Continuum Phase Referencing from Masers

W. D. Cotton, March 25, 2020

***Abstract*—This memo explores the use of a phase calibration technique initially developed by Reid and Menton to use bright masers around evolved stars to calibrate wideband continuum data to allow the detection of the faint photospheric radio emission. The absolute location of the derived images are uncertain due to the poorly know location of the maser spot(s) used as a phase reference but the relative astrometry of the masers and the continuum should be very accurate. An example is given using EVLA A configuration, Summer time data demonstrating its efficacy.**

***Index Terms*—phase calibration**

I. INTRODUCTION

THERMAL emission from stars more distant than the Sun is difficult to detect at radio wavelengths due to their small apparent size. Furthermore, the spectrum of photospheric emission rises with frequency so it is desirable to observe these sources at high frequency and relatively high (sub arcsecond) resolution where tropospheric phase fluctuations are large and rapid. Fortunately, red giant stars, some of which have an angular size large enough to resolve with instruments like the VLA, may also have bright circumstellar masers of molecules like H_2O and SiO. A technique for using these masers to phase reference the continuum data to masers was developed in [1] and [2].

The technique described in [1] and [2] was for a relatively narrow band system for which adequate prior delay calibration was applied to the observations and did not need to be applied during the data analysis. The current EVLA system has much wider bandwidth and delay calibration must be incorporated into the data analysis. This memo explores incorporating phase referencing to circumstellar masers into wideband continuum observations. The technique described here has been implemented in the calibration software in the Obit package [3] [1].

II. MASERS AND EVOLVED STARS

Low mass stars ($< 8\mathrm{M}_\odot$) eventually deplete their hydrogen and the outer parts expand and cool and may develop pulsational instabilities. During this "red giant" phase, much of the mass of the star is dispersed to interstellar space. In oxygen rich stars, molecules such as SiO and H_2O form in the extended atmospheres and form masers. These nonthermal masers can be very bright, greatly exceeding the brightness of the thermal photosphere, albeit over a very narrow frequency range.

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[1]http://www.cv.nrao.edu/∼bcotton/Obit.html

III. WIDEBAND PHASE REFERENCING

The EVLA has the capability to simultaneously record a wideband (up to 8 GHz) continuum data and narrowband data for spectroscopy. Since both data streams are derived from the same front end signals, calibration derived from one can be applied to the other. Calibration consists of a number of components, group delay, bandpass, amplitude and phase.

The standard calibration of continuum data uses observations of standard calibrators to derive the various calibration parameters which are then applied to the target. Delay, bandpass and amplitude calibration are generally stable enough that this calibration transfer work well but the phase is less stable at short cm - mm wavelengths as the calibrators are observed at a different time and with different paths through the troposphere. Rapid position switching between a very nearby calibrator and the target reduces this problem but with a large calibration overhead.

The line data also includes the calibrators which can be used for bandpass calibration but may be inadequate for delay calibration. A bright, simple (or self calibrated) maser can be used for measuring the time dependent phase fluctuations.

The general technique described in this memo is to first do a standard external calibration on the continuum data and then apply the derived gain table to the line data. The line data is then bandpass and Doppler calibrated and a strong, simple maser feature identified. A self calibration of this maser feature produces a gain table which can then be applied to both the full line spectrum and the continuum data.

A. Delay and Phase Transfer

The major complication is that measured "phase" is really a phase delay which is ambiguous - by some unknown number of turns. For a non dispersive medium such as the troposphere at radio wavelengths, the measured phase residual (ϕ) is a function of the group delay residual (τ):

$$\phi \ = \ 2\pi\tau\nu$$

where ν is the observing frequency. Since the spectral windows in the line and continuum data may be at different frequencies, a correction to the phase must be included in transferring phases from one dataset to another when the group delay is known.

