable of solving for an unpolarized source, the accuracy of the resulting leakage terms may be inferior to those that could have been produced via C1 (or C5) by assuming an unpolarized source to begin with. This will be particularly relevant for observations with limited parallactic angle coverage. An option to remedy this situation is to define a new scan intent in CASA to specify when a calibrator should be assumed unpolarized (e.g. `CALIBRATE_POL_LEAKAGE0`). However, for now, this option is not recommended. Instead, as indicated in Figure 8, the pipeline should discriminate between C1 and C4, and between C5 and C3, by examining the total

---

[22] This is consistent with the general pipeline philosophy to provide little to no support for poorly formatted input data.

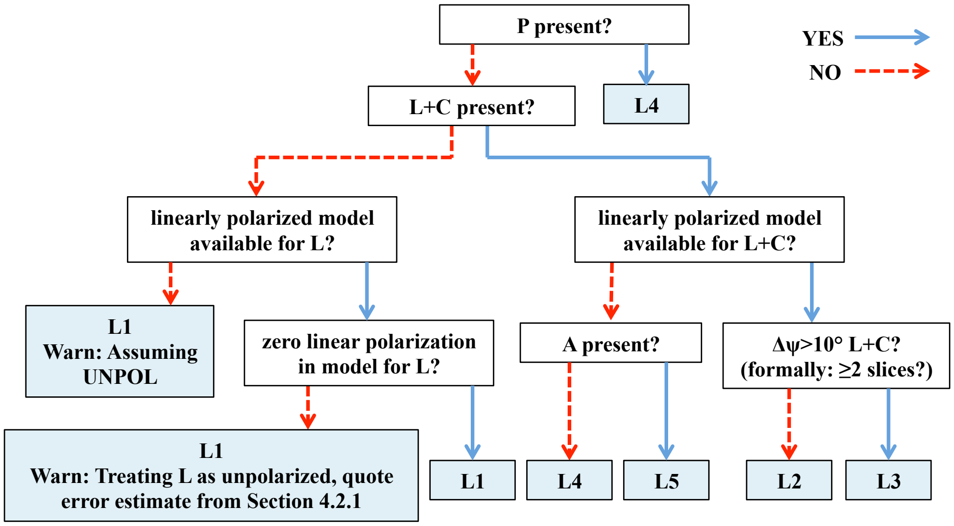

Figure 7 Calibration strategy selection in the linear basis. See Section 6.2 for details. Notation for calibrators that are identified by scan intent(s): L = leakage, C = crosshand phase, L+C = both L and C, A = position angle, P = polarization (P only used for backward compatibility with pre Cycle 5 data). For example, if a field is marked with scan intents for both leakage and crosshand phase calibration, the observed source satisfies identification as an L, C, and L+C calibrator.

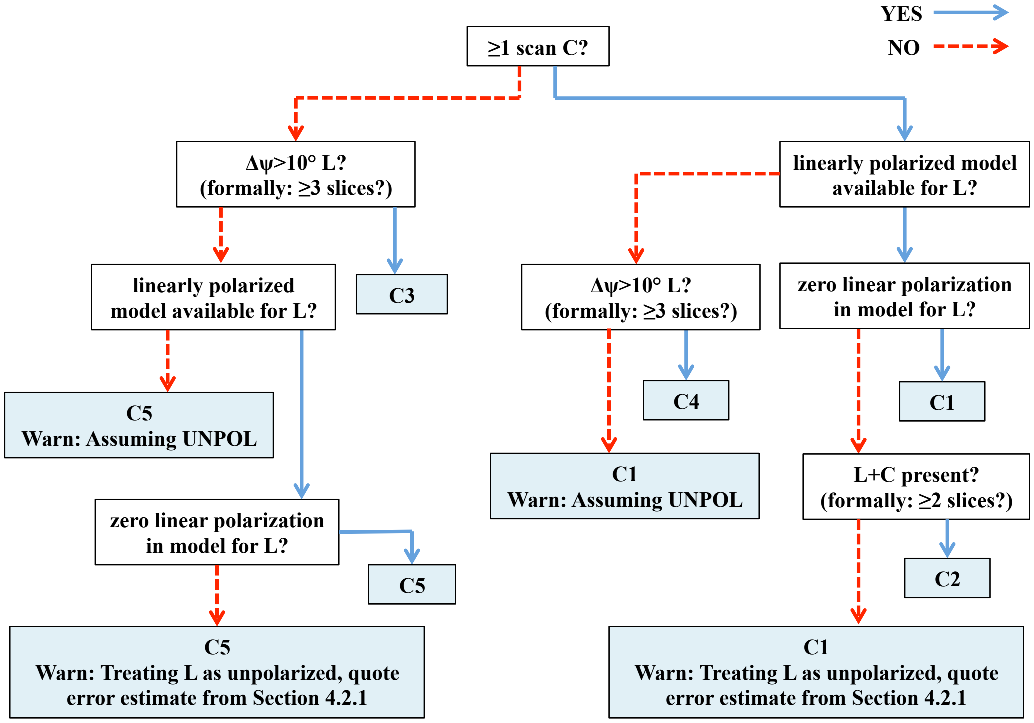

Figure 8 Calibration strategy selection in the circular basis. See Section 6.2 for details. Notation for calibrators that are identified by scan intent(s): L = leakage, C = crosshand phase and/or position angle (A is not explicitly required in the circular basis as it is synonymous with C), L+C = both L and C.

parallactic angle range ($\Delta\psi$) over which the leakage calibrator was observed. This check should account for all scans on-source. Figure 5 indicates that scans need to be separated by at least 10° in parallactic angle to enter parameter space where an acceptable calibration solution may be obtained. Figure 1 indicates that the maximum rate of parallactic angle change is $< 1.2°$/min for sources at any declination when antenna elevations are limited to $< 80°$, corresponding to a minimum timespan of 8 min to cover 10°. It is unlikely that users intending to perform C1 or C5 with a short leakage calibrator observation will require more than an 8 min on-source. It is also unlikely that users would ever intentionally design their observations to perform C4 or C3 with $\Delta\psi < 10°$. Therefore, $\Delta\psi = 10°$ enables practical discrimination between C1 and C4, and between C5 and C3. Offline documenation should be made available to users, pointing out that if they intend for the pipeline to perform the C1 or C5 calibration strategies using a calibrator observed over a wide range in parallactic angle, they should specify `CALIBRATE_POL_LEAKAGE` for only a subset of scans ocurring within $\Delta\psi < 10°$.

The observation preparation tool (OPT) for the VLA does not offer `CALIBRATE_POLARIZATION` as a scan intent. However, for completeness, if this intent does appear in VLA data, ignore all matching scans. If a valid calibration strategy cannot be identified using the remaining sources, then disable polarization processing. The ambiguity of this intent rules out mapping to all but the linear basis L4 strategy for ALMA, where it will (ideally) provide backward compatibility for existing (pre Cycle 5) polarimetric data.

CASA does not currently store polarization models internally (LPOL, CPOL, EPOL, UNPOL), unlike total intensity (e.g. 3C286), though this may change in the future. Until then, the pipeline code should internally store models for standard polarization calibrators, or draw them from an external database in a manner similar to antenna position corrections. Importantly, the polarization models should be stored in units of flux density, i.e. $[\mathcal{I}, \mathcal{Q}, \mathcal{U}, \mathcal{V}]$, rather than fractional polarization scaled to unit flux density. This will ensure consistency with the output of the regular total intensity pipeline. In the circular basis, this will also ensure correct scaling for leakage calibration when incorporating existing gain amplitude calibration (which by this stage in the pipeline will have been flux density scaled[23]). Additionally, care needs to be taken to identify the appropriate category for stored calibrators (i.e. LPOL, CPOL, EPOL, UNPOL). For example, an LPOL calibrator by definition has unknown Stokes $\mathcal{V}$. If circular polarization is set in the model to a default value such as zero, then a query to the database should not incorrectly infer that the calibrator is type EPOL with known Stokes $\mathcal{V}$. Perley & Butler (2013) provide details for 4 LPOL calibrators: 3C48, 3C138, 3C147, and 3C286. These are suitable for frequency space between 1–50 GHz, with the following exceptions: 3C48 is suitable at S band and higher frequencies, 3C147 is suitable at X band and above. 3C138 is variable; if used, the pipeline should warn users that results may be affected by variability. For all VLA data containing these calibrators, when observed in any configuration except D, the pipeline should inform users that the resulting polariza-

---

[23] For completeness, the pipeline's general flux scaling workflow is outlined as follows. The ALMA pipeline performs `bandpass` with `solnorm=True` and `gaincal` with `solnorm=False`. The VLA performs both with `solnorm=False`. To perform flux density bootstrapping, the ALMA and VLA pipelines read the dictionary produced by `fluxscale`, write the recovered model(s) to the measurement set using `setjy`, then perform amplitude `gaincal`.

tion calibration may exhibit systematic errors because the assumed models from Perley & Butler (2013) are based on D configuration observations; any structure at higher angular resolution is not included in the models. An effort is currently underway to identify standard polarization calibrators for ALMA (see CSV-3263 and SCIREQ-580).

