NEAR: Low-mass planets in αCen

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ABSTRACT

ESO in collaboration with the Breakthrough Initiatives works to modify the VLT mid-IR imager VISIR to greatly enhance its ability to search for potentially habitable planets around both components of the binary Alpha Centauri, part of the closest stellar system to the Earth. Much of the funding for the NEAR project is provided by the Breakthrough Initiatives, and ESO mostly provides staff and observing time. The concept combines adaptive optics using the deformable secondary mirror at UT4, a new annular groove phase mask coronagraph optimized for the most sensitive spectral bandpass in the N-band, and a novel internal chopper system for noise filtering based on a concept for longer wavelengths invented by micro-wave pioneer Robert Dicke. The NEAR (New Earths in the Alpha Cen Region) experiment is relevant for the ELT/METIS instrument, as the knowledge gained and proof of concept will be transferable.

Keywords: Extreme Adaptive Optics, High-contrast Imaging, Exoplanets, Coronagraphy, Mid-Infrared

1. N-BAND IMAGING OF HABITABLE PLANETS IN ALPHA CEN

Detecting potentially habitable planets orbiting other stars is a cornerstone of the European Extremely Large Telescope (ELT) science case. One favorable wavelength regimes for such observations is the N-band in the thermal IR, where the black body emission of potentially habitable planets, i.e., planets with a temperature and an atmospheric pressure suitable to sustain liquid water on the surface, peaks. N-band spectral diagnostics are dominated by a very strong Ozone band around 9.6 μm, which is as good a biosignature as O_2.

Alpha Centauri is a pre-eminent star system for searching for Earth analogues. The system consists of the solar-type binary αCen A and B and the late M-star Proxima Cen around which a likely terrestrial planet has recently been discovered (Anglada-Escudé et al. 2016). At a distance of just 1.35 pc or about 4 lightyears, the alpha Centauri stars are our nearest neighbors, and Earth analogue planets there would be significantly brighter than for the next nearest stars and the contrast to the stars would be of the order of 10^{-6}.

As the proximity of αCen A and B pushes the HZ out to about 0.6″ – 1.5″ angular separation from the stars, current 8-m class telescopes may already have a chance to reach the required N-band spatial resolution, contrast and sensitivity to detect an Earth analogue. The second next systems with sufficient angular separation of the HZ, Sirius and Procyon, are 15 and 45 times harder to observe, because the required integration times scale with the inverse of the planet's brightness squared. In addition, both these stars have white dwarf companions in a relatively small (~20 AU) orbit, which would have negatively impacted on planet habitability during their evolution. Earth analogues in εEri, τCeti and εIndi can currently not be separated from the star optically and will be observed in N-band with ELT/METIS (Quanz et al. 2015).

