Identifying Transients in Real-Time with Image Subtraction for Wide-Field Surveys

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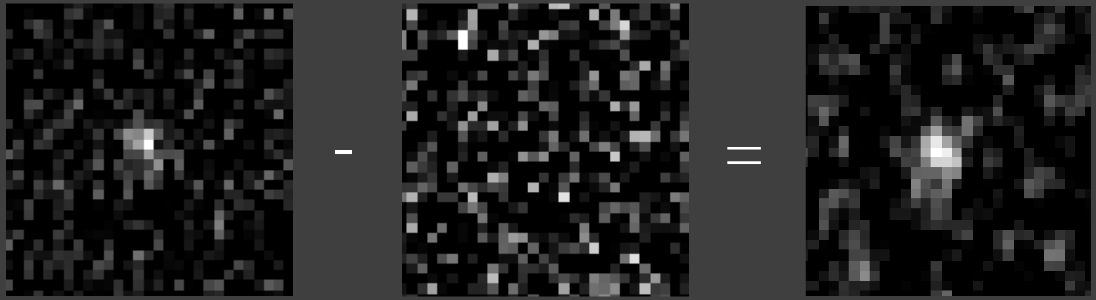
We are now in the era of wide-field survey astronomy. Finding transients quickly for broadband follow-up is more important than ever. The most effective way to find changes in the sky is with **image subtraction**, finding the difference in flux between two images from different epochs. With an unprecedented number of stars per exposure and the largest image sizes yet, computing these subtractions in **real time** presents a new set of challenges.

The Gravitational-wave Optical Transient Observer, **GOTO**, is a wide-field survey in the search for counterparts to Gravitational-Wave events and is the **pathfinder** for the next generation of high cadence wide-field surveys. Therefore, GOTO marks the opportunity for the development of tools for the **rapid identification of Transients in wide-fields**.

GOTO under the Milky Way

Image Subtraction has two main requirements that are made significantly harder with fast, wide-field, optics. The first is image registration, or **source alignment**, which is the process of making sure stars line up on the same pixels in both images. The second is Point Spread Function **(PSF) modelling**, estimating the shapes that point sources appear as in the image.

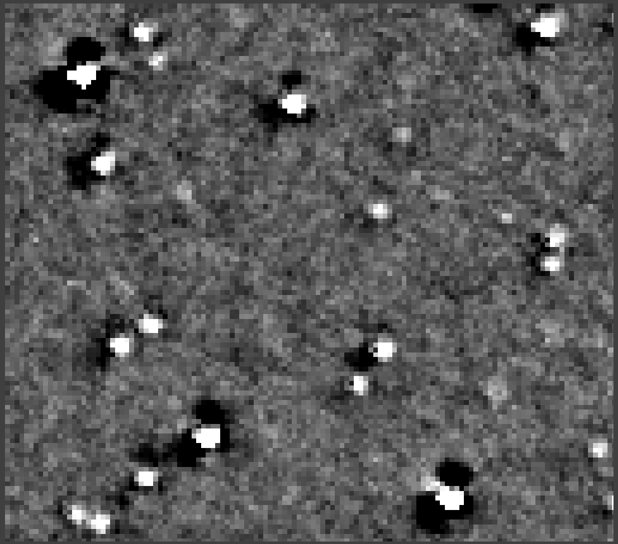
A wide-field requires higher order transforms to successfully align the whole image, and **multiple models** are needed to create a spatially varying PSF kernel. The PSF is not static across the entire image. This poster will show the development of a **python package** designed to **build subtraction pipelines** for wide field surveys.