4. If needed for the strategy selected above, import the appropriate Stokes model(s) from the polarization calibrator database to the `model_data` column, doing so in a manner similar to (or using a future modified version of) `setjy`. This will overwrite any existing models that may have been used for total intensity calibration[24] (though only effectively changing at most the Stokes $\mathcal{Q}, \mathcal{U}$, and $\mathcal{V}$ portions of the previous model, as the replaced total intensity component should be identical). Note that CAS-9388 contains a script that demonstrates how to set the the position angle portion of the polarization model for 3C48. Should limitations persist within `setjy`, until fixed, the script version could be modified to assign the complete polarization model for 3C48.

The linear and circular basis workflows are described in the following sections. In general, the workflows only provide details for non-default parameters; unspecified parameters should be assumed to be the CASA default values (e.g. `gaincal solint='inf'`). For all calibration tasks, specify the same consistent reference antenna that was used to perform flagging in `hif_checkrefantflag` above, unless noted otherwise[25].

6.2.1 Linear feed basis: `hif_linfeedpolcal`

The telescope-independent linear basis calibration workflows should proceed as follows.

L1:

1. Calculate `'G'` gains for the leakage calibrator:
   `gaincal gaintype='G' calmode='ap' solint='int'`
   - Include in `gaintable` the standard total intensity caltables that would normally be included in a first call to `gaincal` (i.e. WVR, T_{sys}, antenna position corrections, bandpass; do not include any existing gain caltables). This set of caltables will be incremented upon in the steps below, as indicated.
   - Save solutions to a new `#.G` caltable
   - If no solutions can be found[26], remove `#.G` and reattempt with `solint='inf'`

---

[24] As an aside, if the selected calibration strategy involves a leakage calibrator with unknown linear polarization (L4,L5,C3,C4), do not remove any Stokes models that may be present for these calibrators. Removal would not be problematic in the linear basis workflows presented later, but this would cause a flux density inconsistency in the circular basis workflows, leading to corrupted leakages.

[25] Technically it is not necessary to specify a reference antenna for crosshand delay or crosshand phase calibration, as the prior application of calibration tables through `gaintable` effectively registers all data to the crosshand phase frame of the gain reference antenna. Any specified reference antenna will be ignored. However, currently, crosshand delay calibration in CASA requires a reference antenna to be specified due to inheriting this check from regular delay calibration. This will be addressed in a future CASA fix. For now, to avoid any possible conflict, this document recommends continuing to specify a reference antenna for crosshand delay and phase calibrations.

[26] In this and the other strategies, the calibrator should be bright enough to easily obtain solutions on `int` timescales (assuming standard practice where the calibrator is not observed at high time resolution), otherwise polarization calibration is unlikely to be successful.

up to scan boundaries. If again no solutions can be found, disable polarization processing and inform the user.

2. `polcal poltype=‘Dflls’ refant=specified`
   - Include in `gaintable` the standard total intensity caltables as well as `#.G`
   - If leakage solutions are recovered for less than 50% of attemptable channels in any spectral window ($< N_i/2$ in i’th spectral window, where N_i is attemptable channels, not total), use `tb.selectrows` and `tb.removerows` to remove all solutions for that spectral window. Rerun `polcal` with `append=T` and pre-average every 2 channels by specifying `solint=‘inf,2ch’`. If less than 50% of these expected solutions are obtained (i.e. $< N_i/4$), attempt 4-channel pre-averaging using `solint=‘inf,4ch’`. If $< N_i/8$ of these solutions are obtained, do not perform any further pre-averaging because spectral structure in the leakages may become poorly sampled[27]. Note that `polcal` does not currently output channelized attempted/solved statistics; this functionality needs to be implemented in CASA to support the pipeline workflow described here[28]. Perform linear interpolation (default) when applying these calibration solutions later in `applycal`. If pre-averaging is performed as above, inform the user and warn that the quality of fractional polarization spectra for science targets may be slightly degraded. If *no* solutions can be found across *all* spectral windows of a given bandwidth (different bandwidth spectral windows may be present within a correlator setup), rerun `polcal` for those spectral windows using the channel-independent `poltype` for the requested calibration strategy (i.e. `Dlls` rather than `Dflls` here). Warn the user that the signal to noise was too low to permit channelized leakage solutions, and that as a result they should cautiously interpret fractional polarization spectra for their science targets. For simplicitly, the scheme above will not allow for both channelized and non-channelized solutions to be present for different spectral windows, if these windows are of the same bandwidth (including spectral windows with the same bandwidth but different channelization).
   - Spurious leakage amplitudes approaching and even exceeding unity may be recovered if solutions cannot be obtained on the reference antenna or if RFI is present. For any channel (or spectral window if channel-independent `poltype` was used) where a leakage solution is not recovered on the reference antenna, or where the leakage amplitude for any antenna is greater than 80%, flag all antennas in the calibration table for that channel. The value of 80% is chosen as it is unlikely that any legitimate data will exhibit higher leakages, while also being large enough to permit pipeline calibration of test data where unusually

---

[27] Identifying parameter space where further averaging may be performed without penalty (e.g. smoothing tests) is beyond the scope of this document; it is assumed here that demand for this functionality will be negligible.

[28] If such functionality is not made available, then it is still possible for the pipeline to temporarily calculate the statistics itself. The total number of attemptable channel (N_i) can be defined by counting, for each channel, the number of antennas to which to at least `minblperant` baselines are available containing unflagged visibilities in all four polarization products. N_i is then given by the sum of these channels counts (i.e. N_i could be as high as the number of channels multiplied by the number of antennas). The number of flagged solutions can then be obtained by subtracting from N_i the number of leakage solutions in the spectral window of interest (similarly summed over channels and antennas).

high leakages may be present (note from Section 4 that typical leakages for ALMA and the VLA are an order of magnitude smaller).

   - The default spectral interpolation mode used later in `applycal` is `linear`. To ensure appropriate behavior in `applycal`, if channelized leakage solutions are obtained, check that gaps between solutions are ≤ 4 channels wide in units of un-averaged channel widths. If any larger gaps are found (for example, data where `solint='inf,4ch'` was used and where leakage solutions contain missing gaps spanning > 1 contiguous post-averaged channels within a particular spectral window), flag the cross-hand visibility data within the gap channels on the offending antenna for all fields in the measurement set. This will ensure that interpolation cannot proceed across arbitrarily large gaps when applying calibration to the science targets (and calibrators), and will help to optimize crosshand phase and position angle calibration below.

3. Relabel the leakage calibration table to ensure it will be applied with full general matrix algebra to the parallel hand visibilities in addition to the cross hands:
   `dgenPIPE dtab=#.D dout=#.Dgen`
   This task is described toward the end of this section.

4. Calculate gain phase solutions for the crosshand phase calibrator:
   `gaincal gaintype='G' calmode='p' solint='int'`
   - Include in `gaintable` the standard total intensity caltables that would normally be included in a first call to `gaincal`, with the addition of `#.Dgen`
   - Append solutions to `#.G`
   - If no solutions can be found, use `tb.selectrows` and `tb.removerows` to remove all solutions for the crosshand phase calibrator and reattempt with `solint='inf'` up to scan boundaries. If again no solutions can be found, disable polarization processing and inform the user.

5. If the crosshand phase calibrator was observed over multiple scans, select the scan, denoted below by `KXscan`, for which $\mathcal{U}_\psi$ will be maximized for the majority of spectral windows. To do this, use the observed parallactic angles and the known Stokes vector, calculated for simplicity at the central frequency of each spectral window. If the maximum predicted $\mathcal{U}_\psi$ is less than 10% of the fractional polarization of the crosshand phase calibrator in any spectral window, provide a warning to the user that the crosshand phase calibrator was likely observed at a sub-optimal parallactic angle (this could also arise due to a calibrator with significant rotation measure, but such a source is unlikely to be used in the present context as a crosshand phase calibrator with known Stokes vector).

