

Optical Aperture Synthesis

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Abstract

Optical aperture synthesis (OAS) from an aircraft platform is considered. Critical technical risks for implementation of OAS are examined for active and passive systems. The improved range for target recognition and identification makes OAS an attractive high-risk, high-payoff proposition.

Keywords: Synthesis Imaging; Optical Aperture Synthesis; Fourier Telescoping.

Introduction

This paper describes a low-level feasibility study on Optical Aperture Synthesis (OAS) for application from mobile platforms. The scope for this study derives from a ‘Solicitation for Research Proposal on Optical Aperture Synthesis’ from the EMRS DTC to Heriot-Watt University in May 2003. The Solicitation was for a study of ‘...the possible improvements in spatial resolution obtainable by deploying two EO apertures, placed at the wingtips of...an Airplane...’. An initial 3-month study between July and September 2003 was followed by a further brief study from February to March 2004.

Optical image formation may be viewed as an interference process, Roddier (1), Greenaway (2). From this basic fact 14 significant technical risks have been identified and classified as *critical*, *severe* or *important*. Three risks were classified as *critical* – failure to mitigate these leads to failure to improve resolution using OAS. Risks classified as *severe* or *important* may obstruct useful application but are amenable to incremental improvement.

These critical risks, and the fact that no risks were identified as *minor*, underlines the high-risk nature of research on mobile OAS. However, mobile OAS offers a >100-fold increase in the information content of surveillance images or a >10-fold increase in range. This shows the significant rewards from a successful implementation of OAS.

The three *critical* technical risks were identified as:

- a. Instrument calibration
- b. Pointing and beam-feeding
- c. Optical path-length balancing.

The principles of OAS will be discussed below before the *critical* technical risks are considered.

Principles of OAS

An OAS array and its associated PSF (point spread function) are shown in figure 1. The PSF is exactly the image of a point source obtained using a single lens covered by an opaque mask containing a series of pinholes whose relative size and positions match the size and positions of the apertures in the array.

The angular resolution in an ideal imaging system depends on wavelength λ and D , the maximum baseline over which the light collected is brought coherently to focus. For OAS, D is the largest spacing between two apertures in the array giving,

$$\alpha \sim \frac{\lambda}{D}. \quad (1)$$

The OAS array in figure 1 gives $\sim 14x$ the image resolution from a single aperture in the array, thus approx. $200x$ the image information content. OAS can easily be designed to give >10 times the resolution – or $100x$ more information content – than available in the image from a single array aperture. If sensitivity is adequate, this extends the range of a surveillance system by a factor of 10.



Figure 1: Schematic of a self-calibrating OAS system and the resulting snapshot PSF. Redundant Spacings Calibration (RSC) provides self-calibrated data from which diffraction-limited snapshot imaging can be achieved. On the right a single collector PSF would fill the picture (low-level sidelobes, not easily seen above, extend to the edge of the image). The central spot is slightly 'superresolved' - the sidelobes are a penalty paid for enhanced resolution. This 21-aperture arrangement is probably too complex for military applications, but shows what can be achieved through OAS.

Each possible OAS aperture pair produces a fringe characterized by its *period*, *visibility*, *orientation*, and *phase*, Greenaway (2). The *period* and *orientation* of the fringe depend on the vector spacing between the aperture pair generating the fringe. The length of the vector determines the fringe *period*, the fringe *orientation* lying normal to the vector. The *orientation* and *period* of the fringes are denoted by the spatial frequency or (u,v) co-ordinates of the

Fourier spectrum. The fringe *phase* measures the location of the fringe crest relative to the optic axis and the fringe *visibility* is a measure of fringe contrast.

For a well-corrected PSF all fringe *phases* are $< \pi/2$, leading to re-enforcement of the fringes from all aperture pairs and the co-location of the central (axial) crest of all fringes, whatever their *period* and *orientation*. In a well-designed imaging system (lens or OAS array) not only do the fringes re-enforce on axis but they largely cancel off axis, leading to a sharp and compact PSF. In an aberrated system the phase errors of the fringes exceed $\pi/2$, leading to an increase in the width of the central spike in the PSF and, for severe aberrations, to the break-up of the central spike and the production of multiple sidelobes. The separate measurement of the phase on multiple fringes with the same period and orientation provides, Greenaway (2), the means by which RSC provides target-independent snapshot calibration of the array.

OAS for airborne applications

Experience gained in OAS in astronomy is relevant to its military use. However, the astronomical application differs in many aspects that must be taken into account in design of OAS for military application. Amongst the important differences are:

1. Military targets, embedded in a cluttered scene with characteristics managed to minimise their signature, make it hard to ensure that all images from the array are locked onto the same target point – which is essential to get interference...
whereas astronomical targets are usually compact sources on a dark background
2. The collector array design is more constrained on an airframe than at an observatory...

on a military platform the space between collectors will be crowded with other instrumentation. This dictates the use of waveguides and appropriate dispersion control

3. Military use requires data reduction and display in real-time from a small volume of data...
astronomers can use 12 hr observations and reconfigure the array for better (u,v) coverage
4. Military targets are at ranges where active target illumination is possible and can be used to replace or to supplement ambient radiation...
astronomical targets are rather far away.

These differences must be borne in mind when addressing the 3 critical errors identified earlier.

