High resolution Imaging of Satellites in Daylight

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- Ground-based imaging of satellites during the daytime represents a formidable challenge due to the strong turbulence induced noise in the imagery and the high background noise.
- Restoration of imagery in this regime requires a multi-frame blind deconvolution (MFBD) algorithm, which estimates the turbulence blur and the object intensity distribution. Successful restoration requires modeling the high spatial frequencies of turbulence induced perturbations in the wave front.
- In cases of daylight imaging, the sampling of the WFS will be insufficient for fully characterizing these high spatial frequencies. In such regimes additional information about the temporal correlations in the data must be included in the MFBD algorithm.
- This is the motivation for the Daylight Object Restoration Algorithm (DORA) [1], which uses WFS data together with a frozen flow model of the atmosphere to estimate spatial frequencies beyond those measured by the WFS.

On June 8th, 2018, the ENVISAT remote sensing satellite was observed in full daylight using the AEOS 3.65m telescope on Mt. Haleakala. An example of a raw image frame from the Advanced Research Daylight Imaging (ARDI) camera [2] is shown in the left panel of Fig. 1. This imagery has no AO correction and was obtained in turbulence conditions a factor of 2 more severe than that experienced at night time.

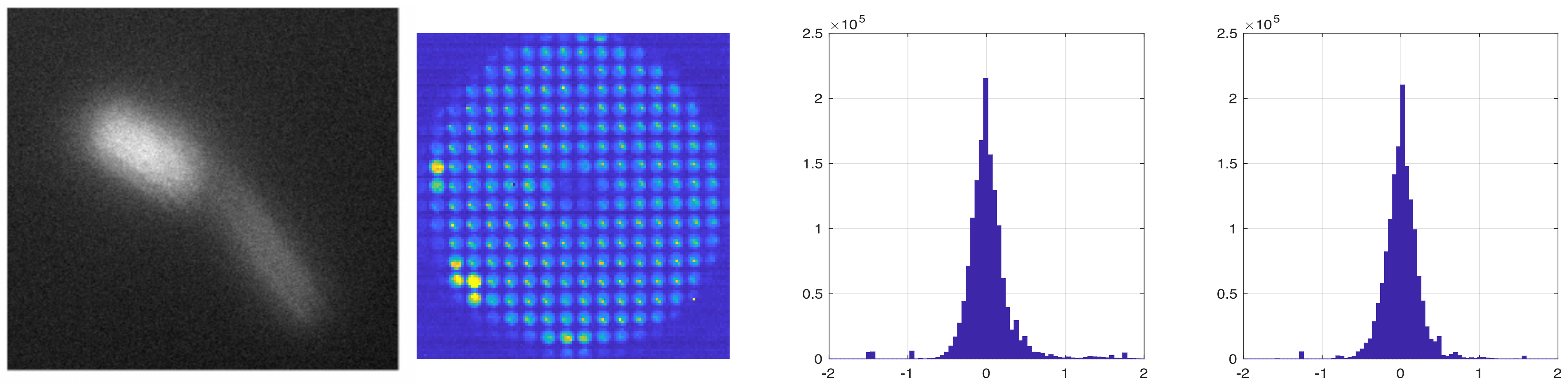

Fig. 1. Left pane: Raw speckle (no AO correction) Second panel: A DORA-WFS image [3] (16x16 sampling) showing the saturation at some sub-apertures. The two panels on the right show a histogram of the measured x/y-gradients. The outlier slope values correspond to the slope measurements computed at noise corrupted sub-apertures.

During daylight observing, the slope value computed at each sub-aperture can become contaminated by noise at different times in the pass. This most likely results from glints off the telescope head ring and spider vanes occurring as the telescope slews. These noise corrupted sub-apertures are identified by analyzing the temporal statistics of the computed slopes and flagging sub-apertures where the computed slopes do not match the expected statistics of the measurements, i.e. zero mean Gaussian variates (see right two panels in Fig. 1).

Modeling the wave front using a FFM requires knowing the wind velocities of all significant layers of turbulence in the atmosphere. These are computed from an autocorrelation of the WFS measurements as shown in Fig. 2

References

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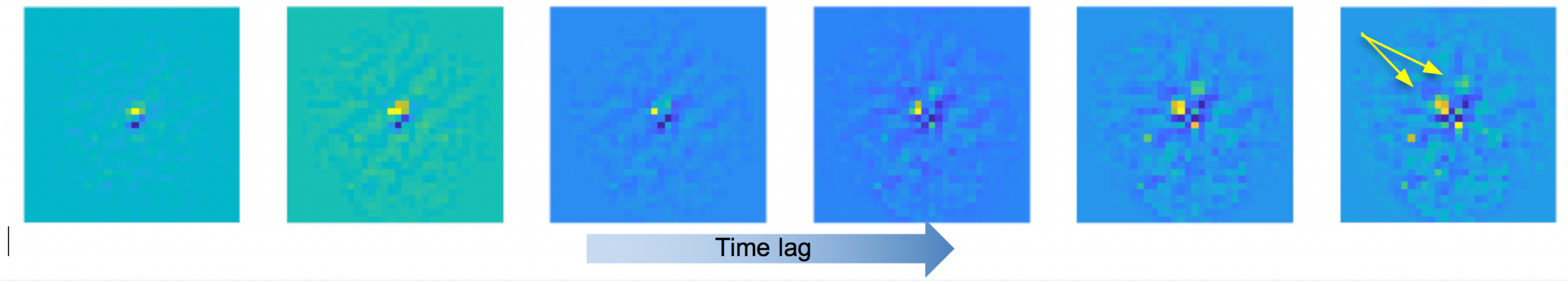


Fig 2. Consecutive time-lag slices from the 3D autocorrelation of the ENVISAT WFS data. Two frozen layers, a strong slow ground layer (moving toward 10 o'clock position) and one fast upper layer (moving toward 1 o'clock position) denoted by the arrows in panel 6.

