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# NEAR: First Results from the Search for Low-Mass Planets in α Cen

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**ESO, in collaboration with the Breakthrough Initiatives, has modified the VLT mid-infrared imager VISIR to greatly enhance its ability as a planet finder. It has conducted a 100-hour observing campaign to search for low-mass planets around both components of the binary α Centauri, part of the closest stellar system to the Earth. Using adaptive optics and high-performance coronagraphy, the instrument reached unprecedented contrast and sensitivity allowing it to see Neptune-sized planets in the habitable zone, if present. The experiment allowed us to characterise the current limitations of the instrument. We conclude that the detection of rocky planets similar to Earth in the habitable zone of the α Centauri System is already possible with 8-metre-class telescopes in the thermal infrared.**

## From an idea to the telescope

The α Centauri system is uniquely suited to the search for signatures of low-mass planets in the thermal infrared. The *N*-band at around 10 μm is best suited for such observations, because this is where a planet with a temperature like Earth's is brightest. The α Centauri binary consists of the solar-type stars α Centauri A and B, and the planet-hosting (Anglada-Escudé et al., 2016) M-dwarf star Proxima Centauri. In a previous Messenger article (Kasper et al., 2017), we provided details of how we planned to modify the existing VISIR instrument to conduct the necessary observations with the Very Large Telescope (VLT). This article describes how VISIR was moved to UT4, the innovations and new technologies that were implemented and how they work, concluding with the execution of the NEAR (New Earths in the α Centauri Region) experiment — a unique 100-hour observation of the α Centauri system, which took place in early June 2019.

Three years were needed to develop the NEAR experiment from the initial idea, from the Phase A review held in July 2016 to the observing campaign in June 2019. Between January and July 2018, ESO's mid-infrared detector test facility Thermal Infrared MultiMode Instrument (TIMMI2), a decommissioned instrument from the ESO 3.6-metre telescope at La Silla, was modified and used to carry out the acceptance tests of the internal chopper. This was followed by a performance evaluation of the Annular Groove Phase Mask (AGPM) coronagraph with a dedicated optical setup incorporating a line-tunable $CO_2$ laser, elliptical mirrors and germanium lenses. Four AGPM coronagraphs were tested, three specifically optimised for the NEAR filter (10–12.5 μm) and an older sample manufactured in 2012 and optimised for wavelengths between 11 and 13.1 μm. Surprisingly, the older coronagraph performed best, with a rejection ratio of up to 400 at 10.5 μm, and a contrast level of $< 10^{-4}$ at 3 $\lambda/D$.

After passing Provisional Acceptance Europe (PAE) in November 2018, the NEAR hardware was shipped to Paranal. At the same time, VISIR was dismounted from UT3 (Melipal) and brought to Paranal's New Integration Hall (NIH) in preparation for the on-site installation starting in early January 2019. As expected, three cool-downs of VISIR were required to successfully implement all the new modifications. First, the aperture wheel was rearranged with the help of the Paranal mechanical workshop to include two new AGPMs and a special optical mask (ZELDA, N'Diaye et al., 2014) to measure and pre-compensate optical aberrations in the instrument. New Lyot filters were mounted and mechanically centred with the cold stop of VISIR to an accuracy of better than 175 μm (i.e., 1% of the pupil diameter). The internal chopper, the wavefront sensor arm and the calibration unit were installed with the help of the contractor KT Optics, and all units were successfully tested. In particular, the alignment of the calibration unit, which uses an elliptical mirror with an aberration-free field of view of around 0.1 mm in diameter was laborious and required some modifications of the mechanical mounts on-site.

Following the completion of the assembly integration and verification (AIV) activities, VISIR was transported and mounted to UT4 (Yepun) in mid-March 2019 (see Figure 1). After measuring the expected residual misalignment between the instrument and telescope pupil on-sky on 24 March, VISIR was taken off the telescope again for adjustment by tilting