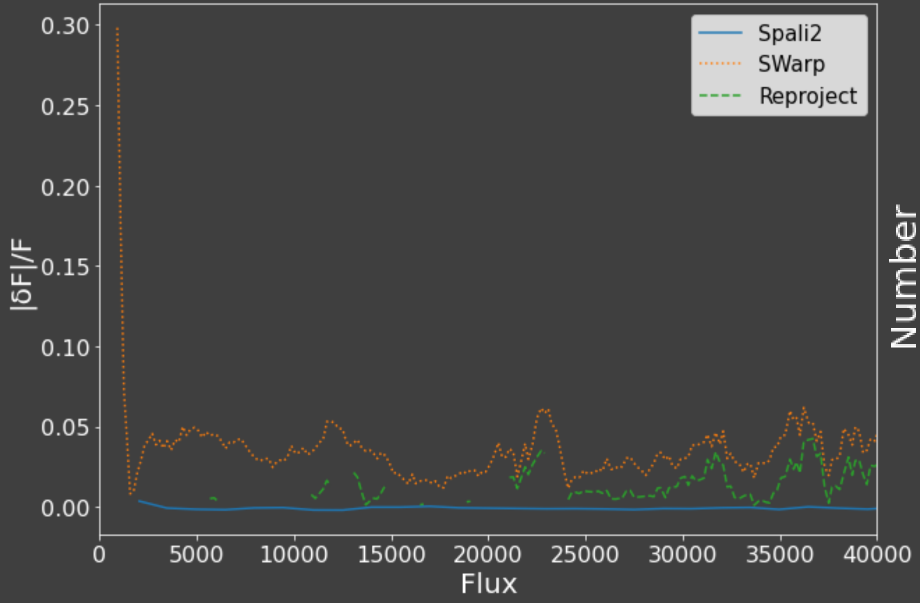
Example of image subtraction

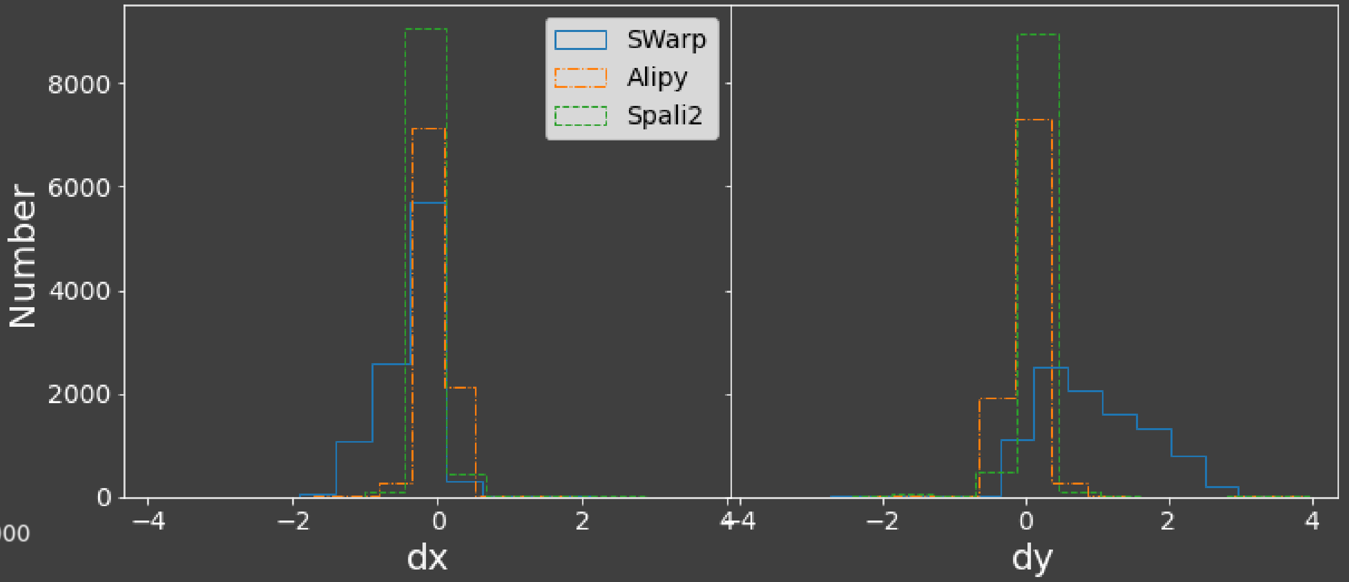
Aligning Wide-Field Images

If an image is not aligned with its partner, residuals will be left in the subtracted image that do not correspond to astrophysical changes. Wide-fields cannot be aligned simply with linear mapping, shown on the right. This can be due to the optics of a wide-field telescope, but also due to the **curvature of the sky**. To fix this, a regular affine transform is used on the centre of the image, and a **spline** in employed to account for the higher order transforms needed to correctly align the images. This new method is called **Spali2**.

