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Colour Transformations for ESO Near-Infrared Imagers

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ESO operates four near-infrared (NIR) imagers, namely the High Acuity Wide-field *K*-band Imager (HAWK-I), the VISTA InfraRed CAMera (VIRCAM), the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE), and Son OF ISAAC (SOFI). In addition, data for the two decommissioned instruments the Infrared Spectrometer And Array Camera (ISAAC) and the Nasmyth Adaptive Optics System/COudé Near-Infrared CAmera combination (NAOS-CONICA, or NACO) are available from the science archive[1]. Because these instruments have different effective bandpasses, the magnitudes measured with them are difficult to compare and doing so can lead to inconsistencies if the colour of an object is not taken into account. In this article, we present colour transformations between the ESO NIR imagers and the Two Micron All-Sky Survey (2MASS) photometric system in the *J*, *H*, and *Ks* bands. The coefficients can be used to compare and convert magnitudes derived from different ESO and non-ESO instruments.

Introduction

ESO telescopes are equipped with several NIR imagers, some of which have been serving the community for decades. Although these instruments share the most used photometric bands (for example, *J*, *H*, and *Ks*), it is not straightforward to compare 2MASS magnitudes obtained with different instrumentation to a precision of few percent. This is because of differences in the filter transmissions and detector efficiency. Over the years, many authors have computed colour transformations to allow comparison between NIR observations carried out with ESO telescopes and the most commonly used photometric systems (for example, van der Bliek, Manfroid & Bouchet, 1996). For all ESO NIR imagers with the exception of ISAAC, the colour transformations to the 2MASS photometric system (Cohen, Wheaton & Megeath, 2003) are available in the literature, and we reproduce them here. We also compute the colour transformation between ISAAC and 2MASS, previously not available in the literature. Another ESO NIR imager, SPHERE, is not included in this comparison because these data cannot easily be photometrically calibrated, nor is this necessary for typical science use cases.

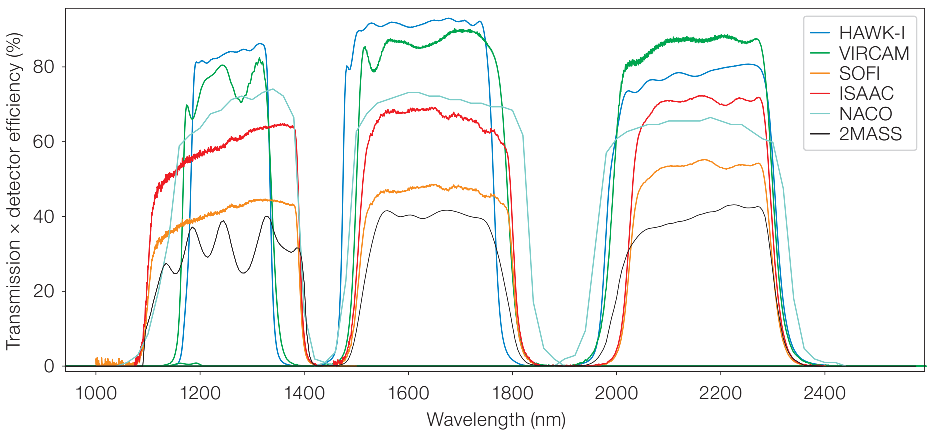

Figure 1. Comparison between the combined contribution of the filter transmission and detector efficiency for the *J*, *H*, and *Ks* filters of ESO near-infrared imagers and 2MASS. Filter transmissions and detector efficiencies are available online for ESO filters[5,6,7] and for 2MASS[8]. The curves do not include atmospheric transmission.

Colour transformations between all ESO NIR imagers and 2MASS.

In Figure 1 we compare the *J*, *H*, and *Ks* filter efficiencies of the ESO imagers with those of 2MASS. The curves include the detector efficiency but do not include atmospheric transmission. The filter shapes are quite different, although one can see that the HAWK-I *J*-band filter is the one that deviates most from 2MASS, and that there is a certain similarity between SOFI and ISAAC, and between all instruments except NACO in the *Ks* band. In principle, these curves could be used to compute colour transformations, assuming specific input spectra. However, in practice it is often more useful to compute the difference between catalogued and observed magnitudes as a function of colour from observed spectra. In this section, we list the results for each of the above-mentioned imagers.

