Waveband Choice and Systems Architectures for Long Range Air-To-Ground ID Using Optical Aperture Synthesis.

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Abstract

Optical aperture synthesis (OAS) is a promising technique for long range air-to-ground target ID, providing high spatial frequency information without a huge objective lens. There are several candidate system architectures. Before deciding on a system architecture relevant atmospheric propagation characteristics should be understood: the choice of waveband and system architecture is intimately linked. Here we present some findings on atmospheric propagation before discussing the implications on choice of systems architecture. The main architectures considered are 1) a multiple sub-aperture array of receivers 2) Fourier telescopy and 3) Stitched speckle patterns.

Keywords: optical aperture synthesis, LRTID, infrared synthetic apertures, passive detection, active detection, telescopes, multiple apertures, Fourier telescopy,

Introduction

Long-range air-to-ground target identification at slant ranges of around 20 km is difficult, generally a large aperture telescope system must be used. Optical aperture synthesis, using coherent combination of wavefront information over the same area as a monolithic objective, offers the potential to achieve comparable angular imaging resolution with reduced mass and volume.

The transmission of the atmosphere is a major factor in the choice of waveband for electro-optical systems. In the case of an aperture synthesis system designed to image at long-range, the system losses can be dominated by atmospheric transmission. Also, in real world scenarios, there are deviations from ideal “clear-air” models.

In this paper an attempt is made to quantify some of differences in the sensitivities to non-ideal atmospheric conditions for high transmission wavebands in the infrared.

Around the clock operation is required, as is a degree of covert operation. Therefore visible/NIR wavelengths are not appropriate. In the NIR scattering can also reduce transmission. Finally turbulent distortion of the atmosphere is reduced at longer wavelengths. In this work the shortest waveband considered has been that around 5800-7000 cm^{-1} (1.4-1.8 µm). The long wavelength limit considered was around 900 cm^{-1} (~11 µm) in the LWIR band.

The principal tool used in this propagation study is MODTRAN[1], which allows sets of standardised or bespoke model atmospheres to be used. This study has used standard model atmospheres and aerosol profiles. The major difference between model atmospheres is the water vapour profile. For simplicity we discuss the US standard atmosphere as an example of a moderately dry atmosphere and the tropical model exemplifying a wet one. Ten standard aerosol options were used. In this paper we discuss only the rural 23km visibility model and the urban 5km visibility model.

A reference scenario was defined. This was an aircraft flying at an altitude of 5 km (above the densest part of the atmosphere) observing a target at a ground range of around 15-25 km. We start with clear air conditions and observe degradation from this position.

Figure 1 shows two one-way clear air transmission spectra at a reference scenario ground range of 20 km for two atmospheric models. The effect of more moisture in the tropical model can be seen, especially in the LWIR. This starting point is used to define high transmission wavebands for further study. These are the bands around 6420 cm^{-1} (~1.56 µm), 4675 cm^{-1} (~2.2 µm), 2670 cm^{-1} (~3.8 µm), and 1110 cm^{-1} (~9 µm) and 990 cm^{-1} (~10 µm) in the LWIR.

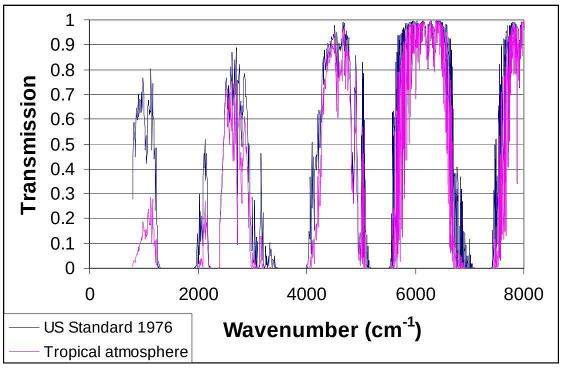

Figure 1 *Transmission spectra for reference scenario for two atmospheric models.*

Figure 1 could be interpreted as showing that LWIR wavelengths are unsuitable for operations in many parts of the world. This is true for active systems where two-way (out and return) transmission is required. However, these clear air spectra do not give a complete picture.

