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VLBI Requirements for CASA

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1 INTRODUCTION

Once completed and operational as a connected-element interferometer, the Atacama Large Millimeter/submillimeter Array (ALMA) will unlock the Millimeter and submillimeter sky with unprecedented sensitivity, imaging dynamic range and spectral coverage. By adding an observing mode in which all ALMA antennas are phased together into a single effective aperture, ALMA can further serve as the most important element in Global mm and submm VLBI arrays, which are capable of resolving super massive black holes on Schwarzschild Radius (Rsch) scales. The ALMA Board has formally endorsed development of a phasing system for ALMA, and an international team has secured resources and funding for the project. An advanced design for the ALMA phasing system has already been developed and implementation is underway, with a projected completion date by 2015.

Once complete, a phased ALMA will anchor the highest angular resolution ground-based VLBI array ever assembled[*], making possible extraordinary progress on scientific questions of broad impact. The VLBI data products from such an array will be of exceptionally high signal-to-noise and have great scientific value, but they will require specialized processing and analysis techniques. Currently, VLBI analysis software packages that are in widespread use by the astronomy community cannot optimally reduce (sub)mm VLBI data sets, which are characterized by extremely short atmospheric coherence times.

We describe the necessary improvements to the CASA package to support reduction of (sub) millimeter VLBI data. Addition of these elements to the CASA package will allow ALMA to deliver an important and fundamentally new capability to the global astronomy community, enhancing the flexibility and impact of the ALMA facility. These requirements and effort estimates formed the foundation for our ALMA Development proposal to implement the requirements identified for the phase ALMA case described below.

2 JUSTIFICATION

2.1 Science Case

Previous observational results using VLBI at 1.3mm wavelength have resolved structures near the Event Horizon of the black holes powering SgrA*, the radio source at the center of the Milky Way (Doeleman et al 2008), and M87, the giant elliptical galaxy in Virgo. The most recent 1.3mm VLBI observations show strong evidence for time-variability in SgrA* on these same scales (Fish et al 2011). *These observations, and the successful technical developments leading to them, have made it clear that the long-standing astronomical goal of directly studying a black hole on Event Horizon size and time scales is within reach.* Because it doubles angular resolutions and increases array sensitivity by an order of magnitude, phasing ALMA will transform the current (sub)mm VLBI array, and represents the single most important step towards this goal. The Event Horizon Telescope project (www.eventhorizontelescope.org) organizes efforts to expand the (sub)mm VLBI network for these observations, and supports (sub)mm VLBI observations at multiple facilities, including: Plateau de Bure, the IRAM 30m, APEX, ASTE, SMTO, SMA, CSO, CARMA. When phased ALMA joins this array, it will

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[*] While RadioAstron in conjunction with Earth-based antennas will offer higher resolution in some circumstances, the sensitivity will be very low and will fall short of probing the immediate regions around black holes because of scattering.

enable true imaging of the SgrA* and M87 event horizons. In addition to this exciting event horizon work, phased ALMA opens many other opportunities through joining established VLBI networks (e.g. EVN and VLBA) at longer wavelengths (7mm and 3mm). This work includes ultra-high resolution studies of Active Galactic Nuclei (AGN) and investigation of the kinematics and chemistry of astronomical masers. Here we present several specific areas in which a new VLBI capability in CASA can lead to transformative science results.

2.1.1 Constraining Emission at the Event Horizon with VLBI Closure Phase

SgrA* is highly underluminous, with a bolometric luminosity that is 10^{-8} times its Eddington limit. The family of emission models most applicable to SgrA* are Radiatively Inefficient Accretion Flows (RIAF) which are characterized by geometrically thick disks where the electron and ion temperatures are decoupled. The cooler electrons radiate only weakly, while the ions store the accretion energy as heat, which either disappears through the event horizon or drives outflows (Yuan 2003). Past EHT work to set limits on RIAF parameters has been limited to using only 1.3mm VLBI amplitude information due to lower signal to noise detections on the VLBI array (Fish et al, 2009a; Broderick, Fish et al, 2009; Broderick, Fish et al, 2011a).

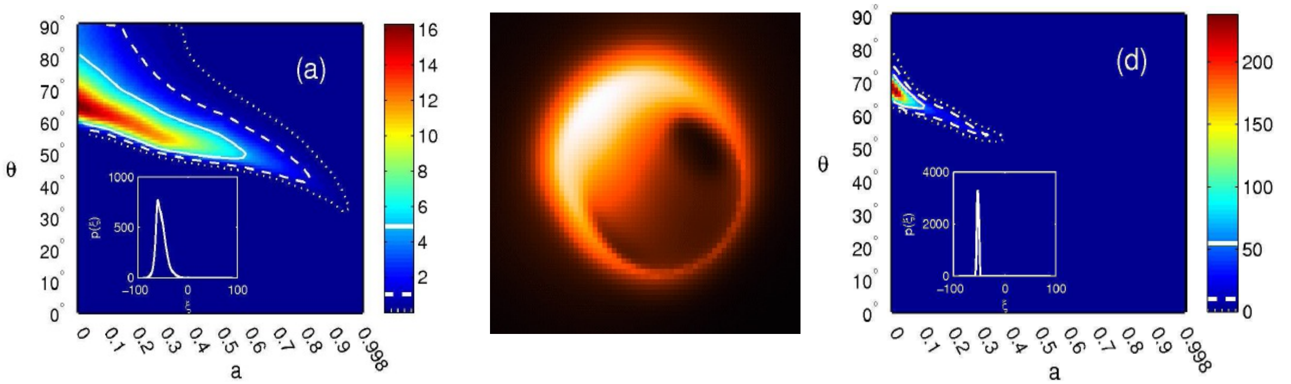

Figure 1: Constraints on physical models of SgrA*. (Left) Probability distribution for black hole spin (a), disk inclination (θ), and spin position angle (inset graph) for a RIAF model of SgrA* using only 1.3mm VLBI visibility amplitudes from 2007 and 2009 observations. (Center) The best-fit RIAF model from the probability distribution at left (Broderick, Fish et al, 2009). (Right) Probability distribution over a family of RIAF models if closure phase were to be measured on the current VLBI array plus ALMA. This assumes the model shown (center) is correct. Estimates of all RIAF parameters are considerably tightened by measuring closure phase (Broderick, Fish et al 2011b).

The ability to extract closure phases from new data sets that include phased ALMA, will provide an entirely new and powerful constraint on physical parameters of RIAF models for SgrA*. This is primarily due to the order of magnitude increase in sensitivity on ALMA baselines that translate into high signal-to-noise measurements of interferometric phase. New formalisms for incorporating closure phase measurements into RIAF model-fitting have been developed, and inclusion of closure phase decisively removes symmetry-flip degeneracies that persist when using only VLBI amplitudes (Broderick, Fish et al 2011b). It is clear from this work that even a handful of closure phases determined *on the current 3-station 1.3mm VLBI array* will have a large effect on RIAF solutions, and measurement of closure phase on baseline triangles to ALMA will produce exceptionally tight constraints within the context of this family of models (Figure 1). We have now entered an era in which (sub)mm VLBI will be a critical component in constraining any proposed emission mechanism for SgrA*.

2.1.2 *Resolving Orbits near the Event Horizon*

One of the most promising areas where VLBI with phased ALMA can make new contributions to the study of black hole physics is in searching for time variable structures due to inhomogeneities in the accretion flow surrounding SgrA*. Localized heating in the inner accretion flow is a natural consequence of magnetic turbulence (Broderick and Loeb, 2006; Dexter et al 2010) and can give rise to orbiting 'hot-spots', which have been used to explain the pronounced X-ray, NIR and submm flares in SgrA* (Yusef-Zadeh et al., 2006; Eckart et al., 2006; Marrone et al., 2008). VLBI cannot image these time-variable structures since they would be smeared out over a single observing epoch – for SgrA*, the ISCO has a period of 30 minutes for a non-spinning black hole (a=0), and only 4 minutes for one that has maximum spin (a=1). However, clear signatures of 'hot-spots', should be detectable by using closure phase.

Prior work (Doeleman et al 2009, Fish et al 2009b) has shown that planned ALMA baselines can not only detect such hot-spots using closure phase, but will have sufficient sensitivity to detect periodicity if the hot-spots persist for multiple orbits in the accretion flow. Detection of periodicity would result in a new way to measure black hole spin and test the validity of the Kerr metric. Figure 2 shows the power of this non-imaging VLBI technique.

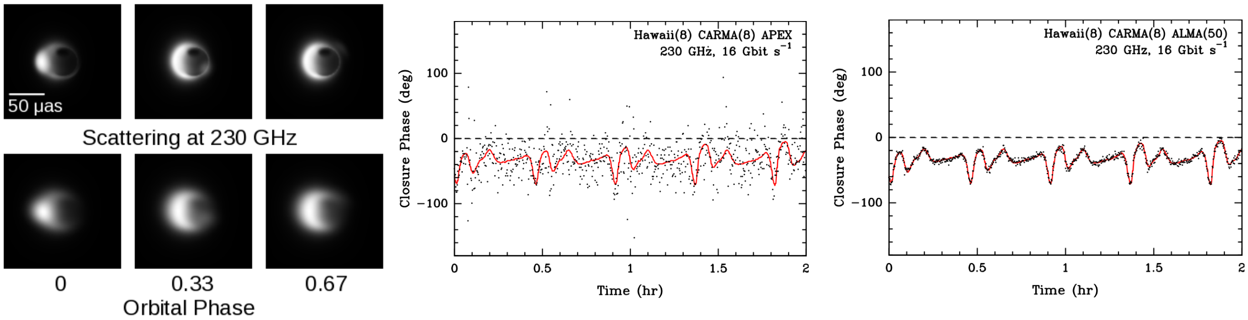

Figure 2: Signature of a hot-spot orbiting a spin zero black hole at a radius of 3 Rsch (period 27 minutes). Model is shown for 3 orbital phases, with and without scattering due to the ISM. Plots show expected closure phases from the model (red) and simulated 10 second closure phase points on a 1.3mm VLBI array consisting of Hawaii, CARMA, and either 1 or 50 phased dishes of ALMA at 16 Gbit s^{-1} recording rate. With one dish in Chile the closure phases average to less than zero, implying asymmetric structure (middle). But phasing 50 ALMA dishes enables detailed monitoring of orbiting structures in the accretion flow (right). Extracting the orbital period from such measurements can yield estimates of black hole spin.

2.1.3 *The No-Hair Theorem: Testing General Relativity with (sub)mm VLBI.*

A well known prediction of GR is that a black hole surrounded by a near optically thin plasma (as from accretion or outflow near SgrA*) will exhibit a "shadow", or dim center, due to strong gravity effects (Falcke et al. 2000). General relativity predicts that the shape of the photon orbit is approximately circular for all values of the black hole mass and spin (Takahashi 2004, Johannsen & Psaltis 2010b). But in non-GR spacetimes, the shape of this "shadow" can take on very different appearances.

One way to parameterize non-GR metrics is to violate the "no-hair" theorem, which states that the exterior spacetime of a Kerr (spinning) black hole can be defined purely in terms of its monopole moment (mass) and dipole moment (spin). The simplest deviations from general relativity can therefore be parameterized by adding a residual quadrupole moment to the value predicted by the Kerr metric (Glampedakis & Babak 2006, Johannsen & Psaltis 2010a). This perturbation produces photon orbits and shadows that are highly noncircular (Johannsen & Psaltis 2010b), resulting in VLBI signatures with clear deviations from the expected shadow morphology. Figure 3 shows the effect on the best-fit SgrA* RIAF model of including a parameterized independent quadrupole moment: $Q = -M(a^2 + \varepsilon M^2)$, where $\varepsilon = 0$ means the 'no-hair' theorem is valid. The images resulting from these different space-times clearly exhibit very different shadow shapes, and the accompanying VLBI simulation shows that baselines to phased ALMA are especially sensitive to the different structures. This preliminary and promising work underscores the ability of VLBI to address fundamental questions at the intersection of astronomy and physics. It is our experience that these types of studies are generating keen interest in ALMA, and (sub)mm astronomy in general, amongst our theoretical colleagues

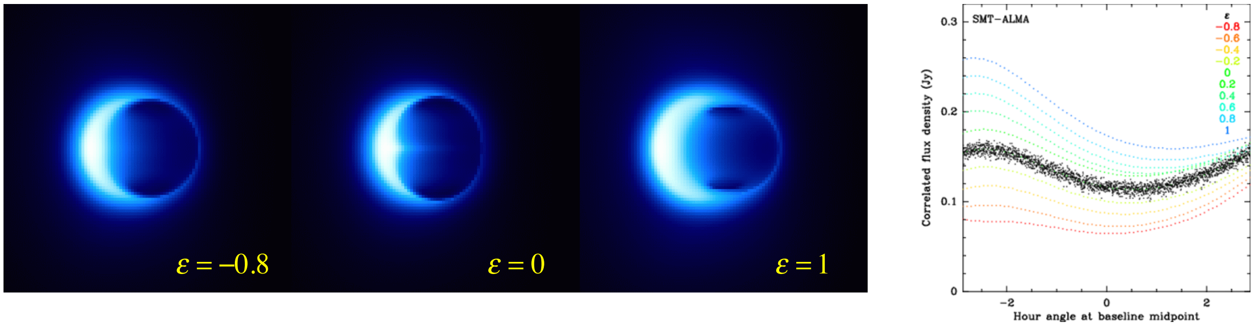

Figure 3: Testing GR. The left three images show the best-fit RIAF model for SgrA* ray-traced through space times with $\varepsilon = -0.8$, $\varepsilon = 0$, and $\varepsilon = +1$. If $\varepsilon \neq 0$, then SgrA* is either not a GR black hole, or GR does not describe the space-time of black holes. On the right are visibility curves for each of the images, plotted with simulated VLBI data on the SMT (Arizona) – ALMA (Chile) baseline for the $\varepsilon = 0$ case. The scatter in the points shows that on this baseline the sensitivity is more than sufficient to differentiate between the images. Images courtesy Broderick & Psaltis.

