Improving GRAVITY towards observations of faint targets

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ABSTRACT

Since its first light at the Very Large Telescope Interferometer (VLTI), GRAVITY has reached new regimes in optical interferometry, in terms of accuracy as well as sensitivity.[1] GRAVITY is routinely doing phase-referenced interferometry of objects fainter than K > 17 mag, which makes for example the galactic center black hole Sagittarius A*[2] detectable 90 % of the times. However from SNR calculations we are confident that even a sensitivity limit of K $\sim$ 19 mag is possible. We therefore try to push the limits of GRAVITY by improving the observations as well as the calibration and the data reduction. This has further improved the sensitivity limit to K > 18 mag in the beginning of this year. Here we present some work we are currently doing in order to reach the best possible sensitivity.

Keywords: Interferometry, near infrared, GRAVITY

1. INTRODUCTION

GRAVITY is a second generation instrument at European Southern Observatory Very Large Telescope Interferometer (VLTI). It is a near infrared interferometer which coherently combines the light from four telescopes of the VLTI. Since its first light in 2016 GRAVITY is routinely doing phase-referenced interferometry of objects fainter than K > 17 mag.[1,3] The main science driver for GRAVITY was the observation of the super massive black hole Sagittarius A* (Sgr A*) in the center of the milky way[2] and the stars orbiting around it.[4] With the unique resolution of GRAVITY the flux variable Sgr A* is observable 90 % of the time.

Since the first light of the instrument the magnitude limit of GRAVITY has been pushed down by improving differnet aspects of the instrument, the observation and the data reduction. However, from SNR calculations we are confident that we can reach a sensitivity limit of K $\sim$ 19 mag. Pushing down the sensitivity limit is very important for the observations of the galactic center as we hope to find faint stars close to Sgr A* which are not discovered yet. Such faint stars in close orbits around Sgr A* would help to further characterize the black hole and its properties.[5]

In order to reach the aimed sensitivity goal we show here two different approaches. Firstly, we built up a data driven and spectrally resolved system model of GRAVITY, which helps us to estimate noise sources and

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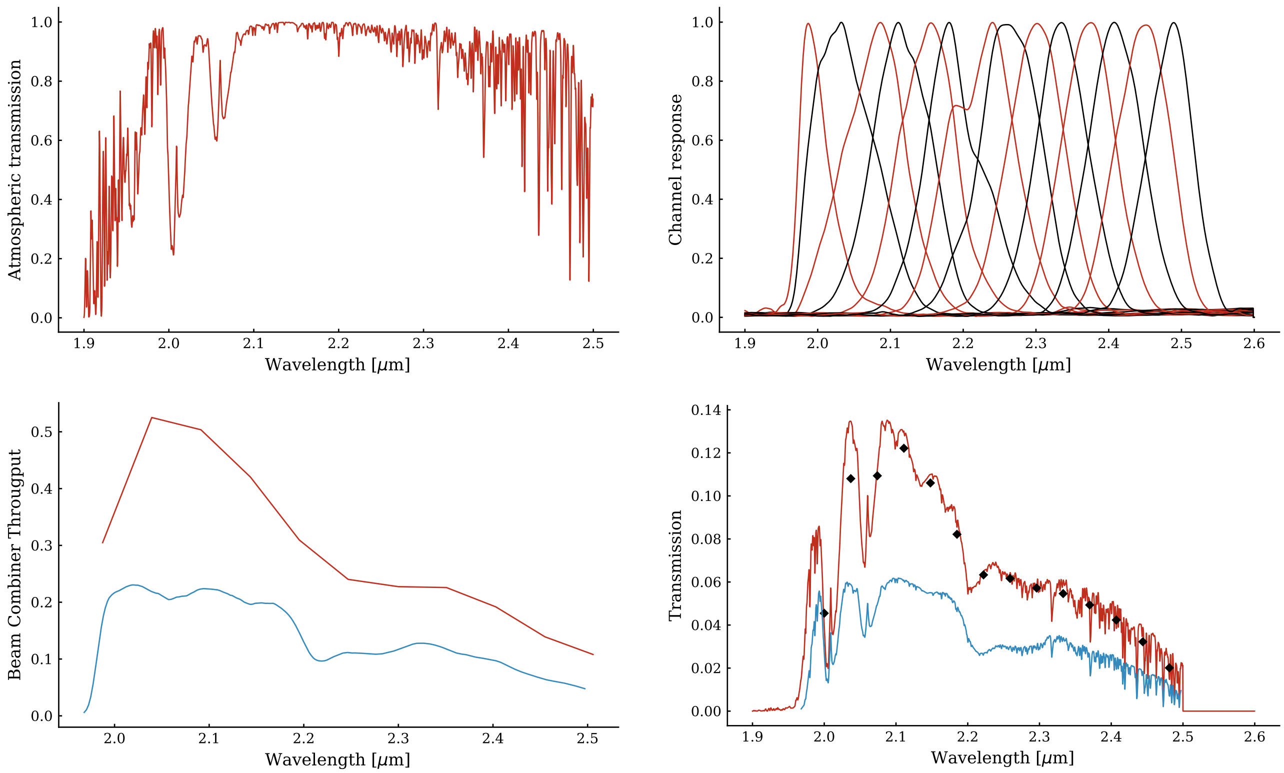

