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Improving flux scale calibration with maser monitoring

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Accurate flux density measurement with general purpose radio interferometers is a challenge because various poorly characterized systematics often end up dominating the error budget. The long-term (more than 150 epochs spanning 7 years of regular observations) maser monitoring program with the Australia Telescope Compact Array (ATCA) proved to be a useful source of insights into calibration systematics. This is because one of the masers (an astronomical source of narrow spectral line emission) observed in the program (the 9.9 GHz class I methanol maser in G331.13-0.24), turned out to have a rather consistent behavior losing about 160μJy per day. This work had begun using the standard calibration procedure recommended by the ATCA user's guide. It was found that the standard calibration delivers the flux density measurements consistent to about a few percent for most of the epochs. However, there were still notable outliers not always attributable to non-ideal observation conditions like poor phase stability and/or extended array configurations (and, in contrary, a flux density rather consistent with the expected trend was sometimes obtained for epochs observed in more marginal conditions). The second class of outliers were the epochs for which the flux density obtained using different methods (triple products, uv-flux following phase self-calibration, as well as a method suggested in this work which is based on the Rician distribution parameter estimator) had discrepancy exceeding the formal uncertainty.

Investigations of each outlier epoch led to several improvements in the calibration procedure resulting in a more consistent flux density across different epochs. The largest effect was caused by imperfections of the flux scale calibration step which relied on good cross-calibration of individual antennas with respect to each other. In the case of weather conditions with reduced phase stability (i.e. typical daytime conditions in the Australian summer, even at cm-wavelengths and without adverse weather around), the residual errors in the usual calibration step using calibrator + target loop are coupled with the flux scale calibration despite the fact that the latter is based on the triple products in MIRIAD (the software commonly used for the ATCA data reduction) and would normally be expected to be independent on visibility phases. The initial adopted solution was the extension of the flux scale calibration procedure based on the triple products to solve for per-antenna scaling factors. This worked well for the majority of the epochs observed with the current ATCA 4cm receivers but gave a measurable (and unacceptable) bias of about 1-2 percent for the first 1000 days of the project when at least some antennas had older, less sensitive receivers. This behavior was traced to insufficient signal-to-noise ratio in the primary calibrator visibility data. To address this issue, a new calibration procedure based on parameter estimation of the Rician distribution and working with visibility amplitudes has been developed. It still performs a non-linear least-square fit like in the ordinary gain calibration, but gains (in this case essentially the scaling factors) are real and the equations are no longer a simple product of gains with model visibilities but have a more complicated form taking into account the Rician distribution of the measured amplitudes. A variant of this procedure was also implemented to solve jointly for the flux density of the astronomical source (assuming it is unresolved) and the noise levels for each antenna. This way of obtaining flux densities complements the other methods used in the project but typically didn't show a clear advantage over the triple products method.

The modified calibration procedure (along with several secondary effect fixes) notably improved the consistency in the flux density measurement and enabled investigation of residuals, after the linear 160μJy per day trend was taken out. The systematic revealed this way had a quasi-periodic appearance with ~1 year period which was traced to the residual uncorrected gain-elevation dependence (and the annual periodicity was caused by some ATCA scheduling regularities throughout the year). However, there are indications that the gain-elevation effects of the ATCA require further study as they may be responsible for the remaining systematics in the data. The currently achieved level of consistency in the flux density measurement is about 1 percent. The remaining variations (i.e. likely further systematics) are at the level of 2σ.