

Image Restoration from Sodium Guide Star Observations in Daylight

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ABSTRACT

Current ground-based resolved imaging of resident space objects is mostly limited to dawn and dusk, thus severely restricting the timing of observations. The possibility of daylight imaging represents an advance that would increase the amount of sky accessible for space surveillance operations while enormously relaxing timing restrictions on data collections. Imaging in full daylight represents a challenge because of the level of atmospheric turbulence noise, high sky background, and the damaging effects of Rayleigh scattering on the signal-to-noise ratio. An important part of overcoming this challenge is the collection of wave-front sensor (WFS) measurements contemporaneous with the focal plane imagery. These measurements are used both to estimate frame-by-frame point-spread functions and to estimate the number and velocities of turbulent layers in a frozen flow model of the atmosphere. This approach, which yields improved estimates of high spatial frequency wave-front errors, is part of the Daylight Object Restoration Algorithm (DORA) currently being implemented at the AEOS 3.6 m telescope.

During daylight, measuring the wave front using reflected light from the object itself is limited to the brightest objects in the sky because of the high background illumination. A sodium laser guide star (Na-LGS) with a narrow-band filter ahead of the WFS offers a means to overcome the problem. Observations of several objects made in this way were obtained in May 2018 using the 3.5 m telescope at the Starfire Optical Range (SOR) with the adaptive optics system operating in closed loop. The WFS measurements from the Na-LGS and independent tip/tilt measurements from the object were analyzed by DORA to estimate the wave fronts after AO correction. Because of the iterative nature of the algorithm, it is able to overcome the focus anisoplanatism associated with LGS. The estimated wave fronts were used by DORA to compute high resolution imagery of space objects during full daylight. We present additional results computed from open-loop daylight observations of a satellite at the AEOS telescope.

1 INTRODUCTION

The capabilities of ground-based EO/IR telescopes supporting Space Situational Awareness (SSA) are presently severely restricted during the day. Photon noise from the bright sky background obscures the signal from resident space objects (RSO). High-resolution observations supported by wave-front sensor (WFS) measurements either through adaptive optics (AO) or numerical post-processing are hampered by low signal-to-noise ratio (SNR) and saturation of the WFS. Furthermore, solar heating of the ground leads to thermal plumes in the layer of air above it that degrade the natural seeing conditions by a factor of roughly 2 or 3 compared to night-time conditions, making it all the more challenging to collect resolved images of any intelligence value. The lack of access to round-the-clock observation has unfortunate consequences for space surveillance by limiting the efficiency of sensors in collecting data of both tactical and strategic importance.

In daylight conditions, AO compensation and a direct long integration on the imaging camera is very difficult for objects that are too faint to offer a reference for wave-front sensing. Daytime sky surface brightness is typically $m_v = 4-5$ magnitudes per sq. arcsec. In the short exposures needed by high-resolution imaging systems to freeze the atmospheric aberration, a faint satellite blurred by seeing to 1 arcsec must therefore be as bright as $m_v = 9$ simply to be detected with an adequate SNR of 10. This challenges even those AO systems which rely on one or more laser guide stars (LGS) to provide the wave front information since tip-tilt is not measurable from the LGS signals. On the other hand, numerical restoration from sequences of short exposures remains feasible. The fundamental difference is that in the case of AO, if the tip-tilt compensation is incorrect the RSO image is irretrievably blurred by image motion, even if higher order aberration is removed, whereas post-processing, relying on sequences of short exposures, can take

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the time to find the optimal image restoration. Our work, and this paper, therefore focus on techniques to enable numerical restoration as a means to recover high-resolution imagery.

2 THE DAYLIGHT OBJECT RESTORATION ALGORITHM

To that end, we have developed the Daylight Object Restoration Algorithm (DORA) to address regimes of poor seeing encountered during the day 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 that capture high spatial frequency information about the object, albeit corrupted by speckle structure introduced by atmospheric aberration in the system point-spread function (PSF). 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. Finally, DORA estimates 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 frozen flow model (FFM) [1,2]. The use of the FFM results in better sampling of the high spatial frequencies of the wave front which is crucial in obtaining a high fidelity model of the atmospheric PSF, particularly under the poor turbulence conditions expected during the day. Studies of the atmosphere at Mt. Haleakala have suggested that there are typically 2-3 such layers [3]. We refer the reader to Ref. 4 for the details of the DORA algorithm.