Figure 1. Spectrally resolved inputs for the simulated signal. Top left: atmospheric transmission over the spectral range. Top right: Response function for the 14 used channels in the low resolution mode. Bottom left: transmission curves of the beam combiner in low (red) and medium (blue) resolution mode. Bottom right: Full transmission of atmosphere, telescopes and beam combiner. Fully resolved in red and for the 14 channels in low resolution mode shown as black diamonds. The full transmission for the medium mode is shown in blue.

their influence on the observation. It also helped us to estimate the best integration time for different observing modes. The system model and its application are described in section 2. Secondly, we looked at the usual observation scheme and searched for improvements to increase the time on the science object without decreasing the quality of the data. This is described in section 3 before the results are summarized in section 4.

2. SYSTEM MODEL

So far a system model of GRAVITY was only available from the initial signal-to-noise ratio (SNR) calculations, which were not spectrally resolved. We did a data driven approach to a spectrally resolved model, by simulating the signal and measuring the noise from different datasets.

2.1 Signal

To understand the signal we first looked at all the different transmission effects, shown in Figure 1. One major component here is the atmospheric transmission for which we used a modeled curve from ATRAN. As shown in the top left image of Figure 1, the transmission is high in most of the K-Band with strong absorption features to the edges. Another major component is the transmission of the actual beam combiner of GRAVITY. This has bean measured directly[1] and is shown in the lower left image of Figure 1 for the low and medium resolution. Of course one also has to account for the transmission of the VLTI up to the lab where GRAVITY is located. This transmission is accounted with a constant factor of 0.35.[6]

Taking all this into account we computed the full transmission for the whole K-Band in the lower right figure of Figure 1 as well the average transmission for the 14 channels in the low resolution mode. In general the transmission in the medium resolution mode is about a factor two smaller than in the low resolution mode,

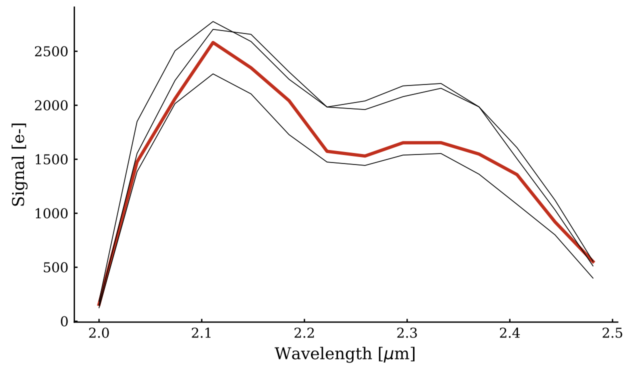

Figure 2. Comparison of simulated signal of S2 and a real observation. The figure shows the low resolution case with the simulated signal in red and real data in black.

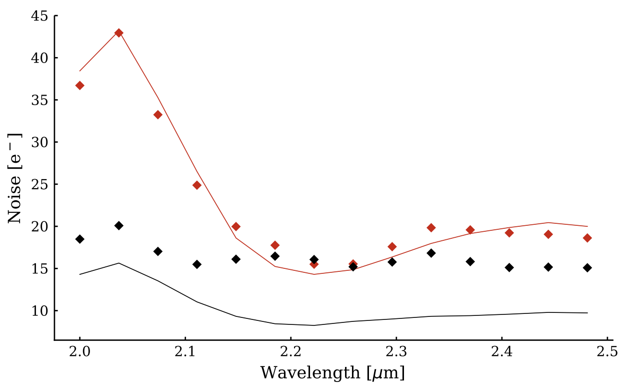

Figure 3. The dots show the measured pixel-to-pixel noise for a ten second integration (red) and a one second integration (black). The lines in the same color show the square root of the corresponding signal as an estimation of the photon noise.