2.1.4 Observations of M87: Resolving a Black Hole Accretion Disk.

The giant elliptical galaxy, M87, exhibits a relativistic jet from sub-pc to kpc scales and is possibly the best candidate for the study of jet formation and collimation on small scales with VLBI (Kovalev et al 2007; Ly, Walker & Junor 2007; Hada et al 2011). At a distance of 16 Mpc the ~6.4x10^9 Msun central black hole (Gebhardt & Thomas, 2009) has an Rsch ~ 8μas, only slightly smaller than that of SgrA*. Provisional 1.3mm VLBI results (Figure 4) show that the size of the M87 core is only 5 +/- 0.2 Rsch (3s) in diameter, which makes it significantly smaller than the size of the Innermost Stable Circular Orbit (ISCO) for a non-spinning black hole with the mass of M87. Furthermore, recent VLBA results, published in Nature (Hada et al 2011) show that the base of the M87 jet is nearly coincident (to a few Rsch) with the central super massive black hole. These results combine to make it very likely we have resolved this archetypal black hole – accretion disk system. If the jet base size is set by the inner edge of the accretion disk, most plausibly associated with the ISCO, then the black hole must have non-zero spin, and the disk must be rotating in a prograde sense.

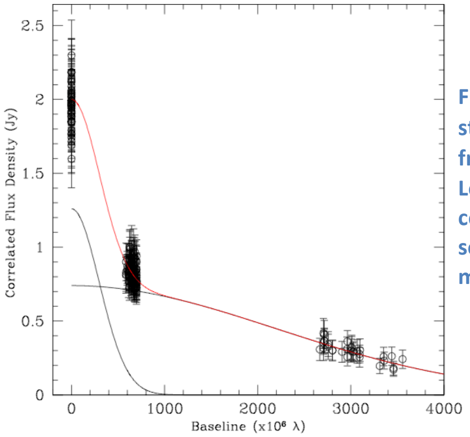

Figure 4: The correlated flux density vs. baseline length for M87 from a 3-station 1.3mm VLBI array. The shortest baselines (30kλ) show strong emission from the large-scale jet (as a circular Gaussian component with size >300 μas). Longer baselines are used to derive a size of ~40μas for the most compact component (also modeled as a circular Gaussian). The sum of both yields the solid red line. These data represent the highest resolution observations ever made of this archetypal AGN.

The detection of Rsch scale structures in M87, the strong evidence for non-zero spin, and a prograde accretion disk present a rare scientific opportunity. Recent theoretical work on AGN jet launching has merged emission mechanisms with ray tracing algorithms suitable for the strong field case (Broderick & Loeb 2009). The resulting simulations show that (sub)mm VLBI with ALMA can decisively distinguish between jet launch models for this nearby AGN, and constrain parameters of the black hole – disk system. To show the power and promise of incorporating phased ALMA into (sub)mm VLBI arrays, we have created simulated images of two competing jet models for M87 (Broderick & Loeb 2009, Dexter et al 2012), and reconstructed images using VLBI baseline coverage expected when a phased ALMA comes on line (Figure 5). Even with only four to seven antennas, phased ALMA enables clear distinction between these modes, which differ mostly on scales of just a few Schwarzschild radii. This represents a clear opportunity to test state-of-the-art jet models against the first observations that directly resolve the jet launch region on Rsch scales.

2.1.5 *ALMA and Global Millimeter VLBI*

While the above description of black hole science describes a particular, very exciting, science case that will be enabled by VLBI at ALMA, other, more conventional, VLBI science will thrive with the inclusion of ALMA and data reduction within CASA. 86 GHz (3 mm) is a fairly standard observing frequency. 8 VLBA antennas, the GBT, and several antennas/arrays in Europe are outfitted at this frequency. Currently most 3 mm VLBI is coordinated through the "Global Millimeter VLBI Array" (see http://www.mpifr-bonn.mpg.de/div/vlbi/globalmm/) which observes twice per year for about 5 days each. The GMVA is an ad hoc array and no one data reduction package can conveniently or optimally assist with reduction of the data. In particular, polarimetry has proven very difficult. Most of the science at 3 mm has focused on imaging studies of AGNs and circumstellar SiO masers. In both of these cases polarized emission plays a key role in understanding the physics in these extreme regions.

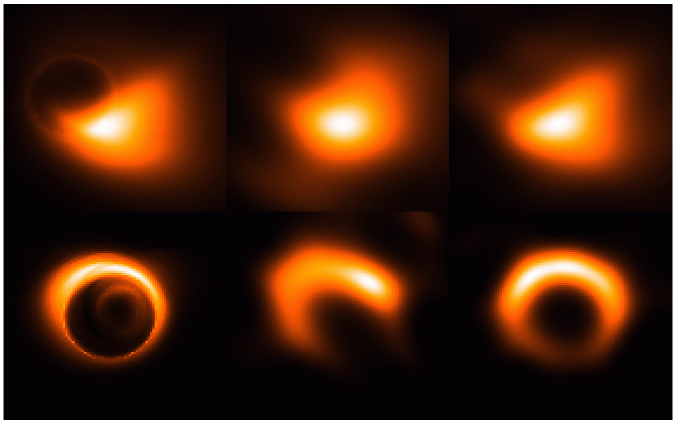

Figure 5: Imaging simulations of M87. Panels show model images (left), reconstructions using only simulated data from phased Hawaii, phased CARMA, ARO/SMT, and phased ALMA (middle), and reconstruction from a 7-telescope array also including the IRAM 30m, phased Plateau de Bure, and the LMT (right). The top row shows a standard jet model (Broderick & Loeb 2009), while the bottom row shows a new class of models (Dexter et al 2012) in which the emission comes from the lensed counterjet (Dexter et al. 2011). First VLBI images with ALMA can differentiate between the models; later images may even be able to resolve the photon orbit, providing a test of general relativity and allow the mass of M87 to be determined by measuring the 'shadow' of the black hole. The scale of each panel is ~120 μas across.

It is anticipated that ALMA will be outfitted with receivers capable of tuning to 43 GHz (7 mm) in the near future. This is another standard VLBI observing frequency, which, due to increased ease of use and availability, enables more varied VLBI science than 3 mm including improvements to the celestial reference frame through geodetic observing and Galactic and extra-Galactic astrometry.

2.2 Technical Case

The rich and high signal-to-noise VLBI data sets expected as phased ALMA comes on-line will benefit from refinement of postprocessing software in order to maximize scientific output. Currently the best algorithms for VLBI data reduction are spread between three packages. AIPS has the most complete set of VLBI calibration routines (especially regarding amplitude calibration); HOPS (Haystack Observatory Processing System) has the most reliable and flexible fringe-fitting algorithms tailored for mm/submm observations and makes the best use of pulse-calibration; and CASA, the ALMA standard data processing package, has the best infrastructure for data editing and imaging, but currently lacks VLBI-specific calibration routines. The ultimate goal is to assemble the best VLBI calibration and analysis algorithms into CASA to maximize the scientific potential and ease of use through pipelining of all VLBI observations, including standard imaging experiments, geodesy, and (sub-)mm VLBI. Within this proposal, we envisage two main elements of new code to be incorporated in CASA: a) specialized mm/submm VLBI routines from HOPS; and b) complete VLBI calibration routines from AIPS.

2.2.1 Short Coherence Time Algorithms (HOPS)

At (sub-)mm wavelengths, turbulence in the atmosphere is what limits the time over which the VLBI signal can be coherently integrated, with typical coherence times below ~10 sec. Thus, both mm and submm VLBI data reduction requires specific routines to determine the atmospheric coherence time of the data, and to segment the data into short coherent intervals that can be incoherently averaged to build signal-to-noise (Rogers, Doeleman & Moran 1995). Once optimal coherence times are determined, fringe detections on individual baselines are found through searches over interferometer delay and delay rate using incoherently averaged amplitudes (examples in Figure 6). This scheme has been very useful for data from the current 1.3mm VLBI array and also from the GMVA (Global millimeter VLBI Array), which is run and organized by the Max Planck Institute fur Radioastronomie. Future VLBI arrays that include ALMA at 7, 3, and 1.3mm will consist of many more antennas than are employed in current arrays, and these specialized HOPS routines should optimally be included in CASA where calibration and imaging routines can easily handle data reduction and analysis tasks for large experiments. This is a task that is well suited to joint collaborative work between the CASA team and the MIT Haystack (sub-)mm VLBI group.

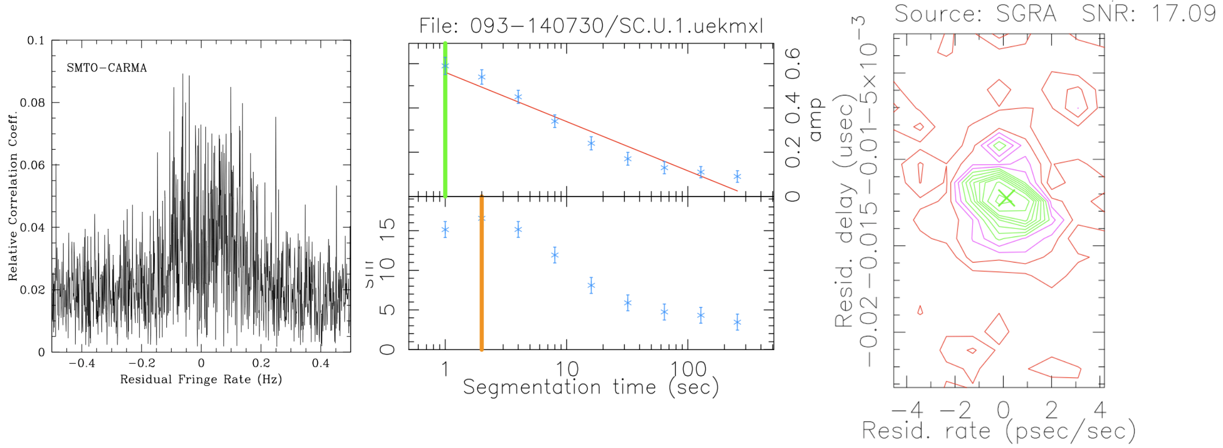

Figure 6: Example of the preliminary (sub)mm VLBI software applied to a 1.3mm VLBI detection of SgrA* on the SMT - CARMA baseline. The left panel shows the fringe rate spectrum from a 900s coherent integration in which the spread in fringe rate indicates a ~few second coherence time. The middle panel shows the fringe amplitude and SNR after segmenting the scan into fine time slices and incoherently averaging. The right panel shows a new fringe search based on incoherently averaged SNR made at the optimal segmentation time (2 seconds as determined from the middle plot). The new detection is at a signal to noise of 17, while the original coherent detection was a marginal SNR=7.

2.2.2 VLBI Calibration Framework (AIPS)

AIPS has long been the primary data reduction package for reduction of NRAO VLBI data and is the most complete package for conventional VLBI data reduction. The algorithms and techniques needed for (sub-)millimeter VLBI are not implemented in AIPS, most notably support for mixed polarization bases and advanced fringe fitting. These features are being developed in the Haystack Observatory Postprocessing System (HOPS).