Wave-front sensing during daylight conditions may be enormously enhanced by the use of a LGS and very narrow band filter centered on the laser wavelength. Beckers and Cacciani [5] suggested in 2001 that the value of extremely large astronomical telescopes of 25 m and bigger could be extended by using them with laser-guided AO at thermal infrared wavelengths during the day since the limitation imposed by the sky background in these bands is no worse than at night. They described a practical daytime AO system that could be implemented with a sodium LGS when the WFS employs a magneto-optical filter (MOF) [6-8]. A MOF offers a transmission profile of typically just 10 pm width [9] which passes the LGS light with high efficiency but blocks light at all other wavelengths, very effectively reducing the sky background. We have shown experimentally that the combination of a Na-LGS and MOF is viable for daytime AO wavefront sensing [10]. The same method may be used to support high-resolution daytime image restoration of artificial satellites [11] with DORA by providing high SNR wave-front data even in the presence of a bright daytime sky background.

A practical challenge to wave-front sensing in daylight arises because of sunlight glinting off the telescope structure, particularly the secondary mirror spider vanes. The effect is illustrated in the saturated subapertures of the WFS frame shown in Figure 1, recorded at the AEOS telescope during the day as the telescope tracked a satellite across the sky. Affected subapertures can usually not be used in the wave-front estimation. Furthermore, because of the generally rapidly changing solar phase angle, as well as telescope clocking angle with respect to the sun, the impacted subapertures change throughout the pass. It is therefore not possible simply to exclude all of them in the wave-front reconstruction without a severe impact on the accuracy of the recovered phase. Instead, DORA implements a dynamic subaperture selection mechanism that excludes unusable subapertures on a frame-by-frame basis.

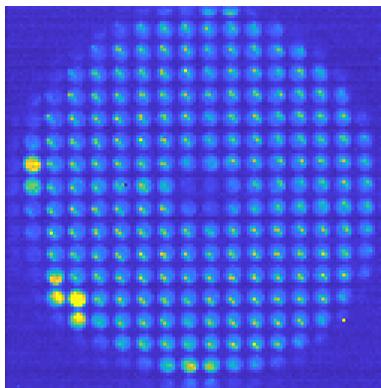


Figure 1. Example frame from the DORA WFS on the AEOS telescope illustrating the impact of sunlight glints on the left and lower left edges.

In this paper we present results of DORA restorations carried out on daylight observations of satellites from the 3.5 m telescope at the Starfire Optical Range (SOR) with simultaneous Na-LGS wave-front measurements. We show additional results from the 3.6 m AEOS telescope on Mt. Haleakala, also recorded during the day, with an infrared WFS looking at the object itself.

3 OBSERVATIONS

Image sequences of Landsat 4 (NORAD ID: 13367) were acquired during the day of 24 May 2018 at the SOR 3.5 m telescope using the sodium laser guided AO system. The observations were made approximately 1.5 hours after sunrise. Examples of the raw image data are shown in Figure 2. Simultaneous WFS data from the LGS were recorded. Separately, on 18 June 2018, the ENVISAT remote sensing satellite (NORAD ID: 27386) was observed in daylight at the AEOS telescope, approximately 2.5 hours after sunrise. In this instance, simultaneous WFS and focal imagery were obtained on the target using the DORA-WFS, in the so-called natural guide star (NGS) mode, operating at $1.6 \mu\text{m}$ [12] and the ARDI imaging camera [13] respectively. The WFS has selectable lenslet arrays; in this case it was operated in coarse mode with 16×16 subapertures across the 3.6 m pupil (Figure 1) to achieve adequate signal-to-noise ratio. A sequence of speckle images of ENVISAT from the data sequence is shown in Figure 3. The integration time for this data set was 10 ms per frame, with the WFS running at 500 fps. An analysis of the measured tip/tilts yields an estimate for D/r_0 of 34. This level of turbulence is almost twice the typical values seen during twilight observations at the site.

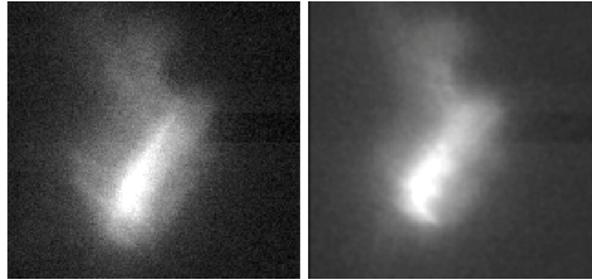


Figure 2. Examples of daylight image data collected on Landsat 4 with LGS AO at the SOR 3.5 m.

