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HIGH RESOLUTION IN THREE DIMENSIONS WITH SWIFT AND PALM3K

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Abstract. SWIFT is a visible light (650-1000nm) integral field spectorgaph fed by the Palomar extreme adaptive optics system PALM3K. With a subaperture spacing of 8cm, PALM3K is capable of delivering diffraction limited performance even in the visible. With SWIFT providing spatially resolved spectroscopy at R=4000, this provides a truly unique facility for high resolution science in three dimensions. We present here some results from the first year of PALM3K+SWIFT science. We also report on our experience of operating a small field of view instrument (1"x0.5") with a high performance AO system, and hope the lessons learned will provide valuable input to designing successful and productive AO plus Instrument combinations for ELTs.

1. Introduction

The SWIFT spectrograph [1] was built at the University of Oxford from 2004-2008, and is currently in use with the adaptive optics system at the Palomar 200-inch Hale telescope. SWIFT is an image slicer based integral field spectrograph, which provides a simultaneous spectrum from 650nm to 1050nm at a spectral resolution ($\lambda/\delta\lambda$) of approximately 4000 for every point in a 90x44 spaxel field of view. SWIFT provides several spaxel (**spa**tial pi**xel**) scales ranging from 0.24"/spaxel down to 0.016"/spaxel, equating to fields of view of 22"x11" down to 1.44"x0.70"

SWIFT was originally built for the core science of studying the dynamics of distant galaxies, utilizing the original PALAO-LGS [2] system to provide moderate spatial correction on these very faint targets. With the upgrade of PALAO to the high-order PALM3K system [3], LGS operation is no longer supported, and the system has been refocused on providing the very highest spatial correction on bright natural guide star targets. To take advantage of these different AO capabilities, SWIFT has been refurbished and retro-fitted with a new diffraction-limited spaxel scale. In this presentation, we provide an overview of SWIFT's new capabilities, and a brief summary of the early science observations performed with high resolution in three dimensions

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2. Diffraction limited upgrade

2.1. 16mas spaxel scale

SWIFT originally carried three spaxel scales of 235, 160 and 80 milli-arcsec/spaxel, suited to the image quality delivered by PALAO. As PALM3K can deliver Strehl ratios of up to 40% in the *I*-band, we replaced the 160 mas/spaxel with a much finer scale of 16 mas/spaxel which samples the diffraction limited FWHM of the 200-inch telescope at 800nm.

The design of the SWIFT pre-optics requires a 2:1 anamorphic magnification of the field onto the image slicer. This is achieved with a combination of cylindrical and spherical lenses. The extremely slow f/ratio required by the new scale meant that even stock lenses could be used to deliver excellent image quality (>99% Strehl) across the whole field of view.

2.2. Blocking bar for bright targets

One of the obvious science drivers behind high quality adaptive optics are high contrast observations near bright targets. SWIFT was never designed with this in mind originally, and does not include any easy facility to install a coronagraph. To at least allow more efficient observations of bright targets without saturating the detector, we installed a blocking bar after the image slicer to act as a pseudo-coronagraph. A shaped bar is rotated into the exit slit of the image slicer, to sequentially block light from central slices of the IFU from entering the spectrograph. Fig. 1 shows the effect of this on a flat field.

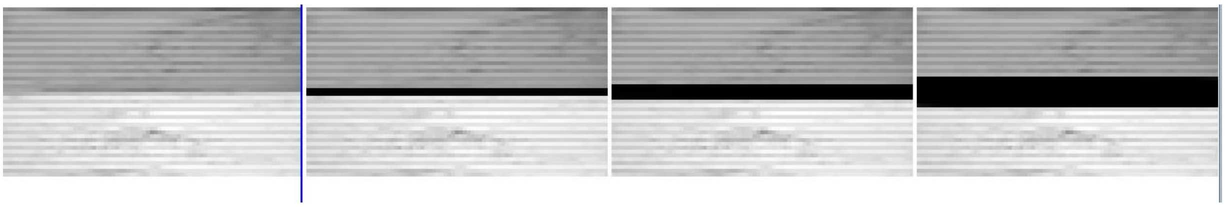

Fig. 1: A reconstructed flat field image showing the SWIFT field of view with (L to R): no blocking bar, 2-slices, 4-slices and 8-slices blocked.

