EFFORTLESS: EFFICIENT OPTIMAL IMAGE RECONSTRUCTION FOR THE NANCY GRACE ROMAN SPACE TELESCOPE AND BEYOND

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Abstract

The forthcoming Nancy Grace Roman Space Telescope will revolutionize astrophysics by generating huge amounts of data of unprecedented quality. To properly address the data deluge and fully realize its potential, analysis tools that are both efficient and optimal are needed. EFFORTLESS (previously known as Fast IMCOM) is a new algorithm for linear image reconstruction. Like its predecessor IMCOM, it offers control over point spread functions in output images; by avoiding laborious calculations, it is tens of times faster and has a smaller memory footprint. In this paper, I apply EFFORTLESS to simulated Roman images and present promising first results. With ideal point sources, I illustrate that a single image reconstructed by EFFORTLESS, combined with the post-measurement calibration procedure described in a companion paper, can lead to better measurements than a set of ~ 6 images coadded by IMCOM. While both algorithms were originally designed for weak gravitational lensing cosmology, EFFORTLESS can benefit studies of static features and dynamic aspects of the Universe alike. Moreover, the efficiency and interpretability of EFFORTLESS provides new possibilities for further reducing errors in measurements. The implementation of EFFORTLESS is detailed in the companion paper.

Methods

A linear image reconstruction scheme is formulated as a linear transformation from input signals $I_{\boldsymbol{i}}^{(\bar{i})}$ to each output signal $H_{\boldsymbol{\alpha}}$:

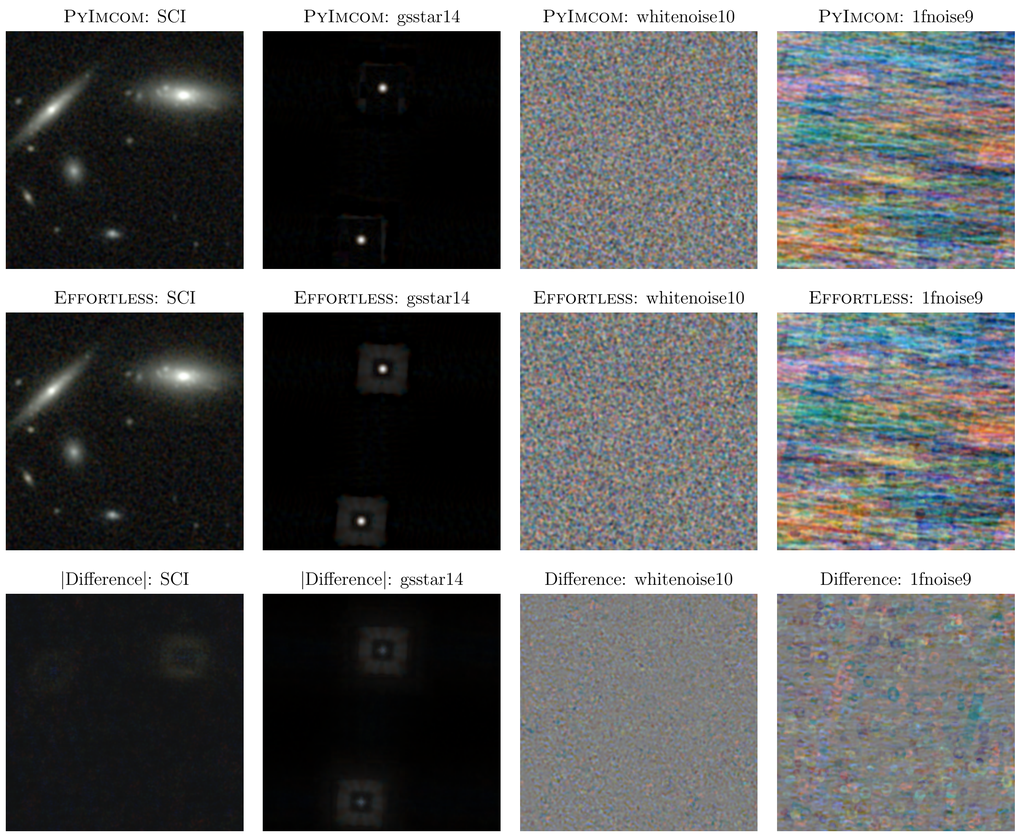
$$H_{\boldsymbol{\alpha}} = \sum_{\bar{i}} \mathcal{N}_{\bar{i}} \sum_{\boldsymbol{i}\in\bar{i}} T_{\boldsymbol{\alpha i}}^{(\bar{i})} I_{\boldsymbol{i}}^{(\bar{i})}, \tag{1}$$

