

# Lucky Imaging Using Phase Diversity Image Quality Metric

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## Abstract

*This paper reports on progress towards the development of a lucky imaging system based on the use of a phase diversity image quality metric for identifying lucky subframes in imagery recorded over long ranges through atmospheric turbulence. A distortion compensation algorithm has been developed which permits the accurate stitching together of lucky image fragments obtained at different instants. The technique has been previously demonstrated over a 4.3 km ground-to-ground path with up to a factor of 2 improvement in image quality. Recent improvements to the distortion compensation algorithm have resulted in a resolution improvement of up to a factor of 3 under stronger turbulence conditions over a 1.8 km roof-to-ground path.*

## Introduction

Long range visible and near-IR imagery is degraded by atmospheric blurring, consequently limiting the range for recognition and identification. Frame selection, or lucky imaging, is a concept that relies on the fact that very occasionally atmospheric turbulence results in no wavefront aberration, so that there is a finite probability that a short exposure snapshot will not suffer from significant resolution degradation. Under anisoplanatic conditions these “lucky moments” will occur at different times for different parts of the field-of-view (FOV), so that selection must be done on a subframe basis, taking lucky image fragments and stitching them together into a complete image.

A lucky imaging system using subframe selection is able to mitigate the deleterious effects of turbulence, enabling higher resolution visible and near-IR imagery over long atmospheric paths.

A key component of any lucky imaging system is the image quality metric which

identifies the lucky moments in the data stream from the sensor. This metric is usually based on direct analysis of the image data, and can often perform poorly in the presence of noise. Sophisticated noise-invariant metrics are available, but incur significant computational cost.

Under this EMRS-DTC programme we have developed an efficient and robust lucky imaging system using a novel “phase diversity” image quality metric, which is based on a wavefront sensor concept, indirectly identifying lucky moments by looking for low wavefront aberrations rather than by direct image analysis.

This paper summarises the development of the phase diversity lucky imaging system and associated data processing algorithms, and presents the latest results obtained over a 1.8 km range. More extensive detail on the phase diversity metric and optical system design, as well as previous trials results, is available in the previous two EMRS-DTC conference proceedings [1,2].

## Lucky imaging

Lucky imaging is a technique which can overcome image degradation due to atmospheric turbulence in high-resolution long-range visible and near-IR imaging systems.

Turbulence varies randomly on timescales of a few milliseconds, so there is a finite probability that a sufficiently short exposure image may capture a moment when the atmospheric image degradation is low. Due to anisoplanatism these moments will occur at different times for different positions in the FOV.

Lucky imaging works by assessing local image quality across the FOV for a series of short-exposure images and retaining only the best quality image fragments (“lucky sub-frames”) which are then assembled into a complete high-resolution image.

## Phase diversity image quality metric

The conventional approach to identifying low-degradation regions of an image is to calculate a “sharpness metric” from the image data itself. There are many such metrics, ranging from simple  $I^2$  image sharpness to complex algorithms such as eigenvalue sharpness and bicoherence techniques [4,5]. Unsurprisingly, more complex metrics perform better, but take much longer to compute. It is desirable to perform the lucky imaging processing quickly in order to obtain a lucky image in as short a time as possible, so simpler, faster, metrics are advantageous. However, simple metrics like  $I^2$  are particularly sensitive to low signal-to-noise ratio (SNR) since the uncorrelated noise from pixel to pixel looks like high spatial frequency information and hence  $I^2$  will rate a low SNR image as sharper than a high SNR image of the same resolution.

We have developed an alternative method for estimating image quality, based on wavefront sensing principles using phase diversity. The technique relies on the through-focus symmetry of the point-spread-function (PSF) for an unaberrated imaging system. As shown in figure 1, the PSF symmetry is broken when the incoming wavefront is not flat. Thus, two phase diverse images corresponding to image planes either side of focus, will be identical only in those parts of the FOV imaged with zero aberration, i.e. lucky sub-frames. A “phase diversity image quality metric” can thus be derived from a simple comparison of the two phase diverse (PD) images.

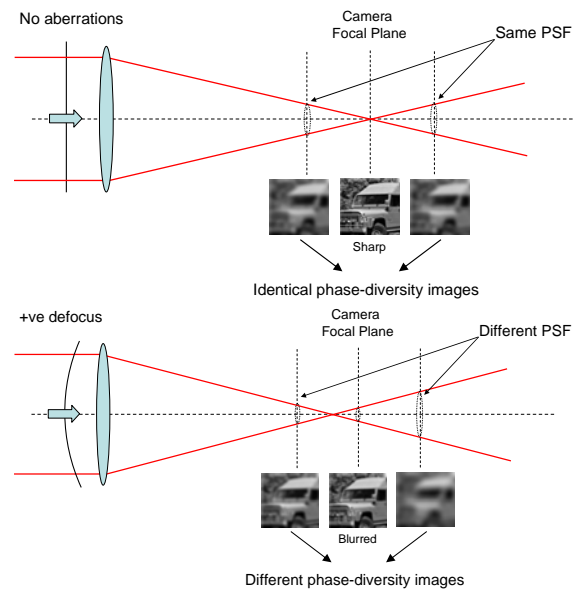


Figure 1. The PSFs in two symmetrically defocused image planes are only identical when there is no wavefront error.