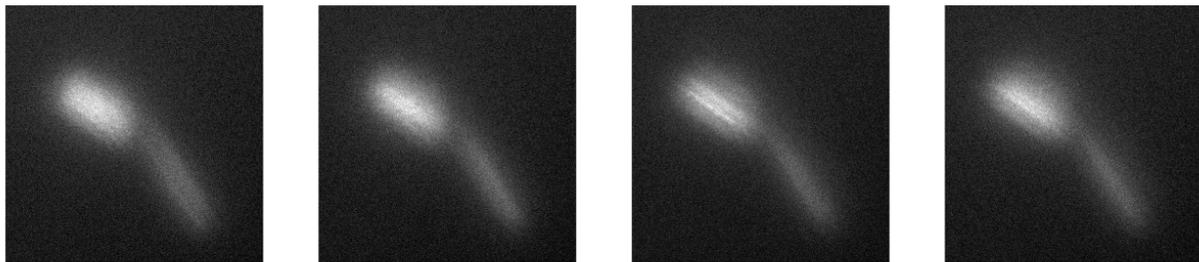


Figure 3. Images of ENVISAT acquired at the AEOS telescope at an exposure time of 10 ms.

4 RESULTS

The Landsat 4 images shown in Figure 2 were taken with closed-loop AO running on the Na-LGS, and tracking on the object itself. Yet much of the information about the wave front captured by the WFS is not exploited by the AO system in driving the system's deformable mirror. This is in part because of inevitable shortcomings in the hardware, the necessary simplicity of the wave-front reconstruction and control algorithm, and the fact that there is (also inevitably) a time delay between measuring and correcting the atmospheric aberrations. When one has the luxury of time (that is, more than a millisecond) in computing an answer as well as knowledge of both past and future history, as is the case for post-facto image restoration, the result can be substantially improved. Figure 4 shows part of a sequence of images restored by DORA from the full pass where the features of the satellite are clearly much better resolved than with AO control alone. A cartoon of the satellite in Figure 5 highlights some of the features observable in the restored images. The high-gain antenna dish on its extended arm and the solar panel array (seen almost edge-

on extending to the upper right) are distinct and well separated. The small GPS antenna can be distinguished, and features on the attitude control module can be seen.

An important additional reason why DORA is able to arrive at a better solution than laser-guided AO alone is that the latter suffers from focal anisoplanatism because of the difference in range between the beacon and the object: the volume of air sampled by the beacon differs from that encountered by the more distant object. This error term comprises three components: aberration at ranges beyond the beacon, unsensed aberration outside the cone defined by beacon light but encountered by light from the object, and radial magnification of the sensed aberration as the beacon cone expands to fill the telescope pupil. The first of these is generally negligible, but the remaining two typically dominate the error budget of a laser-guided AO system, substantially degrading the system PSF. While an AO system can do very little to address these sources of residual wave-front error, DORA operates on *both* the image data and the WFS data. It is free to adjust the object estimate in a manner that is consistent with the image data and the assumption that the object is the same in all image frames even if the result is not fully consistent with the WFS data. In practical terms, the WFS data provide a good starting point to estimate the PSFs in each image, but are not enforced as rigid constraints on the object solution. In this way, DORA is able to converge to a good restoration even when the WFS data are imperfect.

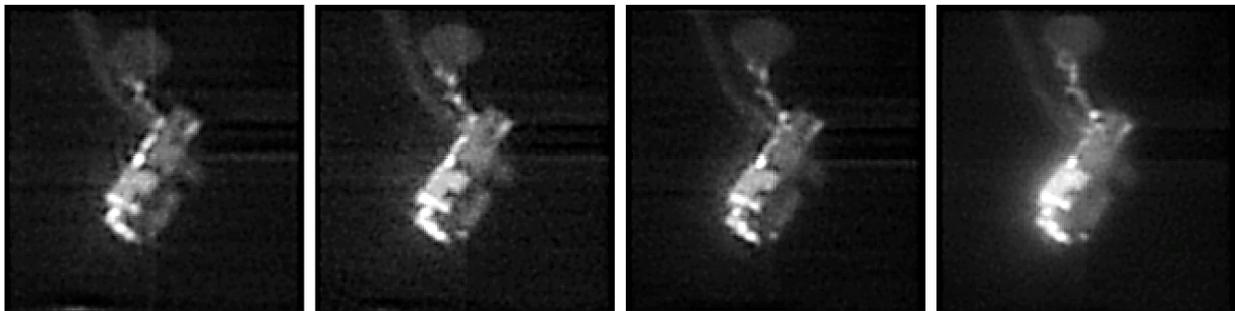


Figure 4. Partial sequence of DORA restorations from Landsat 4 data.

