Optical Aperture Synthesis

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Abstract

Optical aperture synthesis (OAS) for high-resolution imaging in military applications is considered. The use of redundancy in the OAS array is considered as a means for achieving snapshot instrument calibration for atmospheric and vibration-induced instrumental imperfections in both active and passive imaging scenarios. Some preliminary experimental data is presented.

Keywords: Synthesis Imaging; Optical Aperture Synthesis; Fourier Telescopy; Bandpass Telescopy; Redundant Spacings Calibration

Introduction

Optical image formation may be viewed as an interference process, Roddier (1), Greenaway (2). Aperture synthesis aims to use interferometric methods and computer-based data inversion to create the image that would have been seen had the scene been imaged using a diffraction-limited imaging system with a diameter equal to the maximum separation between small apertures in an array operated as an interferometer.

This approach has long been successful in radio astronomy, but has more recently been applied at optical frequencies, Haniff (3).

At optical frequencies, even more than at radio frequencies, the calibration of the imaging performance of the system is vital if high-quality images are to be obtained. This requires an assessment of the phase errors (and, if possible, the optical efficiency) associated with each sub-aperture in the array. In astronomy, the compact and high-contrast nature of the objects imaged and the change in interferometer orientation due to the diurnal rotation of the earth permit one routinely to obtain synthetic images of stunning quality. For military application one must change the mode of operation somewhat and try to obtain instantaneous (i.e. snapshot) images of extended targets in a low-contrast scene. For this reason the use of Redundant Spacings Calibration (RSC) is important (2). Basically, if the same target information is measured twice within an RSC array any difference in the measurement informs one about the instrument – with no need to make models of the scene imaged. If every aperture is involved in at least one repeated measurement one can calibrate the whole instrument and subsequently synthesize the diffraction-limited image in a computer *a posteriori*.

This principle can be extended to active imaging systems as well as to passive imaging systems. In an active system one can use the array of apertures (which now becomes an array of transmitters) to illuminate the target with cosinusoidal fringes. The integrated signal scattered from the fringe-illuminated target is a measure of the Fourier cosine coefficient at the spatial frequency of the fringe.

This is effectively a long-hand Fourier transform. The procedure is known as Fourier telescopy (4).

In Fourier telescopy scatter from the target depends on the product of the localised target albedo, $T(s)$ and the illuminating fringes. The total energy scattered from the target is then

$$F(\omega)=\int_S ds\ T(s)\cos^2(2\pi\omega s) \tag{1}$$

where S is the domain of integration, covering the whole target in this case.

If two projected fringe systems are nominally identical the measured Fourier coefficient should be the same. If the measurement differs it is because the fringe phase has changed – hence once again if using an RSC array the difference in measurements contains information about the imaging instrument independent of the details of the target imaged.

RSC

As already discussed, RSC arrays are constructed such that some of the vector spacings between array elements are repeated. There are two elementary geometric shapes that give the requisite redundancy.

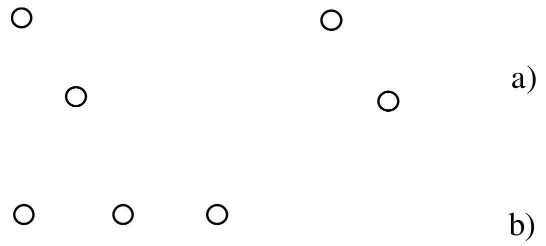

Figure 1 Elementary shapes for RSC arrays; a) parallelogram of 4 apertures; b) straight line of 3 equally-spaced apertures. Note that the parallelogram can be collapsed into a 1-dimensional figure containing 4 apertures.

The parallelogram, shape a), provides two redundancies, whilst the linear shape; b) provides a single redundancy. The principle of RSC calibration uses the measured fringe phases (evaluated by taking the Fourier transform of the interferometric data and using logarithm to extract phases from the autocorrrelation of the OAS array).

