Phase Referencing in Optical Interferometry

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\textbf{ABSTRACT}

One of the aims of next generation optical interferometric instrumentation is to be able to make use of information contained in the visibility phase to construct high dynamic range images.

Radio and optical interferometry are at the two extremes of phase corruption by the atmosphere. While in radio it is possible to obtain calibrated phases for the science objects, in the optical this is currently not possible. Instead, optical interferometry has relied on closure phase techniques to produce images. Such techniques allow only to achieve modest dynamic ranges. However, with high contrast objects, for faint targets or when structure detail is needed, phase referencing techniques as used in radio interferometry, should theoretically achieve higher dynamic ranges for the same number of telescopes.

Our approach is not to provide evidence either for or against the hypothesis that phase referenced imaging gives better dynamic range than closure phase imaging. Instead we wish to explore the potential of this technique for future optical interferometry and also because image reconstruction in the optical using phase referencing techniques has only been performed with limited success.

We have generated simulated, noisy, complex visibility data, analogous to the signal produced in radio interferometers, using the VLTI as a template. We proceeded with image reconstruction using the radio image reconstruction algorithms contained in AIPS IMAGR (\texttt{clean} algorithm). Our results show that image reconstruction is successful in most of our science cases, yielding images with a 4 milliarcsecond resolution in K band.

We have also investigated the number of target candidates for optical phase referencing. Using the 2MASS point source catalog, we show that there are several hundred objects with phase reference sources less than 30 arcseconds away, allowing to apply this technique.

\textbf{Keywords:} optical interferometry

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1. INTRODUCTION

An ideal interferometer will measure the complex visibility of an astronomical object. Image reconstruction deals with inverting the visibility information into an image, given poor Fourier plane sampling and limited phase information.

In an array of $N$ telescopes, signals are combined in $\frac{1}{2} \times N \times (N-1)$ pairs or baselines to obtain $\frac{1}{2} \times N \times (N-1)$ measurements called complex visibilities. These visibilities are related to the object brightness distribution via the van Cittert-Zernike theorem:

$$V(u, v) = \int \int I(x, y) \exp[-2\pi i (ux + vy)] dx dy$$

where $x$ and $y$ are angular displacements on the plane of the sky with the phase center as origin, $I(x, y)$ is the brightness distribution of the target and $u$ and $v$ are the position vectors of the baselines projected on a plane perpendicular to the source direction, which together define the $uv$ plane. In practical terms, the better the sampling of the $uv$ plane in terms of baseline length, position angle, and number of measurements, the more faithful the reconstructed image will be relative to the true brightness distribution.

Radio-type observations are performed by measuring the amplitudes (modulus) and the phases (argument) of the complex visibilities:

$$V(u, v) = A \exp(i \phi)$$

Image reconstruction using the modulus and argument of the visibility function is called phase referencing image reconstruction and is widely used in radio astronomy. Studies of this type were previously attempted by Masoni (2006), Masoni et al. (2005) and Weigelt et al. (2008; private communication).

2. ARRAY CONFIGURATION

Telescope configurations are an essential part of the image reconstruction process. We began by identifying array configurations that allowed the most uniform $uv$ coverage:

- 4 UTs $\times$ 1 night - the chosen configuration when observing very faint sources (Fig. 1);
- 4 ATs $\times$ 3 nights - the case where there is a small number of telescopes (Fig. 2);
- 6 ATs $\times$ 1 night - a 6 telescope extended configuration with one night observation; has less $uv$ points than the 4 AT x 3 nights configuration but comparable $uv$ coverage (Fig. 3).
3. NOISE MODEL

The noise model estimates the uncertainties on the visibility amplitudes and phases assuming an instrument following a multi-axial recombination scheme with a fringe tracker (FT; Jocou et al. 2007).