6. `gaincal gaintype='KCROSS' scan='KXscan'`
   - Note that multi-band solutions, per baseband, are not yet supported for `KCROSS`, unlike for antenna-based global `K`
   - Include in `gaintable` the standard total intensity caltables that would normally be included in a first call to `gaincal`, as well as the `#.Dgen` and gain phase caltables
   - If no solutions can be found, disable polarization processing and inform the user

7. Perform crosshand phase calibration: `polcal gaintype=‘Xf’`
    - Include in `gaintable` the standard total intensity caltables that would normally be included in a first call to `gaincal`, as well as the `#.Dgen`, gain phase, and crosshand delay caltables
    - Perform diagnostics and optimization similar to Step 2, as follows. If solutions are recovered for less than 50% of attemptable channels in any spectral window, attempt 2-channel pre-averaging or, if needed, 4-channel pre-averaging. If no solutions are found across all spectral windows of common bandwidth, or if leakage calibration required channel-independent `poltype` for the spectral window of interest, rerun using channel-independent `poltype` (i.e. `X` rather than `Xf` here). Inform the user if pre-averaging was performed or if channelized solutions were not possible.
    - To ensure appropriate behavior in `applycal`, if channelized crosshand phase solutions are obtained, check that gaps between solutions are ≤ 4 channels wide in units of un-averaged channel widths. If any larger gaps are found, flag the cross-hand visibility data within the gap channels on the offending antenna for all fields in the measurement set. This will ensure that interpolation cannot proceed across arbitrarily large gaps when applying calibration to the science targets.
8. Calculate normalized global X/Y gain amplitude ratio on each antenna using the leakage calibrator:
    `gaincal combine=‘scan,obs’ gaintype=‘G’ calmode=‘a’ solnorm=True`
    - Include in `gaintable` the standard total intensity caltables that would normally be included in a first call to `gaincal`, as well as the `#.Dgen`, gain phase, crosshand delay, and crosshand phase caltables
    - Save solutions to `#.Gxyamp`
9. *Include a placeholder for this step, but do not activate until a leakage calibration database becomes available and the effects of substituting* $\mathbf{D}$ *(absolute) with* $\widetilde{\mathbf{D}}$ *(relative) or* $\breve{\mathbf{D}}$ *(incomplete-absolute) has been fully tested:* Rotate leakage solutions out of crosshand phase frame of gain reference antenna into the reference-antenna-independent alt-az instrument frame. These leakages would then be suitable for plotting, comparison between different measurement sets (especially those using different reference antennas), and storage in a leakage calibration database, but not for application in the measurement equation (i.e. in `gaintable`). The task `dxy` is available as an example of code to perform the rotation. This task is available in `almapolhelpers.py`, though it requires modification to account for $\mathbf{X_r}$ rather than simply $\widetilde{\mathbf{X}}_{\mathbf{r}}$ as currently coded. To be suitable for pipeline use, it will likely require further modification similar to that described for related tasks toward the end of this section.
10. Perform position angle calibration if the intent is specified, and if CASA functionality is available. Include in `gaintable` the standard total intensity caltables as well as the polarization caltables from above. If the position angle calibrator is not also the crosshand phase calibrator, ensure to recover and take into account gain phase `‘int’` solutions, also taking into account in `gaintable` the total intensity and polarization caltables.

L2:

1. `gaincal gaintype='G' calmode='ap' solint='int'`
   - Include in `gaintable` the standard total intensity caltables that would normally be included in a first call to `gaincal` (i.e. WVR, T_{sys}, antenna position corrections, bandpass; do not include any existing gain caltables). This set of caltables will be incremented upon in the steps below, as indicated.
   - Save solutions to a new `#.G` caltable
   - If no solutions can be found, remove `#.G` and reattempt with `solint='inf'` up to scan boundaries. If again no solutions can be found, disable polarization processing and inform the user.
2. If the crosshand phase calibrator was observed over multiple scans (within the narrow parallactic angle range required to trigger this calibration strategy), select the scan with the least amount of flagged data (likely the last scan, due to online flagging), denoted below by `KXscan`. Predict $\mathcal{U}_\psi$ at this scan and perform the same check as described for Step 5 of the L1 calibration strategy.
3. `gaincal gaintype='KCROSS' scan='KXscan'`
   - Include in `gaintable` the standard total intensity caltables that would normally be included in a first call to `gaincal`, as well as the `#.G` caltable
   - If no solutions can be found, disable polarization processing and inform the user
4. `polcal gaintype='Xf'`
   - Include in `gaintable` the standard total intensity caltables that would normally be included in a first call to `gaincal`, as well as the `#.G` and crosshand delay caltables
   - Perform the same diagnostics and optimization as described for Step 7 of the L1 calibration strategy, including possible flagging
5. `polcal poltype='Dflls' refant=specified`
   - Include in `gaintable` the standard total intensity caltables that would normally be included in a first call to `gaincal`, as well as the `#.G`, crosshand delay, and crosshand phase caltables
   - Perform the same diagnostics and optimization as described for Step 2 of the L1 calibration strategy, including possible flagging
6. Relabel the leakage calibration table: `dgenPIPE dtab=#.D dout=#.Dgen`
   This task is described toward the end of this section.
7. Calculate normalized global X/Y gain amplitude ratio on each antenna using the polarization calibrator:
   `gaincal combine='scan,obs' gaintype='G' calmode='a' solnorm=True`
   - Include in `gaintable` the standard total intensity caltables that would normally be included in a first call to `gaincal`, as well as the crosshand delay, crosshand phase, and `#.Dgen` caltables
   - Save solutions to `#.Gxyamp`

8. *Include a placeholder here for functionality as described in Step 9 of the L1 calibration strategy.*

L3:

1. Perform Step 1 from the L2 calibration strategy.
2. Select the scan, denoted below by `KXscan`, for which $\mathcal{U}_\psi$ will be maximized for the majority of spectral windows, as described for Step 5 from the L1 calibration strategy.
3. Perform Steps 3–4 from the L2 calibration strategy
4. Perform Step 5 from the L2 calibration strategy, but without specifying a reference antenna (i.e. `refant=‘’`)
5. Perform Steps 6–8 from the L2 calibration strategy.

L4:

1. Calculate `‘G’` gains for the leakage calibrator, absorbing its polarization:
   `gaincal gaintype=‘G’ calmode=‘ap’ solint=‘int’ smodel=[1,0,0,0]`
    - Include in `gaintable` the standard total intensity caltables that would normally be included in a first call to `gaincal` (i.e. WVR, T_{sys}, antenna position corrections, bandpass; do not include any existing gain caltables). This set of caltables will be incremented upon in the steps below, as indicated.
    - Save solutions to an interim gain caltable `#.Gabsorbpol`
    - If no solutions can be found, remove `#.Gabsorbpol` and reattempt with `solint=‘inf’` up to scan boundaries. If again no solutions can be found, disable polarization processing and inform the user.
2. Estimate calibrator polarization: `S1 = qufromgainPIPE(#.Gabsorbpol)`. This task is described toward the end of this section. This step will recover the fractional Stokes $\mathcal{Q}$ and $\mathcal{U}$ per spectral window (i.e. assuming unit total flux density).
3. Remove `#.Gabsorbpol` and recalculate Step 1, appending results per spectral window, placing the respective estimated polarization from `S1` into `smodel` in each case.
4. Select scan ID, denoted below by `KXscan`, where calibrator polarization is maximum in V_{XY} and V_{YX}. To do this, use the estimated fractional Stokes $\mathcal{Q}$ and $\mathcal{U}$ values per spectral window from `qufromgainPIPE` and the known parallactic angles to select the scan where $\mathcal{U}_\psi$ is maximized for a majority of spectral windows.
5. `gaincal gaintype=‘KCROSS’ scan=‘KXscan’ smodel=[1,`$2^{-1/2}$`,`$2^{-1/2}$`,0]`
    - Include in `gaintable` the standard total intensity caltables that would normally be included in a first call to `gaincal`, as well as the `#.Gabsorbpol` caltable
    - If no solutions can be found, disable polarization processing and inform the user
    - True polarization not required here (or step below) due to phase-only solve

6. `gaincal gaintype='XYf+QU' combine='scan,obs' smodel=[1,`$2^{-1/2}$`,`$2^{-1/2}$`,0]`
   - Include in `gaintable` the standard total intensity caltables that would normally be included in a first call to `gaincal`, as well as the `#.Gabsorbpol` and crosshand delay caltables
   - Save solutions to an interim caltable `#.XYamb`
   - Perform the same diagnostics and optimization as described for Step 7 of the L1 calibration strategy, including possible flagging
7. Resolve phase ambiguity between $(\rho, \mathcal{Q}, \mathcal{U})$ and $(\rho+\pi, -\mathcal{Q}, -\mathcal{U})$ using previous per spectral window estimates of source polarization:
   `S2=xyambPIPE(xytab=#.XYamb,qu=QU,xyout=#.XY)`
   - This task is described toward the end of this section
   - `S2` will contain fractional Stokes $\mathcal{Q}$ and $\mathcal{U}$ per spectral window for a unit total flux density source
8. Use `setjy` to place the revised Stokes vector `S2` from `xyambPIPE` into the model column for the leakage calibrator, overwriting any existing models that may be present.
9. Calculate correct `'G'` gains for the leakage calibrator, accounting for its intrinsic polarization: `gaincal gaintype='G' calmode='ap' solint='int'`
   - Include in `gaintable` the standard total intensity caltables that would normally be included in a first call to `gaincal` (crosshand delay and phase caltables not required here)
   - Save results to a new `#.G` caltable
10. Check for any residual polarization: `S3 = qufromgainPIPE(#.G)`
    - Recovers the Stokes $\mathcal{Q}$ or $\mathcal{U}$ values per spectral window, as well as the mean values over all spectral windows and their rms
    - If any of the Stokes values are greater than 0.5%, warn the user that the calibration may not have been successful (note that comparison of the mean to rms values may be misleading, so it is avoided as a diagnostic here)
11. `polcal poltype='Dflls' refant=''`
    - Do not specify a reference antenna
    - Include in `gaintable` the standard total intensity caltables that would normally be included in a first call to `gaincal`, as well as the `#.G`, crosshand delay, and `#.XY` caltables
    - Perform the same diagnostics and optimization as described for Step 2 of the L1 calibration strategy, including possible flagging
12. Relabel the leakage calibration table: `dgenPIPE dtab=#.D dout=#.Dgen`
    This task is described toward the end of this section.
13. Calculate normalized global X/Y gain amplitude ratio on each antenna using the leakage calibrator:
    `gaincal combine='scan,obs' gaintype='G' calmode='a' solnorm=True`
    - Include in `gaintable` the standard total intensity caltables that would normally be included in a first call to `gaincal`, as well as the crosshand delay, `#.XY`, and `#.Dgen` caltables

- Save solutions to `#.Gxyamp`

14. *Include a placeholder here for functionality as described in Step 9 of the L1 calibration strategy.*

L5:

1. Perform all steps described for L4
2. Perform position angle calibration if the intent is specified, and if CASA functionality is available, as described in Step 10 of the L1 calibration strategy.