2.3. Calibration iris

To compensate for the large spaxel area difference (225x) between the largest and smallest plate scales of SWIFT, we introduced a remotely adjustable iris stop in the calibration system to control the calibration light level. Without this, the smallest scale requires 225x longer exposure time than the largest scale, making calibration very inefficient.

3. Example results

In this section we present a sample of early science observations obtained with SWIFT and PALM3K. Observations presented here were taken in July and October 2012, when seeing conditions were median-to-good for Palomar (1.1—0.8” V-band seeing).

3.1. PSF

The PSF delivered by PALM3K+SWIFT was measured on-sky with a bright (V=5.0) star. Fig. 2 and Fig. 3 show the ensquared energy growth (of primary interest for most spectroscopy applications) and the reconstructed multi-colour PSF. At red visible wavelengths (~800nm), PALM3K is concentrating approximated 50% of the light within a 50mas radius. The reconstructed PSF shows the central core and first airy ring, with an apparent trefoil structure superimposed. The speckle pattern can also be seen scaling with wavelength in Fig. 3. The more complex data reduction process involved in integral field spectrograph data compared to imaging data can introduce a non-trivial contribution to the image quality measurement, and there is no-doubt some improvement to be gained in non-common-path calibration (see §4).

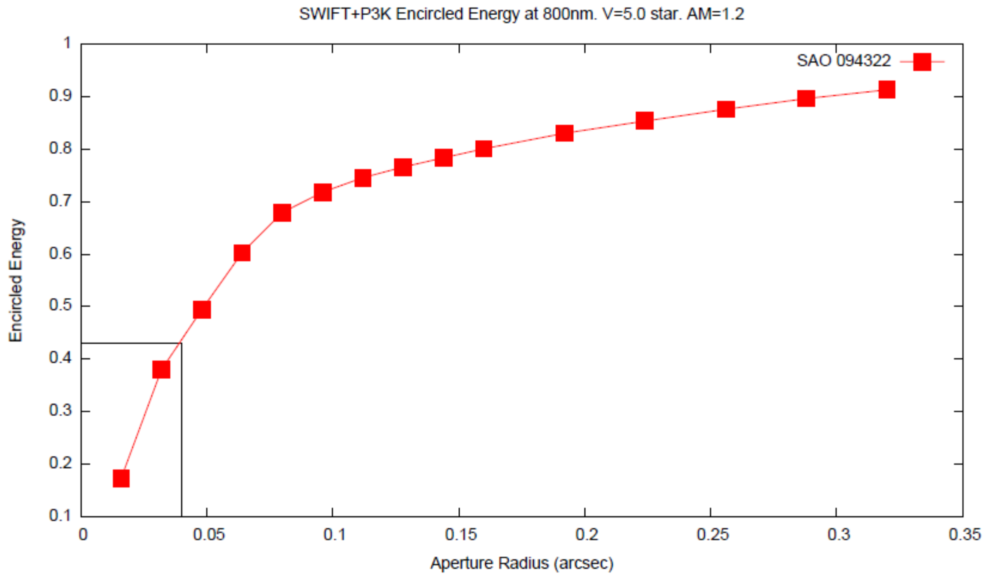

Fig. 2: Ensquared energy as a function of radius (at 800nm wavelength) measured on-sky with a bright star. 50% of the energy is contained within a 50mas radius.