HAWK-I

HAWK-I has been offered since Period 81 and is currently mounted on Unit Telescope 4 (UT4) of the Very Large Telescope (VLT). It is a wide-field imager with a field of view of 7.5 × 7.5 arcminutes, and a pixel scale of 0.1064 arcseconds pixel^{-1} mapped onto a 2 × 2 detector mosaic with a 15-arcsecond gap. It operates in the range 0.85–2.2 μm and has several broad-band (*Y*, *J*, *H*, and *Ks*) and narrow-band (Brγ, CH_4, H_2, 1.061 μm, 1.187 μm, and 2.090 μm) filters. The HAWK-I archive processing done by the Cambridge Astronomy Survey Unit (CASU) and the new ESO HAWK-I imaging pipeline v2.1 uses the 2MASS catalogue to astrometrically and photometrically calibrate the science fields (Neeser et al., 2016). The computation was done using the entire ESO HAWK-I archive up to October 2017, collecting a total of ~ 1.5 million point-like sources in common with 2MASS and covering a colour range of $-0.5 \lesssim (J-H)_{2MASS} \lesssim 3.5$. The colour transformations between the HAWK-I and the 2MASS photometric systems[2] are:

$$J_{HAWK\text{-}I} - J_{2MASS} = -0.15 \times (J_{2MASS} - H_{2MASS})$$
$$H_{HAWK\text{-}I} - H_{2MASS} = 0.06 \times (J_{2MASS} - H_{2MASS})$$
$$Ks_{HAWK\text{-}I} - K_{2MASS} = 0.03 \times (J_{2MASS} - K_{2MASS})$$

The equations do not include constant terms because the filter zero points of HAWK-I are scaled to match to those of 2MASS by the data reduction pipeline. For point-like sources detected in the pipeline output catalogues, an aperture correction has to be taken into account before applying the above transformations. The above equations are also valid for data reduced prior to pipeline version 2.1, although additional constant terms might need to be added because of the different set of standard stars used in the calibration.

VIRCAM

VIRCAM is an imager mounted on the Visible and Infrared Survey Telescope for Astronomy (VISTA), a 4-metre-class telescope mainly used for public surveys that began operating in 2009. It has 16 detectors organised in a 4 × 4 array. Each detector covers 11.6 × 11.6 arcminutes on the sky with a spatial sampling of 0.339 arcseconds $pixel^{-1}$. A sequence of 6 offset exposures ensures a uniform sky coverage of 1.501 square degrees. It operates in the range 0.8–1.2 μm and has several broad-band (*Z*, *Y*, *J*, *H*, and *Ks*) and narrow-band (NB980, NB990, and NB118) filters. The VIRCAM archive processing routinely carried out by CASU using the VIRCAM imaging pipeline (v2.3) includes photometric and astrometric calibration with the 2MASS catalogue (Neeser et al., 2016). A compilation of data taken on photometric nights, with good seeing and for fields with low extinction ($E(B-V) < 0.1$) and high galactic latitude ($|b| > 35$ deg), was used. The colour range of the sources in 2MASS used in the computation is $0 < (J-Ks)_{2MASS} < 2$. In the process, all detectors were normalised to the same approximate gain using the flat-field exposures. The colour transformations used for the conversion between the VIRCAM photometric system and the 2MASS system are:

$$J_{VIRCAM} - J_{2MASS} = (-0.077 \pm 0.006) \times (J_{2MASS} - H_{2MASS})$$
$$H_{VIRCAM} - H_{2MASS} = (0.032 \pm 0.005) \times (J_{2MASS} - H_{2MASS})$$
$$Ks_{VIRCAM} - Ks_{2MASS} = (0.010 \pm 0.007) \times (J_{2MASS} - Ks_{2MASS})$$

The same procedure was also used by González-Fernández et al. (2018), who updated the VIRCAM colour terms using $(J-Ks)_{2MASS}$ colour:

$$J_{VIRCAM} - J_{2MASS} = (-0.031 \pm 0.006) \times (J_{2MASS} - Ks_{2MASS})$$
$$H_{VIRCAM} - H_{2MASS} = (0.015 \pm 0.005) \times (J_{2MASS} - Ks_{2MASS})$$
$$Ks_{VIRCAM} - Ks_{2MASS} = (0.006 \pm 0.007) \times (J_{2MASS} - Ks_{2MASS})$$

The equations do not include constant terms because the filter zero points of all 16 VIRCAM detectors are scaled to match to those of 2MASS by the data reduction pipeline. For point-like sources detected in the pipeline output catalogues, an aperture correction has to be taken into account before applying the above transformations. The above equations are also valid for data reduced prior to pipeline version 2.3, although additional constant terms might need to be added because of the different set of standard stars used in the calibration. Updates to the above relations are available on the CASU webpage[3].

