Image Restoration from Limited Data

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ABSTRACT

Ground-based imagery of satellites is a cornerstone of SSA. The resolution of this imagery is fundamentally limited by turbulence in the atmosphere. Full resolution can be restored by using advanced multi-frame blind deconvolution (MFBD) algorithms which, applied to sequences of short-exposure images, estimate the object scene and point spread functions (PSFs) that characterize the turbulence. Because there are always more variables to estimate than measurements, MFBD is an ill-posed problem. Furthermore, in the regime of limited data, for example a satellite with a rapidly changing pose, the problem is also ill-conditioned because of the lack of diversity in the PSFs. These challenges typically lead to poor quality restorations. The Daylight Object Restoration Algorithm (DORA) overcomes this problem, by using additional simultaneous measurements from a wave-front sensor, along with a frozen flow model of the atmosphere, to achieve high-resolution estimates of space objects from limited data sets. The improvement in image resolution achieved by DORA when compared to current state of the art MFBD algorithms is demonstrated using real data.

1 INTRODUCTION

Our recent research has focused on obtaining high-resolution imagery using both wave-front sensor (WFS) data and high cadence focal plane imagery. Our approach uses a frozen flow model (FFM) of the turbulent layers in the atmosphere, [1] together with the WFS measurements to improve the sampling of the measured wave front, and thus recover high spatial frequencies that are not revealed by a traditional analysis of the WFS data. As we discuss in [1], high spatial frequency aberrations of the wave-front phase become increasingly damaging to image quality as the seeing worsens. These terms rapidly come to dominate the PSF, and so their accurate estimation becomes critical to successful image restoration. For observations acquired through strong atmospheric turbulence, a loss of fidelity at high spatial frequencies in the wave front results in PSF models with a morphology that differs greatly from the true atmospheric PSFs.

The quality of image restorations depends strongly on the fidelity of PSF estimates. In the absence of high spatial frequencies in the wave front, the faint speckles in the wings of the PSF all but vanish. If these speckles are not well modeled by the restoration code, the restored image of the target will suffer from a background fog that may mask nearby debris or microsatellites. In cases where the true background signal is high (e.g., daytime observations), the absence of these faint speckles will be less important, because they will be swamped by shot noise. However, changes in the morphology of the bright PSF speckles will prove disastrous for the restoration. Thus, successful imaging through strong turbulence requires faithful estimation of high spatial frequencies in the wave-front. This is the motivation for the Daylight Object Restoration Algorithm (DORA), a new algorithm [2].

The DORA algorithm is designed to address regimes of poor seeing that go beyond the capabilities of existing MFBD algorithms. It does so by including WFS measurements as constraints on the wave-front phase estimates as well as short-exposure focal plane images. It also incorporates a complete Fourier optical model of the forward imaging problem to model the temporal and spectral integrations that occur in broad-band focal plane images. DORA estimates the critical high spatial frequencies of the wave front by taking into account the fact that the turbulence above most ground-based imaging systems can be characterized by well-separated layers of frozen aberration with different velocity vectors (the FFM) [3]. Studies of the atmosphere at Mt. Haleakala have suggested that there are typically 2-3 such layers [4]. We refer the reader to [2] for the details of the DORA algorithm.

2 LIMITED DATA IN MFBD

Recovery of a 2-D image of a space object, from a sequence of blurred images of the object acquired with a ground-based telescope, using MFBD, requires that the object's pose not change over the data sequence used in the restoration. Practically, satellites in LEO generally change pose quickly, up to several degrees per second, resulting in limited sequences of image data that can be used for image restoration. This limited data can degrade the ability of the multi-frame constraint in MFBD

The change in pose of a satellite in low Earth orbit is best analyzed in the Fourier domain. Using a limited sequence of data, the maximum Fourier amplitude value over the sequence is computed at each spatial frequency. A map of the amplitude values, computed over contiguous sequences of ten data frames or 10 ms is shown in the two panels of Fig. 1. The change in the structure shows that the object has changed pose substantially in this time. In this particular case therefore only a few milliseconds of data could be successfully used by an MFBD algorithm under the assumption of a constant object.

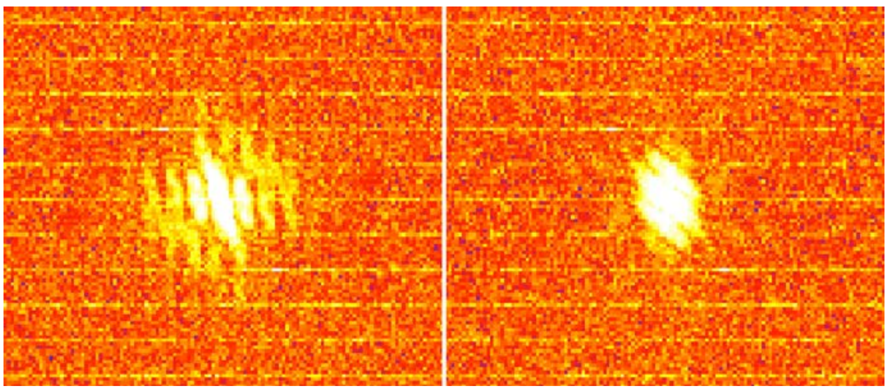

Fig. 1. Maximum signal at each Fourier frequency in the dataset of a satellite in low Earth orbit. The panels show the average of two 10 ms subsets of the data separated by 20 ms. The horizontal lines are the result of periodic noise in the detector.

