Calibration Techniques and Digital Signal Processing in Radio Astronomy

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Radio interferometers and synthesis arrays measure Fourier components of the brightness distribution over some region of the sky. This is done by correlating the signals from the individual antennas with each other. In radio astronomy, these correlations take place in correlators and are called visibilities. Correlators with wide dynamic range are readily implemented digitally, since digital circuits require less adjustment than analog ones and are better suited to replication in large numbers for large arrays.

For such synthesis arrays, to provide meaningful output, accurate calibration is of critical importance. Calibration must solve for the unknown antenna gains and phases as well as the unknown atmospheric and ionospheric disturbances. Calibrating a synthesis array is one of the most difficult aspects of its operation and, in many cases, is the most important factor in determining the quality of the final deconvolved image. Calibration accuracy determines the dynamic range of the final image as any amplitude or phase mismatch produces ghosts of the strongest sources at unpredictable positions. Nonlinearities in the digital signal processing also degrade the final dynamic range, therefore these aspects are particularly important in instruments with a very large instantaneous field of view and high sensitivity, as will be the case for SKA.

The first part of my thesis concerns the conditions of linearity of the quantization process [1]. In order to have a good calibration accuracy the quantization must not introduce nonlinear components in the correlated signals. The input signal was assumed to have a bivariate Gaussian distribution. Various approximations for the distribution have been used to evaluate nonlinearities for quantisation schemes ranging from 4 to 9 bits, and to identify the linear range for the quantised signal. For quantisation with more than 5 bits and a RMS signal level ranging from approximately 4 quantisation units to 0.27 times the maximum quantisation value, the response is linear enough not to require a quantization correction. The autocorrelation calculated with less than 8 bits of signal representation is always distorted, and must be corrected with an appropriate linearising function.

In the second part the calibration problems in the Southern Hemisphere are described and a novel blind calibration technique in the power domain is proposed.

A new generation of radio telescopes is being built or being planned in the Southern Hemisphere. South Africa and Australia, in particular, are actively involved in the development of new arrays like MeerKAT and ASKAP which are both precursor to the Square Kilometre Array (SKA). These instruments have a hierarchical system architecture: the interferometer is formed from several smaller elements called "stations", that are in turn phased-arrays of individual antennas. These stations also require new calibration techniques for these large instruments to achieve their great sensitivity and dynamic range.

In the Northern Hemisphere, in order to accomplish a calibration procedure, some well-known radio sources, called calibrator sources, are used. Unfortunately the Southern Hemisphere is not well served with calibrator sources bright enough for calibration of individual antennas and there are significant gaps in the present calibrator distribution on the sky.

To overcome this problem, it is necessary to develop new techniques and different approaches to calibration, where knowledge of calibrator sources is not used. One of the most promising techniques is the blind calibration [2].

In my thesis I present a novel blind calibration method that estimates the sensor gains and phases as well as the observed scene from the measured array covariance matrix assuming that the observed scene is sparse [3]. Blind calibration based on the array covariance matrix offers a significant computational advantage over blind calibration based on time series (signal domain) data, in particular in scenarios with low SNR where a significant number of time samples is required to obtain meaningful solutions. We successfully demonstrated the effectiveness of the proposed method using simulated data as well as actual data from a LOFAR station.

References

[1] Chiarucci S., Comoretto G., *Quantization noise and nonlinearities in the correlation of two Gaussian signals*, SKA-CSP-Memo 0016

[2] Kazemi S., et. al. *Blind calibration for radio interferometry using convex optimization*

[3] Wijnholds S. J., Chiarucci S., *Blind Calibration of Phased Arrays Using Sparsity Constraints on the Signal Model*, Signal Processing Conference (EUSIPCO), 2016