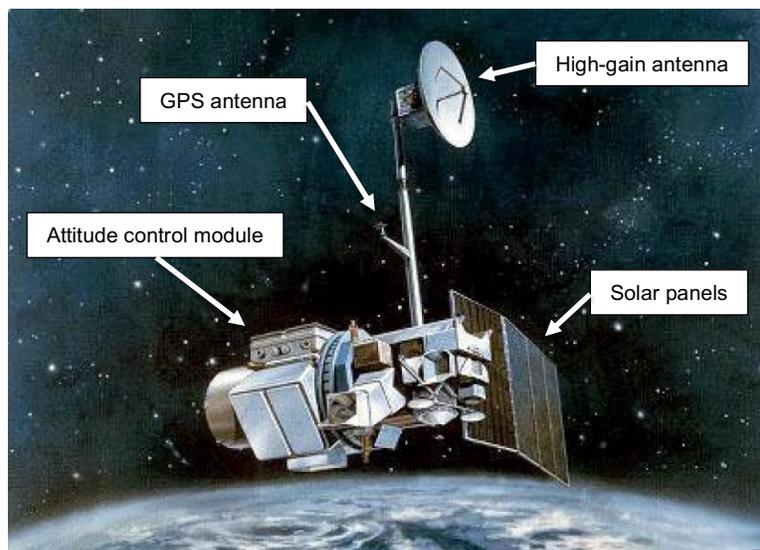


Figure 5. Artist's rendering of Landsat 4 on orbit (USGS, public domain).

The results of three different restorations of the ENVISAT data using the DORA code are shown in Figure 6. In the first panel, a traditional MFBD restoration relies solely on the image data with no WFS data to support independent estimates of the PSFs in each image frame. The second panel illustrates the benefit of including the WFS data, but in this instance, the FFM is not used to estimate spatial frequencies of the wave front higher than those naturally sampled by the WFS subapertures. Finally, the value of including the high spatial frequencies in the image restoration is evident in the striking visual improvement in Figure 6c in which the full-blown DORA algorithm exploits additional wave-

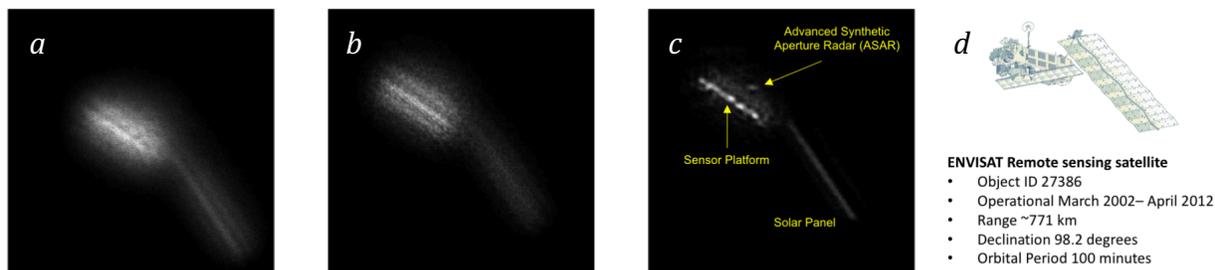


Figure 6. (a) MFBFD restoration using image plane data. (b) MFBFD restoration using WFS data. (c) DORA MFBFD-FFM restoration. (d) Cartoon of the ENVISAT satellite.

front information extracted by applying the FFM to the temporal WFS data sequence. Importantly, this demonstrates that even when WFS data are acquired simultaneously with the imagery, that is insufficient by itself to achieve high-resolution imagery using a myopic deconvolution algorithm like DORA. The coarse spatial frequency sampling of the wave front, just 16 subapertures across the pupil under conditions where D/r_0 is twice that value, limits the fidelity of the PSF estimates. Explicitly modeling the frozen flows allows higher frequencies to be well recovered, leading to improved estimates of the PSFs.