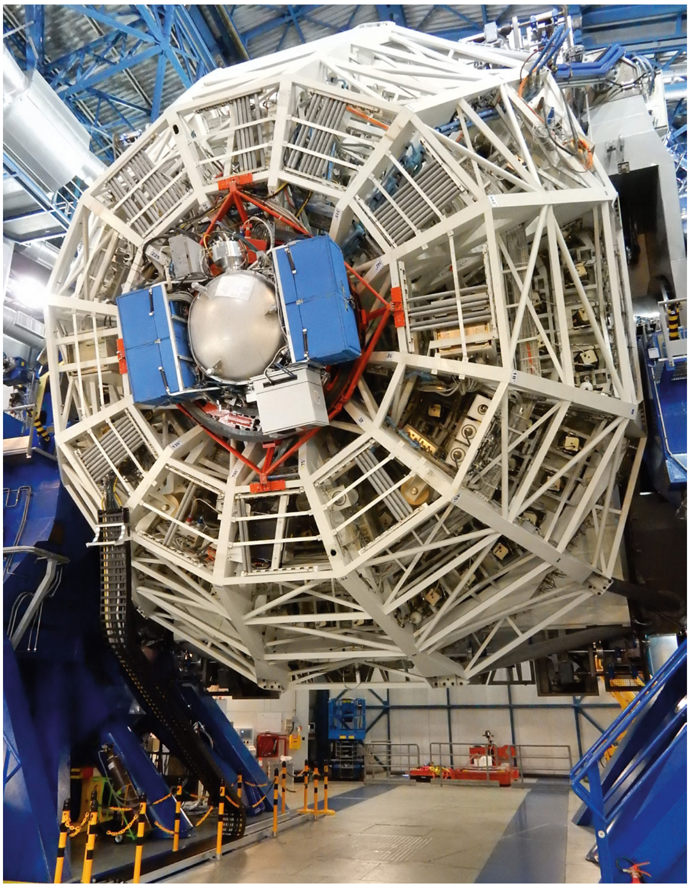


**Figure 1.** (Left) VISIR mounted on UT4 and ready for NEAR. The alternative altitude cable wrap connecting the instrument to the electronics racks and helium compressors on the azimuth platform can be seen on the left hanging down from the mirror cell.

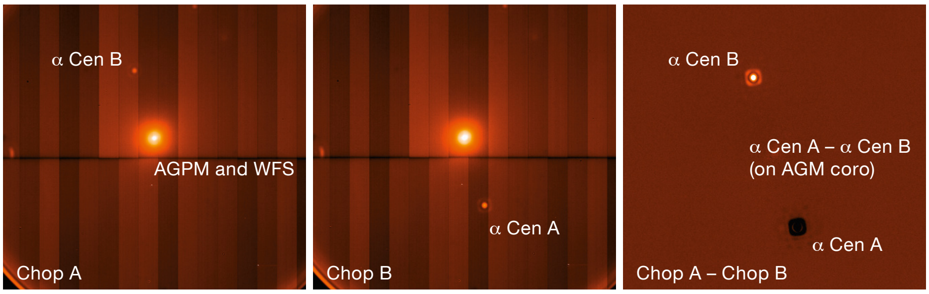


**Figure 2.** (Below) Illustration of the VISIR data acquisition of α Centauri with chopping.

the instrument, and some fine adjustment of the wavefront sensor arm. On-sky commissioning started on 3 April 2019 and lasted for 10 half-nights, during which the various new functions were tested, and operational procedures were tuned.

## Technical innovations, observing modes and performance

NEAR implements several technologies which are either completely new for *N*-band astronomy or have not previously been tested on-sky at this wavelength. For example, the experiment confirmed that atmospheric water vapour content does not significantly impact the adaptive optics (AO) corrected *N*-band image quality, and that mid-infrared spectral filters can be overcoated with chromium masks implementing Lyot stops or apodisers for the coronagraph. We also, for the first time, implemented an alternative altitude cable wrap (see Figure 1), which could also greatly facilitate the operation of other Cassegrain instruments.

