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NEAR: Low-mass Planets in α Cen with VISIR

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ESO, in collaboration with the Breakthrough Initiatives[1], is working to modify the Very Large Telescope 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 (New Earths in the Alpha Cen Region) 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 Unit Telescope 4, a new annular groove phase mask (AGPM) coronagraph optimised 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 the microwave pioneer Robert Dicke. The NEAR experiment is relevant to the mid-infrared METIS instrument on the Extremely Large Telescope, as the knowledge gained and proof of concept will be transferable.

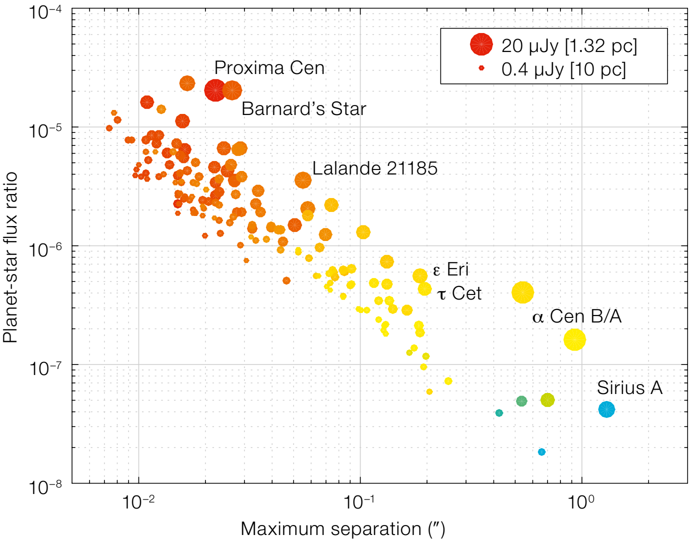


Figure 1. *N*-band flux ratio between Earth-analogue planets and parent stars within 10 pc (from the Hipparcos catalogue). The size of the symbol indicates the planet's apparent brightness, and the colours approximately match those of the stars.

Detecting potentially habitable planets orbiting other stars is a cornerstone of the Extremely Large Telescope (ELT) science case. There are two favourable wavelength regimes for such observations: i) the optical/near-infrared (NIR), where stars emit most of their light and the spectra reflected from planetary atmospheres contain important biosignatures, such as O_2 (transitions in the red and NIR range) and ozone, O_3 (transitions in the ultraviolet); and ii) the *N*-band in the thermal infrared, 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 O_3 band around 9.6 μm, which is as good a biosignature as O_2.

Earth analogues, that is planets of size and temperature comparable to Earth's, appear at small angular separations from their host star and with very demanding imaging contrasts. Such planets orbit their star in the habitable zone (HZ), which is at about 0.1 au for a red dwarf and around 1 au for a solar-type star, and therefore appear at angular separations between 10 milliarcseconds and 1 arcsecond around stars within 10 pc. The corresponding planet-to-parent-star flux ratio is between 10^{-7} and 10^{-10} in the optical/NIR and between 10^{-5} and 10^{-7} in the *N*-band (Figure 1). The shallower contrasts correspond to the red dwarfs and the more demanding ones to solar-type parent stars.

Such optical/NIR spatial resolution and contrast are not achievable with current 8-metre-class telescopes and will only be achieved with the Giant Segmented Mirror Telescopes (GSMT), such as ESO's ELT. There is, however, a pre-eminent star system in which to search for Earth analogues — α Centauri, which contains the solar-type binary α Cen 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, the α Centauri stars are our nearest neighbours, and Earth-analogue planets there would be significantly brighter than around the next nearest stars (see Figure 1).

As the proximity of α Cen A and B pushes the HZ out to an angular separation from the stars of about one arcsecond, current 8-metre-class telescopes may already have a chance to reach the required *N*-band spatial resolution, contrast and sensitivity to detect an Earth analogue. The next systems with HZs at sufficient angular separation, Sirius and Procyon, are 15 and 45 times harder to observe, respectively, 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 ε Eri, τ Ceti and ε Indi cannot currently be separated from the stars optically and will be observed in the *N*-band with the Mid-infrared ELT Imager and Spectrograph (METIS; Quanz et al., 2015).