Experience with the EVLA has show that having multiple reduction paths is very useful when commissioning new hardware. The CASA implementation will provide a parallel data reduction path during the commissioning of the ALMA Phasing project while benefiting from testing and commissioning by experts.

3 REQUIREMENTS

3.1 Design Reference Science Cases

In developing the requirements for support of VLBI in CASA the following use cases were considered:

3.1.1 Continuum imaging

VLBI continuum imaging is used to spatially resolve structures at milliarcsecond scales. In this particular use case it is assumed that the sources being imaged have structure that evolves slowly and smoothly with frequency and that the extent of the object being imaged is tiny compared to the size of the antenna primary beams. Thus primary beam correction can be considered a constant across the image (but perhaps not in time, frequency or polarization). An important special case of continuum is multi-field-center correlation where a separate visibility database is generated by the correlator at several (or even hundreds) of points within the primary beam. Many applications of continuum imaging involve generation of calibrated polarization images. That capability is assumed here.

3.1.2 Spectral line imaging

This second use case is analogous to the first, but where source structure evolves erratically with frequency. In this case generation of spectral line image cubes typically forms the beginning of the astronomical analysis. It is expected that the post-processing software be capable of translating the velocity frame from that used at correlation to that desired by the observer and that instrumental bandpass calibration can be transferred between sources.

3.1.3 Relative astrometry

Relative astrometry is the precise measurement of the separation vector between two sources. Typically a reference source either fixed to the ICRF grid or to a local coordinate system near the object of interest is used as a position calibrator. The position of the target source is determined through phase referencing. Relative astrometry is often used to determine the proper motion, annual parallax, or orbital parameters of compact astronomical sources. Such source scan be continuum emitters (e.g., pulsars) or spectral line sources (e.g., masers). Precision down to 10s of microarcseconds are often achieved; the software should not impose limitations at the 1 microarcsecond level.

3.1.4 Absolute astrometry

Absolute astrometry (or global astrometry) makes use of delay measurements to constrain the relative locations of antennas and sources. Typical observations include short scans on many sources across the sky. Applications include generation and refinement of reference frames (both celestial and terrestrial), determination of earth orientation parameters, and geophysics (e.g., plate tectonics). Unlike the first three use cases which have typically used AIPS and Difmap for data reduction absolute astrometry has historically been based on the HOPS package.

3.1.5 Millimeter-VLBI

This final use case can be considered a catch-all for VLBI applications involving phased-array ALMA. It would also include Event Horizon Telescope (EHT) observations and Global Millimeter VLBI Array (GMVA) observations. The characteristics that set these observations apart include short coherence times and high and/or variable opacity which challenge calibration and detection.

3.2 Data Import

VLBI data sets will typically come in one of two data formats: FITS-IDI and Mark4. Both formats can be produced by the widely used DiFX software correlator. Historical data from the VLBA hardware correlator is only available in FITS-IDI format and much data from the Mark4 series of hardware correlators is only available in Mark4 format. In addition to properly importing visibility data (including auto-correlations), many data tables must be loaded. In addition to describing the input formats that must be supported, this section details some of the general storage requirements that should be met. The AIPS FITS (i.e., UVFITS) format should also be supported. This is the format that the JIVE correlator produced for quite some time and it is also the natural format for transfer from the AIPS environment into CASA.

3.2.1 Data selection

3.2.1.1 Selection during import shall be supported. Where appropriate data selection should apply to calibration tables as well as visibility data.

3.2.1.1.1 Import selection based on Time shall be supported.

3.2.1.1.2 Import selection based on Source shall be supported.

3.2.1.1.3 Import selection based on Spectral window shall be supported.

3.2.1.1.4 Import selection based on Antenna shall be supported.

3.2.1.1.5 Import selection based on Subarray shall be supported.

3.2.2 Precision and data dimensions

3.2.2.1 Both cross- and auto-correlation data shall be supported.

3.2.2.2 Visibility data represented by single precision complex number will suffice.

3.2.2.3 Timestamps on visibility data shall be capable of representing time to 1us precision or better.

3.2.2.4 Databases with up to 64 distinct antennas shall be supported.

3.2.2.5 Simultaneous subarrays of antennas, changing in membership over time, shall be supported.

3.2.2.5.1 At least 16 subarrays shall be supported.

3.2.2.5.2 It shall be possible for the number of subarrays to change in time.

3.2.2.5.3 Only subarray membership must be maintained, unique subarray identity is not required.

3.2.2.5.4 It must be possible to use any data for an antenna, regardless of changing subarray membership, to determine calibration for that antenna.

3.2.2.5.5 It must be possible to apply calibration determined in any combination of subarrays to scans in any other subarray with appropriately similar observing parameters.

3.2.2.5.6 It must be possible to display visibility and calibration data for an antenna as a function of time independent of subarray participation.

3.2.2.6 Visibility integration durations as short as 1ms shall be supported.

3.2.2.7 Spectral resolution as fine as 1 Hz shall be supported.

3.2.2.8 Spectral window bandwidths ranging from 1 Hz to 64 GHz must be supported.

3.2.2.9 A minimum of 131072 (128 Ki) spectral points per spectral window must be supported.

3.2.2.10 Sky frequencies up to 600 GHz must be supported.[†]

3.2.2.11 Continuous observations lasting up to 14 days must be supported.

3.2.3 Meta Data

As available the following tables, as defined by the IDI-FITS convention or as appropriate for other supported formats, shall be importable into CASA data structures:

3.2.3.1 ARRAY_GEOMETRY

3.2.3.2 ANTENNA

3.2.3.3 FREQUENCY

3.2.3.4 SOURCE

3.2.3.5 INTERFEROMETER_MODEL

3.2.3.6 SYSTEM_TEMPERATURE

3.2.3.7 GAIN_CURVE

3.2.3.8 PHASE-CAL

3.2.3.9 FLAG

3.2.3.10 WEATHER

3.2.3.11 MODEL_COMPS

3.2.4 Supported import formats

3.2.4.1 Import of FITS-IDI data, as defined in AIPS memo 114r[‡] shall be supported.

[†] Note requirements 2.1.2.7 and 2.1.2.10 imply double precision floating point or 64-bit integers are required to represent frequencies.

[‡] ftp://ftp.aoc.nrao.edu/pub/software/aips/TEXT/PUBL/AIPSMEM114.PDFftp://ftp.aoc.nrao.edu/pub/software/aips/TEXT/PUBL/AIPSMEM114.PDF

3.2.4.2 Import of data in Mark4 format shall be supported

3.2.4.3 Import of data in the AIPS FITS format, as defined in AIPS memo 117[§] shall be supported.

3.3 Amplitude calibration

The amplitudes of a VLBI data set includes a series of fairly standard calibration steps including:

- Digital corrections to compensate for quantization
- Forming normalized correlation coefficients from raw correlator products
- Multiplying by the system temperature to form visibilities in temperature units
- Correction for atmospheric opacity
- Divide by gain (in "Degrees per flux unit" or K/Jy units) to scale to janskys.

Note that a strict order of operations should not be enforced.

In some cases additional corrections to recover amplitude lost by decorrelation (delay or rate errors causing large phase changes per frequency or time sample respectively). The correction is ideally a function of the total delay and rate compensation applied to the data (rather than being applied step by step as various contributions to delay and rate are applied in series) and depends to some degree on the windows used in final time and frequency averaging (either in the correlator or post-processing). In AIPS some of the necessary information is stored in the "CQ" table.

With the rise of in-beam calibration it is becoming apparent that a mechanism to apply a primary beam amplitude correction for cases where the antenna is not pointing directly at the correlation center will further simplify this powerful technique.

In the case of phased-array antennas as VLBI array elements, it is deemed the responsibility of each phased-array to provide in standard formats metadata required to appropriately calibrate amplitudes in the presence of gradual deterioration of phasing or drift of pointing. At some level and in some cases a constrained self calibration within CASA could be used to make some corrections for these effects.

[§] ftp://ftp.aoc.nrao.edu/pub/software/aips/TEXT/PUBL/AIPSMEM117.PDFftp://ftp.aoc.nrao.edu/pub/software/aips/TEXT/PUBL/AIPSMEM117.PDF

3.3.1 Autocorrelation correction

3.3.1.1 A facility to divide cross-correlation values by the geometric mean of the associated and time-coincident autocorrelations is required.[**]

3.3.1.2 A mechanism to plot the time variability of spectral window average autocorrelations would be useful.

3.3.1.3 Both time averaging (if any) during determination and interpolation (if any) during application should have the capability of respecting scan boundaries.

3.3.2 System temperature

3.3.2.1 System temperature tables imported with visibility data shall be able to be applied to the data and weights.

3.3.2.2 It should be possible to import system temperature data in the standard "TSM" format (See AIPS task ANTAB)

3.3.3 Opacity correction

3.3.3.1 It shall be possible to specify a zenith opacity.

3.3.3.2 It shall be possible to use system temperature measurements made over a specified period as input to solve for zenith opacity.

3.3.3.2.1 For antennas with characterized spill-over and metrology data, the ground temperature should be estimated and removed before solving for zenith opacity.

3.3.3.2.2 It shall be possible to specify an elevation range for data to fit.

3.3.3.2.3 Both pure least squares and alternatives that are robust against errant data points shall be available.

3.3.3.2.4 Fits to system temperature to determine the receiver temperature should be robust against weather-induced variations and biased toward the lower values obtained during relatively clear weather.

3.3.3.3 Given zenith opacity, possibly as a function of time, correction for opacity based on sec(z) shall be possible.

[**] The normal mode of operation is to form an autocorrelation averages across the spectrum and then to divide the cross correlation spectra by these spectral window averages. This prevents this operation from affecting the bandpass. In AIPS this task is done through a combination of ACCOR to determine the autocorrelation correction values and CLCAL to apply it. It is recommended here to take a similar path.

3.3.4 Antenna gain

3.3.4.1 Elevation gain curve tables naturally imported with visibility data should be usable.

3.3.4.1.1 Support for antenna mounts other than alt-az should be supported. This implies the use 2-D gain curves that are functions of both orientation angles.

3.3.4.2 Application of different elevation gain curves on different sub-bands should be supported. This is especially important in cases where dual-band observing (e.g., S-band and X-band simultaneously) is employed.

3.3.4.3 Updated elevation gain curve tables for supported antennas should be downloadable from within CASA.

3.3.5 Decorrelation correction

3.3.5.1 Correlator averaging parameters, possibly as a function of baseline, should be stored with the visibility database.

3.3.5.2 It shall be possible to optionally correct for decorrelation without requiring an additional pass through the data (on-the-fly application)..

3.3.6 Primary beam correction

3.3.6.1 A correction for the antenna primary beam based on the vector offset between the antenna pointing center and the correlator phase center shall be possible.

3.3.6.2 It should be possible to correct for the primary beam without detailed user input, either through built in models or through automated download.

3.3.6.3 It should be possible for a user to supply a detailed primary beam model tabulated in two dimensions.

3.3.6.4 It should be possible for a user to supply a simple radial polynomial model.

3.3.6.5 Beam shape corrections for phased arrays elements shall be possible.

3.3.6.5.1 Input parameters describing a general elliptical Bessel or Gaussian zenith beam shall be supported.

3.3.6.5.2 This zenith beam shall be appropriately stretched as a function of time to account for foreshortening of the array as seen by the source.

3.3.6.5.3 The beam parameters should be scaled in angle with observing wavelength during application.

3.3.6.5.4 Dirty beams separately determined for the phased-array elements shall be usable as good approximations of the phased-array beam.

3.3.7 Digital corrections

3.3.7.1 It shall be possible to apply the Van Vleck (and its >1-bit equivalents) to the visibility data based on state counts inferred from the autocorrelation values.

3.3.8 Calibration editing

3.3.8.1 It shall be possible to manually edit input calibration data (e.g., as tabular data or in the form of a text file).

3.3.8.2 It shall be possible to visually edit input calibration data graphically.

3.3.8.3 It shall be possible to smooth input calibration data, with user selectable options for not smoothing across scan boundaries.

3.4 Pulse Cal data handling

Phase (or equivalently, pulse) calibration is a VLBI technique used to correct the sampled data for instrumental effects. For example, in geodesy one would like the observations to measure the baseline delay to a fixed point on each antenna, typically the intersection of axes. However, the data are sampled on the ground after passing through cables, connectors, down-converters, and filters. By injecting a series of pulses as close to the front end as is practical, a series of tones is produced in the frequency domain, which can be used to solve for both delay and phase effects between the front end and the samplers.