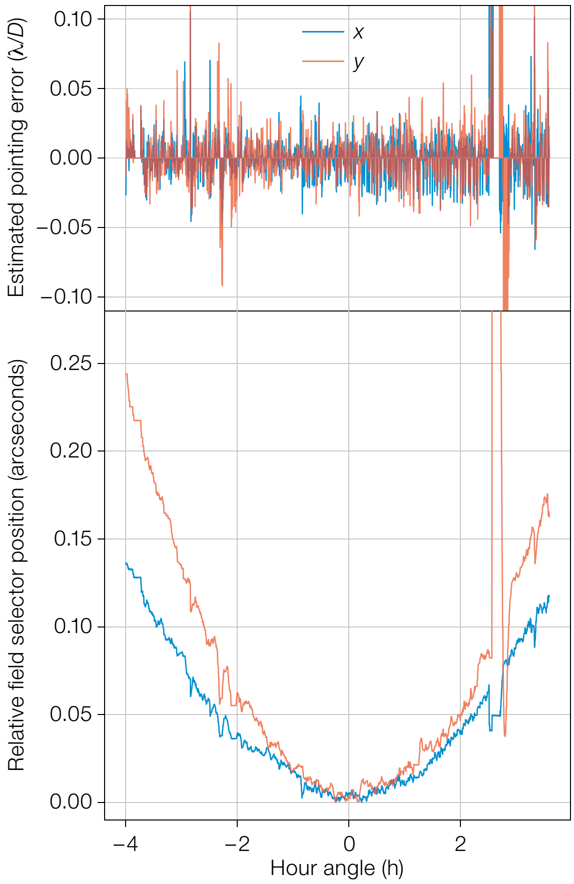
### Chopping, internal and external

Among the new technologies is an internal chopping device, the so-called Dicke Switch, which is described in more detail in Kasper et al. (2017). We tested the Dicke Switch at chopping frequencies up to 10 Hz during commissioning, and it substantially reduces the detector's Excess Low Frequency Noise (ELFN) as foreseen. There is an expected mismatch in the spatial distribution of the sky and internal background, but this mismatch turns out to be stable in time and can be well modelled or subtracted by nodding techniques. This device can be used when external chopping is not possible — when, for example, the source size exceeds the throw range of an external chopper.

The second option, external chopping using the Deformable Secondary Mirror (DSM), worked flawlessly. This option was initially deemed a risky approach, because the chopping action is seen by the AO and could have disturbed its operation. However, the clever design of the DSM and the Standard Platform for Adaptive optics Real Time Applications (SPARTA)[2] made sure that DSM chopping observations are highly efficient and almost transparent to the instrument. In addition, the α Centauri binary offers the possibility of chopping with an amplitude corresponding to the separation between the two stars of about 5 arcseconds in 2019, placing all the time a scientifically interesting target on the coronagraphic mask and doubling the efficiency. Because of these advantages, we used external chopping with the DSM for the α Centauri observations, and Figure 2 illustrates the data as seen by the detector during the two chopping cycles on the left and middle panels, and the chopping subtracted image of the two on the right.

### Coronagraph modes and centring

The light from the star at the location where we search for planets can be suppressed using two different concepts in NEAR. The first is the AGPM, a technical realisation of a Vortex coronagraph using a sub-wavelength grating etched into a diamond substrate (Mawet et al., 2005). The second is a shaped pupil mask



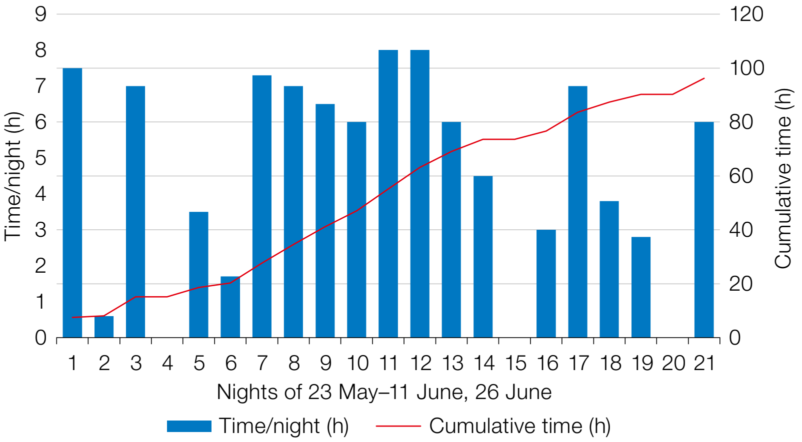


**Figure 3.** (Left) Top: The shifting movement of the star behind the AGPM is measured by the QACITS algorithm in a closed loop during a NEAR observing night. The horizontal axis shows the hour angle and the colours refer to the *x* and *y* directions. Over 4 hours, centered on meridian passage, the rms estimation is 0.015 $\lambda/D$ for both the *x* and *y* directions. Bottom: The relative positions of the field selector recorded in the same night. The variation in the position of the field selector is due to differential atmospheric refraction between the AO wavefront-sensing channel and the science channel of VISIR. There was an AO interruption at hour angle ~ 2.5–3.

**Figure 4.** (Above) Hours of open shutter time over the duration of the NEAR campaign. Only small amounts of data could be collected between 24 and 28 May and between 5 and 11 June, owing to mediocre (mostly cloudy) observing conditions.