SOFI

SOFI is an imager and spectrograph that has operated since 1998. It is mounted on the New Technology Telescope (NTT) at La Silla. Its imaging mode covers a field of view of 4.92 × 4.92 arcminutes with a sampling of 0.288 arcseconds $pixel^{-1}$. In the past, it also offered a finer resolution of 0.144 arcseconds $pixel^{-1}$ over a field of view of 2.46 × 2.46 arcminutes. It operates in the range 1.08–2.3 μm and has several broad-band (*J*, *H*, and *Ks*) and 15 narrow-band filters. The SOFI instrument webpages[4] give colour conversions between SOFI magnitudes and the Persson et al. (1998) photometric system (LCO). Stars with $J-Ks$ colour between 0.24 and 1.28 were used and the data were corrected for atmospheric extinction. Residuals of the SOFI-LCO colour transformations are about 0.01 magnitudes. In addition, Carpenter (2001) provides the colour conversion between the LCO system and 2MASS, using 83 stars from the original list of Persson et al. We therefore used the two colour conversions to derive the conversion between SOFI and 2MASS:

$$J_{SOFI} - J_{2MASS} = (-0.005 \pm 0.002) \times (J_{2MASS} - Ks_{2MASS}) + 0.013$$
$$H_{SOFI} - H_{2MASS} = (0.015 \pm 0.002) \times (H_{2MASS} - Ks_{2MASS}) + (0.023 \pm 0.002) \times (J_{2MASS} - H_{2MASS}) + 0.006$$
$$Ks_{SOFI} - Ks_{2MASS} = (0.006 \pm 0.002) \times (J_{2MASS} - Ks_{2MASS}) + 0.006$$

The above relations are valid if the SOFI observations are flux-calibrated using the standard stars from Tables 2 and 3 of Persson et al. (1998). The constant terms in the equations represent the zero point offset between 2MASS and LCO.

ISAAC

ISAAC is an imager and spectrograph that operated from 1999 to 2013 on UT3 and was then decommissioned. Its imaging mode covers a field of view of 152 × 152 arcseconds with a sampling of 0.148 arcseconds $pixel^{-1}$. It also had a high-resolution mode with a quarter of the field of view and half the pixel scale. It operated in the range 1–5 μm and had several broad-band (*SZ*, *Js*, *J*, *H*, and *Ks*) and 16 narrow-band filters. We employed archival ISAAC data from the ESO-Great Observatories Origins Deep Survey (ESO-GOODS) because it provides a photometric catalogue with accurately characterised uncertainties (Retzlaff et al., 2010). Because there are few sources in common between the ESO-GOODS field and 2MASS, we make use of VIRCAM observations of the same field from the VISTA Hemisphere Survey (McMahon et al., 2013). We then compute the conversion between ISAAC and VIRCAM, and then use the known VIRCAM-2MASS relations to retrieve the ISAAC-2MASS colour terms.

For the ISAAC data, we used the archival file ADP.2014-12-12T10:41:18.833.fits. Magnitudes in the AB system were converted to the Vega reference system (by applying the following offset corrections: $J_{VEGA} = J_{AB} - 0.96$, $H_{VEGA} = H_{AB} - 1.426$, and $Ks_{VEGA} = Ks_{AB} - 1.895$) and corrected for an aperture of 2 arcseconds using the coefficients in Table 3 of Retzlaff et al. (2010). For the VISTA data, we used the catalogue ADP.2018- 02-01T00:59:24.360.0.fits in the ESO archive, that covers 1.9 square degrees. It contains 280 sources in common with the ESO-GOODS catalogue.