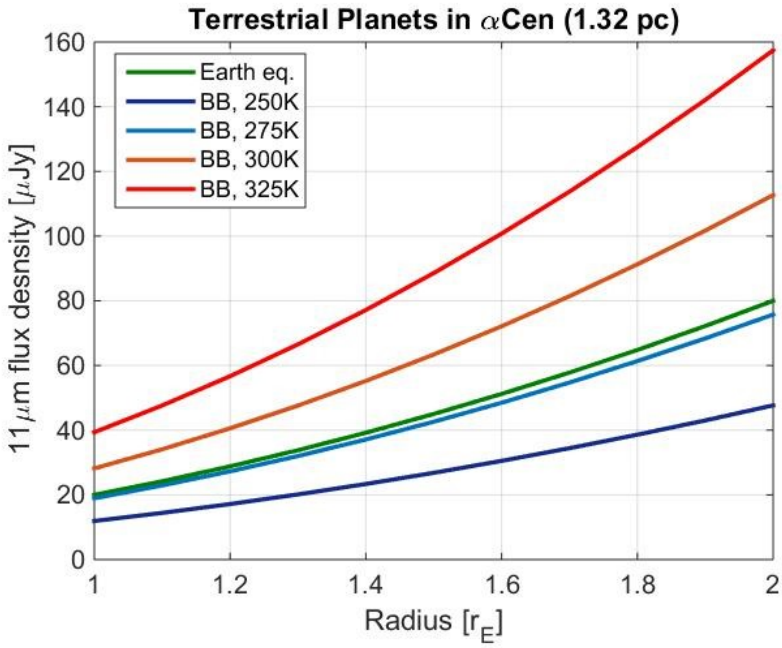

Figure 1. Earth analogue planet N-band brightness in the alpha Cen system as a function of planet radius. The different curves show Earth itself and planets emitting like blackbodies of various temperatures, but still in a potentially habitable regime where liquid water could exist on the surface.

The NEAR experiment to look for potentially habitable planets around alpha Cen A and B was launched in mid-2016 by ESO and the Breakthrough Initiatives, and it is hosted within ESO's Technology Development Programme. Several reviews (phase-A of concept, Interface- and manufacturing readiness of the VFM, overall system) have been carried out since then to mitigate risks involved with the fast-track on which NEAR proceeds.

The next major step will be the delivery of the VFM to ESO early 2018, where it will be tested with the infrared test facility. In parallel, the components for the cryostat (AGPM, NEAR filter, Lyot stop) will be procured. We also plan for a technical run with GRAAL at UT4 to implement DSM chopping and verify whether it is a viable alternative for the NEAR experiment.

The VFM and all other NEAR components will be shipped to Paranal Observatory in late 2018. VISIR will then be transferred from UT3 to the new integration hall for the modifications, and the infrastructure at UT4 will be prepared. After the integration work, a commission run at UT4 will establish a proper functioning of NEAR. During commissioning, SINFONI will temporarily be taken off the telescope. The NEAR observing campaign will start around June 2019 once SINFONI has completed observations of the Galactic Center and is shipped to Europe for integration with the new ERIS instrument.

The NEAR observing campaign comprises 100 hours of telescope time. The observations of alpha Cen will be carried out by the NEAR team operating the instrument and will use as much as possible consecutive nights. Ideally, the campaign would have to be concluded within about 20 days, similar to the time span during which a planet in alpha Cen at one AU from a star would move on its orbit by one diffraction element (~0.3″ at the VLT in N-band) on the sky.

The NEAR campaign foresees observations with 10 Hz chopping (ideally chopping between alpha Cen A and B or alternatively using the internal chopper) and around 4 ms detector integration time (DIT) for a reduced 450 x 450 pixel FoV. The short DITs provide a high observing efficiency for the 10 Hz chopping frequencies needed to reach BLIP performance in the presence of ELFN. The instrument entrance pupil will be stabilized by switching off the Cassegrain rotator and letting the field rotate. This will provide a better performance of the coronagraph, and angular differential imaging techniques can be used to calibrate quasi-static residual speckle noise.

The NEAR observations are otherwise standard with no special needs for daytime calibration or data reduction. One frame per chopping half-cycle will be stored, so 450 x 450 pixel frames will arrive every 50 ms and result in a data rate of 8.1 Mb/s or 30 Gb/h. Assuming an average of 6 observing hours per night, where alpha Cen is sufficiently high on the sky, NEAR will produce about 180 Gb of data each night. The Breakthrough Initiatives plan to make these NEAR data publicly available immediately to benefit from the expertise of interested astronomers world-wide and to create excitement for the search of potentially habitable planets around the nearest stars.

After the campaign, VISIR will eventually move back to UT3. The WFS camera will be removed, but the modifications of the VFM will stay. Also, the 45-degree dichroic will be exchanged with a 90-degree entrance window providing full access to the N- and Q-bands. The Dicke switch may prove highly advantageous in observing extended objects, which presently are difficult to observe due to the limited chopper throw.

2. CONCEPT

The standard approach for reaching high contrast and sensitivity from the ground uses AO and coronagraphy to minimize residual flux from the star and maximize the signal of the planet. The currently seeing-limited VISIR (Lagage et al. 2004) will therefore be moved from VLT Unit Telescope 3 (UT3) to UT4, which has recently been upgraded with a Deformable Secondary Mirror (DSM). Using the DSM in the Cassegrain focus is the most efficient way to equip VISIR with AO, because it does not involve additional ambient temperature mirrors, which are the dominant noise source over large parts of the N-band.

