Keck Adaptive Optics Note #385

Feasibility of LGS AO observations in the vicinity of Jupiter

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1   Introduction

It has been proposed by Imke De Pater and her collaborators to study Io in eclipse using the LGS AO system. The feasibility of this observation depends on the ability to close the tip-tilt (TT) loop on a faint satellite while closing the deformable (DM) loop on the LGS located as close as possible to Io. Similar observations could also be made of other satellites of Jupiter or Saturn. In this KAON, we measure the background on both STRAP and the WFS when the AO system is in the usual LGS AO configuration. We then analyze the centroid error with the measured background as a function of the magnitude of the TT reference and compare the centroid error with what would be expected with a typical sky background.

The red spots of Jupiter were imaged on July 21, 2006. The update to this KAON includes our experience of this observation. While we successfully closed the tip-tilt on Io, with very good STRAP and low-bandwidth wavefront sensor (LBWFS) performance, the DM loop gave us problems due to a fluctuating background.

2   Data acquisition

The data was taken on February 8, 2006. The telescope was first pointed at a bright pointing reference close to Jupiter in order to calibrate the pointing of the telescope. Then the telescope was sent to the center of Jupiter and then offset West from the center in different increments, from 15'' (the radius if Jupiter) to 300''. The test plan is presented in Appendix A. To prevent saturation of the APDs, different ND filters were used, according to the offset from Jupiter, as shown in Table 1.

| Telescope offset West	SFW
15-19"	ND2
20-31"	ND1
34"-300"	OPEN

Table 1: Neutral density filter used in front of STRAP as a function of distance from the center of Jupiter.

3   Data reduction

For each telescope offset position, the averaged counts per APD per second have been measured and divided by the nominal transmission of the neutral density filter used (10% for ND1 and 1% for ND2). To estimate properly the real offset of the STRAP FoV to Jupiter, Jupiter's proper motion (0.173" per minute) was taken into account.

Figure 1, depicts the measured absolute flux as a function of telescope offset. At an offset of 50" the average counts of the APD increased due to additional illumination from Jupiter's moon Europa, which was in the field of view of STRAP.
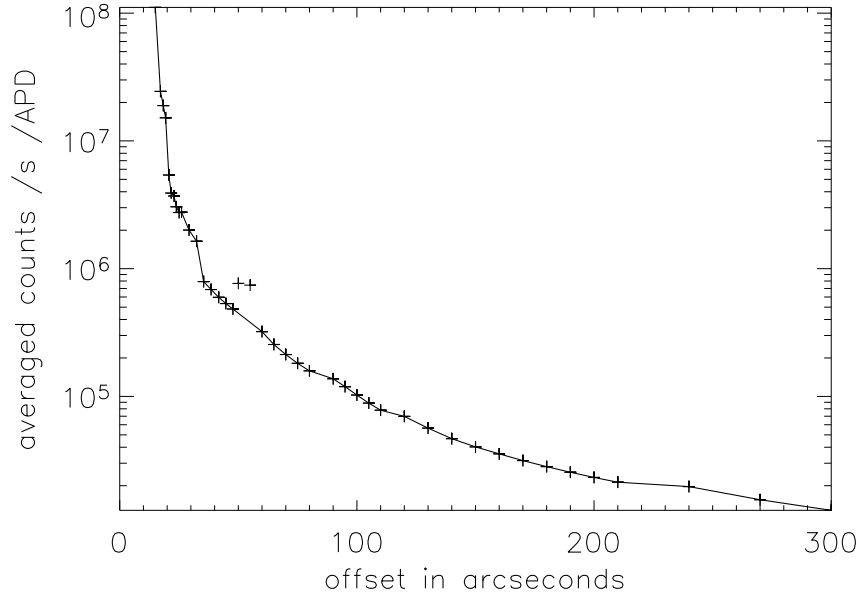
Fig. 1: Illumination of Jupiter on STRAP as a function of its relative offset. The increase in flux at 50" results from the additional light contribution from the Jupiter moon Europa, which was in the field of view of STRAP

The Jupiter background was also recorded on the WFS at 660 Hz. First, the lenslet array (WLS) was sent to block and a new background was taken. This background was used in what follows. Then the median intensity was read from the IDL subaperture intensity display tool. The results are displayed in Figure 2.