When the wavefront error is very large, leading to extremely blurred images, the PD images start to look identical once again. Thus, a comparison which includes only the two PD images cannot distinguish between very good and very poor images. However, the zero order image resolve the ambiguity, since in the case of very large wavefront error the zero order image will appear the same as the PD images, i.e. very blurred.

Aberration	PD images	Zero-order image
Low	Similar	Different from PD
Medium	Different	Different from PD
High	Similar	Similar to PD

We have therefore adopted a “combined metric” which compares all three images. The image quality for the  $k$ 'th subframe is given by:

$$Q_k = \frac{2}{\pi} \arctan \left( \frac{\sum_i |Z_{k,i} - \frac{1}{2}(P_{k,i} + M_{k,i})|}{\sum_i |P_{k,i} - M_{k,i}|} \right)$$

where  $Z_{k,i}$  is the value of the  $i$ 'th pixel in the  $k$ 'th sub-frame, and similarly for  $P$  (plus 1) and  $M$  (minus 1) orders.  $Q$  varies between 0 and 1, with higher values corresponding to better image quality.

The phase diversity metric (PDM) is not invariant to noise. However, since the noise is uncorrelated between the two phase-diversity images, adding noise (decreasing SNR) will tend to make the two images more different, which the PDM will identify as a reduction in image quality. This is the trend one would prefer for a subframe selection process. Image regions dominated by low SNR are considered ‘unlucky’ and would not be used to update the composite frame. A comparison of the noise responses of the PDM with  $I^2$  and eigenvalue image sharpness is shown in figure 2. Note in particular that the simple  $I^2$  metric considers image quality to *increase* with increasing noise. The eigenvalue metric is almost invariant to noise. The PDM regards image quality as *decreasing* with increasing noise, which is the ideal response for lucky subframe selection.

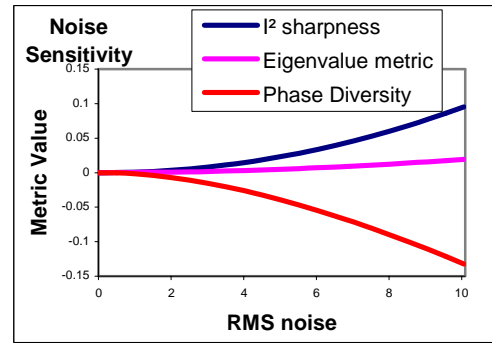


Figure 2. Effect of noise on image quality as measured by PDM,  $I^2$  and eigenvalue metrics.

### Phase diversity imaging system

A lucky imaging system based on phase diversity has been designed and built. The imaging system comprises an Orion Optics Maksutov-Cassegrain telescope with an aperture of 140mm and an f/14 focal plane. Relay optics provides an image on a CCD camera [6] at f/20 magnification. The Rayleigh Diffraction Limit (RDL) is 4.64 $\mu$ rad and the image is Nyquist sampled by the camera (pixel FOV = 2.26 $\mu$ rad). An IMP grating [7] in the re-imaged pupil plane provides the angular separation and defocusing of the phase-diversity images. The grating phase step was chosen to ensure ~33% transmission efficiency into the zero and  $\pm 1$  diffracted orders. The angular separation of the images on the CCD camera was 200 pixels. A field stop in the first image plane restricts the FOV to 200 pixels to prevent overlap between the in-focus zero-order and the defocused  $\pm 1$  order phase-diversity images. A high-transmission ( $T > 95\%$ ) filter centred on 532nm restricts the bandpass to 25nm to reduce the effect of chromatic dispersion in the phase-diversity images. The completed system is shown below:

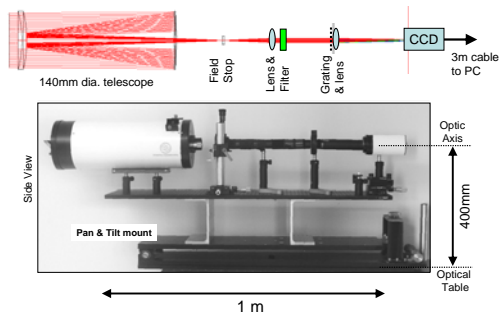


Figure 3. Illustration & side view of the imaging system. The breadboard is attached to a pan and tilt mount for accurate pointing.