At UT3, electrical cables and helium lines between VISIR and its electronics cabinets and compressors located on the azimuth platform are routed through the altitude axis cable wrap. At UT4, the altitude wrap is already rather full and installation of additional cables is tedious. Therefore, NEAR will use a dragging solution, with electrical cables and helium lines being routed through a chain from the M1 cell to the cabinets and compressors on the azimuth platform as shown in Figure 2. The distances are short enough for the VISIR test cables and helium lines to be used, such that the installation at UT3 can remain untouched.

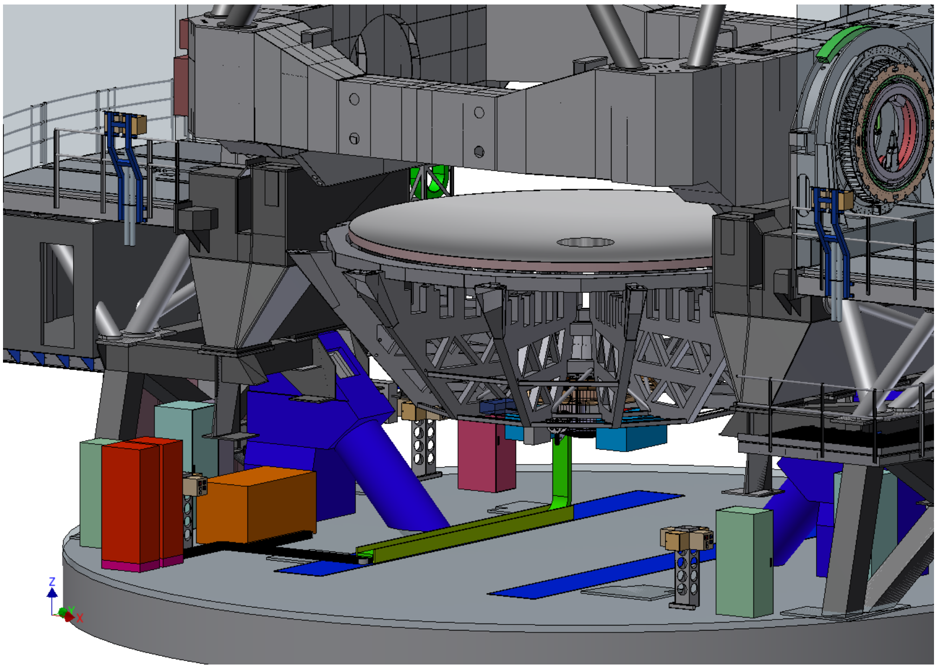

Figure 2. Cables and He lines routed from M1 cell though a chain (green) to electronics cabinets (red) and helium compressors (orange). This configuration is very similar to the baseline design accepted at the VISIR final design review in 1999.

Most modifications necessary for NEAR are implemented in the non-cryogenic instrument flange of VISIR. This VISIR Flange Module (VFM, see Figure 3) will feature a modified relay for the calibration source, an ESO wavefront sensor (WFS) camera including feed optics, and a vacuum optics unit with the internal chopper. The chopper in this location, behind the dichroic, would not disturb the WFS. The VFM is designed, manufactured and tested by Kampf Telescope Optics, Munich.

The AO WFS is part of the VFM. A dichroic transmits the N-band into VISIR and reflects optical light to the wavefront sensor unit (WFSU) as shown in Figure 3. The WFSU will provide ±5″ field selection capability to transmit a 2″ round field of view (FoV) to the Shack-Hartmann WFS. A spectral long-pass filter lets only wavelengths longer than 800 nm pass such that an atmospheric dispersion compensator is not required. The NEAR WFS camera is an ESO standard camera with a 40x40 lenslet array. This camera will be connected via a fiber switch board to the GRAAL real-time computer. Switching between GRAAL and NEAR operation will be done through software configuration only.