(Carlotti et al., 2012), which does not suppress the overall light intensity, but modifies the light distribution in the focal plane so as to carve out a dark high-contrast region at the relevant angular separation. Both concepts work well and improve the contrast by a factor of between 50 and 100. What tipped the balance towards the AGPM as the choice for the NEAR campaign was the higher throughput, resulting in a moderately improved sensitivity overall and, more importantly, the suppression of the high-intensity stellar image, thus avoiding detector electronics “ghosts”.

As with all small inner working angle coronagraphs, the AGPM performance is sensitive to small offsets of the star behind the coronagraph (for example, slow drifts). In order to actively control the centring of $\alpha$ Centauri behind the AGPM during the observation, we implemented an algorithm called “Quadrant Analysis of Coronagraphic Images for Tip-tilt Sensing” (QACITS; Huby et al., 2015). This method estimates the offsets directly from the images recorded on the detector. The tests during the commissioning phase allowed us to optimise the QACITS algorithm parameters and the observing strategy. It was shown that background residuals after chopping have to be subtracted from the images analysed by QACITS. After tuning, QACITS was able to automatically centre the star on the AGPM and keep it there with an accuracy of 0.015 $\lambda/D$ rms, almost one-hundredth of a resolution element (Figure 3).

## One hundred hours of observations

ESO allocated 20 observing nights for the NEAR campaign between 23 May and 11 June 2019 to observe the $\alpha$ Centauri system. Even though the observing efficiency of NEAR is very high, with very small overheads for telescope sky offsets and data transfer (well below 10%), the campaign struggled to collect the 100 hours of data desired.

Figure 4 shows the campaign progress in data hours collected per night. The maximum possible time for which $\alpha$ Centauri could be observed at an airmass smaller than two is about seven hours in a good observing night. Figure 4 shows, however, that there were several consecutive nights during the first and last weeks of the campaign when either no or only small amounts of data were recorded. These nights suffered from extended periods of cloud coverage. Even thin high clouds, which can be acceptable for observations in the near-infrared, are very detrimental for thermal infrared observations, because they lead to very high fluctuations in throughput and sky background.

## Solid $N_2$ on the coronagraph

There were, of course, a number of smaller and larger problems during the long campaign and lots of stories to tell. Here is a particularly interesting one, which concerns one of the unknown unknowns that we encountered.

During the first few nights of the campaign, we noticed that the contrast provided by the coronagraph was less effective than during commissioning, with a continuing slow degradation every other night. While we were expecting a suppression of the central point spread function (PSF) by a factor of about 120, we started

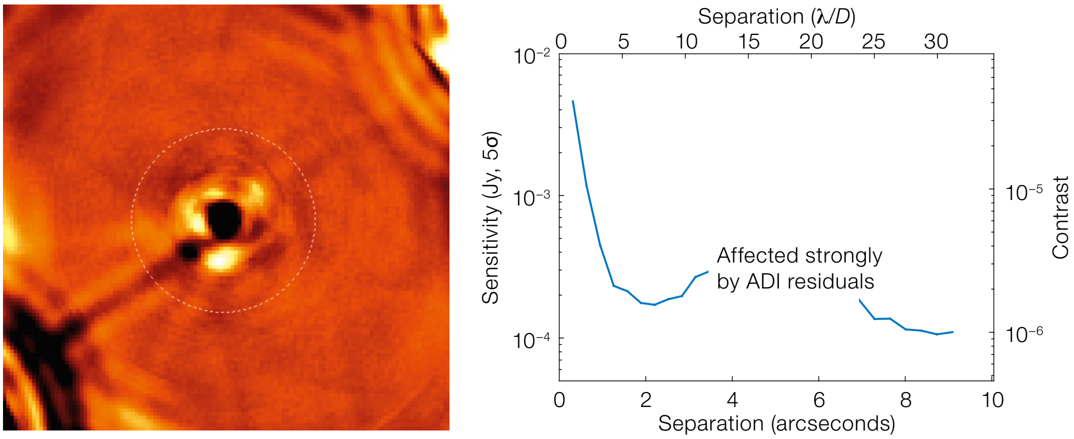


**Figure 5.** Left: The deepest ever view of the habitable zone (indicated by the dashed circle) around α Centauri A; the 76-hour image obtained during the NEAR campaign — ~ 6 × 6 arcseconds. Right: Sensitivity and contrast estimated from the deep image as a function of radial distance to the centre.

with a factor of 80, which degraded to only a factor of 40 about a week into the campaign. Somewhat frustratingly, none of the typical external effects that degrade coronagraph efficiency (for example, Lyot stop misalignments or optical aberrations) could explain the shape of the residual image that we observed. It really looked like an intrinsic degradation of the coronagraphic mask itself.