For example, in the broadband system used for the NASA Space Geodesy Program, pulses are injected at a 5 MHz rate, producing tones (or rails) at 5 MHz intervals. These are extracted in the correlation software and written to a calibration file that accompanies the visibility data, one per antenna. The phase cal data consist of triplets of frequency, amplitude, and phase, tabulated every second.

The fringe-fitting software (e.g., HOPS FOURFIT) finds via FFT the best-fit line of phase as a function of frequency, using all of the tones in a channel or any desired subset thereof (in the case where known RFI corrupts tones). The slope determines a delay, which is then differenced on the baseline and applied to the complex visibility data. The visibilities are also adjusted by the differential phase (at mid-band) of the two fits.

This process allows data that have passed through different anti-aliasing filters and samplers to be registered with one another, thus allowing phase-coherent delay solutions across multiple wide IFs. This technique has been applied with success to group delay extraction over a frequency span of about 6 GHz.

The comb frequency structure causes ambiguities in measured delay; any delay measurement solely determined by a comb with frequency interval Q can only determine delay modulo 1/Q. Resolution of this ambiguity can come from fringe fitting some data. Usually only a very small amount of data for an entire experiment is required as delays typically don't change by more than 10s of nanoseconds and the ambiguities are typically 200 or 1000 nanoseconds. Continuity of delay through time can be used to extend the period of ambiguity resolution. Note that VLBA Scientific Memo 8 contains thoughts on dealing with more than 2 pulse cal tones per spectral window.

3.4.1 Data Structure

3.4.1.1 Import of Pulse Cal data shall be supported

3.4.1.1.1 Pulse cal data attached to a FITS file shall be importable.

3.4.1.1.2 Import of an ASCII text file in TSM format shall be supported.

3.4.1.1.3 Each pulse cal measurement contains a real and imaginary value and the time interval corresponding to that measurement.

3.4.1.1.4 A pulse cal set is the collection of all pulse cal measurements made over one time interval at one antenna.

3.4.1.2 Between 0 and B+1 pulse cal tones per spectral window must be supported where B is spectral window bandwidth in MHz.

3.4.1.3 A cadence as fast as one pulse cal set per visibility integration time should be supported.

3.4.1.4 Time averaged pulse cal data should be supported; averaging intervals may be integer multiples of the visibility integration time or not.

3.4.1.5 An optional "cable cal" value, containing an additional instrumental delay correction, should be handled along with pulse cal data.

3.4.1.6 Different antennas may have different pulse cal intervals and/or number of tones.

3.4.1.7 Single precision floating point is sufficient for the real and imaginary parts of each pulse cal measurement; time should be accurately representable to at least 1ms.

3.4.2 Pulse Cal Data Selection

3.4.2.1 In all cases where pulse cal data is used it shall be possible to select a subset of tones to use.

3.4.2.2 Typical selection by antenna(s), time range, source, and spectral window shall be supported.

3.4.3 Visualization and editing

3.4.3.1 It should be possible to plot a time series of pulse cal amplitude or phase as a function of time for a selection of tones tones. Similarly the cable cal values should be plottable.

3.4.3.2 It should be possible to view the amplitude or phase of the time series of a pulse cal set as a raster image.

3.4.3.3 It should be possible to flag certain pulse cal values based on a priori information or interactive editing processing; flagged values should be ignored in computations involving the pulse cal data.

3.4.4 Calculations to perform

3.4.4.1 It shall be possible to determine the delay as a function of time based on the Pulse Cal data.

3.4.4.1.1 Solutions should be determined separately for each antenna and separately for each spectral window.

3.4.4.1.2 It shall be possible to determine a single delay value from multiple spectral windows.

3.4.4.1.3 It shall be possible to specify the time interval for the solutions (including the case of or one delay solution per pulse cal set).

3.4.4.2 In cases where cable cal data is present there should be the option to include the cable cal correction in the computed delay.

3.4.4.3 The determined delays should be stored in a table that can be further edited and applied as necessary.

3.4.4.4 It shall be possible to time average pulse cal values.

3.4.4.5 It shall be possible to form a bandpass calibration table based on pulse cal sets.

3.4.4.6 It shall be possible to form a gain calibration table by extracting the amplitude and/or phase of a single tone of each sub-band.

3.4.4.7 It shall be possible to use fringe-fit determined delays to resolve pulse cal delay ambiguities.

3.4.4.8 Decorrelation corrections for delays determined by pulse cal data should be handled no matter how the pulse cal data is applied.

3.5 Fringe fitting

Although correlator models are generally sufficient to remove coarse geometric delays and fringe rates on VLBI baselines, the residual delays and rates that remain are typically large enough to prevent coherent integration of VLBI quantities over the observed bandwidth and scan length. Fringe fitting is therefore a sine qua non for VLBI at both centimeter and millimeter wavelengths.

Implementations of coherent fringe-fitting algorithms already exist in AIPS (FRING, KRING). These tasks can be used on a per-baseline basis, but one of their greatest strengths is the ability to use delay and rate closure to calculate a best-fit global solution for the array at once. These solutions are generated at a user-specified solution interval.

Fringe-fitting routines often have a large number of important adjustable parameters, some of which are summarized below:

- Specification of a source model allows fringe fitting on a source with complicated structure.
- The SNR cutoff allows the user to specify a minimum quality of solution.
- Delay and rate windows allow the user to restrict the search space to intervals that are known a priori to be reasonable, allowing somewhat lower-SNR solutions to be obtained in the presence of possible higher-SNR noise spikes outside this range. In HOPS FOURFIT, these windows can be specified on a per-antenna basis and do not have to be centered on zero residual quantities, which can allow the user to uncover even weaker fringes when the expected residual delays or rates can be estimated from other scans.
- Users can solve for any combination of fringe rate, multiband delay, and singleband delay.
- Users can combine data by polarization and IF when appropriate.
- Period of time being fringe fit. This could be a whole scan or a fixed interval. In cases where an integral number of fixed intervals do not span a scan, some intelligent algorithm to prevent solutions on very small time intervals must be invoked.

Special considerations apply to fringe fitting at millimeter wavelengths due to the short atmospheric coherence time. These are covered in section 5.

Fringe fitting is also a necessary part of VLBI polarimetry, since cross-polarized delays (and phases) must be determined. The AIPS task RLDLY contains one possible implementation of a cross-polarized delay calibration algorithm.

3.5.1 General Delay Fitting Requirements

3.5.1.1 It shall be possible to determine singleband delay, multiband delay, and rate solutions on a single baseline.

3.5.1.1.1 It shall be possible to enforce a zero solution for any of the parameters (pre-fit or post-fit) without biasing the results because of fit covariances.

3.5.1.2 It shall be possible to determine global antenna-based single-band delay, multiband delay, and rate solutions on an array of baselines or subset thereof.

3.5.1.2.1 It shall be possible to include in the fit a dispersive multi-band delay component proportional to 1/freq^2. This is relevant for ionospheric calibration.

3.5.1.3 Changes in reference antenna shall be supported in cases where antennas come and go during observing.

3.5.1.4 It shall be possible to determine and correct cross-polarized delays and phases.

3.5.2 Selection

3.5.2.1 It must be possible to select data to fringe fit by spectral channel and spectral window.

3.5.2.2 It must be possible to select subsets of data by time range.

3.5.3 Modes of operation

3.5.3.1 It must be possible to specify a source model for fringe fitting.

3.5.3.2 It must be possible to specify a desired solution cadence (equivalent to the SOLINT parameter in the AIPS task FRING).

3.5.3.2.1 It shall be possible to overlap time ranges by a specified amount (see the SOLSUB parameter for AIPS task FRING).

3.5.3.2.2 In cases where the cadence does not evenly span the data valid period of a scan an intelligent algorithm to shift the intervals shall be invoked.

3.5.3.3 It must be possible to request a single fringe solution on each and every scan.

3.5.3.4 It must be possible to request fringe solutions spanning more than one scan.

3.5.3.5 [low priority] It shall be possible to fit delay as a spline function over a period of time possibly greater than the coherence time.

3.5.3.5.1 The user shall have control over the spline degrees of freedom.

3.5.3.5.2 Continuity of the spline across scan boundaries must be selectable.

3.5.3.5.3 It should be possible to construct a spline solution based on tabulated solutions.

3.5.3.6 It should be possible to solve for any subset of singleband delay, multiband delay, and rate simultaneously.

3.5.3.7 It should be possible to combine data by IF and/or polarization prior to determination of the delay paramters.

3.5.3.8 It shall be possible for the user to specify delay and rate windows in which to search.

3.5.3.8.1 It shall be possible for user-specified delay and rate windows to be centered at any arbitrary value, not just at zero residual.

3.5.3.8.2 It shall be possible for delay and rate windows, both center and width, to be specified by the user on a per-antenna basis.

3.5.3.9 It must be possible for the user to specify the minimum SNR of acceptable solutions with a sensible default value.

3.5.3.10 It shall be possible to employ baseline stacking to improve detectability of fringes.

3.5.4 Visualization

3.5.4.1 It is desirable to have a FOURFIT-like visual display of fringe solutions.

3.5.4.1.1 A fringe rate spectrum (Amplitude vs. Delay rate) shall be plotted.

3.5.4.1.2 Single-band delay spectrum (Amplitude vs. Single-band delay) shall be plotted.

3.5.4.1.3 Multi-band delay spectrum (Amplitude vs. Multi-band delay) shall be plotted.

3.5.4.2 It shall be possible to plot the lag spectrum (FT of visibility spectrum) both before and after application of delay calibration.

3.5.4.2.1 Data selection and averaging parameters comparable to CASA's bandpass plotting capability shall be supported.

3.5.4.2.2 It shall be possible to calculate fringe amplitudes and SNRs on a per-baseline basis over a regular grid of values in delay and rate spanning the relevant ambiguity windows or user-specified subsets thereof.

3.5.4.2.3 It is desirable that the user be able to specify whether the grid in 2.4.4.2.2 should be centered on zero residual delay and rate or on a nonzero delay and rate solution that has been previously obtained.

3.5.4.2.4 It shall be possible to obtain the location of the maximum in either amplitude or SNR, with interpolation between nearby points used to increase the precision of this solution beyond the grid spacing interval. Implementation note: Depending on how coherent and incoherent fringe searches are implemented, this may be trivially satisfied by other requirements elsewhere in the document

3.5.4.2.5 It shall be possible to produce a two-dimensional plot of the fringe amplitude or SNR as a function of delay and rate. This plot will also show the location of the peak from 2.4.4.2.4 graphically and report the SNR in text form. Implementation notes: delay and rate are the two axes, user may select either amplitude or SNR, it is acceptable for this function to be plotted either as contours or as a greyscale/colorscale plot

3.5.4.2.6 It is desirable that, if the a priori expected location of the peak in delay/rate space on a baseline can be determined from known good fringe solutions on other baselines that close, this location can also be plotted in 2.4.4.2.5.

3.5.4.2.7 It shall be possible for the user to interact with the plots in 2.4.4.2.5 to accept or reject solutions. Intent/implementation note: It is important to be able to keep track of which scans/baselines/spectral-windows/polarizations have produced good fringes and which have not, so that the user may restrict further fringe searches to the list of non-detections (and perhaps use closure relations among the list of detections to assist in fringe finding).

3.5.4.2.8 It shall be possible to redo fringe fitting on only that subset of scans which are marked as non-detections, either due to user rejection via 2.4.4.2.7 or due to a user-specified SNR cutoff.

3.5.4.2.9 The above requirements apply to both coherent and incoherent fringe searches.

3.6 Short coherence time algorithms

At millimeter wavelengths, variable atmospheric delays due primarily (though not exclusively) to tropospheric water vapor imprint a rapidly-varying phase on incoming radiation. The coherence timescale of the atmosphere is highly dependent on the weather but ranges from less than a second to about 20 seconds at typical millimeter VLBI sites at 230 GHz. As data are coherently integrated (i.e., vector averaged) over increasingly longer timescales, this results first in a loss of amplitude, then in a loss of SNR. Consequently, millimeter VLBI data must be segmented into short time intervals over which the atmospheric phase is roughly constant, then the segments must be incoherently averaged (i.e., scalar averaged), with a resulting loss of SNR compared to coherent integration.