Unfortunately, the FCS stage, which is the stage that the WFS sits on, was probably left at the NGS focus (conjugate to infinity) rather than at the LGS focus (conjugate to 90-200 km depending on the elevation of the target). So the results reported here on the WFS background are not valid.
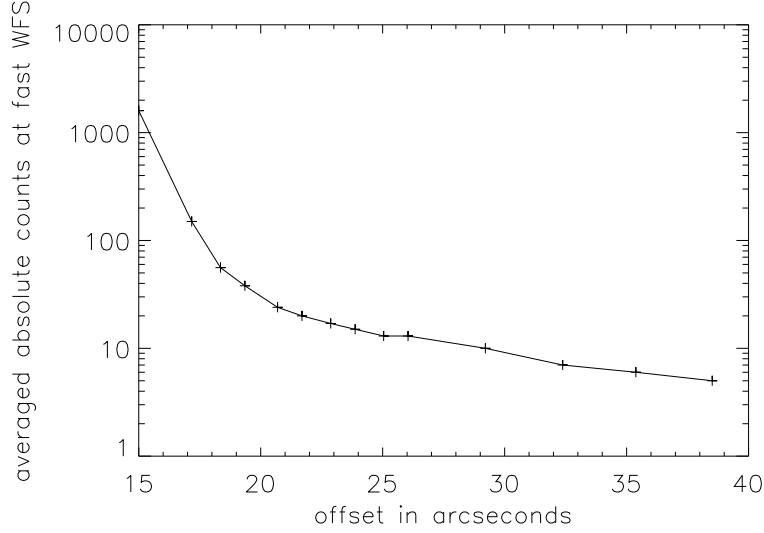
Fig 2: Average subaperture counts on the WFS as a function of distance from Jupiter

Since the LGS can be moved away 10'' from the science object without a significant reduction in performance, we conclude that the Jupiter background will not affect the performance of the LGS loop.

4   Background illumination effects on centroiding accuracy

In this section, we compute the effect of the background photons originating from Jupiter in terms of centroiding accuracy and the impact to the limiting magnitude of the useable TT guide star.

The expected number of photons per second per APD for a given guide star brightness can be calculated according to:

$$m_R = 26.0 - 2.5\log_{10}(counts_{APD})$$

where m_R is the R-band magnitude of the star and $counts_{APD}$ is the average number of counts per APD per second, and 26.0 is the STRAP photometric zero-point. The resulting centroiding variance can be modeled by:

$$\text{var} = \frac{(counts_{APD} + d + b)}{4(counts_{APD} \cdot T)^2} \cdot T$$

where d is the average dark current of the APDs per second, T the integration time in seconds and b the additional background photons from the night sky and further bright objects. An upper limit for the variance, where the TT-loop still can be closed, is given assuming only night sky background (1750 counts per second per APD). In such a case, the limiting visual magnitude of the useable TT guide star is between 18 and 19 mag, in average to good seeing.