Under these conditions, not only is the image data available for object restoration very limited, but the atmospheric aberration in the wave front does not have a chance to fully decorrelate over the length of the data sequence. MFBD essentially relies on strong diversity in the PSFs in order to isolate the object as the common component of all the images. If PSF diversity is low, there are likely to be constant components across the dataset that will be very hard for any algorithm to separate from the object estimate.

Examples of high-resolution wave fronts obtained from DORA in the limited data regime are shown in Fig. 2. Two consecutive high resolution wave-fronts reconstructed from a 32x32 Shack-Hartmann WFS are shown, together with corresponding images of the object acquired simultaneously with the WFS data in the case of a LEO satellite. The wave front estimates are extremely similar, and the diversity in the images is correspondingly low. By themselves, these two images would represent a very challenging MFBD job even with WFS data included.

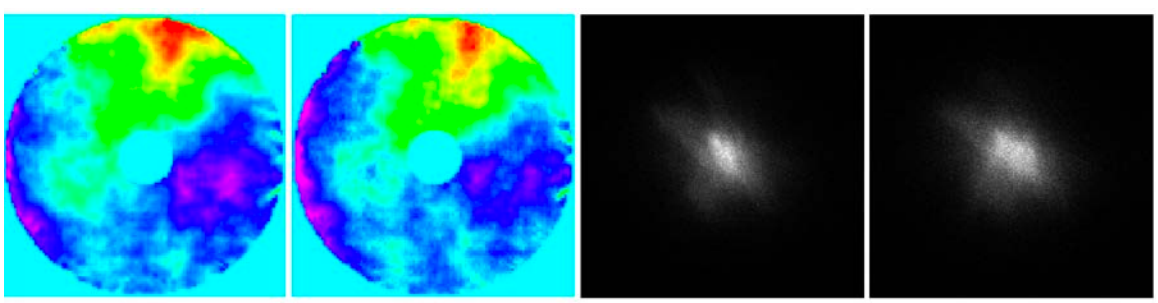

Fig. 2 Two consecutive wave front estimates (left and middle left) obtained using DORA, and their corresponding data frames (middle right and right), respectively.

3 RESULTS

DORA's ability to restore images with limited data has been tested using image and WFS data acquired by a 3-m class telescope. The improvement in image restoration quality through the use of WFS data was assessed using a limited sequence of 10 image frames, spanning just 160 ms of total integration time, of the space object Cosmos 1606. The results are summarized in Fig. 3. Shown are a sample data frame, a conventional MFBD restoration, a DORA restoration, and a closed-loop AO image of the object. The quality of the MFBD and DORA restorations can be compared to the AO image. (Note, the AO image and DORA restoration are not contemporaneous as the object has changed pose.) In both cases, the image is sharpened to a level comparable to the AO image, and the background of scattered light, attributable to the halo of light in the PSF that is uncorrected by the AO system, is substantially reduced. The quality of the DORA image improves on the MFBD image because of the availability of accurate wave-front estimates with high spatial frequency content enabled by the FFM.

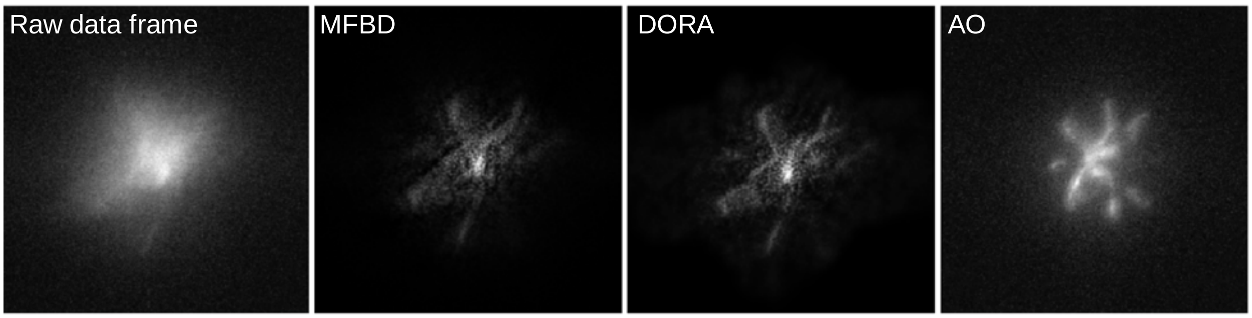

Fig. 3. From left to right: sample raw data frame; MFBD restoration; DORA restoration; closed-loop AO image of the object. The additional high spatial frequencies in the DORA estimate of the wave front improved the image restoration, as evident by more clearly defined structure on the object.

4 CONCLUSIONS

We have demonstrated the DORA algorithm using real data, and shown how the use of both WFS measurements and focal plane imagery can improve the quality of the image restoration from limited data when compared to that from an MFBD algorithm. The ability of DORA to obtain improved restoration quality from limited data is ideally suited to observations of objects with large apparent angular motion for a ground-based observer.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

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