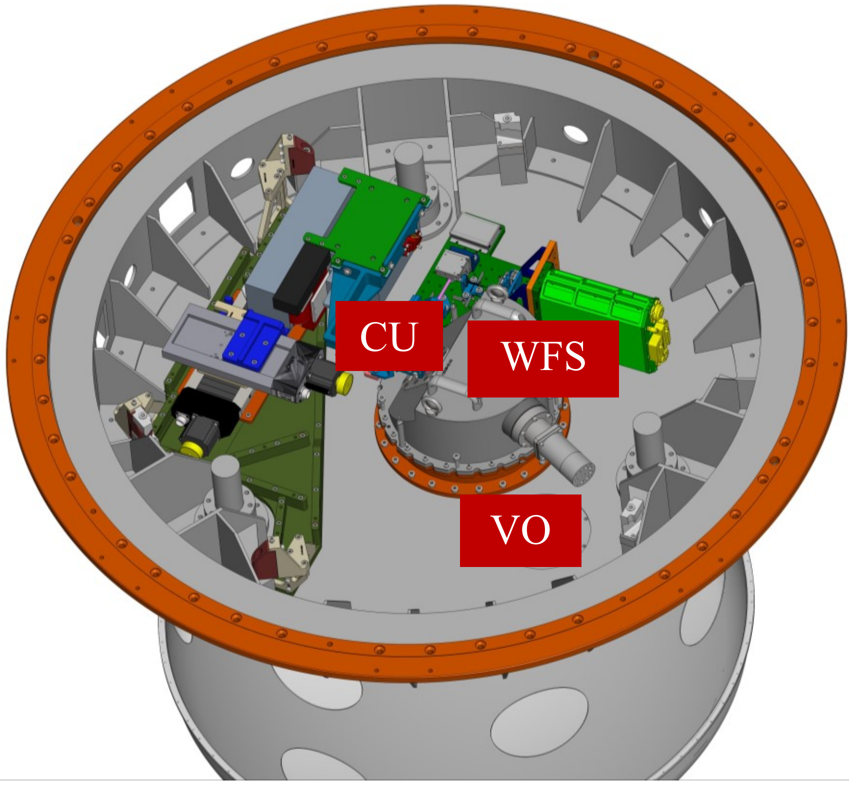

Figure 3. VISIR Flange Module (VFM, design KTO) hosting Wavefront Sensor Unit (WFSU), Vacuum Optics Unit (VOU), and the Calibration Unit (CU). The Dicke switch is part of the VOU.

A new small electronics rack for the WFS power supply and Peltier controller will be attached to VISIR. Controllers for the other new functions provided by the VFM will be installed in the already existing VISIR racks. Fortunately, VISIR currently employs several expendable components, which will be removed in turn such that the NEAR modifications will maintain the weight of the overall instrument.

One of the benefits provided by AO is a corrected point-spread function (PSF) with an N-band Strehl ratio next to one, which maximizes the planet signal. The AO further allows us to control and remove quasi-static aberrations. These produce speckle noise in the region around the PSF where a potential planet would be located and are the ultimate obstacle for reaching very high imaging contrasts. The minimization of quasi-static aberrations is helped by the superb optical quality of the dichroic, which is the only optical component in front of the focal plane not seen by the WFS. Optical aberrations in the WFS arm itself will be calibrated with a dedicated light source during integration. Another important task of the AO is to maintain a precise positioning of the PSF on the coronagraphic mask.

3. TECHNICAL INNOVATIONS

A new spectral filter will maximize NEAR's signal to noise ratio (SNR) for the detection of an Earth analogue. Figure 4 below shows the average Paranal sky background and the expected emission of the telescope with a freshly coated M1. On one hand, a wide spectral range captures more photons of the object. On the other hand, even state-of-the art coronagraphs have a limited bandpass, and there are spectral regions, which are not favorable for high SNR observations. At a wavelength shorter than 10 µm, absorption by atmospheric ozone reduces signal transmission and increases sky background. The same happens longward of 12.5 µm because of atmospheric CO_2. The maximum SNR is therefore obtained when observing between 10 and 12.5 µm, where the background is dominated by telescope emission, and sensitivity to atmospheric conditions is reduced.