The quantity we procure is the total number of detected photoevents per integration time per pixel per baseline in the interferometric channel:

\[ \bar{N}_i = \frac{N_{\text{total}} f}{N_{\text{pix}} N_{\text{base}}} \]

where \( f \) is the fraction of the beam that goes into the interferometric channel (90%), \( N_{\text{pix}} \) is the number of pixels needed to read the interferometric channel (600), \( N_{\text{base}} \) is the number of baselines and \( N_{\text{total}} \) is the total number of detected photoevents per integration time per pixel in all channels:

\[ N_{\text{total}} = F_0 \times 10^{-0.4 \text{mag}} \times t_{\text{int}} \times N_{\text{tel}} \times \pi \times R^2 \times \Delta \lambda \times \text{trans} \times \text{Strehl} \]

Here \( F_0 \) is the photon flux of a zeroth magnitude star (Jocou et al. 2007), \( \text{mag} \) is the object magnitude in the observing band, \( t_{\text{int}} \) is the integration time, \( N_{\text{tel}} \) is the number of telescopes (6 or 4), \( R \) is the radius of the telescopes (4.1 for UTs and 0.9 for ATs) assumed for simplification to have no central hole, \( \Delta \lambda \) is the spectral bandwidth (chosen), \( \text{trans} \) is the total instrument transmission including quantum efficiency (Jocou et al. 2007), and \( \text{Strehl} \) is the Strehl ratio and depends on wavelength (Jocou et al. 2007).

Therefore, the total number of detected photoevents in the interferometric channel is:

\[ N_i = \bar{N}_i \times N_{\text{pix}} \times N_{\text{int}} \]

where \( N_{\text{int}} \) is the number of independent integrations (depends on magnitude and FT presence).

The object intrinsic visibility, \( V \), must be corrected for the instrumental visibility loss (80%) and the instrumental visibility loss induced by the FT (90%). The correlated flux per baseline is therefore:

\[ F_{\text{cor}} = N_i \times \frac{V'}{2} \]

and finally the error in visibility is given by:

\[ \text{error}_V = \sqrt{F_{\text{cor}} + N_{\text{int}} \times N_{\text{pix}} \times \sigma^2} \]

where \( \sigma \) is the readout noise of the detector (15 e-).
4. UVFITS FILE GENERATION

UVFITS is the file format in which radio astronomical data are written and used for phase referencing image reconstruction. UVFITS format is designed so that different categories of information are stored in distinct tables within a file and can be cross-referenced one to another. Each UVFITS file table stores specific parameters that include important interferometric observables and system information.

Key science images were generated and provided by the science case groups (Garcia et al. 2007). Using aspro, an image simulation tool originally created for IRAM, and the configurations above, K band "images" of the sources were created assuming that all sources were observed at the fixed declination of −60 degrees.

It was assumed also that during the night, the telescope configurations would remain fixed and that one calibrated \( uv \) point per baseline should be obtained every hour. The actual on-source integration time is, however, 10-15 minutes per hour due to overheads. The total integration time assumes an entire transit (9 hours).

5. PHASE REFERENCING THEORY

A radio interferometer works by phase referencing. The interferometer observes a science target and records the visibility modulus and phase for each baseline. It also observes a reference target used to calibrate the visibility modulus and phase for atmospheric variations. Therefore, as opposed to conventional optical interferometry, phase referencing makes use of crucial information contained in the phases to recover the brightness distribution of a source.

![Figure 3.](image)

Given an incoherent source, the observed brightness distribution in a direction \( \vec{s'} \) is given by:

\[
I_{\text{obs}}(\vec{s'}) = I_{\text{obs}}(x, y) = PSF(x, y) \ast I_{\text{true}}(x, y) + N(x, y)
\]

where \( PSF(x,y) \) is the instrumental point spread function, \( I_{\text{true}}(x,y) \) is the true object brightness distribution, \( N(x,y) \) is the noise and the asterisk denotes convolution.

In practice, interferometry does not make measurements in the image plane but in Fourier space. The relevant quantity is called the complex visibility and is measured at each \( uv \) point, the position vector of the baseline on a plane perpendicular to the source direction:

\[
V_{\text{obs}}(u, v) = S(u, v) \times V_{\text{true}}(u, v) + N'(u, v)
\]

where \( S(u,v) \), the sampling function, is the Fourier transform of the \( PSF(x,y) \), \( V_{\text{true}}(x,y) \), the true visibility, is the Fourier transform of the true brightness distribution \( I_{\text{true}}(x,y) \) and \( N'(u,v) \) is the noise in the Fourier space.