Concept

The standard approach for reaching high contrast and sensitivity from the ground uses adaptive optics (AO) and coronagraphy to minimise residual flux from the star and maximise the signal from the planet. The VLT Imager and Spectrometer for mid-InfraRed (VISIR; Lagage et al., 2004), which is currently seeing-limited, will therefore be moved from VLT Unit Telescope 3 (UT3) to UT4, which has recently been upgraded with a Deformable Secondary Mirror (DSM), see Arsenault et al. (2017). Using the DSM at 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 arduous. Therefore, NEAR will use a dragging solution, with electrical cables and helium lines being routed through a chain from the primary mirror (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.

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 WFS unit (WFSU) as shown in Figure 3. The WFSU will provide ±5-arcsecond field selection capability to transmit a 2-arcsecond round field of view (FoV) to the Shack-Hartmann WFS. A spectral long-pass filter allows only wavelengths longer than 800 nm to pass, such that an atmospheric dispersion compensator is not required. The NEAR WFS camera is an ESO standard camera with a 40 × 40 lenslet array. This camera will be connected via a fibre switchboard to the GRound-layer Adaptive optics Assisted by Lasers (GRAAL) real-time computer. Switching between GRAAL and NEAR operation will be done through software configuration only.

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 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 close to one, which maximises the planet signal. The AO further allows us to control and remove the quasi-static aberrations. These aberrations produce speckle noise in the region around the PSF, where a potential planet would be located, and are the ultimate obstacle to reaching very high imaging contrasts. The minimisation 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.

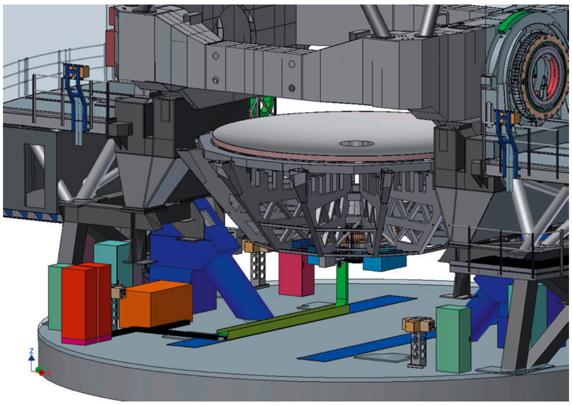


Figure 2. (Left) Cables and He lines routed from the M1 cell though a chain (green) to electronics cabinets (red) and helium compressors (orange). This configuration is very similar to the baseline design accepted at the VISIR Final Design Review in 1999.

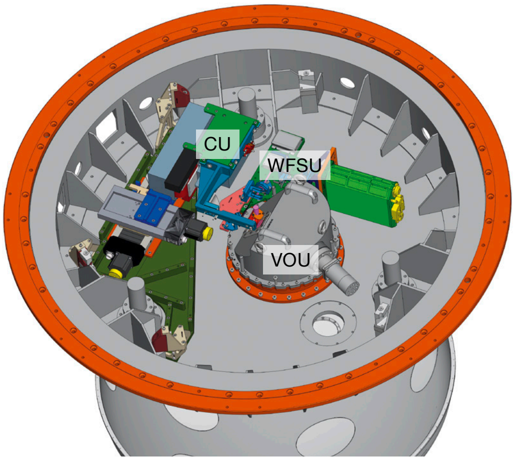


Figure 3. (Right) VISIR Flange Module (VFM) hosting the Wavefront Sensor Unit (WFSU), Vacuum Optics Unit (VOU), and the Calibration Unit (CU). The Dicke switch (see Figure 6) is part of the VOU.

Innovations

A new spectral filter will maximise NEAR's signal-to-noise ratio (SNR) for the detection of an Earth analogue. Figure 4 shows the average Paranal sky background and the expected emission of the telescope with a freshly coated M1. On the one hand, a wide spectral range captures more photons from the object, but on the other hand, even state-of-the art coronagraphs have a limited bandpass, and there are spectral regions which are not favourable 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.

In addition, NEAR will feature a new 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 (Figure 5) and allows for coronagraphic imaging of close companions and disks around bright stars. The modelled 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 back side, 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 arcseconds. The NEAR coronagraph will be designed and produced by a team of researchers at the University of Liège, the University of Uppsala and Caltech.