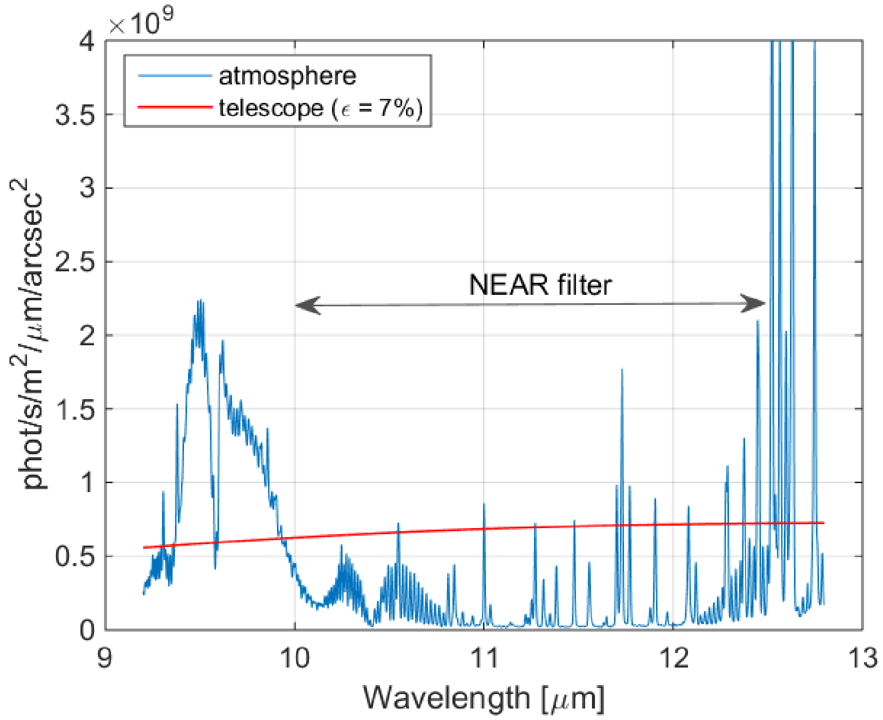

Figure 4. Paranal seasonal average sky background and contribution of the telescope (mirrors at 280K with a combined emissivity of 7%) as calculated by the SKYCALC Sky Model Calculator. The spectral band 10-12.5 µm foreseen for the NEAR filter is indicated.

In addition, NEAR will feature a new Annular Groove Phase Mask (AGPM, Mawet et al. 2005) coronagraph designed for the NEAR spectral filter. The AGPM is a variation of a vortex coronagraph with very small inner working angle and high throughput. It consists of a rotationally symmetric subwavelength grating and allows for coronagraphic imaging of close companions and disks around bright stars. The modeled null depth, i.e., the suppression of the PSF's central core, over the NEAR spectral range is shown in Figure 5. The figure also displays the effect of the anti-reflection grating (ARG) on the AGPM's backside, which reduces the intensity of the optical ghost image. Together with a properly designed Lyot stop, the AGPM will provide a raw PSF contrast of the order 10^{-5} at angular separations between 0.7" and 1.5". The NEAR coronagraph will be designed and produced by a team of researchers at the University of Liège, University of Uppsala and Caltech.