The van Cittert-Zernike theorem states that the true brightness distribution can be obtained by the inverse Fourier transform and deconvolution of the observables:
\( I_{true}(x,y) \ast PSF(x,y) = \int \int V_{true}(u,v) \times S(u,v) \exp[2\pi i(ux + vy)] \, du \, dv \)

The role of image reconstruction is to obtain the best approximation, \( F^{\text{prox}}(x,y) \sim F^{\text{obs}}(x,y) \sim F^{\text{true}}(x,y) \), to the true brightness distribution.

In radio-like phase referencing image reconstruction, the data are gridded, interpolated and inverse Fourier transformed to yield a model representation of the sky:

\[ I_{\text{dirty}}(x,y) = I^{\text{approx}}(x,y) \ast PSF_{\text{dirty}}(x,y) + N(x,y) \]

where \( I_{\text{dirty}}(x,y) \) is called the dirty map and \( PSF_{\text{dirty}}(x,y) \) is called the dirty beam.

The NRAO Astronomical Image Processing System (\textit{aips}), is a baseline-based reconstruction method used in radio interferometry. The UVFILES generated by \textit{aspro} were imported into \textit{aips}. We have tested the results using the \textsc{clean} algorithm (Högobom 1974), which corrects for the effect of poor Fourier plane sampling. \textsc{clean} grids, Fourier transforms and deconvolves the dirty beam from the dirty image in an iterative fashion given an initial guess for the beam and the brightness distribution. \textsc{clean} then finds peaks in the residual image and subtracts \( \delta \) functions of the appropriate strength at those positions. The final map is a convolution of all the \( \delta \) functions with a \textsc{clean} beam plus the residual map.

### 6. IMAGE ANALYSIS

In order to compare the reconstructed with the synthetic images, \textit{aspro} was used to generate the point spread functions (PSF) for the 6 AT \( \times \) 1 night, 4 AT \( \times \) 3 nights and 4 UT \( \times \) 1 night configurations (Table 1). The synthetic images were then convolved with a Gaussian of the measured PSF parameters (\textsc{iraf} program \textsc{gauss}).

| Configuration       | FWHM | \( \sigma \) | e  | r   | PA  |
|---------------------|------|-------------|----|-----|-----|
| 4 UT \( \times \) 1 night | 4.45 | 1.89        | 0.08 | 0.85 | -9.0 |
| 4 AT \( \times \) 3 nights  | 3.51 | 1.49        | 0.38 | 0.45 | -83.0 |
| 6 AT \( \times \) 1 night  | 5.17 | 2.20        | 0.42 | 0.41 | -85.0 |

Relative astrometry information was obtained for the images using \textit{ds9}. Photometry of the image components was performed using \textsc{iraf} procedure \textsc{phot}. \textsc{SNR} is the ratio of the mean pixel value to the standard deviation measured on the reconstructed images.

### 7. PHASE REFERENCING IMAGE RECONSTRUCTION

|          | Image 4 UT | AIPS 4 UT |
|----------|------------|-----------|
| flux sublimination | 84.9%      | 97.0%     |
| flux torus      | 15.1%      | 3.0%      |
| ratio           | 5.6        | 32.3      |
| sublimation diameter | 50         | 45        |
| torus diameter  | 260        | -         |
| SNR             | -          | 89        |
Figure 4. A simulated AGN with jet component and torus, 0.1 mas/pixel sampling; convolved image, 4 UT × 1 night configuration, 0.5 mas/pixel sampling, 4.45 mas FWHM resolution; AIPS reconstruction 4 UT × 1 night configuration, 0.1 mas/pixel sampling.

Figure 5. A low mass evolved star system with an outflow, 0.1 mas/pixel sampling; convolved image, 4 AT × 3 nights configuration, 0.5 mas/pixel sampling, 3.51 mas FWHM resolution; AIPS reconstruction 4 AT × 3 nights configuration, 0.1 mas/pixel sampling; convolved image, 6 AT × 1 night configuration, 0.5 mas/pixel sampling, 5.17 mas FWHM resolution; AIPS reconstruction 6 AT × 1 night configuration, 0.1 mas/pixel sampling.