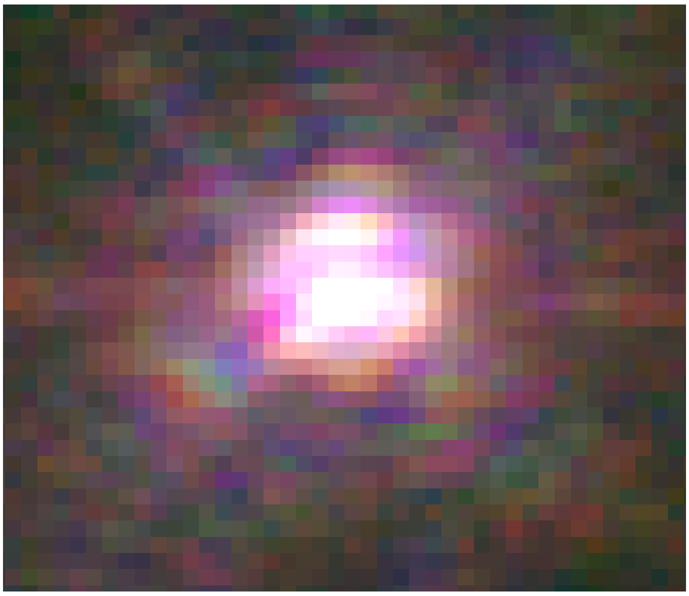

Fig. 3: Colour PSF reconstructed from three channels of the IFU datacube at 700, 850 and 1000nm. Eah spaxel in this image is 16mas, and the FWHM of the PSF is about 50mas at 850nm. The chromatic effect caused by the diffraction pattern scaling with wavelength can be seen.

3.2. Galilean Moons

In October 2012, SWIFT and PALM3K observed the Galilean moons around Jupiter over several nights. The goal of the programme is to measure compositional differences across the surfaces of the moons, and map albedo asymmetries between the leading and trailing hemispheres to understand alteration due to magnetosphere-surface interactions. In addition, we hope to spatially map the depth of the water ice band at 1.04 µm and search for any species not previously identified in the lower-spectral-resolution observations of Galileo and Cassini. At the time of writing this analysis is on-going. Here we present initial images of the moons extracted from the 3-D datacubes. In all cases, the moon itself was used as the AO reference object.

Fig. 4 shows images of Ganymede (right) and Callisto (left) taken with the 80mas spaxel scale. This is substantially larger than the PSF FWHM delivered by the AO system, and each spaxel is effectively an independent resolution element (see the PSF in the top-right of Fig. 4). Each spaxel corresponds to approximately 250 km on the surface of the moons. Distinct surface features are clearly resolved, and an image generated from in-orbit Galileo data is given for comparison.