The variance was calculated for a hypothetical integration time of 1 s. Since there is no read noise, the variance is inversely proportional to integration time. The solid line in Figure 3 shows

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the resulting centroid error as a function of guide star magnitude assuming only night sky background contribution. The other curves depict the impact of photons from Jupiter at selected offsets.
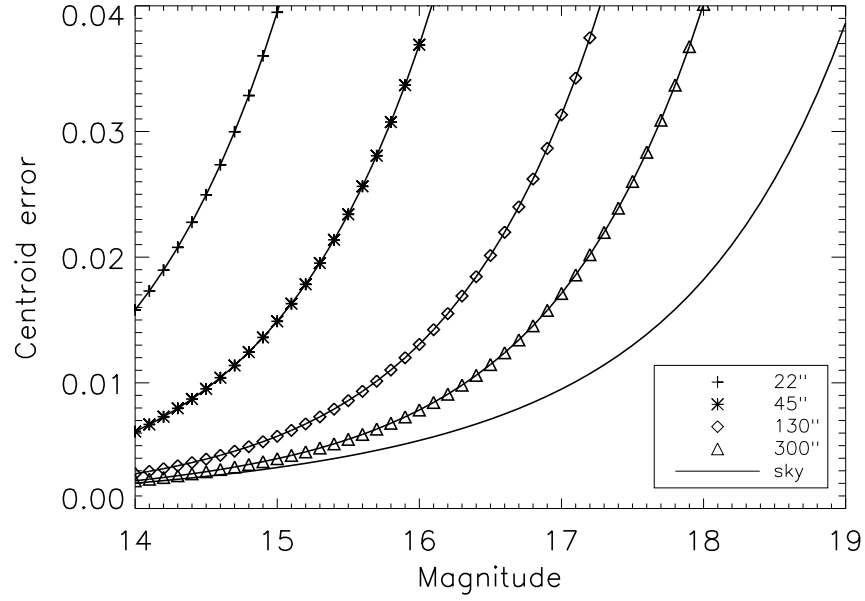
Fig. 3: Estimated variance of centroiding accuracy of STRAP unit as a function of guide star magnitude for different distances to Jupiter and hence different levels of background illumination. The intersection point with the top y-axis give the limiting magnitude for a given brightness level.
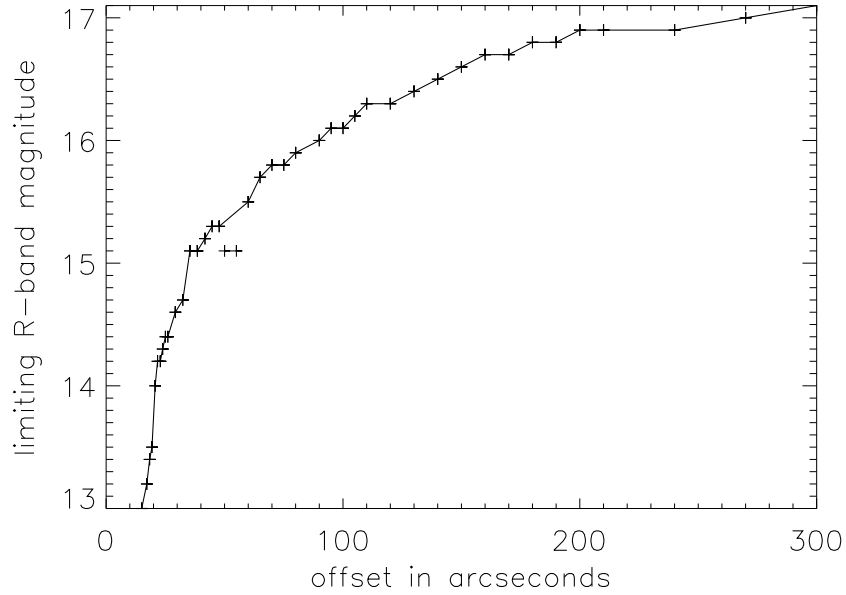
Fig. 4: Limiting magnitude as a function of Jupiter distance and hence different levels of background illumination. As reference for the limiting magnitude, the resulting centroiding

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variance of an 18th magnitude star has been chosen assuming only night sky background illumination.

Finally, Figure 4 shows the resulting limiting magnitude as a function Jupiter distance and hence different levels of background illumination. As a reference for the limiting magnitude, a resulting centroid variance has been chosen in the case of an 18th magnitude TT-guide star assuming only night sky background illumination. This graph reveals remaining constraints on the limiting TT-star magnitude even for offsets of 300".