where $\bar{i} \subset \mathbb{Z}^2$ is the collection of available pixel indices in an input image, $\mathcal{N}_{\bar{i}}$ is the meta-weight assigned to input image $\bar{i}$, and $T_{\boldsymbol{\alpha i}}^{(\bar{i})}$ are the reconstruction weights. Such a linear transformation also constructs an output PSF $\Psi'_{\boldsymbol{\alpha}}$ from properly shifted input PSFs $G_{\boldsymbol{i}}^{\prime(\bar{i})}$:

$$\Psi'_{\boldsymbol{\alpha}}(\boldsymbol{s}) = \sum_{\bar{i}} \mathcal{N}_{\bar{i}} \sum_{\boldsymbol{i}\in\bar{i}} T_{\boldsymbol{\alpha i}}^{(\bar{i})} G_{\boldsymbol{i}}^{\prime(\bar{i})}(\boldsymbol{R}_{\boldsymbol{\alpha}} - \boldsymbol{r}_{\boldsymbol{i}}^{(\bar{i})} + \boldsymbol{s}), \tag{2}$$

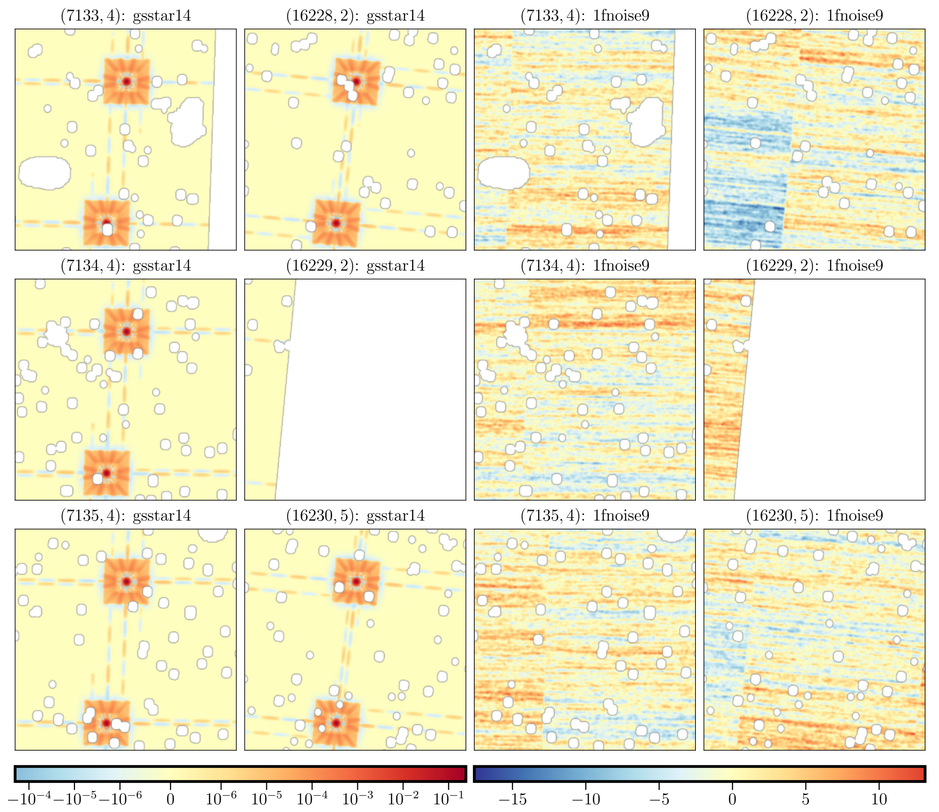
where $\boldsymbol{R}_{\boldsymbol{\alpha}}$ and $\boldsymbol{r}_{\boldsymbol{i}}^{(\bar{i})}$ are the positions of output pixel $\boldsymbol{\alpha}$ and input pixels $\boldsymbol{i}$ in input image $\bar{i}$, respectively. Both IMCOM and EFFORTLESS aim at minimizing the discrepancy between Equation (2) and some user-specified target output PSF Γ'.