Table 3. Evolved Star. Diameter units are pixels.

|                  | Image 4 AT 3 | AIPS 4 AT 3 | Image 6 AT | AIPS 6 AT |
|------------------|--------------|-------------|------------|-----------|
| flux star        | 21.9%        | 29.4%       | 21.9%      | 28.7%     |
| flux wind        | 78.1%        | 70.6%       | 78.1%      | 71.3%     |
| ratio star/wind  | 0.3          | 0.4         | 0.3        | 0.4       |
| inner wind diameter | 50 × 35     | 50 × 35     | 50 × 35    | 50 × 35   |
| outer wind diameter | 100 × 85    | 100 × 85    | 100 × 85   | 100 × 85  |
| SNR              | -            | 46          | -          | 23        |

8. DISCUSSION

If we compare the reconstructed images with the convolved images, we see that the phase referencing image reconstruction has yielded good results. Most of the flux is recovered in the individual image elements and the
Figure 6. A simulated stellar surface of a M giant, 0.1 mas/pixel sampling; convolved image, 4 AT × 3 nights configuration, 0.5 mas/pixel sampling, 3.51 mas FWHM resolution; AIPS reconstruction 4 AT × 3 nights configuration, 0.1 mas/pixel sampling, SNR = 34; convolved image, 6 AT × 1 night configuration, 0.5 mas/pixel sampling, 5.17 mas FWHM resolution; AIPS reconstruction 6 AT × 1 night configuration, 0.1 mas/pixel sampling, SNR = 24.

Figure 7. A simulated stellar surface of a supergiant, 0.1 mas/pixel sampling; convolved image, 6 AT × 1 night configuration, 0.5 mas/pixel sampling, 5.17 mas FWHM resolution; AIPS reconstruction 6 AT × 1 night configuration, 0.1 mas/pixel sampling, SNR = 216.

Table 4. Microlensing. Distance units are pixels.

| Image 4 UT | AIPS 4 UT |
|------------|------------|
| A flux     | 12.8%      | 12.9%      |
| B flux     | 19.2%      | 19.6%      |
| C flux     | 68.0%      | 67.5%      |
| ratio C/A  | 5.3        | 5.2        |
| ratio C/B  | 3.5        | 3.4        |
| distance AC| 45         | 45         |
| distance BC| 70         | 70         |
| distance AB| 50         | 50         |
| SNR        | -          | 99         |
Figure 8. A simulated microlensing event, 0.1 mas/pixel sampling; convolved image, 4 UT × 1 night configuration, 0.5/pixel sampling, 4.45 mas FWHM resolution; AIPS reconstruction 4 UT × 1 nights configuration, 0.1 mas/pixel sampling.

Figure 9. A simulated image of the pinwheel nebula at 0 degree inclination, 1.0 mas/pixel sampling; convolved image, 1.0 mas/pixel sampling, 5.17 FWHM, 6 AT × 1 night configuration; AIPS reconstruction 6 AT × 1 night configuration, 0.1 mas/pixel sampling. A simulated image of the pinwheel nebula at 60 degree inclination, 1.0 mas/pixel sampling, 5.17 FWHM, 6 AT × 1 night configuration; AIPS reconstruction 6 AT × 1 night configuration, smoothness regularization, 0.1 mas/pixel sampling.

| Table 5. Pinwheel Angle Image 6 AT | AIPS 6 AT | SNR |
|-----------------------------------|----------|-----|
| inner spiral 0 deg                | 24 × 30  | 24 × 24 | 281 |
| inner spiral 60 deg               | 24 × 24  | 24 × 22 | 404 |

Astrometry is excellent. A clear example of this is the reconstructed stellar surface images. Most of the flux is recovered in a compact region and careful inspection of the reconstructed images shows correspondence with individual brightness regions in the convolved image. The edges of the stellar surface are also well reproduced.

For an array of $N$ telescopes, the total number of measurements per observing night per integration point (moduli plus phase over each baseline) in phase referencing is $N \times (N - 1)$ compared to $\frac{(N-1)}{2} \times (\frac{3}{2}N - 2)$ closure phases plus squared visibilities in conventional phase closure techniques. As an example, when $N = 4$, there are...
Figure 10. A simulated stellar surface of the structure of inner disks surrounding YSOs, 0.1 mas/pixel sampling; convolved image, 4 UT × 1 night configuration, 0.5 mas/pixel sampling, 4.45 mas FWHM resolution; aips reconstruction 4 UT × 1 night configuration, 0.1 mas/pixel sampling; convolved image, 4 AT × 3 nights configuration, 0.5 mas/pixel sampling, 3.51 mas FWHM resolution; aips reconstruction 4 AT × 3 nights configuration, 0.1 mas/pixel sampling; convolved image, 6 AT × 1 night configuration, 0.5 mas/pixel sampling, 5.17 mas FWHM resolution; aips reconstruction 6 AT × 1 night configuration, 0.1 mas/pixel sampling.