No iteration is required for the L1 calibration workflow because leakage calibration is performed on an unpolarized calibrator and thus does not require knowledge of the crosshand phase. No overall iteration is included within the L2-L5 workflows. It is possible that iteration may provide higher formal accuracy for these workflows. However, in practice, improvements are expected to be negligible for most data because gain and crosshand phase calibrations are only weakly affected by unknown leakages. If additional iteration is found to be necessary for some data, then the pipeline can be upgraded in a future release, ensuring careful consideration of prior caltables, the reference frames in which they are supplied, and the consequences of using relative leakages in L2.

The L4 & L5 calibration workflows require functionality contained in the tasks `qufromgain`, `xyamb`, and `Dgen` from `almapolhelpers.py`[29]. The pipeline should not import these tasks. Instead, the pipeline should contain a temporary dedicated copy of these tasks, referred to as `qufromgainPIPE`, `xyambPIPE`, and `DgenPIPE` in the workflows above. These pipeline-internal versions need to contain the following important modifications:

`qufromgainPIPE`:

`qufromgain` prints the estimated Stokes $\mathcal{Q}$ and $\mathcal{U}$ per spectral window to the screen, but the variable returned to the user only contains the average Stokes $\mathcal{Q}$ and $\mathcal{U}$ over all windows. `qufromgainPIPE` should be modified to retun a dictionary containing Stokes $\mathcal{Q}$ and $\mathcal{U}$ per spectral window. It should also be modified to accept field specification, to support a caltable containing multiple calibrators.

(Note that the rms of Stokes $\mathcal{Q}$ and $\mathcal{U}$ values over all spectral windows could potentially be used in the future to inspect for high rotation measures.)

`xyambPIPE`:

`xyamb` performs a phase ambiguity check per spectral window, but can only accept a single source polarization vector that is assumed to be the same for all spectral windows. `xyambPIPE` should be modified to accept the Stokes $\mathcal{Q}$ and $\mathcal{U}$ dictionary produced by `qufromgainPIPE`, and to use this dictionary to perform the phase ambiguity check per spectral window. It should also be modified to accept field specification, to support a caltable containing multiple calibrators.

(Note that this is still not an ideal setup; calibrators with high rotation measures or sloped fractional polarization spectra may still cause problems. Ultimately, a channelized source polarization solver `XYf+QUf` with inbuilt phase ambiguity solver is required; this is included as an item for future development in Section 8.)

---

[29] To import, type:
`execfile(os.getenv("CASAPATH").split(' ')[0]+'/lib/python2.7/recipes/almapolhelpers.py')`

`dgenPIPE`:

> `dgen` will modify a leakage calibration table to ensure that solutions are applied to the parallel hand visibilities in addition to the cross hands (linear basis only). `dgenPIPE` should be modified to accept field specification, to support a caltable containing multiple calibrators.

These tasks should ultimately be migrated from `almapolhelpers.py` to CASA proper. Once this has taken place, the pipeline should access their functionality directly from CASA.

This document does not recommend any special handling of polarization calibrators if spectral window mapping was used for them earlier in the pipeline to obtain gain solutions. In such cases, the heuristics described above will likely attempt data averaging and possibly interpolation; polarization processing will be terminated if calibration solutions cannot be recovered.

Successful polarization calibration is defined here as the scenario where the combination of all caltables contains sufficient solutions to ensure that at least 1 channel in 1 spectral window will remain unflagged following `applycal` with `applymode=calflagstrict`; this condition of success can be tested without needing to run `applycal` on the data. If this condition is met, ensure that the context is set so that `applycal` will include the following caltables for all targets except the leakage calibrator: standard total intensity caltables that would normally be included in a first call to `gaincal` (i.e. WVR, T_{sys}, antenna position corrections, bandpass), gain phase (from total intensity pipeline), `‘T’` gain amplitude (from total intensity pipeline), `#.Gxyamp`, crosshand delay, crosshand phase, and generalized leakage solutions (`#.Dgen`). When performing `applycal` on the leakage calibrator, do not include the `‘T’` gain amplitude or `#.Gxyamp` caltables, but instead include the `#.G` caltable.

If polarization calibration is ultimately unsuccessful, then the attempted polarization calibration tables should be bundled and saved for the user, including all modified gain caltables. This should include explicit warnings in the weblog and in a readme file located within the directory containing the bundled caltables, stating that polarization calibration failed and that the caltables are provided for manual diagnostic followup. The flagging state from Step 1 of Section 6.2 should be reinstated. The context should be reset accordingly. In the ALMA pipeline, this will result in the original total-intensity-only caltables being passed to the `applycal` stage of the pipeline.

6.2.2 Circular feed basis: `hif_circfeedpolcal`

The workflow for circular basis calibration strategies can be streamlined more easily than in the linear basis. The telescope-independent circular basis workflow should proceed as follows.

1. `gaincal gaintype=‘KCROSS’ combine=‘scan,obs’` for strategies C1-C4 only:
    - Include in `gaintable` the standard total intensity caltables that would normally be included in `applycal` to form `corrected_data` for the polarization calibrator (i.e. antpos, requantizer, TEC, delay, bandpass, phase & amplitude gains). This set of caltables will be incremented upon in the steps below, as indicated.
    - If no solutions can be found, disable polarization processing and inform the user.

2. `polcal` with appropriate `poltype` for all strategies C1-C5:
    - Include in `gaintable` the standard total intensity caltables that would normally be included in `applycal` to form `corrected_data`, with addition of the crosshand delay calibration table from Step 1 above (except C5).
    - Perform the same diagnostics and optimization as described for Step 2 of the L1 calibration strategy in Section 6.2.1, including possible flagging
3. `polcal poltype='Xf'` for strategies C1-C4 only:
    - Include in `gaintable` the standard total intensity caltables that would normally be included in `applycal` to form `corrected_data`, with addition of the crosshand delay and leakage calibration tables.
    - Perform the same diagnostics and optimization as described for Step 7 of the L1 calibration strategy in Section 6.2.1, including possible flagging
    - If no solutions can be found, warn user that only partial polarization calibration was possible (leakages only); absolute position angle calibration could not be performed.

As with linear basis calibration, this document does not recommend any special handling of polarization calibrators in the circular basis if spectral window mapping was used earlier in the pipeline.

As with linear basis calibration, successful polarization calibration is defined here as the scenario where the combination of all caltables contains sufficient solutions to ensure that at least 1 channel in 1 spectral window will remain unflagged following `applycal` with `applymode=calflagstrict`; this condition of success can be tested without needing to run `applycal` on the data. If this condition is met, ensure that the context is appropriately set so that `applycal` will only include the following caltables when operating on any data (calibrators or science targets): standard total intensity caltables that would normally be included in `applycal` to form `corrected_data` (antpos, requantizer, TEC, delay, bandpass, phase & amplitude gains), crosshand delay (C1-C4 only), leakage, and crosshand phase (C1-C4 only).

If polarization calibration is ultimately unsuccessful, then the attempted polarization calibration tables should be bundled and saved for the user, including all modified gain caltables. This should include explicit warnings in the weblog and in a readme file located within the directory containing the bundled caltables, stating that polarization calibration failed and that the caltables are provided for manual diagnostic followup. The flagging state from Step 1 of Section 6.2 should be reinstated. The context should be reset accordingly. Disable the polarization processing switch.