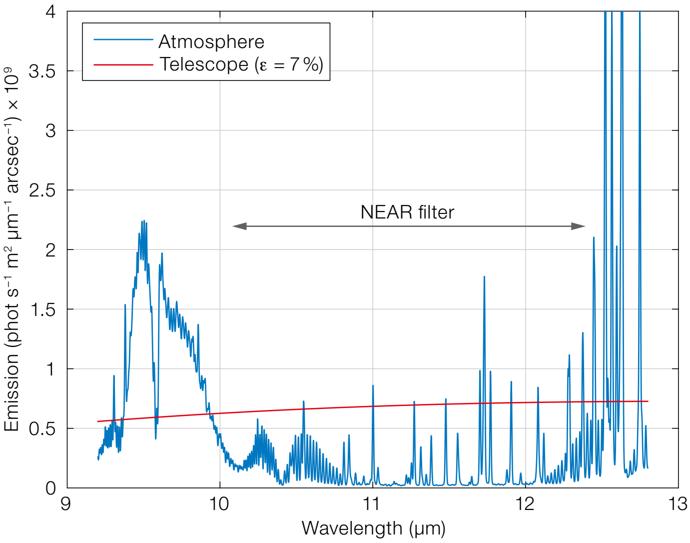
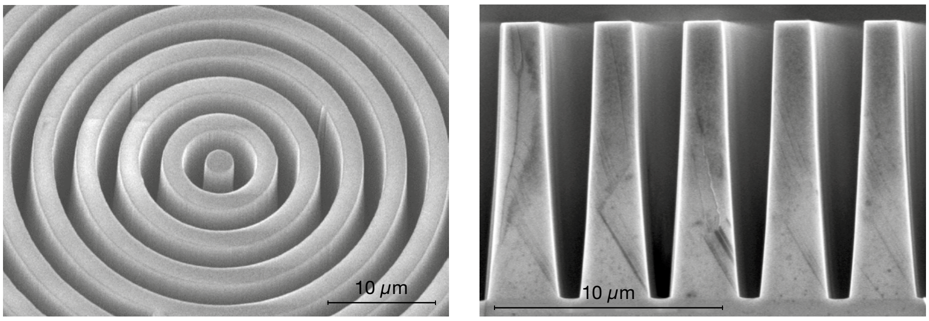


Figure 4. Paranal seasonal average sky background and contribution of the telescope (mirrors at 280 K with a combined emissivity of 7 %) as calculated by the ESO SKYCALC Sky Model Calculator. The spectral band 10–12.5 µm foreseen for the NEAR filter is indicated.



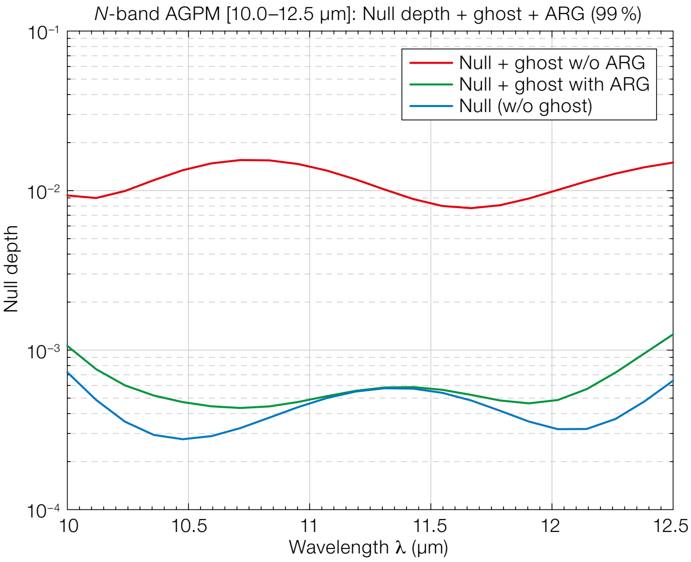


Figure 5. Images and performance of the annular groove phase mask. Microscope pictures of the subwavelength grating are shown above, and the null depth over the NEAR spectral band is shown on the left. See text for more details.

High-SNR observations with VISIR must also consider the excess low frequency noise (ELFN) of the AQARIUS detector. ELFN is temporally correlated noise caused by fluctuations in the space charge, induced by ionisation/recombination in a blocking layer between the 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 increases rapidly with incident flux levels, and the chopping frequency required to remove it also increases (Ives et al., 2014).