The theoretical basis for the proper treatment of segmented millimeter data is worked out in Rogers, Doeleman, & Moran (1995 AJ, 109, 1391). Implementation of these algorithms can be found in several tasks of the HOPS data reduction package. Differences from longer-wavelength data reduction are summarized below.

Fringe fitting. Substantial coherence losses over a scan with a typical duration of a few minutes prevents the coherent fringe detection of all except the strongest sources. Data can be segmented on a timescale appropriate for the atmospheric conditions, but (again, except on the strongest sources) the SNR within a short time segment is insufficient to produce a fringe detection. Weaker sources can be detected via an incoherent search in delay and rate. Visibility data are segmented at the atmospheric coherence time (vector averaging within each segment). The segmented data are then scalar averaged over the scan duration. The peak scalar-averaged, noise-debiased amplitude identifies the location of the potential fringe in delay/rate space. HOPS implements incoherent searching via a multitask approach (FRINGEX, AVERAGE, SEARCH). In principle, it is possible to use a coherent fringe-fitting task (FOURFIT) to perform incoherent searches for delay as well. Rapid atmospheric phase variations introduce smearing of the fringe-rate spectrum. Segmentation in the time domain is mathematically related to convolution in the fringe-rate domain. HOPS FOURFIT contains an experimental mode to allow incoherent fringe fitting in this manner, but its current implementation incorrectly calculates the SNR of detection and is substantially less robust in detecting weak fringes. In contrast, the aforementioned method of segmentation in the time domain is well-tested and conceptually simpler, but opportunities exist for further algorithmic development in the fringe-rate domain if desired.

Amplitude calculation. Visibility amplitudes are positive definite, with the result that a scalar average of a noisy amplitude will be nonzero even in the absence of any signal. The expected amplitude of the noise vector must first be subtracted from the visibility in quadrature before averaging.

Phase quantities. In most cases, the short atmospheric coherence time precludes visibility phase calibration via rapid nodding between a source and a nearby calibrator. Fortunately, atmospheric phase variations are station-based. As a result, closure phases are the robust phase observables in millimeter VLBI. Closure phases, like amplitudes, must be calculated on time-segmented data and then (optionally) averaged over the scan length. Closure phases are somewhat more forgiving than visibility amplitudes in terms of the segmentation time chosen; lengthening the segmentation time nearly always results in some loss of amplitude, while closure phase measurements are mostly unaffected unless the segment length is long enough that the atmospheric phase excursions are large. HOPS implements the algorithms in Rogers et al. (1995), including the use of the bispectrum rather than the closure phase (which is the argument of the bispectrum) when averaging. Reasonable approximations are used to calculate the SNR of the closure phase; opportunities exist to improve upon the SNR estimate if desired.

3.6.1 General

3.6.1.1 It is acceptable to require that segmentation times be an integer multiple of the correlator accumulation period. User-specified values that violate this condition may be rounded to the nearest multiple.

3.6.1.2 It shall be possible to apply a priori phase information (as from water vapor radiometry) in order to improve coherence times.

3.6.2 Incoherent averaging

3.6.2.1 It must be possible to calculate the incoherent-averaged[††] amplitude on a scan and baseline combination, ignoring any flagged data.

3.6.2.2 It must be possible to specify the segmentation time for incoherent averaging.

3.6.2.3 The incoherent average must be noise-debiased.

3.6.3 Coherence time determination

3.6.3.1 Given that fringe solutions can be obtained for a given data set, it shall be possible to determine the coherence times (specified below) of a data set.

3.6.3.1.1 The nominal allowed amplitude loss that defines the no-loss coherence time[‡‡] shall be user-specifiable with a sensible default value.

3.6.3.1.2 The segmentation time at which the SNR of fringe detection is maximized (search coherence time) shall be determined.

3.6.3.1.3 Coherence times shall be determined on a station- or baseline-dependent basis.

3.6.3.2 When fringes are not detected on a source on a baseline, it should be possible to estimate coherence times by interpolating in time, guided by the observed source elevation and other atmospheric information.

3.6.3.3 It should be possible to determine maximum coherence times for an observing array or subset thereof as a function of time. This is the minimum of the coherence times of all selected baselines.

3.6.4 Incoherent fringe fitting

3.6.4.1 It must be possible to perform incoherent fringe fitting.

[††] Incoherent averaging requires vector averaging data within a segment of time and then scalar averaging the amplitudes of each of the segments.

[‡‡] The no-loss coherence time is the maximum segmentation time beyond which amplitude losses are expected to exceed some nominal value (e.g., 1% or 5%).

3.6.4.1.1 Standard input parameters for coherent fringe fitting is required.

3.6.4.1.2 An additional parameter specifying incoherent segmentation time is required.

3.6.4.2 It must be possible to visualize the results of incoherent fringe fitting in order for the user to be able to determine the quality of a solution.

3.6.4.3 It should be possible to derive upper limits on amplitudes from non-detected scans, preferably with a user-specified minimum SNR of detection that has a sensible default possibly derived from the data.

3.6.5 Closure quantities

3.6.5.1 It shall be possible to use as input any measurement set column with standard data selection options.

3.6.5.2 It shall be possible to divide the visibility input by a model image.

3.6.5.3 Closure phases

3.6.5.3.1 It shall be possible to compute and plot closure phases akin to AIPS task CLPLT.

3.6.5.3.1.1 It shall be possible to specify a segmentation time (or solution interval) when computing closure phases, with sensible default.

3.6.5.3.2 It must be possible to time-average closure phases.

3.6.5.4 Closure amplitudes

3.6.5.4.1 It must be possible to compute and plot closure amplitudes.

3.6.5.5 Closure delays and rates

3.6.5.5.1 It must be possible to compute and plot closure delays and rates.

3.7 Polarization

The following requirements relate to the handling of data correlated with full polarization (i.e., all 4 polarization products).

3.7.1 Polarization Calibration

3.7.1.1 It must be possible to determine and correct for antenna polarization leakages.

3.7.1.2 It must be possible to correct observed visibility phases for field rotation angle (parallactic angle) effects.

3.7.2 Polarization Ploting

3.7.2.1 It shall be possible to compute and plot polarimetric amplitude ratios (e.g., RL/LL).

3.7.2.2 It shall be possible to compute and plot polarimetric phase differences (e.g., RL-LL).

3.7.2.3 It shall be possible to estimate *resolved* calibrator polarization components in the instrumental polarization solve.

3.7.3 Polarization Basis Conversion

3.7.3.1 It shall be possible to convert from the observed polarization basis to Stokes quantities.

3.7.3.2 In order to correct for possible small errors in the XY-to-RL polarization basis conversion anticipated for phased ALMA data after correlation, it must be necessary to solve for and apply an additional station-based rotation.

3.7.4 Calibration

3.7.4.1 It shall be possible to transfer delay calibration information across polarizations to increase coherence time:

3.7.4.1.1 It shall be possible to use fringe solutions in one polarization (e.g., RR) to assist in fringe detection in another polarization (e.g., RL) via baseline stacking techniques.

3.7.4.1.2 It shall be possible to use the visibility phases as a function of time on a baseline in one polarization to attempt to extend the coherence time in another polarization.

3.8 Model accountability and manipulation

A key capability of VLBI is to make extremely accurate (sub-nanosecond) delay measurements on long (1000s of km) baselines, enabling absolute astrometry. The geodetic VLBI community has developed a sophisticated framework for long term maintenance of the celestial and terrestrial reference frames based on total delays (or just "totals"). These total delays are measurements made one baseline at a time and consist of two parts: the a priori delay and the residual delay. The first of these is applied at the correlator and the second is determined based on the results of fringe-fitting. The sum of these components is independent of the delay model used to correlate. The delay model only need be precise enough to avoid decorrelation losses inherent in the time and frequency averaging that occurs with correlation. The calculation, tabulation, and export of these total delays will greatly increase the capabilities and interoperability of CASA with other software.

The astronomical VLBI community is starting to recognize the importance of geodetic VLBI approaches and has started making use of a subset of the capabilities to improve the effectiveness of phase referencing. There is enormous room to improve on existing practice and yield higher precision relative astrometry and improved imaging. The specifications found here should be sufficient to compete with current practice in AIPS and form a solid base from which development can continue. A long desired feature has been the ability to replace the delay model used for correlation with an improved model after the fact. In such an operation the delay corrections to be applied to the visibilities are simply the differences between the two models. Such infrastructure will provide a convenient platform on which to experiment with improvements in delay models without requiring many correlation passes. Some model improvements that are desired include better ocean loading, improved use of meteorological data and corrections for antenna thermal deformation.

Conversely, astronomical imaging-based techniques, which largely make use of pure antenna-based calibration in an effort to preserve closure quantities, are being recognized as important for monitoring structure and polarization evolution in reference sources.

Geodetic and astronomical techniques have historically been developed in isolation of each other. It is the goal here to bring the strengths of each into one package (CASA).

3.8.1 Delay model propagation

3.8.1.1 Throughout processing the delay model shall be stored in conjunction with the data, further the delay model shall be kept consistent with the current state of the data.

3.8.1.1.1 Delay model versioning must be maintained even after splitting and recombining measurement sets.

3.8.1.1.2 Throughout processing delays shall be represented to at least1 femtosecond resolution.

3.8.1.1.3 It shall be possible to maintain separation of delay effects (i.e., vacuum propagation, atmospheric terms, etc.) within the delay model.

3.8.1.1.4 It must be possible to store the delay model as a polynomial spline. Polynomials with up to 6 terms must be supported. The interval of validity of a specific polynomial must be stored and can range from 1 second to 1 hour. A given polynomial must be identified with a particular source.

3.8.1.2 The delay model used during correlation shall be imported with the visibility data..

3.8.1.3 All calibrations containing a delay shall modify the delay model table to ensure consistence with the data, in particular the total delay shall be unchanged.

3.8.1.4 During any operation where a new visibility database is formed, a delay model table consistent with the state of the new database shall be written

3.8.2 Delay model adjustments

Earth Orientation Parameters (EOPs) are used to describe the orientation and spin phase of the earth relative to a standard model of a uniformly spinning orb. The deviations from uniform motion are unpredictable as they are largely driven by transfer of angular momentum between the earth's crust, the oceans, atmosphere and earth core. Typically final best estimates for the EOPs are only available a week or two after observation, which may be after correlation.

3.8.2.1 It shall be possible to apply delay corrections to the data with improved EOPs[§§].

3.8.2.2 It shall be possible to correct for antenna position errors.

3.8.2.2.1 New antenna position shall be specified as new ITRF frame coordinates for one or more antennas.

3.8.2.2.2 Antenna position corrections up to 10 meters should be supported.

3.8.2.2.3 The antenna position as reported in the antenna table shall be updated.

3.8.2.3 Source position adjustment should be possible.

3.8.2.3.1 New source positions shall be specified in J2000 frame coordinates.

3.8.2.3.2 The applied correction shall produce phases equivalent to those that would come from correlation with the new source coordinates.

3.8.2.3.3 The coordinates of the correlation center in the data set shall be updated.

3.8.2.3.4 The baseline vectors (U,V,Ws) shall be updated to be consistent with the new correlation center.

3.8.2.3.5 Source position corrections up to 1 arcminute should be supported.

3.8.2.4 Manual delay and rate adjustment shall be supported.[***]

3.8.2.4.1 Data selection options should include time range, antenna, spectral window, and source.

3.8.3 Delay model replacement

3.8.3.1 It shall be possible to derive a delay correction from the difference between the current delay model table and an external delay model.

3.8.3.2 It should be possible to determine which delay model (either the original or some identifier associated with the replaced model) is attached to a particular database or portion thereof.

[§§] The equivalent functionality is implemented in AIPS task CLCOR when using OPCODE = 'EOPS'.

[***] This functionality is implemented in AIPS in task CLCOR with OPCODE='CLOC'.

3.8.3.3 The format of the delay model to import is to be determined.

3.8.3.4 It shall be possible to export the delay model from a visibility database in suitable form to apply it to another database.

3.8.4 Atmosphere / clock solver (equivalent to DELZN in AIPS)

3.8.4.1 It shall be possible to derive and correct clock offsets and atmospheric delays from a set of residual delay measurements.