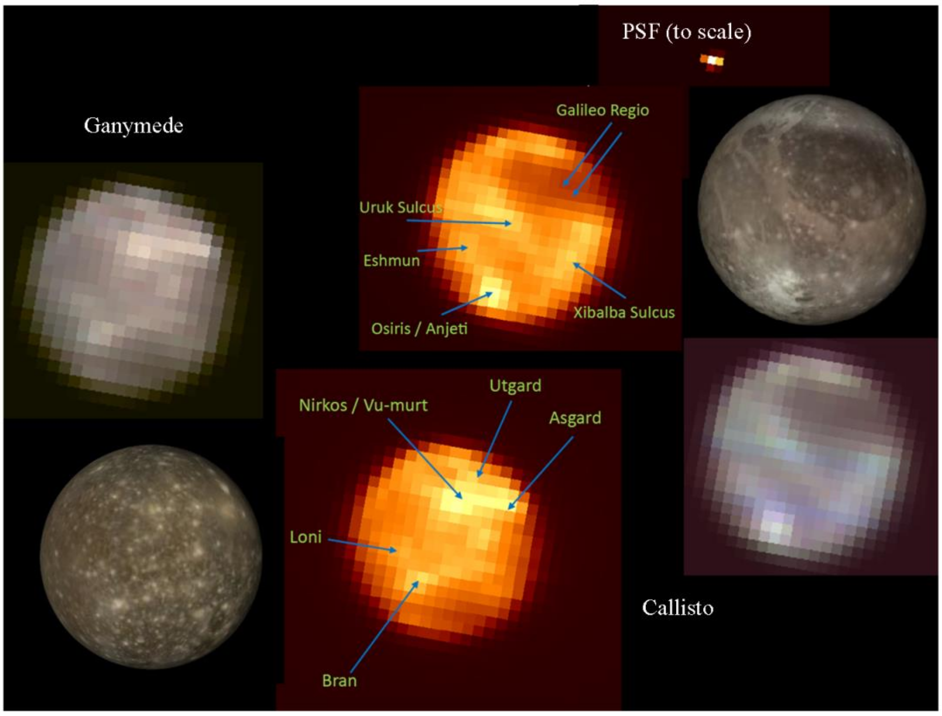

Fig. 4: Composition of images of Ganymede (top row) and Callisto (bottom row) taken with SWIFT and PALM3K at the 80mas/spaxel scale in October 2012. At this scale, each spaxel is effectively an independant element (see PSF in top-right)

One of the problems with observing solar system objects with SWIFT is their size – the field of view of the diffraction limited scale is only 1.4x0.7”, meaning a mosaic is required to cover even the moons of Jupiter! Fig. 5 shows a reconstructed mosaic (6 exposures at two pointings) of the moon Io. A colour image was constructed from slices at three different wavelengths in the SWIFT data cube. The major volcanic features on the surface of Io are clearly resolved, and the colour difference in the Sulphur ring bottom-centre is obvious. The next step in this data analysis is to extract spectra for each area on the surface, and look for compositional differences across the surface. The unique spectral resolution of SWIFT (δλ=1Å) allows us to investigate very narrow spectral features that are not accessible to standard imaging filters.

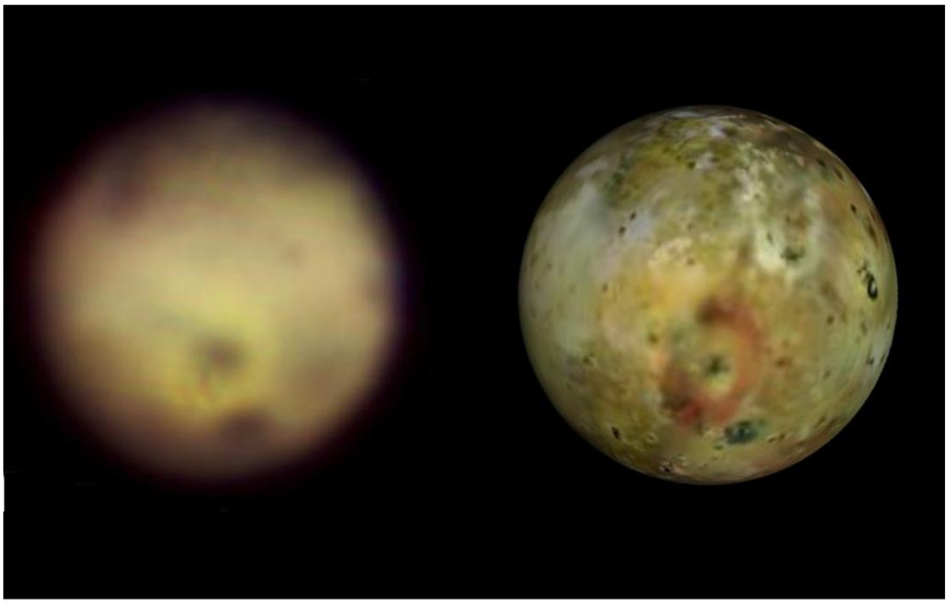

Fig. 5: Io imaged with SWIFT and PALM3K at 16 mas/spaxel (left), compared with an image generated from in-orbit imaging obtained by the Galileo spacecraft (right). The broadband colour image from SWIFT is generated from three slices of the datacube at approx. 660nm, 800nm and 1000nm.