5   Experience on the sky

The new red spot on Jupiter, red spot Jr., was imaged on July 21, 2006 (UT). The observing plane is attached in Appendix B. First, the system was run in LGS AO mode while guiding on Io. STRAP and LBWFS both reported good performance: the angular extent of Io is small enough to comfortably fit in the LBFWS subapertures and within the STRAP diaphragm.

When we offset to about 5" from the limb of Jupiter, we found that about half the wavefront sensor was flooded by the out-of-focus Jupiter. We needed to move about 15" away in order to not see this effect. When we closed the DM loop, the DM diagnostics showed very good correction. Unfortunately, the LBWFS reported large and fluctuating values for focus and low order aberrations. At the time, we struggled to understand this problem and played with the settings at our disposal: turning the focus compensation gain down and even disabling it. This did not make any difference.

We believe that the reason for these fluctuating aberrations was that the background on the wavefront sensor was not uniform and was fluctuating rapidly. Reasons for this fluctuation include the fact that Jupiter was moving relative to the wavefront sensor and that the FCS was also moving as it tracked Jupiter. We might have had more success if had taken frequent WFS backgrounds between science exposures and if we had the laser more or less stationary relative to Jupiter. In addition, having a much faster LBWFS (running at a few Hz rather than 0.1 Hz) could mitigate the effect of the fluctuating sky background.

6   Conclusion and discussion

We have measured the STRAP and WFS background in the vicinity of Jupiter. Closing the tip-tilt loop on a faint satellite close to Jupiter may or may not be possible. For example, for an object 45'' from the center of Jupiter, the object is effectively 3 mag fainter as far as STRAP is concerned, so a realistic limiting magnitude for such a tip-tilt reference is 15 mag.

The WFS background was initially believed to be negligible, because the test was carried out with FCS set to the NGS focus. However, experience on the sky demonstrated that the out-of-focus Jupiter flooded the WFS for distance smaller than about 15". In addition, the fluctuating background caused chaos for the WFS, with large and rapid fluctuations in low order aberrations, including focus, measured with the LBWFS.

Appendix A: Engineering test plan

Note: there is no mention of FCS being set to the LGS position; therefore the FCS was more than likely incorrectly left at the NGS position!

1. Set AO system for LGSAO
2. Select opt-axis for PO
3. Correct pointing on star close to Jupiter
4. Setup strap for 15th magnitude and record background close to the star, setup WFS for 660 Hz, gain 2, and record background.
5. Set STRAP filter wheel SFW to block
6. Ensure that AFM is set to open, TSS to optsodstrap and SOD to sodiumDichroic.
7. Make sure Jupiter coordinates has been added to the target list and slew to Jupiter using coordinates from starlist
8. From Jupiter offset 100arcsec West (Jupiter is about 30arsec Diameter)
9. Open SFW
10. Offset back towards Jupiter in steps of 5''. For each offset:
a. Record counts on STRAP
b. Record counts on WFS
c. When close to Jupiter, put NDs on SFW if STRAP is saturated and keep measuring light on WFS.


Appendix B: Jupiter observing test plan

High-resolution LGS-AO imaging of Jupiter's binary red spots

Primary Goal

Determine velocity field of Great Red Spot (GRS) and Red Spot Jr, to investigate possible interaction of flows and to measure energetics and dynamics of the vortices.