RSC calibration for an OAS array consists in arranging the optical sub-assemblies in such a way that at least $P=N-3$ elementary shapes of the form shown in Figure 1 are present in the arrangement. If all of these shapes are of type b) a 15-aperture array would require $P\geq 12$ redundancies. Use of some type a) redundancy increases slightly the level of redundancy required but, if used with care, leads to greater stability in instrument calibration. An array having $\geq P$ elementary shapes of the types shown in Figure 1 gives rise to a matrix equation in which the matrix is full rank and in which the condition number can generally be kept small (indicating stable data inversion). Increasing the number of redundancies above this minimum might be expected to give improved stability in the solution. However, we are dealing with phase values and thus with modulo arithmetic. For this reason it is frequently necessary to pre-process over-redundant data in order to ensure a unique solution to the modulo arithmetic problem (5).

However, it is not essential to solve the matrix equations in order to make the RSC calibration effective.

On the redundant baselines in an array, the visibility can be maximised by changing the phase of just one of the apertures contributing to the measurement on the redundant baseline. The visibility on the redundant baseline reaches a maximum when the phases of the fringes from the redundant baselines are identical. The change of phase does not affect the fringe visibility on the non-redundant baselines (the diagonals in Figure 1.a) and the longest baseline in Figure 1.b)). Conceptually one can imagine that the 3 non-driven apertures in Figure 1.a) define a plane and the phase of the fourth aperture is changed until it lies on the same plane. Such a procedure permits one to calibrate the RSC array adaptively in real time, without the need to evaluate fringe phases explicitly. This gives a consequent saving in non-linear analysis at the expense of some minor trial and error requirements.

Figure 2 shows some experimental results from adaptive calibration of an array of the type shown in Figure 1.a). The phase of the single driven aperture here is controlled using a single-element liquid crystal phase modulator. The simultaneous maximum reached on the redundant baselines is the condition required to achieve maximum image sharpness and is equally applicable to passive and to active OAS. This is essentially a demonstration of Parseval's theorem.

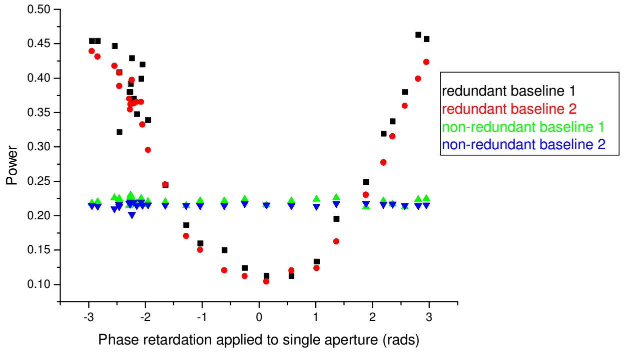

Figure 2: Experimental demonstration of adaptive RSC calibration in OAS. The figure shows the measured power on the 4 fringe systems in an RSC system of the type shown in Figure 1.a) as the phase of one aperture in the system is scanned. The power on the two non-redundant baselines (on the diagonals in Figure 1.a)) is independent of the aperture phase and close to the theoretical value of 0.25. The power on the redundant baselines should peak at 0.5 when the aperture phase correctly cancels any aberrations and should fall to zero when the driven aperture phase is exactly π radians from the optimum value. Deviation from these theoretical values are probably due to variations in aperture size and positioning accuracy. The measurements show that the power on both redundant baselines peaks simultaneously, demonstrating that the system can be calibrated as an adaptive array.

One attractive aspect of the use of the parallelogram arrangement is that the short baseline, on which the fringe visibility is likely to be highest, can be used to calibrate a long baseline, on which the visibility is likely to be low. Such ability reliably to calibrate information at the OAS diffraction limit from low-resolution measurements is a substantial advantage in high-resolution imaging of extended targets.

OAS-Telescopy

As discussed above, telescopy operates by projecting a sequence of fringes onto the target and integrating the scattered field. Fringes projected through an unstable instrument and/or atmospheric turbulence have undetermined phase. In application there is a challenge to ensure that one can cycle through the requisite set of projected fringes within the shortest time-scale dictated by the atmospheric relaxation time or the instrument stability plus laser pulse length, or laser pulse repetition frequency. Two approaches to this challenge are under investigation. Firstly, an analysis of the full range of data diversity that can be used to compress the data sequence into a minimum number of laser pulses or shortest pulse length is under investigation. Secondly we are examining the use of Bandpass Telescopy to minimize the length (number) of the sequence of fringes that must be projected in order to achieve high-resolution imaging.