6.3 `hifv_applycals`

In the VLA pipeline, total intensity calibration is applied to the data in `hifv_applycals`. Polarization calibration is performed later in the pipeline workflow (see Section 6.2). The VLA pipeline should therefore be modified to attempt a second execution of `hifv_applycals` immediately after `hif_circfeedpolcal`. `hifv_applycals` should be modified as follows:

- If polarization processing was attempted but ultimately failed (e.g. the polarization processing switch is disabled but a readme file exists within a directory for attempted polarization caltables), restore the flagging state to that saved in `hifv_targetflag`[30]
- If the polarization processing switch is disabled, and if this is the second execution of `hifv_applycals`, exit `hifv_applycals`
- Perform `applycal` on the cross-hand visibility data only (using `msselect`, and with pipeline default `applymode=calflagstrict`) for all calibrators and science targets. The reason for only focusing on the cross-hand visibilities here is to prevent unnecessary flagging of parallel-hand visibilities due to any incomplete polarization calibration tables.

Note that a similar upgrade is not required in the ALMA pipeline because `hif_linfeedpolcal` precedes `hif_applycal`.

6.4 Imaging

Both the ALMA and VLA pipelines use the task `hif_makeimlist` to construct a list of bandpass and phase calibrators to be imaged, followed by `hif_makeimages` to perform the imaging. This imaging is performed per spectral window with cleaning. An observer or data analyst can then use these images along with associated statistics and QA2 scoring to rapidly assess the quality of the calibration. The ALMA pipeline performs additional continuum and cube imaging for science targets. Pipeline imaging capabilities are under continued development (e.g. SCIREQ-707).

To enable rapid evaluation of polarization calibrators, the pipeline should be updated to additionally include imaging per spectral window of all polarization calibrators in Stokes $\mathcal{I}$, $\mathcal{Q}$, and $\mathcal{U}$, linearly polarized intensity $\mathcal{L} = \sqrt{\mathcal{Q}^2 + \mathcal{U}^2}$, and fractional linear polarization $\mathcal{L}/\mathcal{I}$. The Stokes imaging should use the existing total intensity infrastructure where possible (e.g. automated cleaning thresholds), noting that Stokes $\mathcal{Q}$ and $\mathcal{U}$ can be positive or negative. The $\mathcal{L}$ image should be constructed from the cleaned Stokes $\mathcal{Q}$ and $\mathcal{U}$ images in each spectral window, with residual rms calculated for display in the weblog using $\sigma_{Q,U} = \sqrt{A_Q\,\sigma_Q^2 + A_U\,\sigma_U^2}$ where $A_Q = 0.2$ if $\sigma_Q < \sigma_U$, $A_Q = 0.8$ otherwise, and where $A_U = 1 - A_Q$ (Hales et al. 2012). The statistics in $\mathcal{L}$ are Ricean (where uncertainties are S/N-dependent). For each spectral window, using only the central pixel[31] in each image, if the ratio between the surface brightness at the central pixel in the $\mathcal{L}$ image and $\sigma_{Q,U}$ is greater than 4.4 (equivalent to a Gaussian S/N of 4.0; Hales et al. 2012), calculate the position angle of linear polarization as $0.5\tan^{-1}(\mathcal{U}/\mathcal{Q})$. If this criteria is met, the position angle should be reported in the weblog and overlaid on the $\mathcal{L}$ image using a single bold vector. If not, the user should be informed that the S/N was too low to reliably recover the position angle from the calibrator images, and the position angle should not be reported or shown. The rms noise for the fractional linear polarization image should be reported as $\sqrt{\sigma_{Q,U}^2 + \sigma_I^2}$ with an indication given that this is a crude estimate. Finally,

---

[30] This is a slightly earlier flagging state than can be returned to directly by `hif_circfeedpolcal`, as currently designed. The loss in pipeline efficiency compared to `hif_circfeedpolcal` returning directly to the `hifv_targetflag` flagging state should be negligible. The important benefit in the proposed design is that `hif_circfeedpolcal` will remain a telescope-independent pipeline stage.

[31] On-axis calibrator. Ignore any possible spatial structure in the calibrator.

plots should be generated showing the spectra of fractional linear polarization and position angle for each polarization calibrator, calculated at the central image pixel and frequencies associated with the spectral window images from above.

For calibrators with significant rotation measures, bandwidth depolarization may occur across a spectral window. While this may be diagnosed under some circumstances, for the present document, management of this potential issue is considered beyond the scope of the pipeline. Beam squint and squash are CASA issues and are considered beyond the scope of this document.

Science target polarization imaging (including cube polarimetry) is beyond the scope of the phase 1 upgrade described in this document. For ALMA, it will likely remain a low priority until Cycle 6 or later (SCIREQ-707). For the VLA, it may be introduced earlier as part of a continuum imaging upgrade currently being planned.

6.5 QA2 scoring

The weblog displays QA2 scores that are calculated by each of the pipeline tasks. Scores can range between 0.0–1.0 and are colored using green for 0.9–1.0 (good), blue for 0.66–0.9 (below standard), yellow for 0.33–0.66 (warning), and red for 0.0–0.33 (error). QA2 scoring for the ALMA pipeline is advanced, while for the VLA pipeline it is still largely under development. The following scoring is suggested for the polarimetry components of the pipeline:

- *Importdata:* Retain total intensity score if polarization processing is enabled. If polarization scan intents were identified but polarization processing needed to be disabled (for any correlator setup in the data), downgrade the score to the mid-point of the next lowest bracket. If already in the lowest bracket, divide the score by 2.
- *Priorcals for VLA:* If external TEC data is requested but unavailable or corrupted, and if the existing score is greater than 0.76, subtract 0.1 from the existing score. Otherwise, drop the score to 0.67 to prevent the score being lowered to yellow purely due to the TEC data (lacking TEC data may not be serious for some low frequency experiments, and in any case the overall results shouldn't be seriously corrupted anywhere within the VLA frequency range considered in this document).
- *Targetflag for VLA:* No modification required. The existing scoring should automatically account for the included cross hand visibilities.
- *Setjy:* This step simply accesses source models, the existence of which for polarization models was previously tested in the importdata stage. If any of the source models cannot be imported (total intensity or polarization), the score should default to 0.1.
- *Polarization calibration (linear and circular bases):* Report the fraction of spectral windows in which valid solutions were obtained versus the number that were expected to have a solution, accounting for all polarization calibration tables appropriate to the nominated calibration strategy (i.e. do not account for missing crosshand delay or phase solutions when examining a spectral setup associated with the C5 strategy). If pre-averaging was included in any of the leakage or crosshand phase calibration solutions,

count these spectral windows as 80% of their nominal fractional contribution to the total. If channelized solutions could not be obtained, count the affected spectral windows as 60% of their original fractional contribution to the total. In the future, customized algorithms may be developed to assess details such as the smoothness of the various calibration solutions within and across multiple spectral windows, or perhaps the quality of the data with all solutions applied (e.g. from calibrator imaging).

- *Applycal:* No modification required in ALMA pipeline. For VLA pipeline, if the second execution of `hifv_applycals` is performed, calculate the incremental flagging as the sum of both executions. The existing QA2 scoring algorithm can then proceed based on the degree of total incremental flagging.
- *Makeimlist:* No modification required. The existing scoring should automatically account for the additional images requested.
- *Makeimages:* The existing scoring should automatically operate on the additional images described in Section 6.4. If the recovered fractional polarization or position angle spectrum for a polarization calibrator can be compared to a database model, and if the difference with the model is greater than 10% at any point in the spectrum, subtract 0.1 from the overall score (perform this check per correlator setup).

6.6 Weblog

The pipeline weblog presents a summary of the data, calibration, and imaging for a measurement set or group of measurement sets (e.g. sessions). The weblog needs to be upgraded to accommodate results from polarization processing within several pipeline tasks. Items to be considered are:

- Include all warning messages described above throughout Sections 5 and 6. For example, if polarization processing is ever disabled, explain why.
- *Importdata:* Report if polarization calibration was initialized or not.
- *Priorcals for VLA:* Include vertical TEC vs time plot (`plotcal yaxis=‘tec’`), if utilized.
- *Targetflag for VLA:* No change. Do not include cross hand visibility data here because polarization calibration has not yet been applied (nor calculated).
- *Polarization calibration:* The weblog should always include a page for `hif_linfeedpolcal` or `hif_circfeedpolcal`, even if polarization calibration was never initialized (e.g. no polarization scan intents are specified in the dataset). If polarization processing is never attempted, then the weblog should simply report "N/A". Report the selected calibration strategy.
- *Linfeedpolcal:* Include polarization model information, if utilized, similar to how this is displayed for total intensity in `hif_setjy`. Where appropriate for the selected strategy, display plots for crosshand delay, crosshand phase (before and after phase ambiguity check), position angle (if installed in pipeline), leakage real and imaginary components, and global X/Y gain amplitude ratios. Note that crosshand delays should be the same

for all antennas within a spectral window, and similar for spectral windows associated with a given baseband. Crosshand phases and leakage real & imaginary components should all be smooth functions of frequency (though no explicit tests for this smoothness are recommended in this document). A useful diagnostic plot for leakages is to display amplitudes as a function of antenna index, for each spectral window. Indicate the nature of the recovered leakage solutions (see Section 5.3). For the L4 & L5 strategies, report the recovered Stokes vector for the leakage calibrator, and plot gain amplitude polarization ratios as a function of time before and after taking into account the leakage calibrator's estimated Stokes vector[32].