Figure 2 shows the transmission as a function of range for a 50 cm^{-1} band centred around 6420 cm^{-1}. The high sensitivity to the aerosol model is obvious. The important case of the urban 5km model shows very poor transmission

Passive Systems wavelength choice

Photon numbers available in an atmospheric turbulence coherence time are limited from night time targets in all bands shorter than the MWIR. MWIR photon fluxes are in practise not sufficient to give good signal-to-noise for targets that are not above 300 K. Only in the LWIR are there sufficient photons to contemplate a day-night passive OAS system. The optimum wavelength is probably around 990 cm^{-1}. Ranges of 20 km are probably over ambitious for a passive system given the modest transmissions seen above.

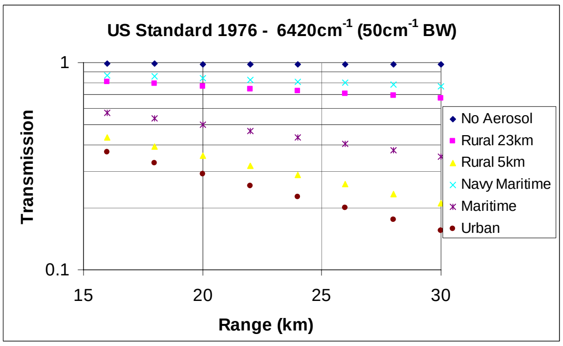

Figure 2 *Variation of transmission at 6420 cm^{-1} with range using US standard atmosphere model. Different coloured symbols represent different aerosol models.*

Active Systems Wavelength Choice

In the case of active systems the wavelength choice is not as obvious. The system as a whole must be considered.

One obvious issue is source availability; if a high efficiency laser with the necessary characteristics is not likely to be available then that waveband is ruled out.

Three possible systems architectures have been examined.

2D Receiver Array

The first architecture is multiple small receiver apertures which effectively form part of a large objective (see Figure 3).

Advantages:

- high total receiver area.
- 2D resolution enhancement.
- An architecture that can be used for a passive system

Disadvantages.

- All sub-apertures must be bore-sighted.

- Phased, calibrated array.
- Need to transport wavefront coherence information to a central point. This could be either optically (low power beam transport) or electrically (heterodyne detection against a common reference phase).

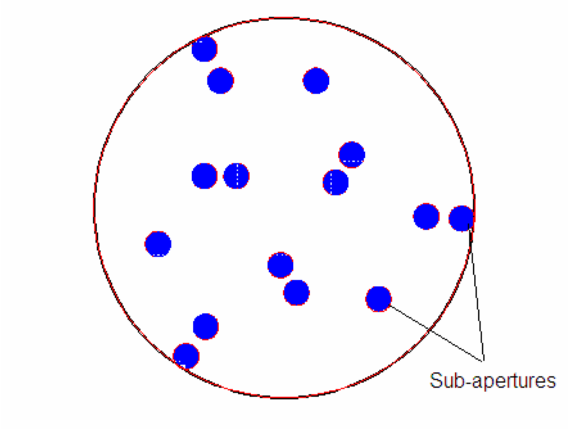

Figure 3. *An array of sub-apertures.*

In the band around 6420 cm^{-1} (~1.56 μm) it is possible to use COTS fibre optic materials, a great practical advantage. Technologies exist for: low loss single-mode polarization maintaining beam transport; controlled phase delays to match Optical Path Differences between the different sub-apertures; detectors for measuring wavefront distortions and low-noise arrays of detectors.

The band at 4675 cm^{-1} (~2.2 μm) could also use silica based fibres, possibly hollow-core fibres as losses in this spectral region can be engineered to be low over the dimensions of arrays envisaged (<2 m).

The MWIR band would have higher losses; there are no waveguides technologies known that have losses approaching those of the telecommunications fibres; the losses will be in the range 0.05-0.3 dB/m.