Table 6. YSO. Diameter units are pixels.

|                  | Image 4 UT | AIPS 4 UT | Image 4 AT | AIPS 4 AT | Image 6 AT | AIPS 6 AT |
|------------------|------------|-----------|------------|-----------|------------|-----------|
| flux star        | 15.7%      | -         | 18.1%      | -         | 18.1%      | 16.7%     |
| flux disk        | 84.3%      | -         | 81.9%      | -         | 81.9%      | 83.3%     |
| ratio            | 0.2        | -         | 0.2        | -         | 0.2        | 0.2       |
| outer diameter   | 60 × 40    | 60 × 40   | 70 × 60    | 70 × 60   | 80 × 70    | 80 × 70   |
| SNR              | -          | 1         | -          | 184       | -          | 530       |

6 measured parameters for phase closure observations and 12 for phase referencing. Therefore, phase referenced reconstructed images should theoretically be more rigorous.
9. OBSERVABLE OBJECTS

In order to perform real time phase referencing observations, it is necessary to have a phase reference source no more than 30" away from the target source. For larger distances, the atmospheric pistons become distinct and the calibration incorrect.

Among the science cases presented, the most crucial in terms of number of phase reference candidates are the AGN, due to their large distances and therefore their K band faintness. We have attempted to quantify the number of AGN for which phase reference imaging is possible by using the Véron-Cetty & Véron (2006) catalog which contains AGNs, QSOs and BL Lac objects. Firstly, we constrained the science targets to those visible to the VLTI: targets were chosen to be between +20 and −90 degree declination. We then searched the 2MASS point source catalog for a nearby (less than 30" from the science target) bright star suitable for both AO wavefront sensing and fringe tracking (i.e., star magnitudes $K < 10$, $R < 16$). Science targets are listed in Table 7.

We have also investigated the number of phase reference targets available from a series of stellar catalogs. No trimming of objects for observability (southern hemisphere or target magnitude) was done. The following catalogs were searched: the de Winter et al. (2001) catalog of southern emission line objects mainly containing Herbig Ae/Be stars and some B[e], LBV and TTauri stars; the Egret (1980) catalog of supergiants; the Fracassini et al. (1994) catalog of stellar radii trimmed to objects with diameters of at least 10 mas; the Ramos-Larios & Phillips (2005) catalog of planetary nebulae; the Herbig & Bell (1995) catalog of pre-main-sequence stars; the Muench et al. (2002) catalog of pre-main-sequence stars in the Orion Trapezium cluster. We have searched for appropriate phase reference 2MASS point sources with K band magnitudes between 9 and 11 less then 30" away from the targets. The results are presented in Table 8 and highlight the potential of phase reference imaging.

10. CONCLUSIONS

Theoretically it is found that phase reference image reconstruction should yield more rigorous images than the classical phase closure method used in optical interferometry, not only because longer integrations times are allowed, but also because the former method measures information related to the visibility phase.

We wished to explore the potential of phase referencing in optical interferometry. We have generated simulated, noise visibility amplitudes and phases using the VLTI as a template and reconstructed images with the classic radio interferometry algorithm clean contained in the AIPS package. Our results show that with this method we will be able to reconstruct images of diverse sources with a spatial resolution of about 4 milliarcseconds in K band.

We have also compiled a list of target sources for which optical phase referencing is possible and found several hundred candidates.