We first computed colour transformations between ISAAC and VIRCAM, and then we derived those between ISAAC and 2MASS by exploiting the known transformations between VIRCAM and 2MASS. To that end, we compared the magnitudes of the common sources and then applied an additional filter to remove outliers, bright saturated sources and faint sources with a large magnitude error. That left 84 objects in common. The comparison of their magnitudes in the 3 bands is shown in Figure 2. In Figure 2 we also show the colour relations between the ISAAC and 2MASS filters, as obtained from the 84 sources in common. We used the orthogonal distance method that accounts

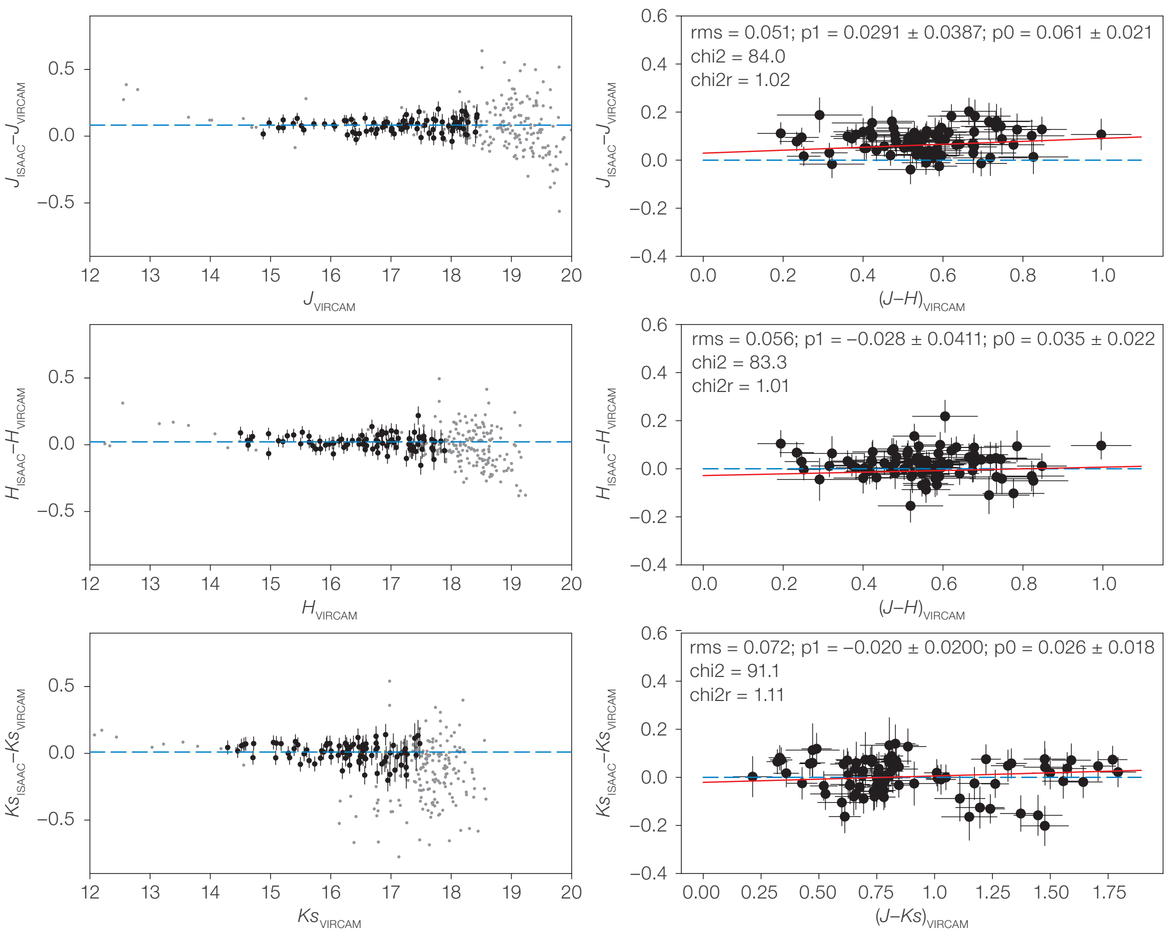

Figure 2. Relations between ISAAC and VIRCAM magnitudes for the *J* (top panels), *H* (middle panels), and *Ks* (bottom panels) bands. Left panels: difference between ISAAC and VIRCAM magnitudes; the grey points indicate all the 280 matches between the 2 catalogues; black circles with error bars show the 84 final matches after the filtering. The horizontal dashed lines indicate the median of the difference between the two magnitudes, computed considering only the 84 final matches. The offsets (ISAAC–VIRCAM) are: 0.083 mag (*J*), 0.022 mag (*H*), and 0.010 mag (*Ks*). Right panels: colour relations between ISAAC and VIRCAM; only the 84 matches in the top panels are used to fit the relations. The best-fit relation (Δmag = p1·colour + p0) is shown in red, and the coefficients and errors are indicated in the panel. The zero (dashed blue) line is indicated as a reference.

for errors on both axes to fit linear relations between the colours. The computed coefficients are then plugged into the known relations between VIRCAM and 2MASS to derive the relations between ISAAC and 2MASS, which are:

$$J_{ISAAC} - J_{2MASS} = (-0.05 \pm 0.04) \times (J_{2MASS} - H_{2MASS}) + 0.061$$
$$H_{ISAAC} - H_{2MASS} = (0.007 \pm 0.04) \times (J_{2MASS} - H_{2MASS}) + 0.035$$
$$Ks_{ISAAC} - Ks_{2MASS} = (-0.01 \pm 0.02) \times (J_{2MASS} - Ks_{2MASS}) + 0.026$$