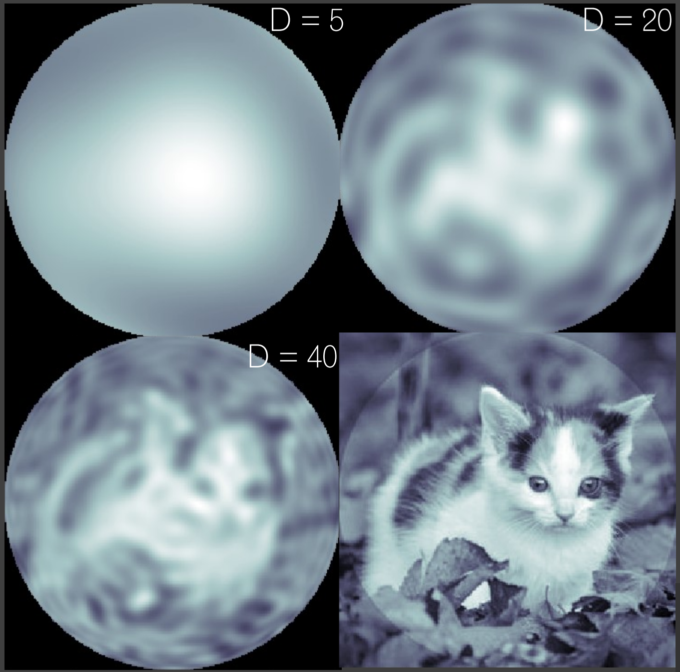


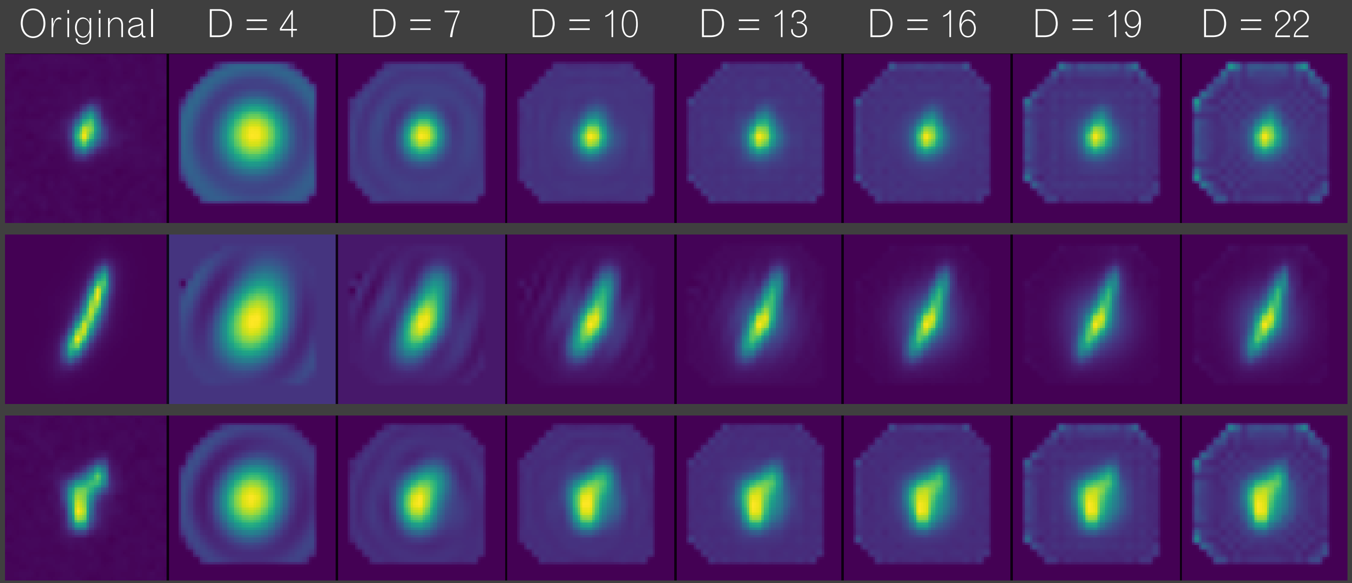
Two key metrics need to be assessed to test alignment performance. **Flux conservation**, shown bottom left, tests how much noise is introduced to the source flux through the transformation. Spali2 has shown to be able to transform images **without introducing noise to source flux**. The other metric is difference in source position, seen bottom right. dx and dy are difference of source barycentre in both images. Compared to other methods used in the literature, Spali2 **is able to align the most sources successfully**.





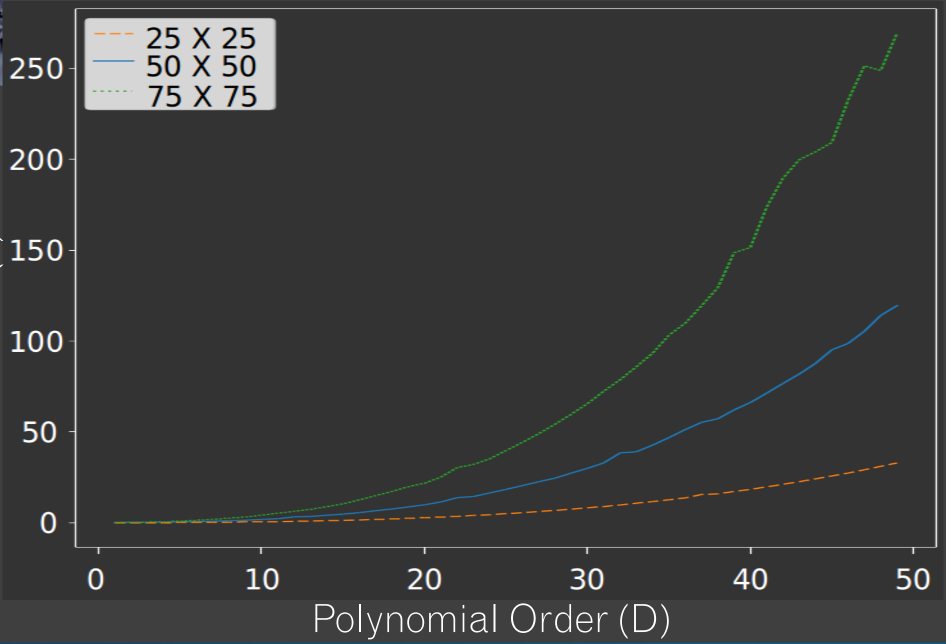
Modelling the PSF Quickly with Zernike Moments