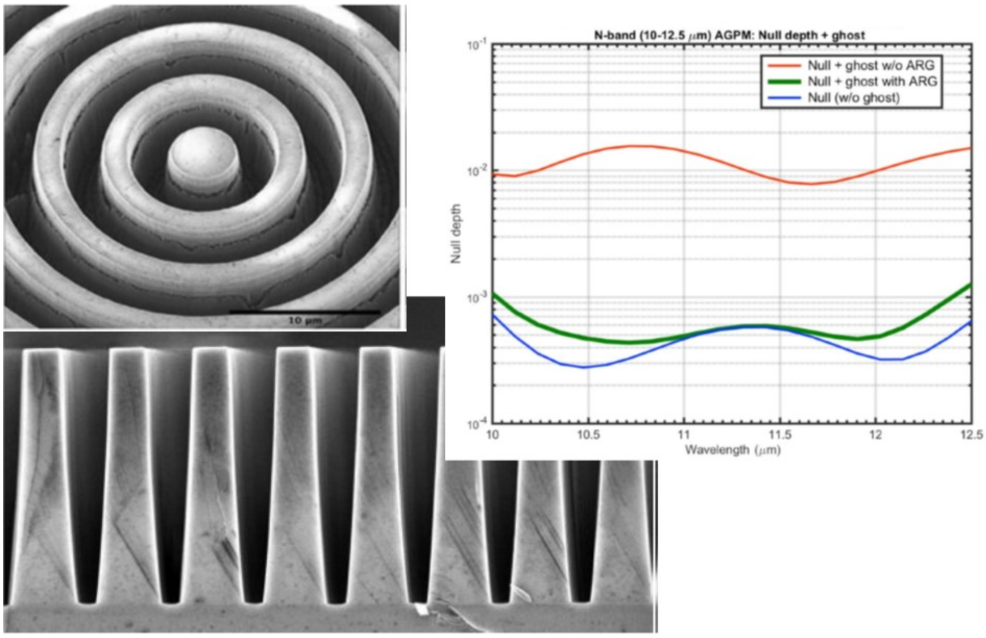

Figure 5. Annular Groove Phase Mask. Microscopic pictures of the subwavelength grating are shown on the left, and the null depth over the NEAR spectral band is shown on the right.

High SNR observations with VISIR must also consider the Excess Low Frequency Noise (ELFN) of the AQARIUS detector. ELFN is a temporally correlated noise caused by fluctuations in the space charge induced by ionization/recombination in a blocking layer between pixels. This correlation can be broken by modulating the incidence of light between source and background, i.e., by chopping at sufficiently high speed. ELFN rapidly increase with incident flux levels, and also the chopping frequency required to get rid of it increases (Ives et al. 2014).

For the expected NEAR flux levels, 10 Hz chopping is needed to effectively suppress ELFN. To avoid synchronization issues and transients with the AO operation, NEAR will employ an internal chopper following the concept of the Dicke switch invented by the microwave pioneer Robert Dicke. A rotating mirror with open areas (in the case of NEAR a D-shaped mirror with one open section spanning 180 degrees) allows VISIR to alternate between observations of the object and of an internal black-body dynamically adjusted to match sky and background flux.

An efficient alternative to observations with the Dicke-Switch could be on-sky chopping with the DSM. By chopping between αCen A and B, one could double the duty cycle of the observations as both stars of the binary are scientifically interesting. The separation between alpha Cen A and B will be about 5″ in 2019, which is still in the range for the DSM to efficiently chop with high-speed and a transition time of the order of 10 ms. The DSM chopping option will be tested with GRAAL before NEAR goes on-sky.