The constant terms in the equations are not part of the colour transformation but are included for completeness; they represent the difference in zero points between the ISAAC and VIRCAM filters for objects with 0 colour in the Vega system.

NACO

NACO is a NIR imager and spectrograph equipped with an adaptive optics system that operated on UT4 (from 2001 to 2013) and UT1 (from 2014 to October 2019). Its field of view and spatial resolution depend on the filter used, ranging from a field of view of 14 × 14 arcseconds sampled at 13.3 milliarcseconds pixel^{-1} with filters below 2.5 μm, to a field of view of 56 × 56 arcseconds sampled at 54.7 milliarcseconds pixel^{-1} with the NB 3.74 and NB 4.05 filter set. The reference photometric system of the reduced data depends on the standard stars used in the observations and data reduction. The pipeline uses static calibration files that contains photometric stars from several systems (UKIRT, SAAO, MSSSO, LCO, Van Der Blieck, and Arnica). Carpenter (2001) provides colour conversions between 2MASS and all these photometric systems; therefore, the user has to adopt the correction from the Carpenter list that matches the photometric system of the stars used in the calibration. However, several authors use stars from the InfraRed Survey Facility (IRSF) system (Tokunaga, Simons & Vacca, 2002) to calibrate NACO observations, despite the fact that these stars are not used by the data reduction pipeline. This choice has the advantage that there is no significant colour dependency between NACO and IRSF (Janczak et al., 2010). The conversion between IRSF and 2MASS is provided by Kato et al. (2007), which can therefore be extended to NACO if the observations are calibrated using IRSF stars. We indicate below only the colour relation obtained for the IRSF system, as its photometric standard stars are not listed in the NACO static calibration. For the other system covered by the NACO pipeline we refer to Carpenter (2001).