For the expected NEAR flux levels, 10-Hz chopping is needed to effectively suppress ELFN. To avoid synchronisation 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 (Figure 6).

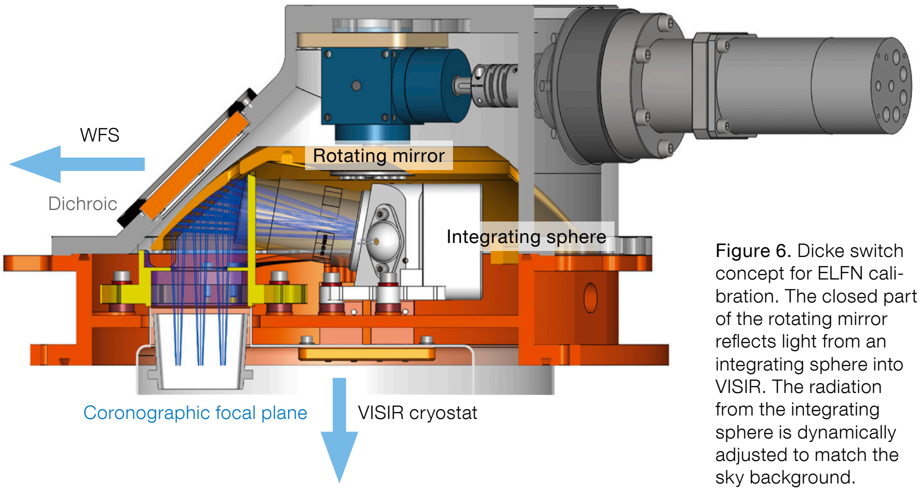


Figure 6. Dicke switch concept for ELFN calibration. The closed part of the rotating mirror reflects light from an integrating sphere into VISIR. The radiation from the integrating sphere is dynamically adjusted to match the sky background.

An efficient alternative to observations with the Dicke switch could be on-sky chopping with the DSM. By chopping between α Cen A and B, one could double the duty cycle of the observations as both stars of the binary are scientifically interesting. The separation between α Cen A and B will be about 5 arcseconds 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.

Performance

Data from an ongoing VISIR programme (098.C-0050, Principal Investigator M. Sterzik) was used to measure the actual point source sensitivity and estimate the expected background-limited imaging performance (BLIP) of NEAR. The data consist of nine one-hour observations of Sirius recorded between December 2016 and March 2017 in the B10.7 filter with 4-Hz chopping. Figure 7 shows the only image of α Cen recorded under the same programme.

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 the *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 (the VISIR pixel scale is 45 milliarcseconds per pixel) is optimum and provides an average BLIP sensitivity of 1.1 mJy (5 σ in 1 hr). 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 (5 σ in 1 hr).

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 analysed 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 nine data sets is diagonal), and noise statistics scale with integration time as expected. 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 a 325 K black body.

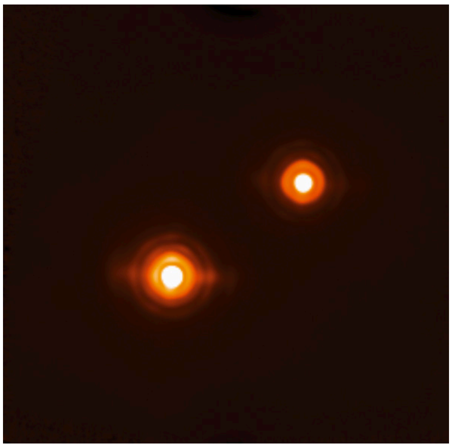


Figure 7. Classical VISIR image of α Cen A/B recorded in March 2017 (data obtained through programme 098.C-0050).

Schedule

The NEAR experiment 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 the concept, interface and manufacturing readiness of the VFM, and for the overall system) have been carried out since then to mitigate risks involved with the fast track on which NEAR is proceeding.

The next major step will be the delivery of the VFM to ESO early in 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 commissioning run at UT4 will establish the proper functioning of NEAR. During commissioning, SINFONI (the Spectrograph for Integral Field Observations in the Near-Infrared) will temporarily be taken off the telescope. The NEAR observing campaign will start around June 2019 once SINFONI has completed observations of the Galactic Centre and is shipped to Europe for integration with the new ERIS instrument.