- *Circfeedpolcal:* Include polarization model information, if utilized, similar to how this is displayed for total intensity in `hifv_vlasetjy`. Where appropriate, display plots for crosshand delay, crosshand phase (a.k.a. position angle), and leakage real and imaginary components. Indicate that the plotted leakage solutions are relative leakages in the crosshand phase frame ($\widetilde{\mathbf{D}}_\mathbf{r}$). For strategies C3 & C4, report the recovered Stokes vector for the leakage calibrator.
- *Applycal:* Include cross hand visibility data in the plots as they now include polarization calibration.
- *Makeimlist:* Include column specifying Stokes parameter.
- *Makeimages:* No change to core infrastructure. Include the polarization plots described earlier.

6.7 Output data products

The additional calibration solutions and plots produced by the polarization-enabled pipeline, possibly including failed solutions from an aborted polarization run, need to be delivered to the user as part of the output data package. These outputs will be of similar form to existing pipeline outputs. For example, refer to the documentation for QA2 data products from the Cycle 3 pipeline[33]. Note also CAS-7788.

7 Plan of Work

The priority list for implementing the phase 1 polarimetry upgrade is as follows:

1. VLA strategies C1 and C4, without including any diagnostics or optimization steps. The aim is to have a minimal working version to support preliminary VLASS testing.
2. ALMA strategies L2 and L4, similarly without including any diagnostics or optimization steps.
3. Full implementation of VLA strategies C1 and C4

---

[32] Plot the raw gain ratios, not the rms of ratios around unity, as the latter may be biased by flagged data.

[33] https://almascience.nrao.edu/documents-and-tools/cycle3/ALMAQA2Products3.0.pdf

4. Full implementation of ALMA strategies L2 and L4
5. Full phase 1 upgrade including all ALMA and VLA calibration strategies

The timeline for implementing the phase 1 polarimetry upgrade is then as follows:

1. Commence building code scaffolding based on early version of this document (October 3, 2016)
2. Review of this document by scientific and software engineering staff (deliver: December 14, 2016)
3. Incorporate feedback from above, upgrade this document, and release Version 2.0 (deliver: December 16, 2016)
4. Implement code for ALMA L2 & L4 and VLA C1 & C4 stratgies and complete minimal verification of performance. Do not include any diagnostic or optimization steps. Release code within internal 5.1P1 version. Commence validation and review process. (deliver: March 1, 2017)
5. Incorporate feedback from above. Implement full phase 1 upgrade for ALMA L2 & L4 and VLA C1 & C4 strategies and complete minimal verification. Release code within internal 5.1P2 version. Commence validation and review process. (deliver: June 1, 2017)
6. Complete acceptance testing, incorporate any final changes, public release CASA 5.1 (deliver: 1 September 2017)

There are a limited number of essential items that must be addressed as soon as possible to support development toward 5.1P1. These include policy decisions and CASA improvements, as follows:

- Outline plan for adding new scan intent `CALIBRATE_CROSSHAND_PHASE` to the SDM master listing. Detail the process by which this intent can be incorporated into observation preparation and execution at ALMA. Detail the process by which this intent can be incorporated within the VLA OPT. If this intent will not be added for Cycle 5, then it will still be possible to differentiate between the strategies in Figure 7 (particularly the priority L4 and L2 strategies), but this is not ideal.
- Decide if functionality from `almapolhelpers.py` should be implemented temporarily within the pipeline as described toward the end of Section 6.2.1, or if there is time prior to 5.1P1 to incorporate this functionality within standard CASA tasks or tools. See CAS-9106 and CAS-9469.
- Decide if the ability to account for TEC corrections is needed within source polarization solves in `polcal`, to support the VLASS priority C4 calibration strategy. If so, this functionality upgrade needs to be a priority for the CASA 5.0 release. See CAS-9472.

- Improve the flexibility of `setjy` to define polarization models. E.g. add parameter to clearly enable the position angle at zero wavelength to be set in combination with a rotation measure; consider options to store known polarization models similar to existing total intensity models (Section 6.2). See CAS-9388 and CAS-9412.
- Create a new mode in `flagdata` to flag all integrations in which a specified antenna is flagged, similar to the custom CASA task `antintflag` described in Section 6.1. See CAS-9473.

Items to address prior to the pipeline public release in CASA 5.1 are:

- Upgrade `polcal` to deliver channelized attempted/solved statistics. See CAS-9470.
- Decide if and when to deprecate use of `CALIBRATE_POLARIZATION` as a scan intent (currently used for ALMA L4 strategy observations)
- Prepare a workflow for data analyst QA2, including careful review of weblog, QA2 scoring, and output data
- The following is a non-exhaustive list of suggested improvements to CASA. They are not essential to support the phase 1 upgrade, though they may be of interest now for planning purposes. Note that the implementation of some of these items may require modification to the workflows presented in this document.
  - Consider upgrading `setjy` to access known polarization calibrator models
  - Multi-band (per-baseband) `KCROSS`, similar to how this can be done for `K`
  - Remove requirement to specify a reference antenna for `KCROSS`
  - Improve `tec_maps` to better handle corrupted TEC data upon import
  - Upgrade CASA's internal model of the Earth's magnetic field from IGRF-10 to the latest version IGRF-12 (CAS-8564)
  - Improve `plotcal` to highlight observing time frame within available TEC measurements
  - Design a method to plot line-of-sight atmospheric rotation measures, similar to how this can be plotted for TEC values
  - If not made available for 5.1P1, enable functionality to support TEC corrections within source polarization solves in `polcal`
  - Position angle calibration support in the linear basis
  - General crosshand phase versus position angle semantic improvements
  - Enable full channelized calibration in combination solves, e.g. `Df+QU` → `Df+QUf`
  - Decouple combination solves, e.g. perform `XYf+QU` in two distinct steps
  - Streamline linear and circular basis solvers, e.g. move `XYf+QU` for linear basis into `polcal` instead of current placement within `gaincal`, similar functionality move from `Dflls` into `polcal`
  - Improve `polcal` leakage behavior if reference antenna unavailable (don't allow near-unity leakage amplitudes to be returned)

  - Improve `dxy` to de-rotate using $\mathbf{X_r}$ rather than $\widetilde{\mathbf{X}}_\mathbf{r}$, include circular basis support, consider implications of using relative leakage terms in this de-rotation
  - Include second order terms in solver to enable C6 strategy

8 Future Upgrades

Issues to consider on a longer timescale beyond phase 1 include:

- Decide if a new scan intent is needed to specify an assumed unpolarized calibrator. This would remove degeneracy with existing calibration selection schemes.
- Decide if a new scan intent is needed to specify a circular polarization calibrator, of particular relevance for the linear feed basis. Note that `CALIBRATE_POL_ANGLE` may be effectively used as a proxy, but the nomenclature isn't particularly clear.
- Discuss the need for better polarization models for standard sources, for example VLA characterization in configurations larger than D
- Decide how the polarization calibrator database should be set up in the long-term. Internal to CASA like existing total intensity models? Temporarily hardcoded into the pipeline? External database similar to antenna position corrections?
- Determine plans for establishing a calibration database, including stability requirements and types of leakage solutions to be accepted
- Determine if a polarization equivalent to CAS-7420 is needed, if calibrator polarization characteristics change significantly over a short period of time
- Prioritize functionality to process increased observational parameter space, e.g. spectral line polarimetry, ALMA ACA, total power, circular polarimetry, revisit assumptions of phase 1 upgrade such as mixed basis polarimetry
- Plan for science target polarization imaging, continuum, cube, rotation measure synthesis
- Investigate need for improved diagnostics and heuristics, e.g. search for large scatter in leakage solutions
- Improved QA2 scoring

Acknowledgements: I thank the following for insightful discussions: George Moellenbrock, Bob Sault, Brian Kent, Lindsey Davis, Vincent Geers, Kumar Golap, Jeff Kern, Joe Masters, and Claire Chandler. I thank the ALMA Integrated Science Team for reviewing this document, specifically Robert Laing, Darrel Emerson, and Al Wootten. I thank the anonymous referee for their thoughtful review of Hales (2017), which in turn led to the improvement of this memo.