The image data from the camera is streamed to disk at a frame rate of 10 fps (with no pixel binning) via a custom Labview interface. Typically 250-1000 frames are captured per data set, which is then processed off-line.

### Distortion compensation and lucky image composition

Geometric distortion is the result of anisoplanatic tip/tilt wavefront errors, and is not associated with blurring. It is essential to correct for the distortion to permit proper alignment of lucky sub-frames from different source images. A distortion compensation algorithm has been developed in which a low-resolution but geometrically correct reference image is obtained by summing the zero-order images. Each zero-order image is sequentially warped into alignment with the reference image based on intensity difference minimisation using a geometric distortion model encompassing local translation. This process can now be iterated, summing the aligned images to provide an improved reference image, and repeating the alignment procedure. The phase diversity image quality map is also warped into alignment using the alignment information computed from the zero-order images. The final lucky image is assembled by extracting lucky sub-frames from the aligned zero order images according to the

highest N values of the phase diversity image quality metric. Setting  $N > 1$  can improve the subjective quality of the final image by increasing SNR at the cost of slightly reduced resolution, as shown in figure 4.

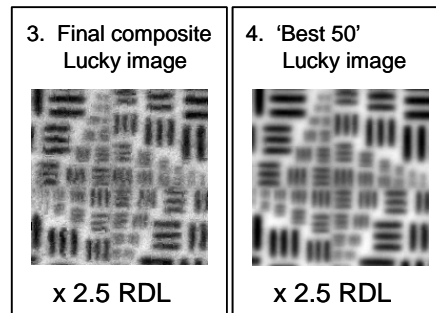


Figure 4. Comparison of lucky images for  $N=1$  (Left) and  $N=2$  (Right).

The data flow for the phase diversity lucky image processing is shown in figure 6.

A limitation of the current processing is that distortion compensation is applied to all the image data, most of which is subsequently discarded. An initial study into the effect of applying distortion compensation only to the lucky subframes showed that unacceptable alignment errors were introduced. These errors could be mitigated by retaining the low quality image data at reduced resolution (8x8 pixel binning).

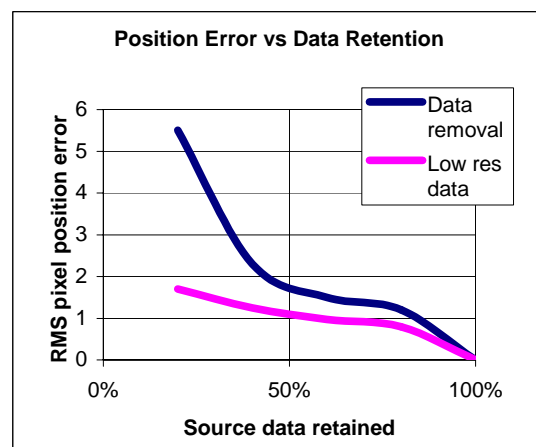


Figure 5. Alignment algorithm performance with partial image data.