Technique

Obtain high resolution images of the spots, separated by about 1 hr. Need to get images as close to 6:30 UT as possible; then again near 7:30 UT.
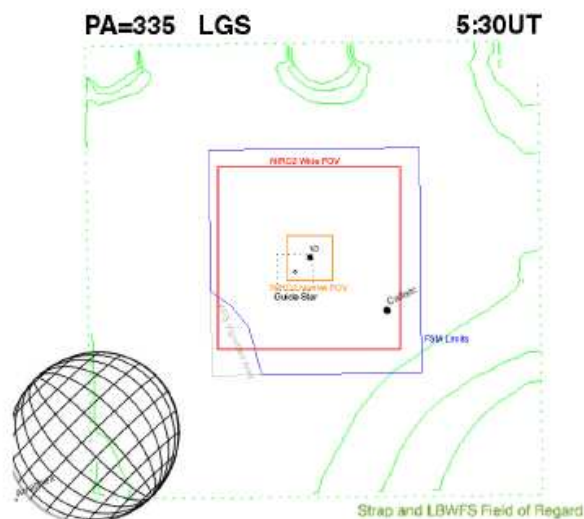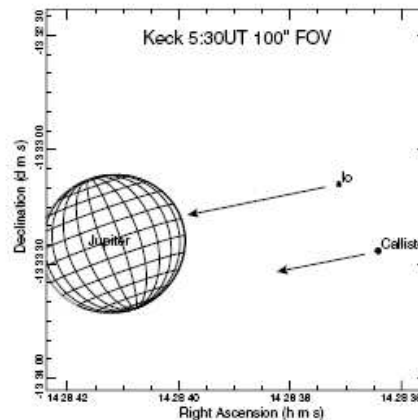

LGS Checkout

PA=19.5 of Jup. axis

Use PA=335 deg; so Jupiter's equator is diagonal on the detector

Lock on Io to check image quality.

Acquire Io as tiptilt ref; lower integration time for LBWFS (probably 0.1 sec; 1x1 binning; There is a ND3 neutral density filter).

Move LGS 4" from Io, propagate laser (or sooner, if possible), close loop, take image of Io, with LGS.

PA=335 LGS **6:00UT**

Strap and LBWFS Field of Regard

PA=335 LGS **6:30UT**

Strap and LBWFS Field of Regard
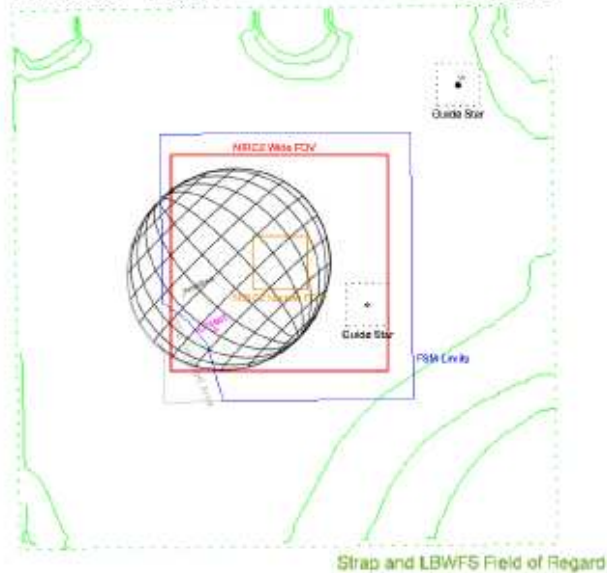
Move to Jupiter

Move laser to offlimb position (check starlist), close loop.

Set laser to NOT follow telescope (aofsmmove and aolpmove set to 0; slaved mode, we think).

Offset to Jupiter (using en commands). GRS will be in lower left corner.