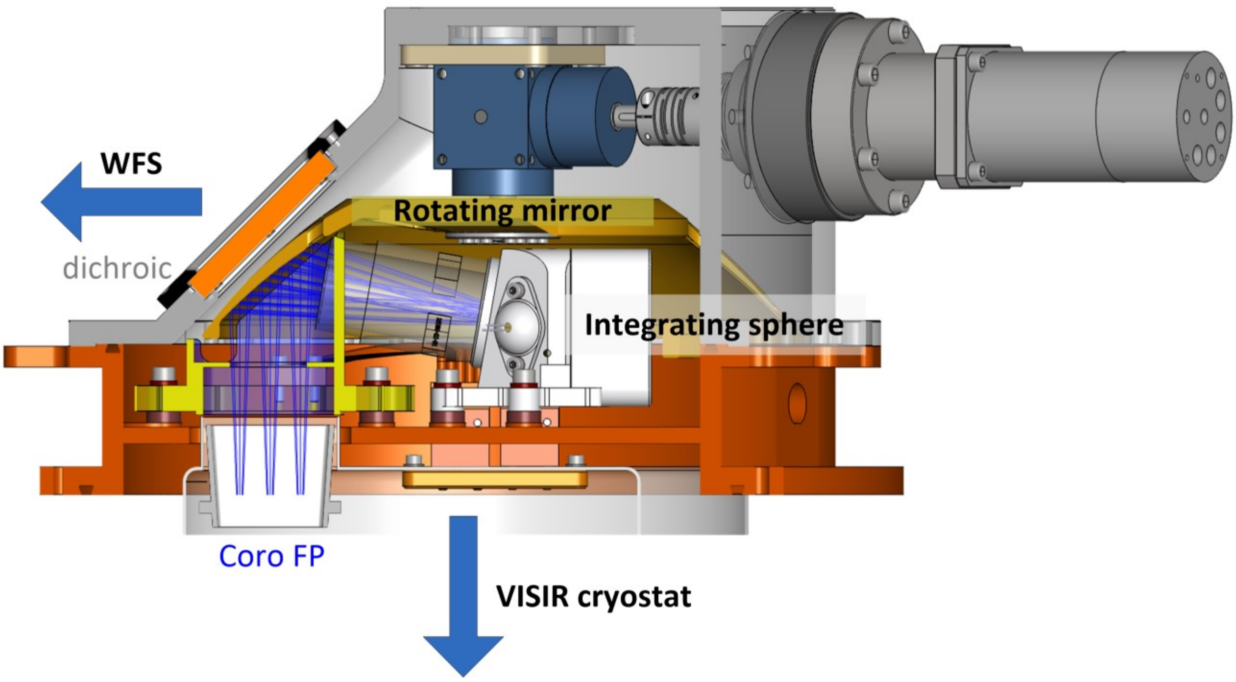

Figure 6. Dicke-Switch concept for ELFN calibration. The closed part of the rotating mirror reflects light from an integrating sphere into VISIR. The radiation from the integrating sphere is dynamically adjusted to match the sky background.

4. PREDICTED SENSITIVITY

Data from an on-going VISIR program (program 098.C-0050(A), PI M. Sterzik) was used to measure the actual point source sensitivity, and estimate the expected Background Limited Imaging Performance (BLIP) of NEAR. The data consists of 9 one-hour observations of Sirius recorded between Dec 2016 and Mar 2017 in the B10.7 filter with 4 Hz chopping. Figure 7 shows the image of the only αCen observation recorded under the same program.

We measured the total flux of Sirius and used it to scale the VLT's Airy pattern. This is a reasonable assumption given the nearly perfect AO-corrected PSF in N-band. The background noise per pixel was also measured. The resulting SNR was derived for different photometric aperture diameters. An aperture of 1.25 λ/D diameter containing 60% of the total flux spread over 50 pixels (VISIR pixel scale is 45 mas / px) is optimum and provides an average BLIP sensitivity of 1.1 mJy (5σ / h). Scaling the SNR of the classical VISIR data to the new NEAR configuration considering the various changes in the setup (spectral filter, AGPM, Lyot stop, AO correction, dichroic, etc) yields the expected NEAR BLIP sensitivity of 0.7 mJy (5σ / h).

We also investigated whether multiple observations would beat down the noise as the inverse of integration time. Pixel intensities over an empty part of the detector were analyzed and combined for all the data sets. The analysis shows that the noise is indeed spatially and temporally uncorrelated (the noise covariance matrix between the 9 data sets is diagonal), and noise statistics scale with integration time as expected (see Figure 8). Therefore, we expect a final sensitivity of the 100-hr NEAR campaign of 70 μJy, which is sufficient to detect a 1.9 Earth radii planet with an Earth-like emission spectrum or a 1.3 Earth radii desert planet emitting like of 325 Kelvin black-body.