Could air, entering the cryostat through a known tiny leak, freeze out on the 20-Kelvin cold coronagraphic mask and produce the loss of contrast? A back-of-the-envelope estimate showed that such a leak could indeed build up an ice layer of a few microns thickness every day. With the refractive index of solid nitrogen, the main constituent of air, ice partly entering the grooves of the AGPM coronagraphic mask could change the optical depth of the grooves sufficiently to degrade the performance.

So, how were we to test this theory, and even more importantly, fix it during the campaign as it was running? Solid nitrogen starts to sublimate at a sufficiently high rate to de-ice the coronagraph mask at temperatures that are only moderately higher than the nominal 20 Kelvin. It turned out that the temperature after the first stage of the instrument warmup, lasting just a few hours, is 35–40 Kelvin. Tricking the PLC-controlled system into stopping the warmup sequence after the first stage and going into cooling again was risky (a glitch could have resulted in a full warmup which would have taken out VISIR for several days), but it paid off. A procedure was developed to carry out the mini-warmup and cool-down in the morning and be back in business in less than 10 hours, sufficiently quick to be ready for the following observing night. And it was a success! The coronagraphic rejection recovered with each mini-warmup, and starting from 1 June we repeated this procedure approximately every three days.

## The data and preliminary results

The campaign data were taken at a VISIR/NEAR detector frame rate of 166 Hz, i.e., the detector integration time (DIT) was 6 ms. Chopping ran at 8.33 Hz for most of the campaign, and each chopping half-cycle thus lasted 60 ms. During this time span, 48 ms or 8 DITs were averaged into a single frame, and 12 ms or 2 DITs were skipped for the transition of the DSM between the two chopping positions. Each 30-second data file consists of 500 half-cycle frames, and the 100 hours of data add up to 6 million frames or 6 Tb.

Before entering advanced high-contrast imaging data reduction, some pre-processing was necessary to remove bad frames and reduce the data volume to a more manageable size. We removed frames with extremely high or variable background produced, for example, by thin clouds or low encircled energy for the off-axis stars during ineffective AO correction, and frames with low coronagraphic suppression through bad centring of the PSF on the coronagraph mask. Finally, we cropped the images to 400 × 400 pixels, carefully centred them to the position between the two off-axis PSFs and binned the surviving 76 hours of data to 1-minute time resolution, which is short enough to avoid any noticeable smearing of the images because of field rotation. This procedure compressed the full campaign into ~ 4600 frames or 3 Gb.

A relatively simple high-contrast imaging analysis can help evaluate the detection limits reached during the campaign. By sorting all the frames according to their parallactic angle, we run a PSF calibration procedure based on principal component analysis using all the frames, i.e., processing the campaign as a whole rather than night-by-night. The calibrated images are then combined using noise-weighted averages in order to properly take into account the rather large variations in the sky background.

Figure 5 shows the result of this simple data reduction and the contrast sensitivity achieved. The 5σ background-limited sensitivity far away from the star is of the order of 100 μJy, which is consistent with our initial goals. At ~ 1.1-arcsecond separation, i.e., at the angular size of the habitable zone around α Centauri A, the sensitivity is reduced to about 250 μJy mostly by the central glow of the AGPM. This does not yet mean that a point source can readily be detected at this level, but first estimates using a fake injected source show that a planet of ~ 350 μJy brightness corresponding to a temperate Neptune could indeed be seen.

No planet candidate of the size of Neptune or larger was found in the data so far. While we were obviously hoping for a detection, the result can also be seen as good news for the existence of rocky planets, which may therefore still exist in the habitable zone of $\alpha$ Centauri in a stable orbit. There is also a roughly 35% chance that an existing planet would have been hidden by the star as the result of an unfavourable projected orbital position during our single-epoch observation. In addition, the image in Figure 5 shows some straight lines connecting the coronagraphic centre field with the off-axis stellar image to the lower left. These streaks appear because of a small persistence in the detector, i.e., the pixels remember the stars being dragged over the detector during the chopping transition. This feature is difficult to model and may hide another 5–10% of the possible planet orbits.