Set laser to follow telescope (aofsmmove and aolpmove set to 1). We leave it "fixed" for rest of night.
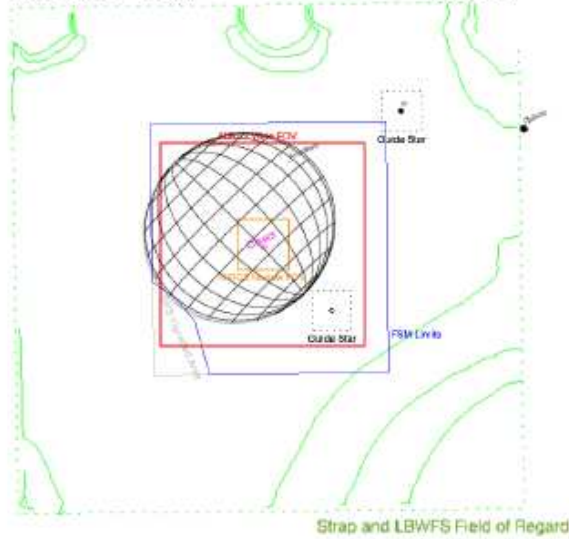
Both LGS and telescope are locked to Io. We take images while letting Jupiter drift through NIRC2 FOV... until sometime between 6:30 and 7:00 UT...

PA=335 LGS   **7:00UT**

Strap and LBWFS Field of Regard
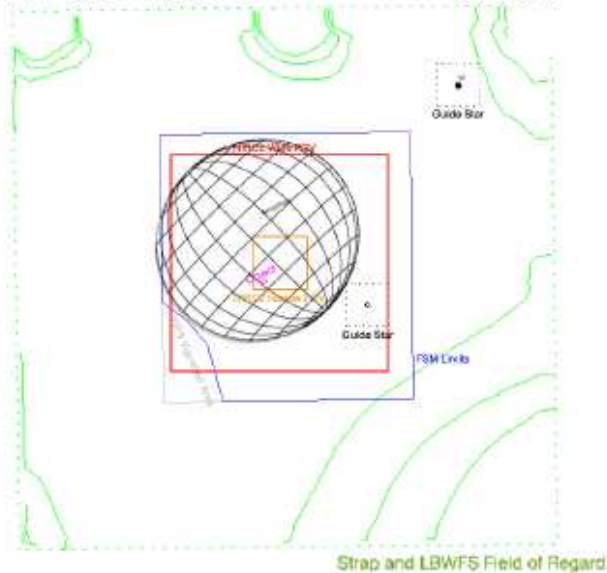
## Manually track the spots

Since the tip tilt moon is moving towards Jupiter, we use manual offsets to keep the spots in the NIRC2 narrow FOV. But we wait to do this until the spots have drifted into the narrow camera FOV, at about 6:40 UT.

At some point we may move off Jupiter to take skys. Afterwards, we will resume LGS-AO again as described on pages 1–2 (lock tiptilt and LBWFS on Io, offset to laser position, close loops, offset to Jupiter).

PA=335 LGS   **7:30UT**

Strap and LBWFS Field of Regard
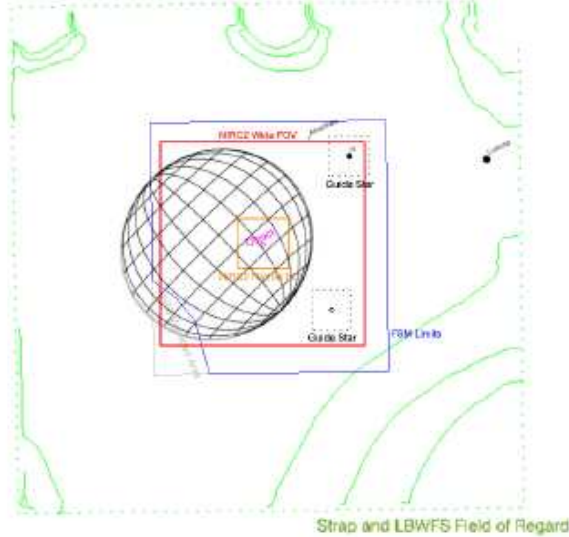
Backup plan: NGS mode

If LGS is not available or not succeeding, we will switch to NGS-AO by 7UT, with Io as far in the upper right corner of the FSM range as possible. By 7:30UT we will be able to get narrow camera images of the spots as they drift into the FOV.

Backup backup plan: NGS asteroids and/ or Io