5 CONCLUSIONS

The capability of DORA to deliver high quality image restorations has been demonstrated using daylight imagery acquired at the 3.5 m telescope of the SOR with the Na-LGS and at the 3.6 m AEOS telescope in NGS mode. An unanticipated benefit of the post-detection image restoration approach in the former case is that it overcomes the focal anisoplanatism attributable to the LGS wave-front measurements. This is a major source of residual wave-front error in closed-loop AO systems, generally dominating other terms and thereby limiting the achievable Strehl ratio. The DORA restoration algorithm, however, is subtler than the control algorithm of a laser-guided AO system which simply assumes that the LGS wave-front measurement represents the error that must be corrected by the deformable mirror. Instead, DORA first uses PSF estimates derived from the WFS signals to arrive at an approximate estimate of the object, analogous to the AO-corrected image. But then the algorithm is able to improve the estimate by allowing its internal representation of the wave fronts in each data frame to diverge from the corresponding WFS measurements while iterating on the object. The first step provides an excellent seed for the second step, pushing DORA close to the optimal solution from where further iterations are able to drive the result to convergence.

DORA is now being transitioned to service at the AMOS site. The code, normally driven from a user interface, is being integrated into the site environment to operate in a headless mode that supports the automated processing of data delivered by the AEOS telescope sensors.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

- [1] Jefferies, S. M. and Hart, M., “Deconvolution from wave front sensing using the frozen flow hypothesis”, *Optics Express*, 19, 1975-1984 (2011).
- [2] Jefferies, S. M., Hope, D. A., Hart, M., and Nagy, J. G., “High-resolution imaging through strong atmospheric turbulence and over wide fields-of-view,” AMOS Technical Conference, Kihei, HI, (2013).
- [3] Rimmele, T., “Haleakala turbulence and wind profiles used for adaptive optics performance modeling”, ATST Project Document RPT-0030 (2006).
- [4] Hart, M. et al., “Multi-Frame blind deconvolution for imaging in daylight and strong turbulence conditions,” *Proc. SPIE* 8165, 81650L, (2011).

- [5] J. M. Beckers and A. Cacciani, "Using laser beacons for daytime adaptive optics," *Exp. Astr.* 11, 133–143 (2001).
- [6] A. Cacciani and A. M. Fofi, "The magneto-optical filter II: Velocity field measurements," *Sol. Phys.* 59, 179–189 (1978).
- [7] C. Y. She, J. R. Yu, H. Latifi, and R. E. Bills, "High-spectral-resolution fluorescence light detection and ranging for mesospheric sodium temperature measurements," *Appl. Opt.* 31(12), 2095–2106 (1992).
- [8] H. Chen, M. White, D. A. Krueger, and C. Y. She, "Daytime operation of Na temperature lidar using a dispersive Faraday vapor filter," in *Application of Lidar to Current Atmospheric Topics (Proc. SPIE)*, A. L. Sedlacek, Ed., 2833, 46–52 (1996).
- [9] W. Kiefer, R. Löw, W. Jörg, and I. Gerhardt, "Na-Faraday rotation filtering: The optimal point," *Nature Scientific Reports* 4 (6552), 1–7 (2014).
- [10] M. Hart, S. M. Jefferies, and N. Murphy, "Daylight operation of a sodium laser guide star for adaptive optics wave-front sensing," *JATIS* 2, doi:10.1117/1.JATIS.2.4.040501 (2016).
- [11] M. C. Roggemann, D. Douglas, E. Therkildsen, D. Archambault, R. Maeda, D. Schultz, and B. Wheeler, "Daytime image measurement and reconstruction for space situational awareness applications," in *Proc. AMOS Tech. Conf.*, S. Ryan, Ed. (2010).
- [12] M. Hart, S. M. Jefferies, D. A. Hope, J. Nagy, O. Durney, and R. Codona, "Quantitative measurements of daytime near infrared sky brightness at the AEOS 3.6 m telescope," *AMOS Technical Conference*, Kihei, HI, (2014).
- [13] S. Griffin, B. Calef, J. Lucas, R. Swindle, and L. Schatz, "Aperture Partitioning Element Results," *AMOS Technical Conference*, Kihei, HI, (2017).