Zernike Polynomials were first introduced in 1934. They work on an **orthogonal basis** (no two polynomials have overlapping information) and **form a complete set**, meaning that they can recreate arbitrarily complex surfaces, shown above.

Zernike Moments are the projection of an image onto a set of complex Zernike polynomials. Using a **spatially varying function**, multiple PSFs can be modelled from one image. Demonstrated by the figure in the top right .



Being able to replicate complicated source shapes is not a problem for Zernike Moments, A Polynomial order of 22 suffices for even the most complex **PSF kernels**.

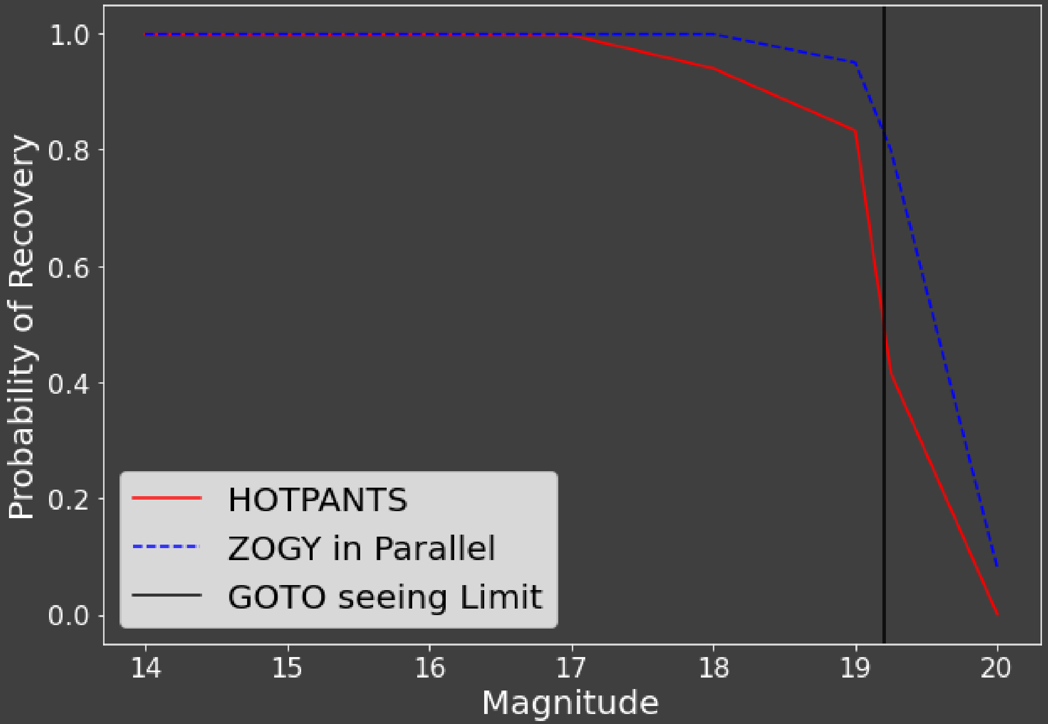
Even for the largest kernel sizes the models will take **~30 seconds**, but for GOTO, each kernel can be built in **under 10 seconds**. The centre figure highlights the modelling speed for different kernel sizes.

ZOGY in Parallel

The image subtraction method of choice, ZOGY (also known as Proper Image Subtraction), is regarded as the optimal way to subtract two photometric images. The figure on the right shows transient recovery as a function of magnitude for different subtraction methods. Using a parallelised algorithm combined with the ZOGY functions, one can subtract an entire GOTO image (8000 x 6000 pixels) in less than 30 seconds. This is 8 times faster than the original ZOGY implementation and over twice as fast as ZOGY's competitor, HOTPANTS. This python package is called ZOGY in Parallel (ZiP).

The ZiP Package contains parallelised co-addition functions for stacking, the high order alignment technique, Spali2, for wide-field image registration, and the Zernike Moment PSF modelling technique. All of these features are integrated into the ZiP architecture. This allows users to make an entire real-time subtraction pipeline all within the ZiP framework.

Combining this with machine learning, GOTO can flag transient candidates within a minute of an image being taken. Presenting a new paradigm for rapid transient follow-up.



As seen in Gompertz et al (2020)

https://github.com/GOTO-OBS/ZiP

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