3.3. Neptune

At 2.5 arcseconds in diameter, Neptune is at the upper end of PALM3K's ability to lock the loop on extended objects. Nevertheless, we have been able to obtain several impressive datasets on Neptune allowing us to study the spatially (and temporally!) changing nature of Neptune's atmosphere. The strong spectral features from Neptune (Fig. 6) show the power of an integral field spectrograph, allowing one to probe the different structure seen just 10nm apart in wavelength. Fig. 7 shows how this structure changes with time and wavelength. The spectral and spatial sampling provided by SWIFT and PALM3K allows us to build a three dimensional model of Neptune's atmosphere, and probe compositional and structure differences across the planet [4].

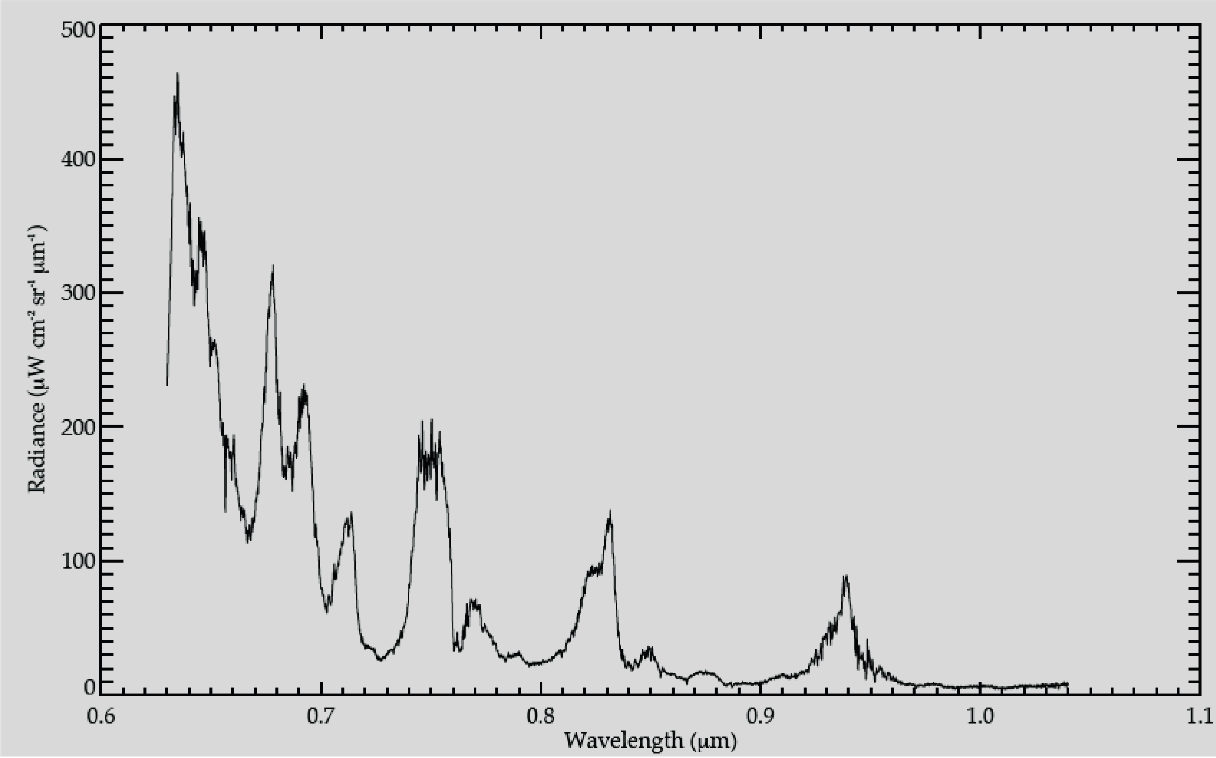

Fig. 6: SWIFT spectrum of Neptune showing the strong spectral features which make a high spectral resolution IFU the ideal tool to study its atmosphere.