## Trials results

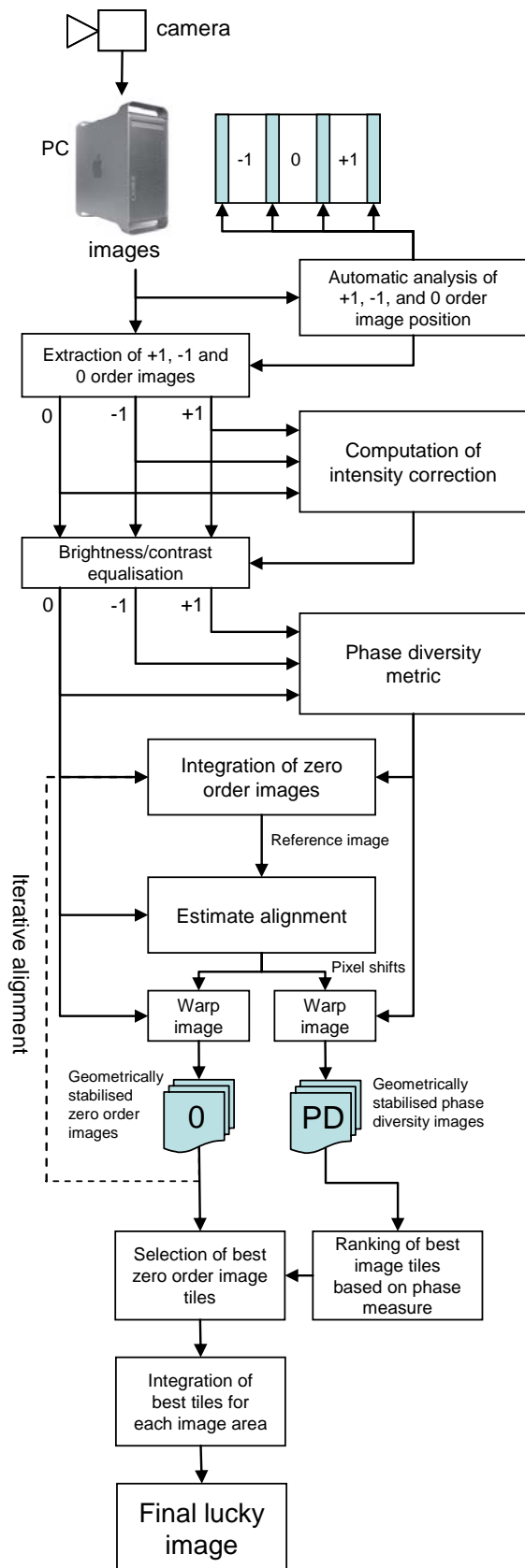


Figure 6. Lucky imaging data processing.

The lucky imaging system has been previously trialled over a range of 4.3 km during the Hydra Vision trials at Dstl Porton Down [3]. The processed data from these trials showed an improvement in resolution by a factor of 2, from 5.7 to 2.85 times the diffraction limit [2].

Following refinement of the distortion correction algorithm, including the re-estimation of the reference image from the aligned images, further trials were carried out at QinetiQ Malvern over a 1.8 km range. The trials were conducted during the summer to test the system under conditions of higher turbulence (i.e. warmer).  $C_n^2$  was estimated from long exposures of a point source beacon and varied from  $2 \times 10^{-14} \text{ m}^{-2/3}$  to  $4 \times 10^{-14} \text{ m}^{-2/3}$ .

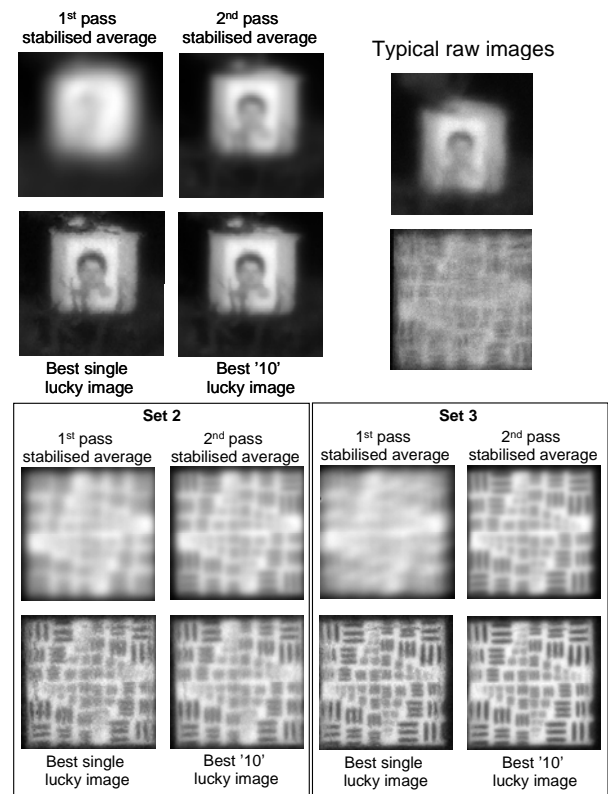


Figure 7. Results from trials of the lucky imaging system over 1.8km range.

Results from resolution chart targets showed an improvement in

resolution by up to a factor of 3, from 8-12 to 3-4 times the diffraction limit. This is shown in figure 7. Also shown are the results from a face image target board.

It is noted that we are still not achieving a diffraction limited image and the most likely explanation is that the exposure time is too long to sufficiently 'freeze' the effects of turbulence. The exposure time in the current system is limited by low SNR which is mainly due to the use of a relatively narrow spectral filter.

Possible options for increasing the SNR are the use of a wider spectral band, requiring a new optical design with chromatic dispersion reduced or eliminated, or increasing the power illuminating the target in the narrow spectral band of the grating based system (i.e. active imaging such as a BIL imaging system). Note that simply using a larger aperture is not a suitable solution to increasing SNR in a lucky imaging system, since the probability of a lucky subframe decreases exponentially with the aperture area.

### Conclusions

A lucky imaging system has been designed, constructed and tested. The system uses a novel phase diversity based metric to identify regions of the field-of-view with low atmospheric degradation.

An algorithm for correcting the image distortion (localised image motion) due to atmospheric turbulence has been developed and incorporated into the system.

The system has been shown in trials to provide an improvement in resolution by up to a factor of 3.

### Acknowledgements

The work reported in this paper was funded by the Electro-magnetic Remote Sensing (EMRS) Defence Technology Centre, established by the UK Ministry of Defence and run by a consortium of SELEX Galileo, Thales UK and Roke Manor Research.

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