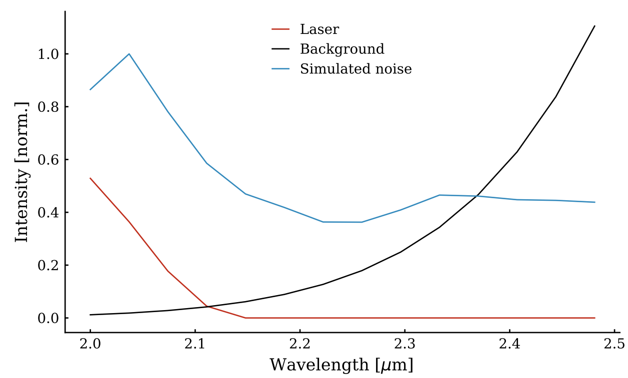

Figure 4. Estimation of the main photon noise sources of GRAVITY. The red line shows the noise from the laser backscatter, while the black line is the noise from the black body emission of the background. The typical noise at the detector is shown in blue.

which is due to the different gratings used in GRAVITY.[1] For a full determination of the signal strength one furthermore has to account for losses for example due to an imperfect fiber placement in GRAVITY and for the actual performance of the AO system.

In general all considerations in this proceeding are done for the unit telescopes (UTs) but can be easily adapted to the auxiliary telescopes (ATs) but using the correct transmission[6] and a higher loss due to the worse correction of the atmospheric turbulence.

With the understanding of the transmission we can now simulate any source signal. We do this by using a given source magnitude and spectral power index as an input and calculate the actual received number of photons per spectral channel. With this information and the transmission curves we get the actual received signal at GRAVITY by integrating the signal, multiplied with the transmission, over the used channel response functions. For the example of the S2 star[4] in the galactic center this is shown in Figure 2. One can see that the simulated signal is in good agreement with the data and can therefore be used for further analysis and tests.

2.2 Noise

Another important part of our system model is to model the expected noise on the detector. In order to do this we used a lot of flat field images from recent GRAVITY observations and analyzed them in terms of pixel-to-pixel noise as well as temporal effects.

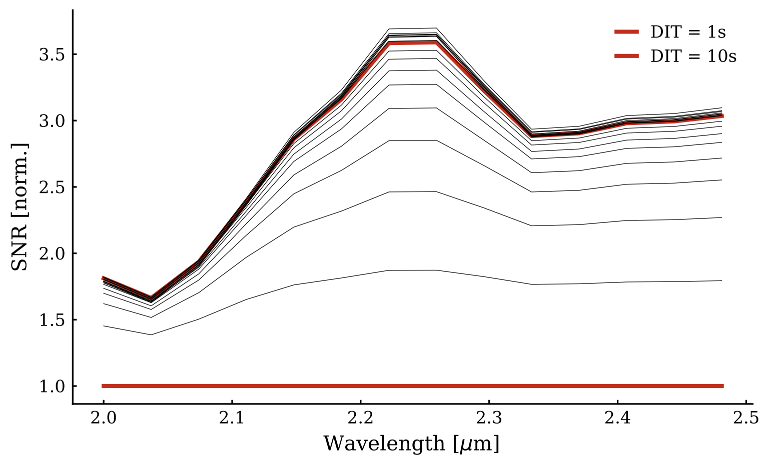

Figure 5. Signal to noise ratio estimation for different integration times, normalized by the SNR of a 1 second integration. The black lines show the SNR with an integration time between 1 and 20 seconds. The lines with 1 and 10 seconds are shown in red.

An example of the pixel-to-pixel noise of a typical measurement can be seen in Figure 3. The noise is shown for an one and a ten second integration, as well as the square root of the corresponding signal. From that one can see that the photon noise clearly dominates for the ten second integration, while the one second integration still has a clear amount of readout noise. With this data we did a noise estimation for each individual channel by fitting a read-out and a photon noise component to the noise from data of different integration times. While the photon noise increases linearly with time, the read-out noise of a non-destructive read detector decreases with increasing integration time. Such a simulated noise is then shown by the blue curve in Figure 4. From this we can clearly identify two major noise sources: In the low wavelength the noise is dominated by the backscatter of the metrology laser,[7] while the noise a high wavelength comes from the black body emission of the background. Scaled with the throughput of the beam combiner, this gives the actual measured noise signal as shown as a blue curve in Figure 4.

2.3 Usage & further work

With a simulated and spectrally resolved signal and noise estimation we can use this now to better plan observations with GRAVITY. We for example tested what the best integration time for the observations of the galactic center is. For a total exposure of five minutes we simulated the signal and noise for each individual frame for frame exposures between 1 and 20 seconds. Figure 5 shows the corresponding SNR normalized by the SNR from the 1 second integration time. One can therefore see how much the SNR increases when one observes longer. From this we concluded that with an integration time of 10 seconds we are in the photon noise regime and do not gain much by integrating longer. We did a similar estimation for the medium resolution which helped us to estimate the feasibility of observations in this instrumental mode.