## Beyond NEAR

Preliminary results of the NEAR commissioning and experiment have triggered substantial interest within the community in this facility, and also for other astronomical observations. ESO therefore issued a call for Science Demonstration proposals, which received a lot of attention and resulted in 26 proposals being submitted for NEAR observing time. Two periods of Science Demonstration were allocated in September and December 2019 to conduct roughly half of the proposed programmes.

While no planet candidates have been found so far, NEAR is already a very successful collaboration between ESO, the Breakthrough Initiatives[1] and many partners in the exoplanet and mid-infrared astronomy communities. Several key technologies for mid-infrared high-contrast imaging were successfully tested on-sky, and many important assumptions were validated — for example, the scaling of the achieved signal-to-noise ratio with the square-root of the observing time.

All raw data obtained during the 100-hour $\alpha$ Centauri campaign are publicly available, and a condensed easy-to-use 3 Gb package of all the good frames is available on request[3]. The on-sky contrast at 3 $\lambda/D$ and the *N*-band sensitivity are unprecedented in ground-based astronomy by a large margin — more than one order of magnitude. The sensitivity limits are well understood and could be improved further by a factor 2–2.5, mainly by removing the AGPM glow by introducing a small optical relay incorporating a cold pupil stop in front of the AGPM. But this is still not the limit for mid-infrared observations from the ground. A novel lower-noise detector technology is emerging, which promises to double the sensitivity once more. These next-generation detectors would allow the VLT to probe the rocky planet regime in the habitable zone around $\alpha$ Centauri. When combined with similar instruments at the other southern hemisphere 8-metre-class telescopes, Gemini South and Magellan, true Earth analogues could soon be discovered.

### Acknowledgements

The NEAR experiment greatly benefited, and still benefits, from the exchange with the exoplanet and mid-infrared scientific community on both sides of the Atlantic. We would like to thank Derek Ives for access to the Infrared Lab at ESO, Paranal's mechanical workshop for the excellent support during the integration on-site, and Rus Belikov, Eduardo Bendek, Anna Boehle, Bernhard Brandl, Christian Marois, Mike Meyer and Kevin Wagner for very helpful discussions and their interest in the data analysis. Many thanks go also to our industrial partners KT Optics, Optoline and the Infrared Multilayer Laboratory of the University of Reading (now Oxford), for their R&D spirit and their willingness to stay with us during the rapid development of the experiment.

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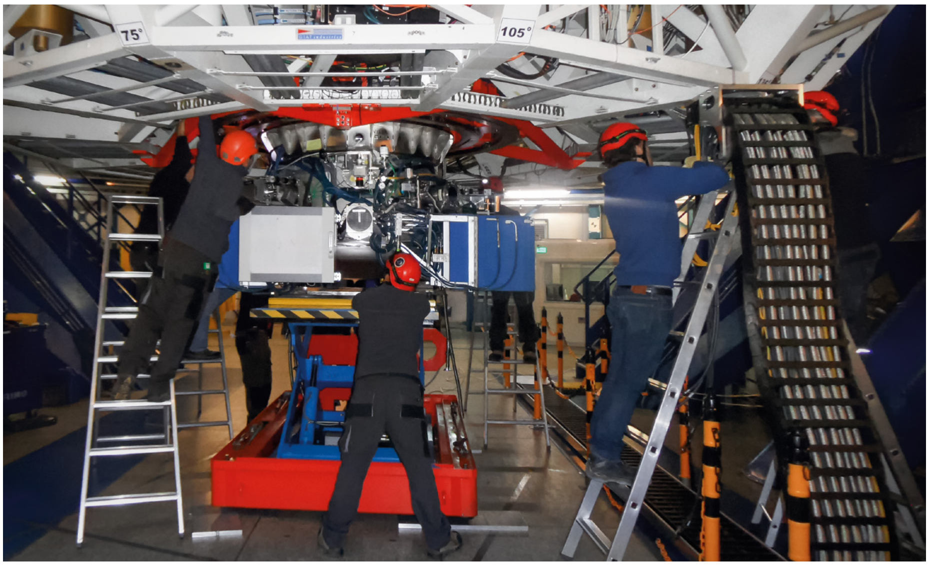
### Links

[1] Breakthrough Initiatives webpage: http://breakthroughinitiatives.org
[2] SPARTA: https://www.eso.org/sci/facilities/develop/ao/tecno/sparta.html
[3] Data can be requested via e-mail from Prashant Pathak (ppathak@eso.org) or Markus Kasper (mkasper@eso.org



ESO/NEAR Collaboration

The NEAR experiment being mounted on the Cassegrain focus of the VLT's UT4 (Yepun).