MRO INTERFEROMETER MEMO
Calibration Requirements
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OBJECTIVE:
To quantify the calibration requirements for the MRO interferometer.

SUMMARY:
A total calibration error of 2 percent rms in V^2 and 0.8 degree rms in the triple product phase is a goal for bright, unresolved sources in "typical" seeing conditions. These errors must be divided amongst the various sources of calibration error, typically of order 1 percent each. The typical calibration procedure is to observe reference stars within 5 degrees and within 10 minutes of time of the target star observation. There is no science requirement for any photometric accuracy.

INTRODUCTION:
For bright objects, visibility calibration uncertainties are the major limitation to image quality in the interferometer. By visibility we here mean the complex visibility consisting of both amplitude and phase, although in practice we will mostly measure the mean squared visibility (denoted here as V^2) and the bispectrum phase i.e. closure phase. We will derive things in terms of a complex visibility to start with, because the rules of thumb for image reconstruction from complex visibilities are better understood than those for images made from power spectrum and bispectrum measurements.

Usually, we adopt a procedure of interleaving observations of the target source and a reference star. The observation of the reference star then gives a measure of the so-called *system visibility*, which is defined as a factor which is assumed to act multiplicatively on the object visibility to give the observed visibility. Calibration errors arise if either (a) the system visibility is incorrectly measured or (b) the system visibility changes between observation of the target and the reference. The main sources of error in measuring the system visibility are instrumental noise, bias and cross-talk, and uncertainties in the diameter of the reference star, and the main causes of change in the system visibility are atmospheric seeing variability and instrumental variability due to e.g. thermal or mechanical changes.

We need to set goals for the visibility calibration in order to set targets for many design decisions including polarisation fidelity, beam-combiner crosstalk, spatial filtering, calibrator star catalogues and so forth.

TOP-LEVEL REQUIREMENT:
There are many possible ways to specify the calibration requirements: we will just point out a few here.

1. Image quality: Image qualities as good as the best Keck aperture masking data i.e. a dynamic range of 200:1 would be adequate. A goal of 500:1 would allow exceptional imaging for an optical interferometer and is within the normal range of current radio interferometers. *Assuming* that calibration errors are independent from one u-v point to another then an image reconstructed from 100 u-v data points would have the required dynamic range if every point has a calibration uncertainty of 2 percent. A high-dynamic-range image would typically be made from many more u-v data points, but the assumption that they all have independent errors is probably incorrect.
2. Prior art: The best calibration achieved to date for a single data point is 0.1 percent (Foresto et al.), but this was on stars brighter than 0 magnitude. More typical values are around 1 percent, still on very bright stars.
3. Equipartition of errors: There is no point in reducing calibration uncertainties if other uncertainties dominate. Crosstalk errors will depend on beam combiner implementation, but errors of order 1 percent or more are typical for many designs. Photon noise errors depend strongly on source brightness and visibility. If we estimate that most observations will have a signal-to-noise ratio of order 1 per coherent integration, then for a 10-millisecond coherent integration we will have a 1 percent rms uncertainty after 100 seconds of incoherent integration.

The above arguments imply that a total visibility calibration error of about 2 percent will be acceptable, and that individual contributions to this level of error on the order of 1 percent are achievable. (Four sources of error each 1 percent in magnitude and acting in quadrature are allowable).

FIRST-ORDER ERROR BUDGETING:

This error can be equally divided between the amplitude and phase components of a complex visibility measurement, leading to a 1.4 percent error for each component of the complex error phasor. What we typically measure in order to infer the amplitude is V^2 which will have approximately twice the error as V, i.e. the V^2 error budget is 2.8 percent, which we will round down here to 2 percent. It is harder to directly relate the error on the triple product phase to that on a single complex amplitude, one argument would suggest that the error allowable is 3 times as much as that allowable on a single phasor, another would argue that it is exactly the same. We will go for the more conservative estimate and allow only 1.4 percent error, i.e. 0.8 degrees of phase error.

These two errors must then be broken down amongst the various error sources. A first order estimate of 1 percent error to each component contributing to V^2 calibration errors and 0.4 degree to each source of error contributing to triple product errors is advised, but will have to be revised as new error sources are accounted for.

REFERENCE STAR REQUIREMENTS:

Atmospheric and instrumental contributions to the system visibility vary both in time and position on the sky, and therefore it is best to perform calibration observations as close as possible in time and space to the reference target.

The availability of reference stars in the close neighborhood of the target is the limiting factor in this procedure. Reference stars should not be too faint or we will not get an accurate measure of their visibility, nor should they be too bright or they will tend to be large and hence resolved. A typical reference star magnitude of V=6 is adopted as a rather conservative (i.e. bright) standard. Approximate figures for the stellar densities at this magnitude are about 1 such star in a 2x2 degree patch on the sky at the North Galactic pole (N.B. this figure needs some further refinement as it is an extrapolation of fainter star counts). Half of these stars will be binary and another half we can assume are unusable for some other reason. Hence there should be a very good chance of finding a reference star in a 10-degree square patch, i.e. roughly within 5 degrees of the target.

Atmospheric seeing fluctuates by factors of order 2 on timescales of both seconds and hours. Experience and practical limitations on SNR, slewing times and observing efficiency suggest that source-calibrator interleaving at 10-minute intervals is about right.

PHOTOMETRIC REQUIREMENTS:

It would be nice (but not essential for most of the science) to do photometry of our science targets, but this is vastly better when done by single telescopes which can observe source and calibrator simultaneously. Photometric errors of less than 1 percent are normal with single telescopes, but an error of around 10 percent in relative photometry is to be expected with any interferometer system that incorporates any form of spatial filtering for visibility calibration purposes (because of Strehl fluctuations).

Photometric observations to determine the system throughput are needed for operational monitoring, but these are perhaps best done with a combination of internal measurements and measurements using the finder cameras to determine the throughput of optics which are difficult to determine with internal light sources, i.e. the large telescope optics.

Relative photometry of the light from different array elements is an important part of visibility calibration when spatial filters are used, but this is distinct from any photometric requirement in the traditional sense.