As we are usually not interested in the actual measured flux but rather in the visibilities and phases we are currently also expanding this work, to estimate the SNR in this modes. This will further help us to better plan observations and to identify the effect of the different noise sources for these measurements.

3. OBSERVING STRATEGY

As GRAVITY is exploring new regimes of optical interferometry, it was not clear in the beginning what the best observation strategy would be. While in the radio interferometry a frequent observations of calibration sources is necessary, classical optical observations usually try to catch as many photons as possible. With GRAVITY it was tried in the beginning to take a path in the middle of these two with semi frequent observations of sky frames and calibrators. This lead to an effective on source fraction of around 40 %. In order to improve the observations we used old data to determine how dependent our results are from the number of skies and calibrators.

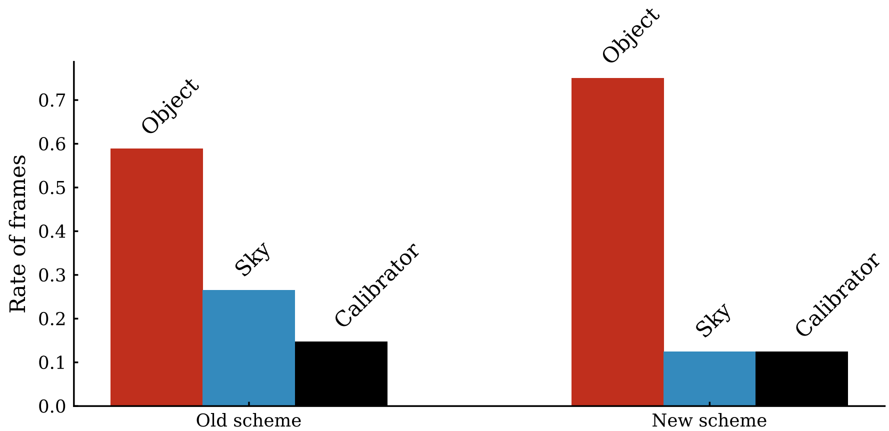

Figure 6. Comparison of the old and new observation scheme. The percentage of object, calibrator and sky schemes is shown for the original scheme on the left and the new scheme on the right.

3.1 Sky frames

To run these tests we used a good dataset from the end of 2017 and rereduced the data with a varying number of sky frames. To get a measurable result we then used the usual binary fitting to the closure phases and squared visibilities[1] as well as the imaging[8] of the data and checked how much the error and the scatter for the point changed for the different data reductions. We also looked at the time series of the data points in order to check if the quality decreases around the omitted sky frames.

When reducing the number of sky frames to only two per night, we could not see a clear change in the result of the test. This gave us the first impression that we actually could significantly reduce the number of sky frames.

This included also using sky frames from previous nights and averaged over several nights. In order to see if there is any dependence on the sky frame we then used a frame from a different month. This significantly changed the scatter of the fitting results and changed the actual separation by a few milliarcseconds. From this we conclude that there is a dependence on the sky frame under current conditions but the frequency of frames can be reduced.

This furthermore strengthens our previous results, that the signal in the sky frame is dominated by the laser backscatter and the black body emission, probably mostly from the lab. However, there is some dependence on the sky frame which excludes ideas such as simulating a general sky frame. This dependency could come from variation in the metrology laser as well as from background signal from the actual sky.

3.2 Calibrator frames

The same test as for the sky frames was then repeated for the calibrator frames. Here we saw a similar effect as before: The results did not change noticeably for a fewer number of calibrator frames but changed significantly when a a calibration from a very different night was used. This was even stronger than for the sky frames, which was expected as the calibrator should be more dependent on the actual conditions.

With the results from these tests we changed our observing strategy in a way that we now usually observe six frames with five minutes each, and do one sky and one calibrator observation for those six frames. A comparison of the on source fraction of the old and new scheme is shown in Figure 6. This new scheme increased our on source time by around 10 %.

4. SUMMARY

With this work we have taken two steps to increase the sensitivity of GRAVITY and especially the observations of the galactic center. We have shown our current state on a spectrally resolves system model which helps us to understand different effects on the data and also to better plan observations of specific targets. Furthermore we showed that we can significantly increase the on source time during an observation by reducing the number of sky and calibrator frames. This is especially valuable for the imaging of the galactic center as we just now start to combine frames for the final images[8] and can therefore reach a higher SNR in the final image. This again helps us to decrease our sensitivity limit and search for fainter stars around Sgr A*. Both parts of this proceeding help us to get the most out of the valuable VLTI observing time and therefore to reach the best possible signal to noise, improve our sensitivity and search for faint targets. This tests were mainly aimed for our observations of the galactic center, but both the system model and the adapted observing strategy can of course be used for all GRAVITY observations.

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