References

Brentjens, M. A., & de Bruyn, A. G. 2005, A&A, 441, 1217

Conway, R. G., & Kronberg, P. P. 1969, MNRAS, 142, 11

Cortes, P. C., Kameno, S., Nakanishi, K., et al. 2015, The ALMA EOC Polarization Commissioning Report (version 23 Nov)

Hales, C. A. 2017, AJ in press, arXiv:1706.06612

Hales, C. A. 2016, antintflag, v1.0, doi:10.5281/zenodo.163546, as developed on GitHub at https://github.com/chrishales/antintflag

Hales, C. A., Gaensler, B. M., Norris, R. P., & Middelberg, E. 2012, MNRAS, 424, 2160

Hamaker, J. P., Bregman, J. D., & Sault, R. J. 1996, A&AS, 117, 137

Noordam, J. E. 1996, The Measurement Equation of a Generic Radio Telescope, AIPS++ Implementation Note, 185 (https://casa.nrao.edu/aips2_docs/notes/185/185.html)

Perley, R. A., & Butler, B. J. 2013, ApJS, 206, 16

Price, D. C., & Smirnov, O. M. 2015, MNRAS, 449, 107

Rayner, D. P., Norris, R. P., & Sault, R. J. 2000, MNRAS, 319, 484

Sault, R. J., Hamaker, J. P., & Bregman, J. D. 1996, A&AS, 117, 149

Sault, R. J., & Perley, R. A. 2013, Determining full EVLA polarization leakage terms at C and X bands, EVLA Memo Series, 170

Smirnov, O. M. 2011, A&A, 527, A106

Appendix: Spurious on-axis leakage

Section 4.2 presented equations to predict the level of spurious on-axis polarization that will be observed for an intrinsically unpolarized target source following the application of imperfect d-term calibration solutions. Using these relationships, Section 4.2.1 presented equations to predict the d-term measurement errors, and in turn the level of spurious polarization, that will result following leakage calibration when using a polarized calibrator that is assumed to be unpolarized. Similarly, Section 4.2.2 presented results from simulations in which d-term measurement errors, and ultimately spurious polarization signatures, were predicted empirically for calibration schemes involving observation of a polarized calibrator over a range of parallactic angles (slices). Derivations for all equations, and details of the simulations, are presented below for the circular and linear feed bases.

Circular basis

Stokes $\mathcal{Q}$ is formed by

$$\mathcal{Q} = 0.5\,\mathrm{Re}\left[\left\langle e^{+i2\psi}\, V_{RL}\right\rangle + \left\langle e^{-i2\psi}\, V_{LR}\right\rangle\right] . \tag{23}$$

If d-terms are recovered with measurement errors Δd (statistical or systematic in origin), an unpolarized target will be observed with spurious fractional polarization

$$\frac{\mathcal{Q}_{\mathrm{spurious}}}{\mathcal{I}} = 0.5\,\mathrm{Re}\left[\left\langle e^{+i2\psi}\, \left(\Delta d_{Ri} + \Delta d^{*}_{Lj}\right)\right\rangle + \left\langle e^{-i2\psi}\, \left(\Delta d_{Li} + \Delta d^{*}_{Rj}\right)\right\rangle\right] . \tag{24}$$

The worst-case spurious polarization will therefore occur for a target observed with limited parallactic angle coverage. If the science target is integrated over a wide range in parallactic angle, then the level of spurious polarization predicted below should be treated as an upper limit. Taking the worst-case scenario of approximately constant parallactic angle, and noting that there are only N_a independent d-terms per polarization, the relationship above can be rewritten in a statistical sense as

$$\frac{\mathcal{Q}_{\mathrm{spurious}}}{\mathcal{I}} \approx \mathrm{Re}\bigg[\,\frac{1}{N_a}\sum^{N_a} \Delta d_{Ri} + \Delta d_{Li}\,\bigg] . \tag{25}$$

For characteristic d-term modulus error σ_d, the variance in $\mathrm{Re}\left[\Delta d\right]$ is given by $\sigma_d^2/2$. The variance in Equation 25 is then estimated as

$$\mathrm{var}\left(\frac{\mathcal{Q}_{\mathrm{spurious}}}{\mathcal{I}}\right) \approx \frac{\sigma_d^2}{N_a} \ . \tag{26}$$

Similar analysis for fractional $\mathcal{U}_{\mathrm{spurious}}$ yields the same result. The predicted level of spurious on-axis fractional linear polarization is then Rayleigh distributed with mean

$$\frac{\mathcal{L}_{\mathrm{spurious}}}{\mathcal{I}} \approx \sqrt{\frac{\pi}{2N_a}}\,\sigma_d \ . \tag{27}$$

No spurious circular polarization is predicted ($\mathcal{V}_{\mathrm{spurious}} = 0$) because its evaluation does not include any leakage products with total intensity (to first order). The results above are presented in Section 4.2.

If a polarized calibrator is assumed to be unpolarized for leakage calibration, any true (linear) polarization will lead to corruption of the measured leakages. The difference between observed and true cross hand visibilities for a single baseline is given by

$$\Delta V_{RL} = \mathcal{I}\left(\Delta d_{Ri} + \Delta d^*_{Lj}\right) - (\mathcal{Q}_{\mathrm{true}} + i\,\mathcal{U}_{\mathrm{true}})e^{-i2\psi} \ . \tag{28}$$

Note that non-zero $\mathcal{V}_{\mathrm{true}}$ will not affect relative leakages that are calculated using only cross hand data (to first order). The equation above is effectively constrained by $N_a - 1$ baselines toward antenna i, in which case

$$\Delta d_{Ri} + \frac{1}{N_a - 1}\sum^{N_a-1} \Delta d^*_{Lj} = \frac{\mathcal{Q}_{\mathrm{true}} + i\,\mathcal{U}_{\mathrm{true}}}{\mathcal{I}} e^{-i2\psi} + \frac{1}{N_a - 1}\sum^{N_a-1} \frac{\Delta V_{RL}}{\mathcal{I}} \ . \tag{29}$$

The ΔV_{RL} term is noise-like. As a result, its average in the right side of the equation can be represented by a vector with characteristic magnitude $\sqrt{N_a}/A$, where A is the full-array dual-polarization total intensity signal to noise of the calibrator within the single spectral channel of interest. The first term in the left side of the equation has characteristic magnitude σ_d. The importance of the next term, containing the average over d-terms, depends on whether the d-terms are correlated between antennas or not. When random errors dominate over systematics from the true source polarization (e.g. for small A), the recovered d-term errors will be effectively uncorrelated. In this case, the term can be viewed as a vector-averaged sample of (σ_d-scale) error vectors, in which case its contribution will be negligible[34] and can be ignored. When source polarization systematics dominate (e.g. for large A), the d-terms will be correlated and the average cannot be ignored. This can be crudely accommodated by replacing Δd^*_{Lj} with Δd_{Ri}, in which case the left side of Equation 29 can be approximated by $2\Delta d_{Ri}$. Thus, the estimated σ_d will be half of the value recovered when assuming uncorrelated d-terms. Given the simplistic nature of this calculation, the larger estimate for σ_d will be adopted; its estimated value presented below should therefore be treated as an upper limit.

By noting that contributions to σ_d on the right side of Equation 29 represent projections onto a 1D vector given by the true d-term (requiring adjustment to variances by factor 1/2),

---

[34] To demonstrate, consider the variance for a sample of unit vectors with random orientations projected along a 1D axis. This is given by $0.5/(N_a - 1)$. The standard error for the left side of the equation can therefore be approximated by $\sigma_d\sqrt{1 + 0.5/(N_a - 1)}$. This indicates a negligible difference of $< 12\%$ for $N_a > 2$.

and by treating the true polarization as a DC offset with magnitude $\mathcal{L}_{\mathrm{true}}$, the d-term modulus error can be estimated in rms-fashion as

$$\sigma_d \approx \sqrt{\frac{1}{2}\left(\left[\frac{\mathcal{L}_{\mathrm{true}}}{\mathcal{I}}\right]^2 + \frac{N_a}{A^2}\right)}\,. \tag{30}$$

The resulting estimate for spurious fractional linear polarization is then obtained using Equation 27, giving

$$\frac{\mathcal{L}_{\mathrm{spurious}}}{\mathcal{I}} \approx \sqrt{\frac{\pi}{4N_a}\left(\left[\frac{\mathcal{L}_{\mathrm{true}}}{\mathcal{I}}\right]^2 + \frac{N_a}{A^2}\right)}\,. \tag{31}$$

These results are reported in Section 4.2.1. Note that if the leakage calibrator is observed over a wide range in parallactic angle (atypical for an assumed unpolarized calibrator), then the predicted spurious polarization should be treated as an upper limit (in addition to the motivation described earlier).

Figure 5 in Section 4.2.2 presents estimates of spurious polarization for calibration strategies involving parallactic angle coverage of a polarized leakage calibrator. To obtain these results, a Monte Carlo simulation code was developed to estimate σ_d and perform conversion using Equation 27. The code focuses on the theoretical aspects discussed in this document by approximating the behaviour of the generalized solvers that exist within software such as CASA, as described below. Full CASA-based simulations using mock or real data were not considered for this document due to the potential for introducing a host of unwanted systematics, which could readily bias interpretation of the fundamental attributes under investigation. The simulation code is available at https://github.com/chrishales/polcalsims .

To estimate σ_d for the calibration schemes examined, the code performs Monte Carlo sampling and examines the distribution of errors recovered when attempting to solve for the d-term for a single polarization on a single antenna. To do this, the code focuses on a single cross product (e.g. V_{RL}) and examines how well the d-term under consideration can be recovered while taking into account all available $N_a - 1$ baselines toward antenna i. The relevant equation is given by Equation 29, with the sum over Δd^*_{Lj} assumed to be negligible. The true source polarization is injected with the appropriate thermal noise at slices that are, for simplicity, spaced equally over the total parallactic angle span under consideration.