3.8.4.1.1 Derivation of delay and delay rates shall be supported.

3.8.4.1.2 An additionally atmospheric mapping function shall be supported.

3.8.4.1.2.1 The trivial term proportional to sec(z) shall be supported.

3.8.4.1.2.2 The Vienna Mapping Function (see http://mars.hg.tuwien.ac.at/~ecmwf1/) shall be supported.

3.8.4.1.2.3 The Niell Mapping Function shall be supported.

3.8.4.1.3 An ionospheric term of the form sec(z)/freq^2 shall be supported.

3.8.4.1.4 All terms shall be optional.

3.8.4.2 Either single- or multi-band residual delays shall be acceptable inputs.

3.8.4.3 It shall be possible to determine solutions with a user specified cadence.

3.8.4.4 It shall be possible to perform linear interpolation on these values during application.

3.8.4.5 It shall be possible to determine a solution based on rates alone to support spectral line cases.

3.8.5 Total delays

3.8.5.1 It should be possible to form total delays from the combination of the initial delay model, any applied calibration data, and residuals determined from fringe-fitting. There should be a table format suitable for storing these data.

3.8.5.1.1 Each set of values should include a reference time, the names of the two antennas forming the baseline, the correlator model delay, applied calibration values, the residual delay found by fringe fitting, and the total of all of these delay values.

3.8.5.1.2 The sign convention and units are to be determined.

3.8.5.2 It should be possible to generate and export a total delay table.

3.9 Data export

It is often useful for a researcher to be able to import and export data and intermediate products from a reduction package, even when the package is fairly complete in terms of the available functionality (e.g., AIPS). Data export can take multiple forms, ranging from ASCII text to more specialized formats.

Millimeter-wavelength VLBI bears some similarities to optical interferometry in that both techniques must contend with a highly variable atmosphere and sparse observing arrays. The main observables of optical interferometry, visibility amplitudes or powers (amplitude squared) and closure phases, are the same observables that are used in millimeter VLBI. Optical interferometric imaging using forward data fitting (rather than deconvolution) have made large advances in recent years, and algorithmic development by the optical interferometric community continues at a rapid pace. While inclusion of optical interferometric imaging algorithms into CASA is an eventual option, a simpler solution is to allow the export of data in the OIFITS format that optical interferometric imaging software expects.

The usefulness of text output (and input) cannot be underrated as a general capability in a wide variety of contexts. Many AIPS users make use of tasks such as TBOUT and UVPRT, as well as adverbs such as OUTTEXT and OUTPRINT, to examine and make use of their data and calibration outside the AIPS environment. These tools give users the flexibility to create tools and use data in ways unanticipated by the package programmers.

Data export should include as complete a collection of associated metadata (calibration, flags, weather, delay models, …) as the output format allows. Reimportation of data exported to formats supported by the required data import formats should result in as identical a measurement set as possible given possible mismatches in format concepts.

3.9.1 Data

3.9.1.1 It must be possible to export data, including visibilities and closure quantities.

3.9.1.2 It shall be possible to export data in AIPS FITS (*UVFITS*) format.

3.9.1.3 It shall be possible to export data in OIFITS format.

3.9.1.4 It shall be possible to export data in Mark4 format.

3.9.1.5 It should be possible to export data in a well-defined text format.

3.9.2 Calibration

3.9.2.1 It should be possible to export calibration information in a well-defined text format.

3.10 Miscellaneous requirements

Most of the following miscellaneous requirements are likely to be implemented already as part of a standard interferometry data reduction package but are included here to ensure the functionality is present.

3.10.1 Calibration

3.10.1.1 It shall be possible to transfer calibration tables derived from one measurement set to another provided the donor measurement set time range spans that of the recipient.

3.10.2 Ionospheric Correction

3.10.2.1 It shall be possible to derive a dispersive delay calibration table from external ionosphere data. (Equivalent to AIPS task TECOR)

3.10.2.2 External ionosphere data in IONEX format should be downloaded on demand from cddis.gsfc.nasa.gov. (For reference implementation, see AIPS task TECOR)

3.10.2.2.1

3.10.2.3 In determining amplitude calibration it shall be possible to include a normalization step to prevent wander of the flux scale.

3.10.2.3.1 It shall be possible to limit that normalization to a subset of antennas and to a subset of elevation angles. Equivalent functionality in AIPS comes in the form of the ANTUSE and CPARM(1) parameters of CALIB.

3.10.3 Spectral Line Considerations

3.10.3.1 Frequency reference frame conversion from barycentric to object LSR shall be supported.

3.10.4 Imaging

3.10.4.1 It shall be possible to reliably image in cases where the polarized flux density exceeds that of Stokes I flux density as can occur with under-sampled VLBI *UV* coverage.

3.10.4.2 Imaging algorithms such as NNLS should be available for the common case of strong partially resolved sources.

3.10.4.3 Sparse, incomplete, and very non-uniform *UV* coverage shall be supported

3.10.4.3.1 Over-weighting catastrophies should be avoidable when applying robust weighting

3.10.4.3.2 Large (up to 50%) positive and negative dirty beam sidelobes should not inhibit imaging

3.10.4.4 2D tapering

3.10.5 Data Weights

3.10.5.1 It shall be possible to plot visibility weights in the same manner that visibility amplitudes can be plotted

3.10.5.2 It should be possible to plot weights as error bars

3.10.5.2.1 For visibility phase

3.10.5.2.2 For visibility amplitudes

3.10.5.2.3 For closure quantities

3.10.5.3 It should be possible to use sigma^-n for n not restricted to 2 in the following cases:

3.10.5.3.1 Data calibration

3.10.5.3.2 Data averaging

3.10.5.3.3 Imaging

3.10.6 Scans

3.10.6.1 A table of scan listings should be importable and exportable

3.10.6.2 It shall be possible for the user to make simple changes to the scan structure (simple meaning such that different observing modes don't get mixed within one scan)

3.10.6.2.1 Change in scan start and stop times

3.10.6.2.2 Subdivision of one scan into two or more

3.10.6.2.3 Merging of two or more scans

3.10.6.2.4 Change of scan intent

4 REQUIREMENT ANALYSIS

For each of the above requirements we have generated an engineering estimate of the time required to implement. An associated priority of each requirement for each of the five design reference use cases has also been determined. This priority scale ranges from 1 to 3, with 1 being the highest priority.

			Priority by Use Case				
Requirement Number	**Brief Description**	**Effort Estimate (FTW-Weeks)**	**Simple Imaging**	**Spectroscopy**	**Astrometry**	**Geodetic processing**	**Phased ALMA**
3.2	**Data Import**						
3.2.1	Data selection						
3.2.1.1	Selection during import shall be supported						
3.2.1.1.1	Import selection based on Time shall be supported.	1					
3.2.1.1.2	Import selection based on Source shall be supported.	1	2	2	2	2	2
3.2.1.1.3	Import selection based on Spectral window shall be supported.	1	2	1			1
3.2.1.1.4	Import selection based on Antenna shall be supported		2	2	2	2	2
3.2.1.1.5	Import selection based on Sub Array shall be supported					2	
3.2.2	Precision and data dimensions		2	1	1	1	1
3.2.2.1	Both cross- and auto-correlation data shall be supported.	0	1	1	1		1
3.2.2.2	Visibility data represented by single precision complex number will suffice.	0					
3.2.2.3	Timestamps on visibility data shall be capable of representing time to 1us precision or better.	0					
3.2.2.4	Databases with up to 64 distinct antennas shall be supported.	0				2	
3.2.2.5	Simultaneous subarrays of antennas, changing in membership over time, shall be supported.	0			2	1	
3.2.2.5.1	At least 16 subarrays shall be supported.	0				1	
3.2.2.5.2	It shall be possible for the number of subarrays to change in time.	1				1	
3.2.2.5.3	Only subarray membership must be maintained, unique subarray identity is not required.	1					
3.2.2.5.4	It must be possible to use any data for an antenna, regardless of changing subarray membership, to determine calibration for that antenna.		3	3	2	2	2
3.2.2.5.5	It must be possible to apply calibration determined in any combination of subarrays to scans in any other subarray with appropriately similar observing parameters.		3	3	2	2	2
3.2.2.5.6	It must be possible to display visibility and calibration data for an antenna as a function of time independent of subarray participation.		3	3	2	2	2
3.2.2.6	Visibility integration durations as short as 1ms shall be supported.	0	3				
3.2.2.7	Spectral resolution as fine as 1 Hz shall be supported.	0		2			
3.2.2.8	Spectral window bandwidths ranging from 1 Hz to 64 GHz must be supported.	0					
3.2.2.9	A minimum of 131072 (128 Ki) spectral points per spectral window must be supported.	0	2	1			1
3.2.2.10	Sky frequencies up to 600 GHz must be supported.[1]	0	2	2	2	2	1
3.2.2.11	Continous observations lasting longer up to 14 days must be supported.	0				2	
3.2.3	Meta Data As available the following tables, as defined by the IDI-FITS convention or as appropriate for other supported formats, shall be importable into CASA data structures:						
3.2.3.1	ARRAY_GEOMETRY		1	1	1	1	1
3.2.3.2	ANTENNA		1	1	1	1	1
3.2.3.3	FREQUENCY		1	1	1	1	1
3.2.3.4	SOURCE		1	1	1	1	1
3.2.3.5	INTERFEROMETER_MODEL				2	1	2
3.2.3.6	SYSTEM_TEMPERATURE		1	1	2		1
3.2.3.7	GAIN_CURVE		1	1	2		1
3.2.3.8	PHASE-CAL		2		1	1	
3.2.3.9	FLAG		1	1	1	2	1
3.2.3.10	WEATHER		1	1	2	1	1
3.2.3.11	MODEL_COMPS		2		2	1	
3.2.4	Supported import formats						
3.2.4.1	Import of FITS-IDI data, as defined in AIPS memo 114r shall be supported.	6	1	1	1	2	1
3.2.4.2	Import of data in Mark4 format shall be supported	12	3		2	1	
3.2.4.3	Import of data in the AIPS FITS format, as defined in AIPS memo 117 shall be supported.	6	2	2	2	2	2
3.3	**Amplitude Calibration**						
3.3.1	Autocorrelation correction						
3.3.1.1	A facility to divide cross-correlation values by the geometric mean of the associated and time-coincedent autocorrelations is required.	2	1	1	2		1
3.3.1.2	A mechanism to plot the time variability of spectral window average autocorrelations would be useful.	2	1	1	2		1

Requirement Number	Brief Description	Effort Estimate (FTW-Weeks)	Priority by Use Case				
			Simple Imaging	Spectroscopy	Astrometry	Geodetic processing	Phased ALMA
3.3.1.3	Both time averaging (if any) during determination and interpolation (if any) during application should have the capability of respecting scan boundaries.	0	1	1	2		1
3.3.2	System temperature						
3.3.2.1	System temperature tables imported with visibility data shall be able to be applied to the data and weights.	1	1	1	2	3	1
3.3.3.3	It should be possible to import system temperature data in the standard "TSM" format (See AIPS task ANTAB)	2	2	2	2	3	2
3.3.3	Opacity correction						
3.3.3.1	It shall be possible to specify a zenith opacity.	1	1	1	3		1
3.3.3.2	It shall be possible to use system temperature measurements made over a specified period as input to solve for zenith opacity.	2	1	1	3		1
3.3.3.2.1	For antennas with characterized spill-over and metrology data, the ground temperature should be estimated and removed before solving for zenith opacity.	1	2	2	3		2
3.3.3.3.3	It shall be possible to specify an elevation range for data to fit.	1	1	1	2		1
3.3.3.2.3	Both least squares and alternatives that are robust agains errant data points shall be available	2	1	1	2		1
3.3.3.2.4	Fits to system temperature to determine the reciver temperature should be robust agains weather-induced variationand biased toward the lower values obtained during relatively clear weather.		1	1	2		1
3.3.3.5	Given zenith opacity, possibly as a function of time, correction for opacity based on sec(z) shall be possible.	2	1	1	2		1
3.3.4	Antenna gain						
3.3.4.1	Elevation gain curve tables naturally imported with visibility data should be usable.	2	1	1	2		1
3.3.4.1.1	Support for antenna mounts other than alt-az should be supported. This implies the use 2-D gain curves that are functions of both orientation angles.		2	2	3	3	2
3.3.4.2	Application of different elevation gain curves on different sub-bands should be supported. This is especially important in cases where dual-band observing (e.g., S-band and X-band simultaneously) is employed.	2	2	2	1		2
3.3.4.3	Updated elevation gain curve tables for supported antennas should be downloadable from within CASA.	4	3	3	3		3
3.3.5	Decorrelation correction						
3.3.5.1	Correlator averaging parameters, possibly as a function of baseline, should be stored with the visibility database.	2	1	2	3		1
3.3.5.2	It should be possible to disable application of this correction.	2	2	2	2		2
3.3.6	Primary beam correction						
3.3.6.1	A correction for the antenna primary beam based on the vector offset between the antenna pointing center and the correlator phase center shall be possible.	0	1		2		1
3.3.6.2	It should be possible to correct for the primary beam without detailed user input, either through built in models or through automated download.	2	2		2		1
3.3.6.3	It should be possible for a user to supply a detailed primary beam model tabulated in two dimensions.	1	3		3		3
3.3.6.4	It should be possible for a user to supply a simple radial polynomial model.	1	2		2		2
3.3.6.5	Beam shape corrections for phased arrays elements shall be possible.		3				1
3.3.6.5.1	Input parameters describing a general elliptical Gaussian zenith beam shall be supported.	2	2		2		2
3.3.6.5.2	This zenith beam shall be appropriately stretched as a function of time to account for fore-shortening of the array as seen by the source.	2	3				1
3.3.6.5.3	The beam parameters should be scaled in angle with observing wavelength during application	2	1		2		1
3.3.6.5.4	Dirty beams separately determined for the phased-array elements shall be usable as good approximations of the phased-array beam.		3				2
3.3.7	Digital corrections						
3.3.7.1	It shall be possible to apply the Van Vleck (and its >1-bit equivalents) to the visibility data based on state counts inferred from the autocorrelation data.	2	1	1	2	2	1
3.3.8	Calibration editing						