B. Obit Task SNCpy

The transfer of gain solutions between dissimilar datasets is implemented in Obit task SNCpy. The solutions are in the form of an AIPS SN table which contains amplitude and phase (as a complex gain), delay and rate. (Rate corrections are generally not needed for EVLA data.) Gain solutions are organized by spectral window (AKA “IF”). For each output spectral window in each antenna, the closest input spectral window in frequency is identified. The time, delay and amplitude (and rate) of this closest input spectral window gain are copied to the output gain record and the phase is adjusted by:

$$\phi_{out} \ = \ \phi_{in} + 2\pi\delta_\nu\tau_{in}$$

where δ_ν is the frequency difference (out-in).

IV. EVLA Example

This technique was applied to 40-48 GHz observations of an evolved (AGB) star showing strong SiO masers using the EVLA in A configuration during the Summer. The data consisted of 58 “continuum” spectral windows and two line spectral windows covering the J=1-0, $\nu = 1$ and $\nu = 2$ SiO masing transitions near 43 GHz. The line data were Hanning smoothed to reduce the Gibbs ringing due to the strong, narrow masers. Amplitude calibration was based on 3C48 which proved difficult and the technique described in [4] was applied. With this modification the continuum data were subjected to the standard external calibration. The gain table (AIPS SN) from the delay and amplitude+phase calibrations were copied to the line data using SNCpy and subsequently applied using CLCal.

Applying this calibration, the line data were then bandpass calibrated using the calibration sources and Doppler corrections applied to correct for the earth’s motion relative to the LSR. Several channels with the strongest maser emission in the $\nu = 1$ data were imaged and self calibrated with several iterations of phase only and one iteration of amplitude and phase self calibration. The self calibration started using the initial phase calibration from the continuum external calibration. This resulted in substantial decorrelation of the data and a several arcsecond apparent position shift but proved good enough for the self calibration to succeed. The final phase only and the amplitude and phase gain tables were copied to both the line and continuum data sets and applied to the CL table sequentially.

The continuum data were then imaged using no further phase calibration using task MFImage and the line cube produced using task Imager. Locations of maser features were determined from fitting Gaussians. The results are shown in Figure 1. The absolute precision of the astrometry will not be very good due to the uncertainty in the position of the phase reference maser but the relative precision should be very accurate.

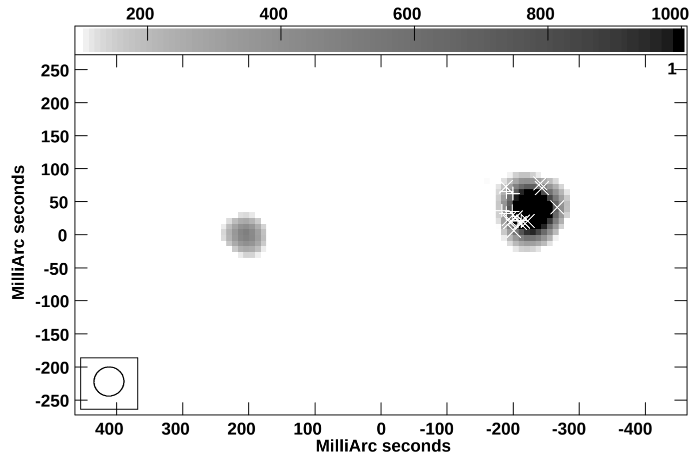

Fig. 1. Example evolved star imaged at 45 GHz using phase referencing to an SiO maser. The continuum image is shown in negative gray-scale with the scale bar in μJy/beam given at the top. The “X” and “+” symbols are the locations of masers in the two Sio transitions. The restoring beam FWHM is shown in the lower left.

V. Conclusions

A wideband extension of the technique of Reid & Menton ([1], [2]) for phase referencing continuum data to a maser feature to the current EVLA wideband system is presented. An example using EVLA 45 GHz data is given. The expected arrangement of the masers around the red giant shown in Figure 1 shows that is has worked as expected.

References

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