Bandpass telescopy exploits a low-resolution imaging system to image the target whilst the sequence of fringes are projected onto it (6). Thus the integration in equation (1) takes place not over the whole target field but over a restricted target area determined by the spatial resolution of the low-resolution imaging system. Such an approach has two advantages.

Firstly, the low-resolution system has a finite aperture size and image resolution (i.e. a known bandpass over which target Fourier coefficients are collected), thus the bandpass of the synthesised aperture is the convolution of the array of delta-functions that represent the fringe sequence with the bandpass of the low-resolution system. This means that the coverage of the target spatial frequencies is achieved very economically and the number of fringes that need to be projected is minimised. In principle, the effective diameter of the synthesised aperture can be three-times that of the low resolution system through use of a system of just 3 fringe-projections.

Secondly, because the data is collected with low spatial resolution on the target the RSC analysis can be implemented over sub-areas of the target (in principle, over a single pixel in the low-resolution image). In principle, a sequence of 3 fringe projections then permits one to divide each low-resolution pixel into 9 sub-pixels – thus tripling the resolution. However, this opens new possibilities whereby the RSC calibration can be performed on a local basis within the low-resolution image (even pixel by pixel). The calibration within each local area can change, allowing image synthesis even under anisoplanatic imaging conditions provided only that the resolution of the low-resolution data collection system resolves the isoplanatic patch. Projecting more fringe patterns permits further sub-division of the low-resolution pixels.

Speckle Effects in Telescopy

A telescopy approach inevitably means that the coherent illumination of a rough target will lead to the production of speckled image data. Such scintillation effects are potentially disruptive of the telescopy process and therefore an investigation of these effects is in hand.

In order to examine the effects of speckle on telescopy in a simple system we have arranged a target consisting of crossed threads against a dark background. This target can be illuminated by fringes produced by projecting a laser (in this case a low-power He-Ne laser) onto the target through a pair of monomode fibres. The spacing between the fibres and the range to the target determine the fringe period and orientation. By stretching the fibres the fringe pattern can easily be scanned in one dimension. This procedure gives a sequence of moving fringes that illustrate the operation of Fourier telescopy. A single frame from a preliminary experiment that produces such a sequence is shown in Figure 3. The difficulty, in a low-cost laboratory experiment, of producing a fibre-linked RSC array means that an absolute calibration is required to synthesise increased resolution images from this data. That absolute calibration is presently in hand.

Note that this simple experiment shows the effect of laser speckle (the horizontal stripes in the data) and therefore allows us to experiment with fibre-linked arrays (the likely implementation route in practice), the effect of laser speckle, the implementation of bandpass telescopy and RSC as a calibration tool for that technique.

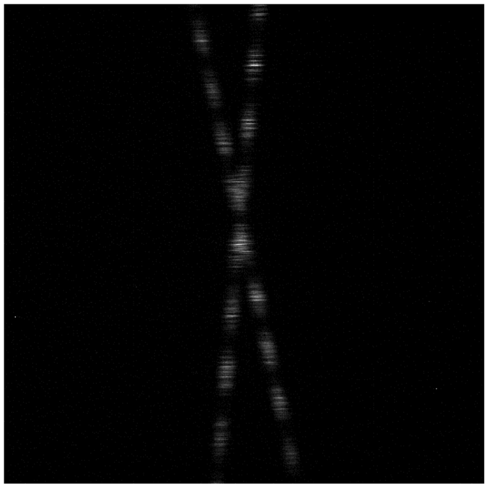

Figure 3. Single frame from a preliminary experiment to implement bandpass telescopy using a fibre-linked fringe transmission system. Note the speckle shown in the horizontal stripes within this data.

Discussion

OAS offers increased range in recognition and identification applications when the use of a single, large-diameter optical system is impractical. Implementation of OAS on military platforms is a high-risk, high-benefit programme. However, implementation of an active OAS system based on bandpass telescopy appears to offer least risk and provides a route for the development of techniques that will be required in any long-term implementation of passive OAS in military applications.

The potential for high-resolution OAS in anisoplanatic imaging situations and the added potential for calibration of long-baseline (high spatial frequency) information using exclusively short-baseline (low spatial frequency data) are exciting prospects for future development.

Acknowledgement

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