			Priority by Use Case				
Requirement Number	**Brief Description**	**Effort Estimate (FTW-Weeks)**	**Simple Imaging**	**Spectroscopy**	**Astrometry**	**Geodetic processing**	**Phased ALMA**
3.3.8.1	It shall be possible to manually edit input calibration data.	2	1	1	2	2	1
3.3.8.2	It shall be possible to visually edit input calibration data graphically.	0					
3.3.8.3	It shall be possible to smooth input calibration data, with user selectable options for not smoothing across scan boundaries.		2	2	2	2	2
3.4	**Pulse Cal data handling**						
3.4.1	Data Structure						
3.4.1.1	Import of Pulse Cal data shall be supported	2	1	1	1	1	2
3.4.1.1.1	Pulse cal data attached to a FITS file shall be importable.	1	1	1	1	1	
3.4.1.1.2	Import of an ASCII text file in TSM format shall be supported.	1	2	2	2	2	
3.4.1.1.3	Each pulse cal measurement contains a real and imaginary value and the time interval corresponding to that measurement.	0					
3.4.1.1.4	A pulse cal set is the collection of all pulse cal measurements made over one time interval at one antenna.	0					
3.4.1.2	Between 0 and B+1 pulse cal tones per spectral window must be supported where B is the spectral window bandwidth in MHz.	0					
3.4.1.3	A cadence as fast as one pulse cal set per visibility integration time should be supported.	0					
3.4.1.4	Time averaged pulse cal data should be supported; averaging intervals may be integer multiples of the visibility integration time or not.	0					
3.4.1.5	An optional "cable cal" value, containing an additional instrumental delay correction, should be handled along with pulse cal data.	2	1	1	1	1	2
3.4.1.6	Different antennas may have different pulse cal intervals and/or number of tones.	0					
3.4.1.7	Single precision floating point is sufficient for the real and imaginary parts of each pulse cal measurement; time should be accurately representable to at least 1ms.	0					
3.4.2	Pulse Cal Data Selection						
3.4.2.1	In all cases where pulse cal data is used it shall be possible to select a subset of tones to use.	0	2	2	2	2	
3.4.2.2	Typical selection by antenna(s), time range, source, and spectral window shall be supported.	0	2	2	2	2	
3.4.3	Visualization and editing						
3.4.3.1	It should be possible to plot a time series of pulse cal amplitude or phase as a function of time for a selection of tones tones. Similarly the cable cal values should be plottable.	3	2	2	2	2	1
3.4.3.2	It should be possible to view the amplitude or phase of the time series of a pulse cal set as a raster image.	2	3	3	3	3	
3.4.3.3	It should be possible to flag certain pulse cal values based on a priori information or interactive editing processing; flagged values should be ignored in computations involving the pulse cal data.	0	2	2	2	2	
3.4.4	Calculations to perform						
3.4.4.1	It shall be possible to determine the delay as a function of time based on the Pulse Cal data.	1	1	1	1	1	
3.4.4.1.1	Solutions should be determined separately for each antenna and separately for each spectral window.	1	1	1	1	1	
3.4.4.1.2	It shall be possible to determine a single delay value from multiple spectral windows.	2	1	1	1	1	
3.4.4.1.3	It shall be possible to specify the time interval for the solutions (including the case of or one delay solution per pulse cal set).	0	1	1	1	1	
3.4.4.2	In cases where cable cal data is present there should be the option to include the cable cal correction in the computed delay.	1	1	1	1	1	
3.4.4.3	The determined delays should be stored in a table that can be further edited and applied as necessary.	0	1	1	1	1	
3.4.4.4	It shall be possible to time average pulse cal values.	0	2	2	2	2	
3.4.4.5	It shall be possible to form a bandpass calibration table based on pulse cal sets.	2	2	2	2	2	
3.4.4.6	It shall be possible to form a gain calibration table by extracting the amplitude and/or phase of a single tone of each sub-band.	2	2	2	2	2	
3.4.4.7	It shall be possible to use fringe-fit determined delays to resolve pulse cal delay ambiguities.	3	1	1	1	1	

			Priority by Use Case				
Requirement Number	Brief Description	Effort Estimate (FTW-Weeks)	Simple Imaging	Spectroscopy	Astrometry	Geodetic processing	Phased ALMA
3.4.4.8	Decorrelation corrections for delays determined by pulse cal data should be handled no matter how the pulse cal data is applied.						
3.5	**Fringe fitting**						
3.5.1	General Delay Fitting Requirements						
3.5.1.1	It shall be possible to determine singleband delay, multiband delay, and rate solutions on a single baseline.	6	1	1	1	1	1
3.5.1.1.1	It shall be possible to enforce a zero solution for any of the parameters (pre-fit or post-fit) without biasing the results because of fit covariances.		1	1	1		1
3.5.1.2	It shall be possible to determine global antenna-based single-band delay, multiband delay, and rate solutions on an array of baselines or subset thereof.	6	1	1	1	1	1
3.5.1.2.1	It shall be possible to include in the fit a dispersive multi-band delay component proportional to 1/freq^2. This is relevant for ionospheric calibration.	2	2	2	2	2	2
3.5.1.3	Changes in reference antenna shall be supported in cases where antennas come and go during observing.		1	1	1		1
3.5.1.4	It shall be possible to determine and correct cross-polarized delays and phases.	3	1	1	1	1	1
3.5.2	Selection						
3.5.2.1	It must be possible to select data to fringe fit by spectral channel and spectral window.	0	1	1	1	1	1
3.5.2.2	It must be possible to select subsets of data by time range.	0	1	1	1	1	1
3.5.3	Modes of operation						
3.5.3.1	It must be possible to specify a source model for fringe fitting.	1	1	1	1	1	1
3.5.3.2	It must be possible to specify a desired solution cadence (equivalent to the SOLINT parameter in the AIPS task FRING).	0	1	1	1	1	1
3.5.3.2.1	It shall be possible to overlap time ranges by a specified amount (see the SOLSUB parameter for AIPS task FRING).	4	1	1	1	1	1
3.5.3.2.2	In cases where the cadence does not evenly span the data valid period of a scan an intelligent algorithm to shift the intervals shall be invoked.	3	1	1	1	1	1
3.5.3.3	It must be possible to request a single fringe solution on each and every scan.	0	1	1	1	1	1
3.5.3.4	It must be possible to request fringe solutions spanning more than one scan.	0					
3.5.3.5	[low priority] It shall be possible to fit delay as a spline function over a period of time possibly greater than the coherence time.	3	3	3	3	3	3
3.5.3.5.1	The user shall have control over the spline degrees of freedom.	0					
3.5.3.5.2	Continuity of the spline across scan boundaries must be selectable.	0					
3.5.3.5.3	It should be possible to construct a spline solution based on tabulated solutions.	0					
3.5.3.6	It should be possible to solve for any subset of singleband delay, multiband delay, and rate simultaneously.	1	1	1	1	1	1
3.5.3.7	It should be possible to combine data by IF and/or polarization prior to determination of the delay paramters.	2	1	1	1	1	1
3.5.3.7	It shall be possible for the user to specify delay and rate windows in which to search.	2	1	1	1	1	1
3.5.3.8.1	It shall be possible for user-specified delay and rate windows to be centered at any arbitrary value, not just at zero residual.	0	2	2	2	2	2
3.5.3.8.2	It shall be possible for delay and rate windows, both center and width, to be specified by the user on a per-antenna basis.	0	2	2	2	2	2
3.5.3.9	It must be possible for the user to specify the minimum SNR of acceptable solutions with a sensible default value.	0	1	1	1	1	1
3.5.3.10	It shall be possible to employ baseline stacking to improve detectability of fringes		2	2	2	1	1
3.5.4	Visualization						
3.5.4.1	It is desirable to have a FOURFIT-like visual display of fringe solutions .	2				1	2
3.5.4.1.1	A fringe rate spectrum (Amplitude vs. Delay rate) shall be plotted.	1				1	2
3.5.4.1.2	Single-band delay spectrum (Amplitude vs. Single-band delay) shall be plotted.	1				1	2

			Priority by Use Case				
Requirement Number	**Brief Description**	**Effort Estimate (FTW-Weeks)**	**Simple Imaging**	**Spectroscopy**	**Astrometry**	**Geodetic processing**	**Phased ALMA**
3.5.4.1.3	Multi-band delay spectrum (Amplitude vs. Multi-band delay) shall be plotted.	1				1	2
3.5.4.2	It shall be possible to plot the lag spectrum (FT of visibility spectrum) both before and after application of delay calibration.	1	1	1	1	1	1
3.5.4.2.1	Data selection and averaging parameters comparable to CASA's bandpass plotting capability shall be supported.	0	1	1	1	1	1
3.5.4.2.2	It shall be possible to calculate fringe amplitudes and SNRs on a per-baseline basis over a regular grid of values in delay and rate spanning the relevant ambiguity windows or user-specified subsets thereof.	2	1	1	1	1	1
3.5.4.2.3	It is desirable that the user be able to specify whether the grid in 3.5.4.2.2 should be centered on zero residual delay and rate or on a nonzero delay and rate solution that has been previously obtained.	0	1	1	1	1	1
3.5.4.3.5	It shall be possible to obtain the location of the maximum in either amplitude or SNR, with interpolation between nearby points used to increase the precision of this solution beyond the grid spacing interval.	2	1	1	1	1	1
3.5.4.2.5	It shall be possible to produce a two-dimensional plot of the fringe amplitude or SNR as a function of delay and rate.	1	1	1	1	1	1
3.5.4.2.6	It is desirable that, if the a priori expected location of the peak in delay/rate space on a baseline can be determined from known good fringe solutions on other baselines that close, this location can also be plotted in 3.5.4.2.5.	2	1	1	1	1	1
3.5.4.2.7	It shall be possible for the user to interact with the plots in 3.5.4.2.5 to accept or reject solutions.	0	1	1	1	1	1
3.5.4.2.8	It shall be possible to redo fringe fitting on only that subset of scans which are marked as non-detections	0	1	1	1	1	1
3.5.4.2.9	The above requirements apply to both coherent and incoherent fringe searches.	0	1	1	1	1	1
3.6	**Short coherence time algorithms**						
3.6.1	General						
3.6.1.1	It is acceptable to require that segmentation times be an integer multiple of the correlator accumulation period. User-specified values that violate this condition may be rounded to the nearest multiple.	2					2
3.6.1.2	It shall be possible to apply a priori phase information (as from water vapor radiometry) in order to improve coherence times.	2	3	3	3	3	2
3.6.2	Incoherent averaging						
3.6.2.1	It must be possible to calculate the incoherent-averaged amplitude on a scan and baseline combination, ignoring any flagged data.	2				1	1
3.6.2.2	It must be possible to specify the segmentation time for incoherent averaging.	1				1	1
3.6.2.3	The incoherent average must be noise-debiased.	3				1	1
3.6.3	Coherence time determination						
3.6.3.1	Given that fringe solutions can be obtained for a given data set, it shall be possible to determine the coherence times (specified below) of a data set.	3	2	2	2	2	1
3.6.3.1.1	The nominal allowed amplitude loss that defines the no-loss coherence time shall be user-specifiable with a sensible default value.	0	2	2	2	2	1
3.6.3.1.2	The segmentation time at which the SNR of fringe detection is maximized (search coherence time) shall be determined.	1	2	2	2	2	1
3.6.3.1.3	Coherence times shall be determined on a station- or baseline-dependent basis.	1	2	2	2	2	1
3.6.3.2	When fringes are not detected on a source on a baseline, it should be possible to estimate coherence times by interpolating in time, guided by the observed source elevation and other atmospheric information.	3				2	1
3.6.3.3	It should be possible to determine maximum coherence times for an observing array or subset thereof as a function of time. This is the minimum of the coherence times of all selected baselines.	1	2	2	2	2	2
3.6.4	Incoherent fringe fitting						
3.6.4.1	It must be possible to perform incoherent fringe fitting.	4					2