Array Calibration

In synthesis imaging (using an OAS array to form an image), good (u,v) plane coverage is required to minimize sidelobe levels in the PSF of a well-calibrated array (i.e. minimal aberrations). Sidelobe levels affect both the resolution and image contrast. Reduction of sidelobes is important because of the snapshot requirements and reduced data volume in military applications. RSC designs can give good image quality and stable data inversion from a design suitable for airframe deployment (figure 2).

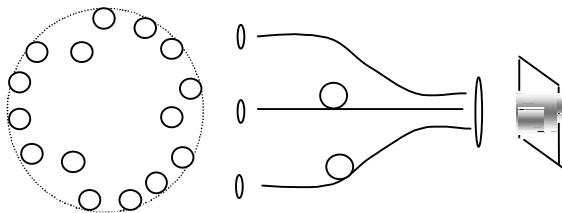


Figure 2: RSC array design with apertures positioned almost in a circular pattern. This design gives a good PSF and seems reasonably well suited to deployment on an airframe. The schematic on the right shows the use of waveguide beam transport with

pathlength and dispersion control required on all but one fibre. The beam combination is illustrated through a simple lens. The near-circular aperture pattern is compatible with the use of optical subsystems such as shown in figure 4.

RSC arrays use redundancy for fast calibration of the array without modeling the target. The calibration can be omitted and the RSC array used adaptively for real-time imaging, Greenaway (3).

Pointing and Beam-feeding

Unlike astronomy applications where (except in CMB studies) the target is a relatively compact source on a dark background, military targets will often be a low-contrast in a cluttered background. This makes it difficult to ensure that all collectors in the OAS array point at the same point on the target. In passive operation, pointing at the same target point is crucial to maximize the low fringe contrast expected from observations of extended targets. Failure to get good beam overlap (to about half a beam width) on the detector means no interference and thus no OAS. The measured calibration phase error depends inversely on the fringe visibility and thus on the image overlap, as shown in figure 3.

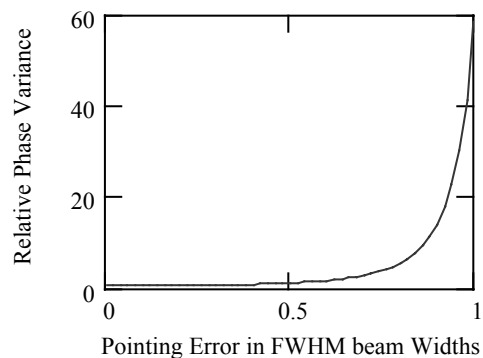


Figure 3: Relative variance of the measured phase against the accuracy with which the images are aligned from the different optical subsystems.

If the target is laser flood-lit, accurate

pointing at the same target spot is vital to avoid spurious target reconstruction - vital for verifiable operation.

Boresight stability between two (or more) separated optical systems is governed by three factors:

1. The line-of-sight deviation induced in each separate optical subsystem by vibration etc.
2. The flexing of the airframe between two optical subsystems
3. Static boresight errors between the two optics.

Through advanced modeling of vibrational, thermal and environmental loads, Thales Optics UK have achieved compact, lightweight optical subsystems that reduce the first factor to μrad level.

The second factor leads to errors at the milli-radian level, with a frequency spectrum dependent on the location of the optical sub-systems on the airframe. These errors may be controlled through inertial isolation (which should effectively mitigate errors above about 50Hz) and/or adaptive pointing control.

The third factor can be treated as a static offset in treatment of the second factor but may require accurate thermal modeling of the airframe and active control to reduce these longer-term environmental variations.



Figure 4: A single-aperture optical system mounted on an aircraft. Such components could be deployed around the aircraft in order to create an OAS array

capable of RSC using the design shown schematically in fig. 2 (or similar design).

Optical path-length balancing

The constraints of a military platform dictate the use of optical waveguides for signal transport with an OAS system. Such waveguides are dispersive and, since in passive operation a wide optical bandwidth is required in order to achieve good sensitivity, dispersion control is vital in order to increase the coherence length and consequent fringe visibility.

Active systems

Active illumination of the target is not generally favoured in military applications, but in OAS where it may increase the stand-off range for target recognition and ID it may represent an acceptable approach, especially if both active and passive operation is feasible with common instrumentation.

Active illumination in OAS offers the advantage that the illumination level can be controlled giving 24hr operation and narrow-bands signals at the dispersion minima for standard optical waveguides.

A second advantage is Fourier telescopy. This relies on the fact that an image is the transform of the target Fourier spectrum. The Fourier spectrum is found by projecting sinusoidal and cosinusoidal functions onto the target and integrating. Thus, using an OAS array to project interference fringes onto the target and integrating the return provides an imaging mechanism. In isoplanatic conditions an extended detector can be used to increase sensitivity. When combined with a low-resolution camera, the Fourier telescopy approach offers a mechanism by means of which the anisoplanatic effects of atmospheric turbulence may be overcome and also relaxes the pointing constraints

compared to other active approaches to OAS.

A disadvantage is that all active illumination induces laser speckle, due both to atmospheric turbulence and to scattering from the rough target.

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, an analysis of the technical risks associated with military use of OAS shows that the critical risks, that have to be solved before OAS can be implemented at any level, do not appear intractable.

Active OAS using Fourier telescoping combined with a low-resolution imaging system appears to offer a means for compensating turbulence-induced anisoplanatism and relaxation of pointing requirements.

References

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