Coadded Images



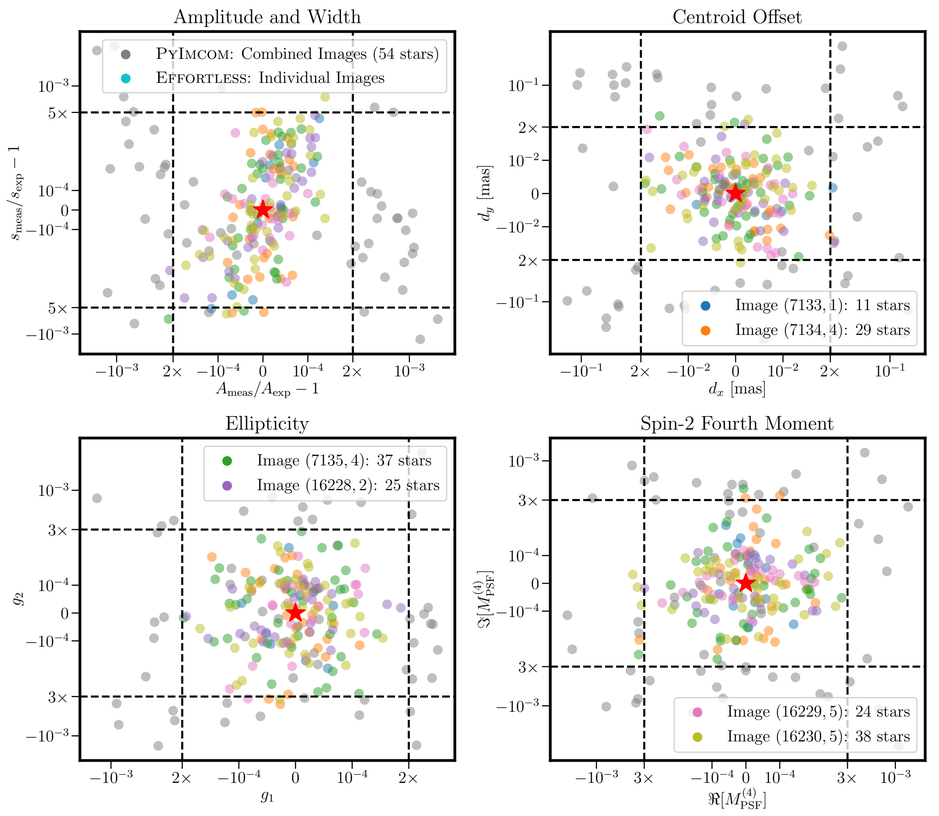
Four layers in a field of $17.5\,\mathrm{arcsec}$ (448 output pixels) on a side, coadded by the Cholesky kernel of PyIMCOM (upper row) and the Σ-first strategy of EFFORTLESS (middle row), along with the differences between them (absolute difference for the first two columns, PyIMCOM minus EFFORTLESS for the last two columns; lower row). Each panel is a Y106 (#001AA6) + J129 (#006659) + H158 (#596600) + F184 (#A61A00) composite; note that these four colors have similar lightnesses and add up to white (#FFFFFF). From left to right, the four layers are: simulated science images ('SCI'), injected stars drawn by GALSIM ('gsstar14'), simulated white noise frames ('whitenoise10'), and simulated $1/f$ noise frames ('1fnoise9').

Reconstructed Images



Two layers in the same field as Figure 1, reconstructed by EFFORTLESS from six individual images in the Y106 band. The left half shows injected stars drawn by GALSIM ('gsstar14') in symmetric logarithmic scale with a linear threshold of 10^{-6}; the right half shows simulated $1/f$ noise frames ('1fnoise9') in linear scale. EFFORTLESS can project individual images onto a common pixel grid and unify the PSFs; such capability enables pixel-by-pixel comparisons between different images for obtaining time-domain information or removing some exposure-specific errors.

Analysis Results



HSM measurements of the 54 injected stars in block $(14, 12)$ in the Y106 band. PyIMCOM results based on the combination of ~ 6 images are shown in gray; calibrated EFFORTLESS results based on the reconstruction of 6 individual images are shown in different colors. Numbers of stars measured from individual images are shown in the legends; measurements of each injected star are provided by at least 1 image. The four panels correspond to amplitude A and shear invariant width s (upper left panel), centroid offset $\boldsymbol{d}$ (upper right panel), ellipticity g_1 and g_2 (lower left panel), and the spin-2 fourth moment $M_{\mathrm{PSF}}^{(4)}$ (lower right panel), respectively. For A and s, fractional errors (measured divided by true minus 1) are shown. All axes are in symmetric logarithmic scales, with different linear thresholds (shown as vertical and horizontal black dashed lines) chosen to enclose most of EFFORTLESS data points. The axis tick label "$n\times$" means "$n\times$" the value of the closest inner label, e.g., $\pm 2 \times 10^{-4}$ for the x-axis of the upper left panel. Correct values are denoted as red stars.