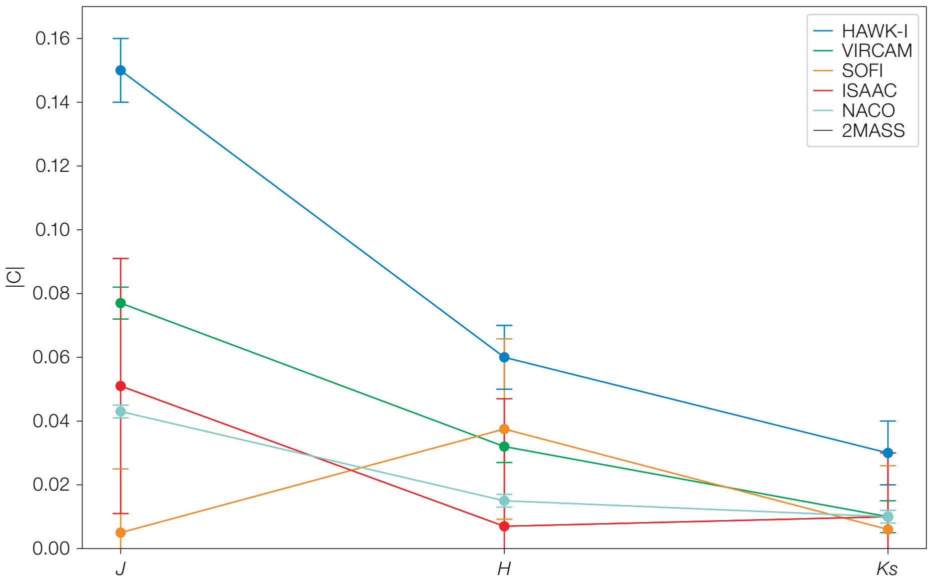

Figure 3. Comparison between the absolute values of the *J–H* (for the *J* and *H* bands) and *J–Ks* (for the *Ks* band) colour terms of all instruments except SOFI, for which the *J–Ks* colour term is given for the *J* band and the sum of the *J–H* and *H–Ks* colour terms is given for the *H* band. Coefficients |C| closer to 0 indicate that that instrument is closer to 2MASS for that filter.

$$J_{NACO} - J_{2MASS} = (-0.043 \pm 0.002) \times (J_{2MASS} - H_{2MASS}) + 0.018$$
$$H_{NACO} - H_{2MASS} = (0.015 \pm 0.002) \times (J_{2MASS} - H_{2MASS}) + 0.024$$
$$Ks_{NACO} - Ks_{2MASS} = (0.010 \pm 0.002) \times (J_{2MASS} - Ks_{2MASS}) + 0.014$$

The above relations were obtained using thousands of sources in the Magellanic Clouds covering a wide range of colours ($0 < J–H < 0.45$; $0 < H–Ks < 2.7$). The constant terms in the equation represent the zero point offset between 2MASS and IRSF.

Discussion

Depending on the instrument, the colour of a source has a significant impact on the difference between instrumental magnitudes and magnitudes listed in 2MASS. The values of the colour terms are listed for each instrument in Figure 3. These values measure how much effective filters deviate from those of the 2MASS system. A coefficient equal to 0 implies no colour correction and indicates that the filters of an instrument are equivalent to those of 2MASS. For an object with 1 magnitude colour (either *J–H* or *J–Ks*) in the Vega system, the colour terms typically represent a few percent of the total magnitude (with the exception of HAWK-I) and they depend on the band. Figure 3 shows that HAWK-I is the instrument most different from 2MASS, in particular for the *J* band in which a ~ 15% difference is observed. This result is qualitatively consistent with Figure 1, which shows that the HAWK-I *J* and *H* filters are those that deviate the most from 2MASS. The transformations provided above, along with transformations for filters other than *J*, *H*, and *Ks*, are also given and constantly updated in the data processing FAQ section of the ESO webpage[9].

References

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Links

1 ESO Archive Science Portal: http://archive.eso.org/scienceportal/home
2 Colour transformations between HAWK-I and 2MASS: https://www.eso.org/rm/api/v1/public/releaseDescriptions/87
3 CASU webpage: http://casu.ast.cam.ac.uk/surveys-projects/vista/technical/photometric-properties
4 SOFI webpages: https://www.eso.org/sci/facilities/lasilla/instruments/sofi/inst/setup/Zero_Point.html
5 ESO Paranal instruments: https://www.eso.org/sci/facilities/paranal/instruments.html
6 ESO Paranal decommissioned instruments: https://www.eso.org/sci/facilities/paranal/decommissioned.html
7 ESO La Silla instruments: https://www.eso.org/sci/facilities/lasilla/instruments/sofi/inst.html
8 2MASS filter details: https://old.ipac.caltech.edu/2mass/releases/allsky/doc/sec3_1b1.html
9 ESO data processing FAQ: https://www.eso.org/sci/data-processing/faq.html

ESO/H. Drass/ALMA (ESO/NAOJ/NRAO)/A. Hacar

This composite image shows part of the famous star-forming region of the Orion Nebula. It combines a mosaic of millimetre wavelength images from ALMA and the IRAM 30-metre telescope, shown in red, with a more familiar infrared view from the HAWK-I instrument on ESO's VLT, shown in blue.