After the campaign, VISIR will eventually move back to UT3. The WFS camera will be removed, but the modifications of the VFM will remain. 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 when observing extended objects, which presently are difficult to observe because of the limited chopper throw.

Observing campaign

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

The NEAR campaign foresees observations with 10-Hz chopping (ideally chopping between α Cen A and B or alternatively using the internal chopper) and around 4 ms detector integration time (DIT) for a reduced 450 × 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 stabilised 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 × 450 pixel frames will arrive every 50 ms and result in a data rate of 8.1 Mb s^{-1} or 30 Gb hr^{-1}. Assuming an average of six observing hours per night, where α Cen is sufficiently high in the sky, NEAR will produce about 180 Gb of data each night. The Breakthrough Initiatives plan to make these NEAR data publicly available immediately in order to benefit from the expertise of interested astronomers world-wide and to foster excitement for the search for potentially habitable planets around the nearest stars.

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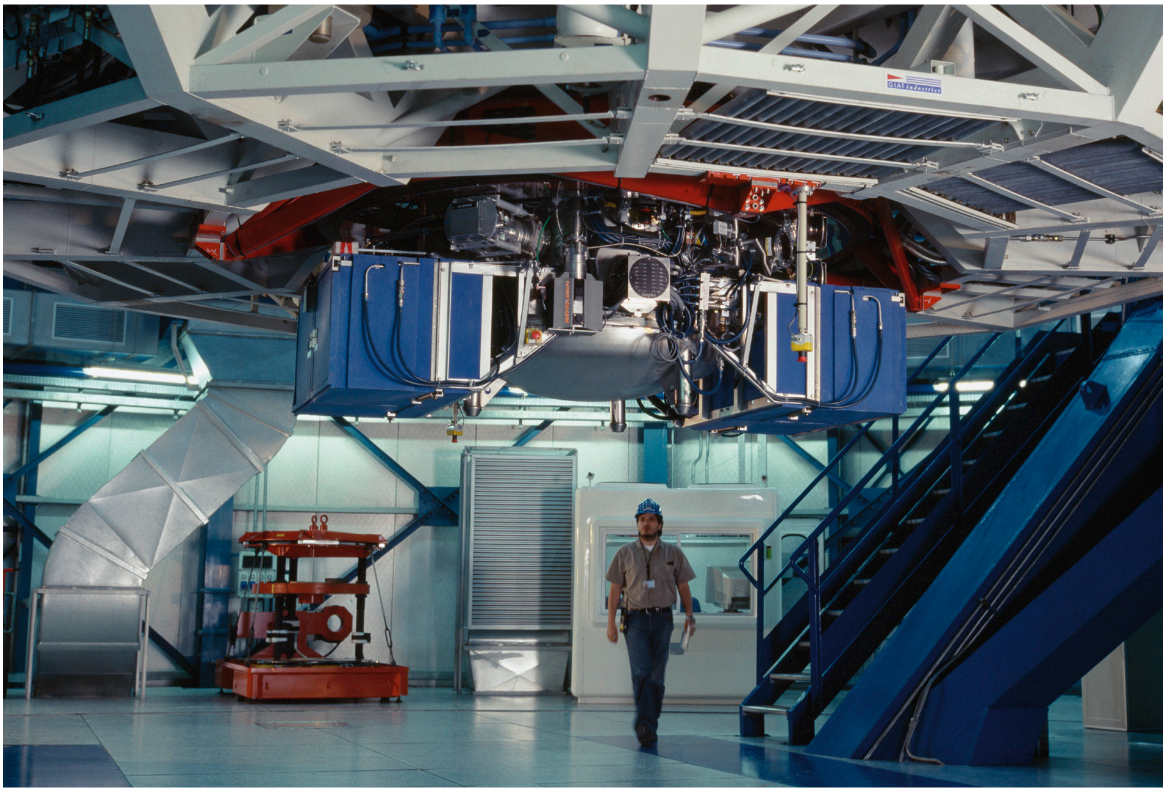
Links

[1] Breakthrough Initiatives: http://breakthroughinitiatives.org



The VLT spectrometer and imager for the mid-infrared (VISIR) mounted at the Cassegrain focus of UT3.