When a calibrator is viewed at different parallactic angles, a circle is drawn in the complex plane for a cross hand visibility, with center offset by the leakages (e.g. Conway & Kronberg 1969). For calibration strategies involving a polarized calibrator with unknown Stokes vector, at least 3 statistically independent slices are required to solve for the d-term (error) as well as Stokes $\mathcal{Q}$ and $\mathcal{U}$. Geometrically, this can be viewed as the need for 3 points to solve for the unknown origin and radius of a circle. When the Stokes vector is known a priori, only two slices are required to locate the origin (the origin degeneracy is broken by the known sense of rotation between the slices). For simplicity, the simulation code does not take into account the sense of rotation between points. As a result, the portion of parameter space containing observations at modest signal to noise ratios over small total parallactic angle ranges displays much noisier solutions than those likely to be recovered in production code. This effect is not significant; results throughout the remaining parameter space are not affected.

The code recovers the distribution of d-term errors for each sampled point in the signal to noise and parallactic angle coverage parameter space. Rather than reporting the mean of this distribution to represent σ_d, the code reports the 95^{th} percentile in order to better accommodate the slightly non-Gaussian nature of the results in a conservative manner. This is consistent with the comments earlier to interpret results as upper limits.

Linear basis

Assuming perfect crosshand phase measurement, $\mathcal{U}_\psi$ is formed by

$$\mathcal{U}_\psi = 0.5\,\mathrm{Re}\left[\langle V_{XY}\rangle + \langle V_{YX}\rangle\right] . \tag{32}$$

The presence of d-term measurement errors will cause an unpolarized target to exhibit spurious fractional linear polarization, described statistically as

$$\frac{\mathcal{U}_{\psi,\mathrm{spurious}}}{\mathcal{I}} \approx \mathrm{Re}\left[\frac{1}{N_a}\sum^{N_a} \Delta d_{Xi} + \Delta d_{Yi}\right] . \tag{33}$$

The worst-case spurious polarization will occur for a target observed with limited parallactic angle coverage. Assuming the worst-case scenario of approximately constant parallactic angle, the variance in Equation 33 is then estimated as

$$\mathrm{var}\left(\frac{\mathcal{U}_{\psi,\mathrm{spurious}}}{\mathcal{I}}\right) \approx \frac{\sigma_d^2}{N_a} . \tag{34}$$

Similar analysis for fractional $\mathcal{V}_{\mathrm{spurious}}$ yields the same result. No spurious $\mathcal{Q}_\psi$ will be produced. As a result, the predicted level of spurious on-axis fractional linear or circular polarization is given by

$$\frac{\mathcal{L}_{\mathrm{spurious}}}{\mathcal{I}} \approx \frac{\mathcal{V}_{\mathrm{spurious}}}{\mathcal{I}} \approx \frac{\sigma_d}{\sqrt{N_a}} . \tag{35}$$

The predicted level of spurious fractional elliptical polarization is then given by

$$\frac{\mathcal{P}_{\mathrm{spurious}}}{\mathcal{I}} \approx \sqrt{\frac{\pi}{2N_a}}\,\sigma_d . \tag{36}$$

These results are presented in Section 4.2.

The results presented in Section 4.2.1 regarding calibration with a polarized yet assumed-unpolarized calibrator can be derived in the same way as presented earlier for the circular feed basis, but replacing $\mathcal{L}^2_{\mathrm{true}}$ with $\mathcal{U}^2_{\psi,\mathrm{true}} + \mathcal{V}^2_{\mathrm{true}}$ in Equation 30. For the linear basis derivation here, it will be assumed that the product of $\mathcal{Q}_{\psi,\mathrm{true}}$ with leakages in the cross hand visibilities is always negligible. This will not always be true in practice, but in such cases the contribution from thermal noise (A) is likely to dominate. The resulting estimates of spurious fractional linear or circular polarization are then obtained using Equation 35, giving

$$\frac{\mathcal{L}_{\mathrm{spurious}}}{\mathcal{I}} \approx \frac{\mathcal{V}_{\mathrm{spurious}}}{\mathcal{I}} \approx \sqrt{\frac{1}{2}\left(\left[\frac{\mathcal{U}_{\psi,\mathrm{true}}}{\mathcal{I}}\right]^2 + \left[\frac{\mathcal{V}_{\mathrm{true}}}{\mathcal{I}}\right]^2 + \frac{N_a}{A^2}\right)} . \tag{37}$$

The estimate of spurious fractional elliptical polarization is obtained using Equation 36, giving

$$\frac{\mathcal{P}_{\mathrm{spurious}}}{\mathcal{I}} \approx \sqrt{\frac{\pi}{4N_a}\left(\left[\frac{\mathcal{U}_{\psi,\mathrm{true}}}{\mathcal{I}}\right]^2 + \left[\frac{\mathcal{V}_{\mathrm{true}}}{\mathcal{I}}\right]^2 + \frac{N_a}{A^2}\right)} . \tag{38}$$

Figure 3 in Section 4.2.2 presents estimates of spurious polarization for calibration strategies involving parallactic angle coverage of a polarized leakage calibrator. To obtain these results, simulation code was developed with similar characteristics to those described earlier for the circular feed basis. Differences are described below. The simulation code is available at https://github.com/chrishales/polcalsims .

The code focuses on a single cross product (e.g. V_{XY}) and examines how well the d-term for the antenna and polarization under consideration can be recovered while taking into account all available $N_a - 1$ baselines toward antenna i. Unlike in the circular basis, measurement of the crosshand phase is required here prior to solving for leakages. The linear basis simulation code therefore takes into account crosshand phase measurement errors due to thermal noise when calculating the d-term measurement errors. The code does not account for errors in crosshand phase measurement due to prior-unknown leakages (such errors are typically negligible in the baseline-averaged crosshand phase solve). The code assumes that Stokes $\mathcal{V}$ is zero for all calibrators. The relevant equation is then a modified version of Equation 13,

$$\frac{1}{N_a-1}\sum^{N_a-1}\frac{V_{XY}}{\mathcal{I}} = \frac{\mathcal{U}_\psi}{\mathcal{I}}e^{i\rho} + \left(1-\frac{\mathcal{Q}_\psi}{\mathcal{I}}\right)e^{i\rho}\,d_{Xi} + \left(1-\frac{\mathcal{Q}_\psi}{\mathcal{I}}\right)\frac{e^{i\rho}}{N_a-1}\sum^{N_a-1} d^*_{Yj} + \frac{1}{N_a-1}\sum^{N_a-1}\frac{\sigma_{V_{XY}}}{\mathcal{I}} \tag{39}$$

in which thermal noise in V_{XY} is included on the right side denoted by $\sigma_{V_{XY}}$, and the left side of the equation acts as a dummy variable. For all multi-slice observing strategies, the simulation code assigns each of the d-terms that appear in the equation above with a user-defined characteristic amplitude and random phase. The error in recovering the input d_{Xi} is then ultimately recorded.

For simplicity, the code assumes that the first observed slice for each calibration strategy is at zero parallactic angle, and that the calibrator's position angle is 45°. These initial conditions should generate generally representative results for the 1 and 2 slice strategies, where the calibrator's Stokes vector is known a priori and may therefore be targeted appropriately by observers. However, note that the initial conditions above (or any others) cannot fully represent all possible observing configurations for the 3 and 10 slice strategies, where the Stokes vector is unknown a priori. It is of course possible that rare specific configurations of these strategies could produce significantly different results than presented. It is worth noting here that when users in the linear feed basis are advised to maximize parallactic angle coverage, this really means they should maximise coverage for $\mathcal{U}_\psi$. For a calibrator with unknown Stokes vector observed over as few as 3 slices, the difference in rare circumstances could be noticeable.

For the 1 slice strategy, the simulation code measures crosshand phase error by solving for a position angle in the noisy frame indicated by Equation 20 (i.e. `Xf` solve). For the 2 slice strategy, the code performs this step using the slice with maximum $\mathcal{U}_\psi$ (known a priori). For the 3 and 10 slice strategies, the code measures crosshand phase error by solving for a linear slope with unconstrained offset, followed by a least squares fit to measure Stokes $\mathcal{Q}$ and $\mathcal{U}$ along this slope given the noisy observed variations of $\mathcal{U}_\psi$ (i.e. `XYf+QUf` solve).

For the multi-slice strategies, the code then performs a least squares fit to solve for two parameters in Equation 39: the observed d_{Xi} and $\sum d^*_{Yj}$. The latter is not needed for further analysis. The former is compared with the input value to compute the d-term error for the Monte Carlo sample under consideration, followed by conversion to spurious polarization using Equation 35. For the 1 slice strategy, the d-term error can be calculated more easily as the offset from the noisy measurement of the known Stokes vector.