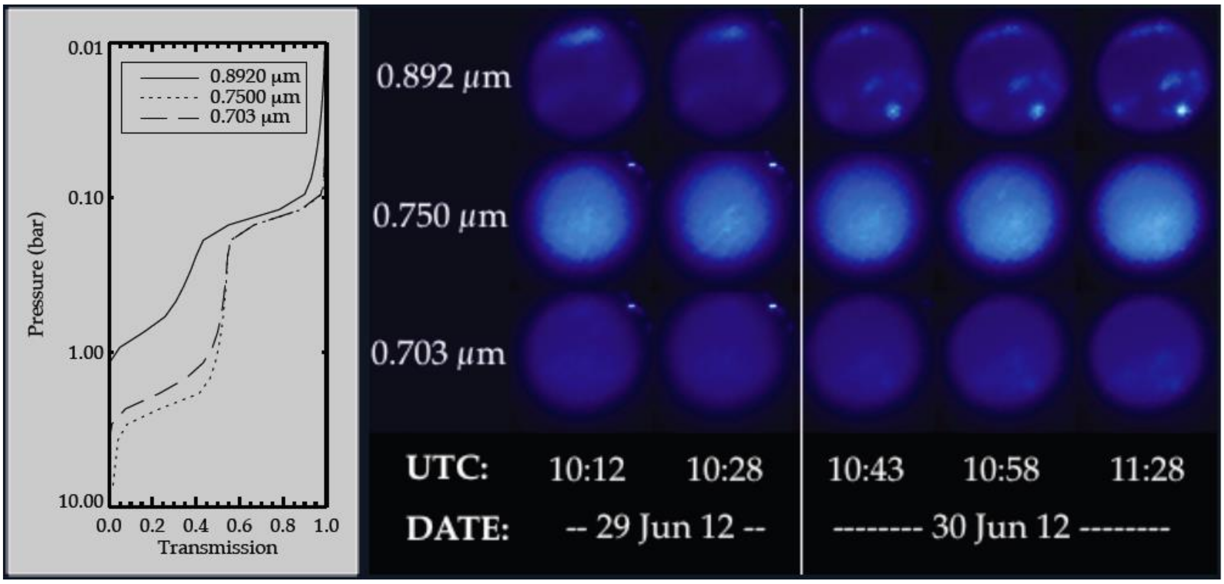

Fig. 7: Data taken over two nights in June 2012 showing how the structure of Neptune's cloud layers change with time (horizontally) and wavelength (vertically). Comparing the structure at different wavelengths gives us a three dimensional probe of Neptune's atmosphere, and enables us to look for compositional/structural differences across the planet.

4. Lessons learned from SWIFT and PALM3K

Though conceptually similar to standard imaging cameras, integral field spectrographs such as SWIFT present their own unique set of features. This is particularly true when operating at the finest spaxel scales and small fields of view. One of the key benefits of retasking SWIFT to operate at the diffraction limit provided by PALM3K has the on-sky experience of dealing with IFS observations at these scales.

Through the initial commissioning and science runs, we have run into numerous effects which were not obvious beforehand. We list them here to provide some input for future instruments.

- Due to the nature of the data format, integral field spectrographs typically have significantly smaller fields of view than imagers (as a significant number of the available detector pixels are used to record spectral data instead of spatial data). The small field of view is challenging, as there are very few reference objects within the field. We therefore require very accurate independent knowledge of the FoV positioning on the sky to enable multiple pointings to be combined effectively.
- The more complex data format of an IFS relies on good processing algorithms to make it usable; one cannot rely on nice uniform square pixels as in a normal imager! The data reduction process can also introduce a non-trivial contribution to the image quality unless carefully controlled.
- Non-common-path calibrations currently limit the ultimate performance of SWIFT+PALM3K. We have struggled to implement NCP calibrations used for other instruments on PALM3K due to the issues listed above. An image slicer specific NCP calibration routine (currently under development) will be needed for SWIFT and future instruments.
- Imaging Spectrographs require calibrating as well as an imager, whilst including effects of a spectrograph! Classical spectrographs just hide how tough the calibration is!

5. References

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