- The pupil wave front is modeled as a sum of independent static turbulent layers (a frozen flow model) propagating with the wind velocities obtained from an analysis of the 3D spatial and temporal auto-correlation of the WFS data (Fig. 2) .
- The use of the FFM results in better sampling of the high-spatial frequencies of the wave front as clearly shown in Figure 3 where the wave fronts from the beginning and end of a sequence of WFS frames corresponding to 38 milli-seconds is shown.
- The first row shows the wave-fronts reconstructed using only the WFS data (low resolution) and second row shows the WFS data + FFM (high resolution). The high spatial frequencies resulting from use of the FFM, which are clearly evident, are crucial for obtaining a high fidelity model of the atmospheric PSF.

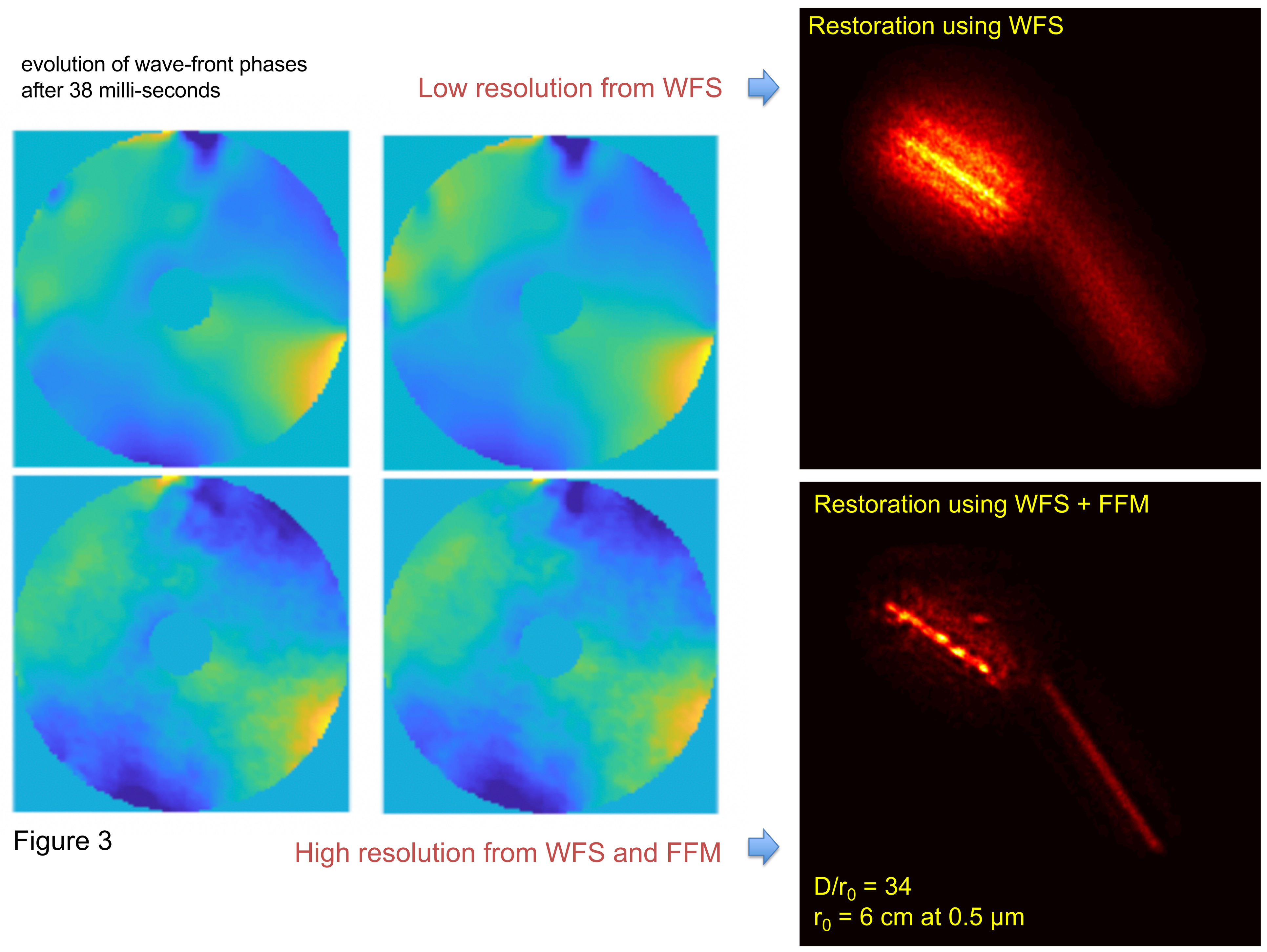
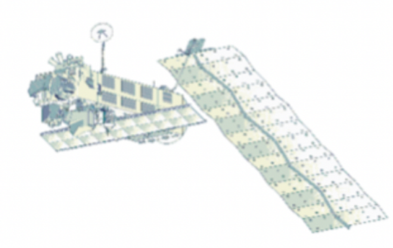


Figure 3

- **The high spatial frequencies computed using the WFS data and FFM clearly have physical meaning. This is evident by comparing the restoration using only WFS data (low resolution phases - top) to the restoration using phases computed from the WFS and FFM (bottom)**



ENVISAT Remote sensing satellite
- Object ID 27386
- Operational March 2002– April 2012
- Range ~771 km
- Declination 98.2 degrees
- Orbital Period 100 minutes

Acknowledgments

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