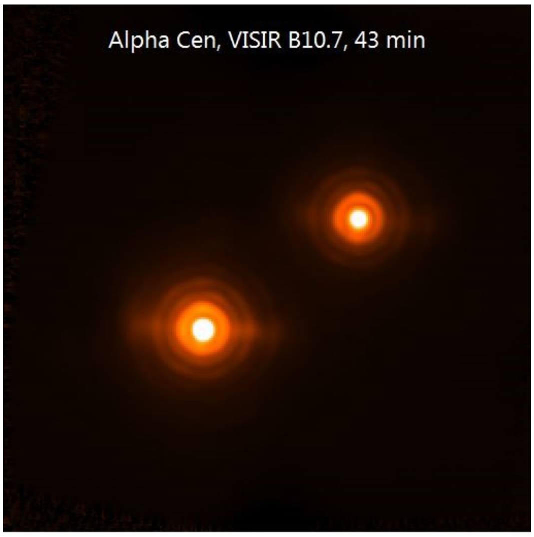

Figure 7. Classical VISIR image of αCen A/B recorded in March 2017 (data obtained through program 098.C-0050(A) (PI M. Sterzik).

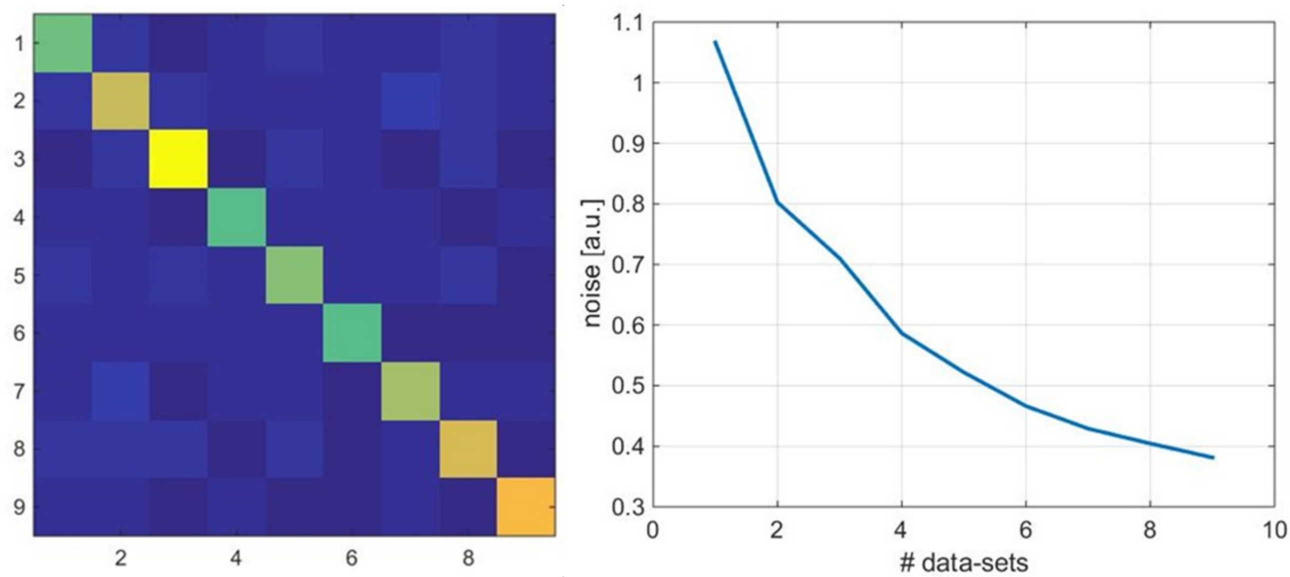

Figure 8. Pixel noise noise covariance matrix for the 9 Sirius data sets (left). Noise scales with 1/sqrt(t) (right).

REFERENCES

[1] Anglada-Escudé, G. et al. 2016, Nature, 536, 437
[2] Ives, D. et al. 2014, Proc SPIE, 9154
[3] Lagage, P. O. et al. 2004, The Messenger, 117
[4] Mawet, D. et al. 2005, ApJ, 633
[5] Quanz, S. et al. 2015, IJAsB, 14, 279