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3.6.4.1.1	Standard input parameters for coherent fringe fitting is required.	0					
3.6.4.1.2	An additional parameter specifying incoherent segmentation time is required.	0					
3.6.4.2	It must be possible to visualize the results of incoherent fringe fitting in order for the user to be able to determine the quality of a solution.	2					2
3.6.4.3	It should be possible to derive upper limits on amplitudes from non-detected scans, preferably with a user-specified minimum SNR of detection that has a sensible default possibly derived from the data.	1					2
3.6.5	Closure quantities						
3.6.5.1	It shall be possible to use as input any measurement set column with standard data selection options.	2					2
3.6.5.2	It shall be possible to divide the visibility input by a model image.	1					2
3.6.5.3	Closure phases						2
3.6.5.3.1	It shall be possible to compute and plot closure phases akin to AIPS task CLPLT.	2					2
3.6.5.3.1.1	It shall be possible to specify a segmentation time (or solution interval) when computing closure phases, with sensible default.	1					2
3.6.5.3.2	It must be possible to time-average closure phases.	2					2
3.6.5.4	Closure amplitudes						2
3.6.5.4.1	It must be possible to compute and plot closure amplitudes .	2					2
3.6.5.5	Closure delays and rates						2
3.6.5.5.1	It must be possible to compute and plot closure delays and rates.	2					2
3.7	**Polarization**						
3.7.1	Polarization Calibration						
3.7.1.1	It must be possible to determine and correct for antenna polarization leakages.		1	1	1	1	1
3.7.1.2	It must be possible to correct observed visibility phases for field rotation angle (parallactic angle) effects.		1	1	1	1	1
3.7.2	Polarization Plotting						
3.7.2.1	It shall be possible to compute and plot polarimetric amplitude ratios (e.g., RL/LL).		2	2	2	2	2
3.7.2.2	It shall be possible to compute and plot polarimetric phase differences (e.g., RL-LL).		2	2	2	2	2
3.7.2.3	It shall be possible to estimate *resolved* calibrator polarization components in the instrumental polarization solve.		2				2
3.7.3	Polarization Basis Conversion						
3.7.3.1	It shall be possible to convert from the observed polarization basis to Stokes quantities.		1	1	1	1	1
3.7.3.2	In order to correct for possible small errors in the XY-to-RL polarization basis conversion anticipated for phased ALMA data after correlation, it must be necessary to solve for and apply an additional station-based rotation.					3	2
3.7.4	Calibration						
3.7.4.1	It shall be possible to transfer delay calibration information across polarizations to increase coherence time:						2
3.7.4.1.1	It shall be possible to use fringe solutions in one polarization (e.g., RR) to assist in fringe detection in another polarization (e.g., RL) via baseline stacking techniques.		2	2	2	2	2
3.7.4.1.2	It shall be possible to use the visibility phases as a function of time on a baseline in one polarization to attempt to extend the coherence time in another polarization.						2
3.8	**Model accountability and manipulation**						
3.8.1	Delay model propagation						
3.8.1.1	Throughout processing the delay model shall be stored in conjunction with the data, further the delay model shall be kept consistent with the current state of the data.	4	2	2	1	1	1
3.8.1.1.1	Delay model versioning must be maintained even after splitting and recombining measurement sets.	1	2	2	1	1	1
3.8.1.1.2	Throughout processing delays shall be represented to at least 1 femtosecond resolution.	0	2	2	1	1	1
3.8.1.1.3	It shall be possible to maintain separation of delay effects (i.e., vacuum propagation, atmospheric terms, etc.) within the delay model.	1	2	2	1	1	1

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3.8.1.1.4	It must be possible to store the delay model as a polynomial spline. Polynomials with up to 6 terms must be supported. The interval of validity of a specific polynomial must be stored and can range from 1 second to 1 hour. A given polynomial must be identified with a particular source.	2	2	2	1	1	1
3.8.1.2	The delay model used during correlation shall be imported with the visibility data..	2	2	2	1	1	1
3.8.1.3	All calibrations containing a delay shall modify the delay model table to ensure consistence with the data, in particular the total delay shall be unchanged.	1			1	1	1
3.8.1.4	During any operation where a new visibility database is formed, a delay model table consistent with the state of the new database shall be written	1			1	1	1
3.8.2	Delay model adjustments						
3.8.2.1	It shall be possible to apply delay corrections to the data with improved EOPs.	2	1	1	1	1	1
3.8.2.2	It shall be possible to correct for antenna position errors.	2	1	1	1	1	1
3.8.2.2.1	New antenna position shall be specified as new ITRF frame coordinates for one or more antennas.	0					
3.8.2.2.2	Antenna position corrections up to 10 meters should be supported.	0					
3.8.2.2.3	The antenna position as reported in the antenna table shall be updated.	1					
3.8.2.3	Source position adjustment should be possible.	2	1	1	1	1	1
3.8.2.3.1	New source positions shall be specified in J2000 frame coordinates.	0					
3.8.2.3.2	The applied correction shall produce phases equivalent to those that would come from correlation with the new source coordinates.	0					
3.8.2.3.3	The coordinates of the correlation center in the data set shall be updated.	0					
3.8.2.3.4	The baseline vectors (U,V,Ws) shall be updated to be consistent with the new correlation center.	0					
3.8.2.3.5	Source position corrections up to 1 arcminute should be supported.	0					
3.8.2.4	Manual delay and rate adjustment shall be supported.	2	1	1	1	1	1
3.8.2.4.1	Data selection options should include time range, antenna, spectral window, and source.	0					
3.8.3	Delay model replacement						
3.8.3.1	It shall be possible to derive a delay correction from the difference between the current delay model table and an external delay model.	2	2	2	2		2
3.8.3.2	It should be possible to determine which delay model (either the original or some identifier associated with the replaced model) is attached to a particular database or portion thereof.	0			2		2
3.8.3.3	The format of the delay model to import is to be determined.	4					
3.8.3.4	It shall be possible to export the delay model from a visibility database in suitable form to apply it to another database.	2	2	2	2		2
3.8.4	Atmosphere / clock solver (equivalent to DELZN in AIPS)						
3.8.4.1	It shall be possible to derive and correct clock offsets and atmospheric delays from a set of residual delay measurements.	3	2	2	1		1
3.8.4.1.1	Derivation of delay and delay rates shall be supported.	0					
3.8.4.1.2	An additional atmospheric mapping function shall be supported	0					
3.8.4.1.2.1	The trivial term proportional to sec(z) shall be supported		1	2	2		1
3.8.4.1.2.2	The Vienna Mapping Function (see http://mars.hg.tuwien.ac.at/~ecmwf1/) shall be supported		2	3	3		2
3.8.4.1.2.3	The Niell Mapping Function shall be supported.		2	3	3		2
3.8.4.1.3	An ionospheric term of the form sec(z)/freq^2 shall be supported.	0					
3.8.4.1.4	All terms shall be optional.	0					
3.8.4.2	Either single- or multi-band residual delays shall be acceptable inputs.	0					
3.8.4.3	It shall be possible to determine solutions with a user specified cadence.	0					
3.8.4.4	It shall be possible to perform linear interpolation on these values during application.	0					
3.8.4.5	It shall be possible to determine a solution based on rates alone to support spectral line cases.			2			

			Priority by Use Case				
Requirement Number	**Brief Description**	**Effort Estimate (FTW-Weeks)**	**Simple Imaging**	**Spectroscopy**	**Astrometry**	**Geodetic processing**	**Phased ALMA**
3.8.5	Total delays						
3.8.5.1	It should be possible to form total delays from the combination of the initial delay model, any applied calibration data, and residuals determined from fringe-fitting. There should be a table format suitable for storing these data.	4			2	1	2
3.8.5.1.1	Each set of values should include a reference time, the names of the two antennas forming the baseline, the correlator model delay, applied calibration values, the residual delay found by fringe fitting, and the total of all of these delay values.	0					
3.8.5.1.2	The sign convention used in this table should be <FIXME>. Units of <FIXME> should be used.	0					
3.8.5.2	It should be possible to generate and export a total delay table.	0			2	2	2
3.9	**Data export**						
3.9.1	Data						
3.9.1.1	It must be possible to export data, including visibilities and closure quantities .		1	1	1	1	1
3.9.1.2	It shall be possible to export data in AIPS FITS (UVFITS) format.	6	1	1	1	2	1
3.9.1.3	It shall be possible to export data in OIFITS format.	10				3	
3.9.1.4	It shall be possible to export data in Mark4 format.	8				2	
3.9.1.5	It should be possible to export data in a well-defined text format.	8	2	2	2	2	2
3.9.2	Calibration						
3.9.2.1	It should be possible to export calibration information in a well-defined text format.	2	2	2	2	2	2
3.10	**Miscellaneous requirements**						
3.10.1	Calibration						
3.10.1.1	It shall be possible to transfer calibration tables derived from one measurement set to another provided the donor measurement set time range spans that of the recipient.	0	2	2	1		2
3.10.2	Ionospheric Correction						
3.10.1.1	It shall be possible to derive a dispersive delay calibration table from external ionosphere data. (Equivalent to AIPS task TECOR)	3	2	2	1		
3.10.1.2	External ionosphere data in IONEX format should be downloaded on demand from cddis.gsfc.nasa.gov. (For reference implementation, see AIPS task TECOR)	2	2	2	1		
3.10.1.3	In determining amplitude calibration it shall be possible to include a normalization step to prevent wander of the flux scale.	1	1	1	1		1
3.10.1.3.1	It shall be possible to limit that normalization to a subset of antennas and to a subset of elevation angles.	1	1	1	1		1
3.10.3 ???	Spectral Line Consideration						
3.10.3.1	Frequency reference frame conversion from barycentric to object LSR shall be supported.	0		1			1
3.10.4	Imaging						
3.10.4.1	It shall be possible to reliably image in cases where the polarized flux density exceeds that of Stokes I flux density as can occur with under-sampled VLBI *UV* coverage.		1	2	2		1
3.10.4.2	Imaging algorithms such as NNLS should be available for the common case of strong partially resolved sources.	4	2	2	2		2
3.10.4.3	Sparse, incomplete, and very non-uniform UV coverage shall be supported	2	2	2	2		2
3.10.4.3.1	Over-weighting catastrophies should be avoidable when applying robust weighting		1	1	2		1
3.10.4.3.2	Large (up to 50%) positive and negative dirty beam sidelobes should not inhibit imaging		1	1	2		1
3.10.4.4	2-D Tapering shall be supported	4	2	2	2		2
3.10.5	Data Weights						
3.10.5.1	It shall be possible to plot visibility weights in the same manner that visibility amplitudes can be plotted	2	1	1	1	1	1
3.10.5.2	It should be possible to plot weights as error bars	1	3	3	3	3	3
3.10.5.2.1	On visibility phase		3	3	3	3	3
3.10.5.2.2	On visibility amplitudes		3	3	3	3	3
3.10.5.2.3	For closure quantities		3	3	3	3	3
3.10.5.3	It should be possible to use sigma^-n for n not restricted to 2 in the following cases:						
3.10.5.3.1	Data calibration	0	2	2	2	2	2
3.10.5.3.2	Data averaging	0	3	3	3	3	3

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3.10.5.3.3	Imaging	0	2	2	2	2	2
3.10.6	Scans						
3.10.6.1	A table of scan listings should be importable and exportable	2	3	3	3	3	3
3.10.6.2	t shall be possible for the user to make simple changes to the scan structure (simple meaning such that different observing modes don’t get mixed within one scan)		3	3	3	3	3
3.10.6.2.1	Change in scan start and stop times	0	3	3	3	3	3
3.10.6.2.2	Subdivision of one scan into two or more	0	3	3	3	3	3
3.10.6.2.3	Merging of two or more scans	0	3	3	3	3	3
3.10.6.2.4	Change of scan intent.	0	2	2	2	2	2