Fourier Telescopy

The second architecture considered is Fourier telescopy[2]. This uses an array of apertures to project different spatial frequencies onto the target. A single intensity detector is required to reconstruct the image. In some ways, this can be viewed as a time-reversal counterpart to the first architecture with source and detector interchanged.

Advantages:

- Requires a single non-imaging detector.

Disadvantages:

- Can only be active
- Still need a phase calibrated array
- Need to collect all spatial frequencies before either perspective or atmospheric properties change.
- Source laser distribution system to several apertures.

Requirements

- Bore-sighted apertures.
- Phased, calibrated array.

Coherent beam transport is essential in this case as is a quick method of switching power between different apertures to obtain different spatial frequencies. The arguments for different wavebands are similar to the previous case. Losses in fibres will tend to lead to heating – changing the fibre refractive index. This is a challenging problem but is being used for CW laser weapons.

Speckle Stitching

The third system architecture considered is referred to here as speckle stitching. This relies on sampling the coherent speckle return field at several points along the direction of travel of an aircraft (Figure 4) One recent example of this technique was given last year in a paper by Lehureau and Colineau[3].

Advantages:

- Single aperture

Disadvantages:

- 1D resolution enhancement only.
- Resolution enhancement is platform speed dependent – aircraft only.
- Side-scan for best resolution enhancement

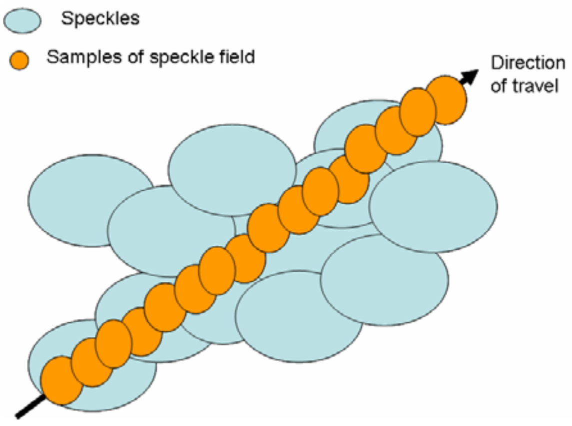

***Figure 4** High resolution in one direction by integrating multiple samples of the returned speckle field.*

Requirements:

- Good pointing accuracy
- Requires speckle overlap.
- Data processing to accurately align speckle patterns.

This OAS architecture is similar to Synthetic Aperture Radar. The technique needs to distinguish between coherent speckle due to the target texture and atmospheric turbulent distortions. Therefore it is likely to be limited to distance close to an atmospheric turbulence transverse coherence length (the Fried parameter). This can be around 40-50 cm in the 6420 cm^{-1} waveband for light turbulent conditions in the standard reference scenario.

Heterodyne detection

Direct detection signal-to-noise of low level signals in the LWIR is limited by detector noise. Heterodyne detection is not so limited – in this case the SNR is limited by the bandwidth of the detector. For a passive system a very high bandwidth detector (>30 GHz) is required. Traditional narrow-gap semiconductor detectors such as HgCdTe or InSb will not work this fast, but specially designed Quantum Well Infrared Photodetectors show promise[4].

A waveband around (987-995 cm^{-1}) is recommended for passive LWIR heterodyne systems.

Conclusions

Passive infrared detection is likely to suffer from insufficient photon flux at SWIR or MWIR wavelengths. The recommended approach for a passive system is LWIR in a band around 990 cm^{-1} using heterodyne detection.

A number of possible systems architectures for active OAS imaging have been proposed. At this point there is no clear favourite architecture. COTS technologies would push the waveband choice to 6420 cm^{-1}, however there are a number of technical reasons to advocate a system using the 4675 cm^{-1} waveband. These include - possible high power lasers, relatively small changes in basic design of components from those existing at the 6420cm^{-1} (~1.6µm) band.

References

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