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Table 7. Science target list of all southern (declination +20° to -90°) AGNs in the Véron-Cetty & Véron catalog (2006) with a bright star ($K < 10$ and $R < 16$) in their isoplanatic patch (i.e., star separation $< 30$ arcsec). These nearby stars are suitable for both AO wavefront sensing and fringe tracking. The $K_{\text{core}}$ magnitudes are the $K$ magnitudes from the 2mass catalog, the $K_{\text{star}}$ and $R_{\text{star}}$ magnitudes are the magnitudes of the nearby stars.

| Name | type | RA | DEC | $K_{\text{core}}$ | $K_{\text{star}}$ | $R_{\text{star}}$ |
|------|-----|----|-----|-----------------|-----------------|-----------------|
| J004336.9+001456 | Sy1 | 00 43 36.0 | +00 14 56 | 14.6 | 9.4 | 10.7 |
| LEDA101303 | LIN | 01 38 52.9 | -10 27 11 | 13.6 | 8.5 | 10.7 |
| NGC 676 | Sy2 | 01 48 57.3 | +05 54 24 | 11.1 | 8.6 | 10.1 |
| J024613.8+105656 | QSO | 02 46 13.8 | +10 56 56 | 13.7 | 9.0 | 10.9 |
| NGC1204 | Sy2 | 03 04 40.0 | -12 20 29 | 11.4 | 9.1 | 10.0 |
| HE 0324-3652 | QSO | 03 26 01.0 | -36 41 49 | 13.9 | 9.7 | 12.8 |
| LEDA13424 | LIN | 03 38 40.5 | +09 58 12 | 12.4 | 8.1 | 12.6 |
| ESO548-81 | Sy1 | 03 42 03.6 | -21 14 37 | 10.5 | 6.0 | 8.4 |
| LEDA 2824014 | QSO | 04 37 36.6 | -29 54 02 | 14.3 | 7.0 | 8.0 |
| LEDA2824155 | Sy1 | 04 56 08.9 | -21 59 09 | 13.4 | 9.6 | 11.0 |
| 4U0517+17 | LIN | 05 10 45.5 | +16 29 57 | 11.6 | 6.2 | 9.2 |
| J052223.1+072513 | Sy1 | 05 22 23.1 | -07 25 13 | 13.0 | 9.5 | 10.5 |
| J062233.8+231743 | Sy1 | 06 22 33.4 | -23 17 42 | 13.0 | 9.4 | 11.3 |
| J063635.8-622032 | LIN | 06 36 35.8 | -62 20 32 | 12.2 | 8.4 | 10.0 |
| J083750.7+091218 | Sy1 | 08 37 50.7 | +09 12 18 | 14.9 | 8.8 | 10.5 |
| 2E2060 | Sy1 | 08 52 15.1 | +07 53 37 | 12.6 | 9.2 | 10.8 |
| J091034.3+031328 | AGN | 09 10 34.3 | +03 13 28 | 14.0 | 9.7 | 11.3 |
| J091430.4+104906 | Sy1 | 09 14 30.4 | +10 49 06 | 14.7 | 9.3 | 10.5 |
| J095916.7-073517 | Sy1 | 09 59 16.7 | -07 35 17 | 13.1 | 9.2 | 11.1 |
| LEDA31718 | Sy1 | 10 39 46.3 | -05 28 59 | 12.8 | 9.2 | 11.3 |
| MGC 24800 | AGN | 11 48 16.0 | -00 03 29 | 14.0 | 9.7 | 11.3 |
| J120001.9+023418 | Sy2 | 12 00 01.9 | +02 34 18 | 14.1 | 9.5 | 11.2 |
| J120848.9+101343 | AGN | 12 08 48.9 | +10 13 43 | 14.3 | 9.8 | 11.0 |
| J121855.8+020002 | QSO | 12 18 55.8 | +02 00 02 | 14.8 | 9.6 | 11.1 |
| J130335.3-004912 | Sy1 | 13 03 35.3 | -00 49 12 | 14.7 | 9.2 | 11.5 |
| HE 1304-0541 | QSO | 13 06 47.6 | -05 57 35 | 14.7 | 8.1 | 10.2 |
| J130838.2-825934 | QSO | 13 08 38.2 | -82 59 34 | 14.6 | 8.7 | 11.4 |
| J132301.0+043951 | BLL | 13 23 01.0 | +04 39 51 | 14.4 | 9.7 | 10.9 |
| LEDA 170317 | Sy2 | 13 58 59.7 | -20 02 43 | 12.3 | 8.2 | 8.0 |
| J152929.3+033137 | Sy2 | 15 29 29.3 | +03 31 37 | 14.7 | 9.1 | 11.2 |
| MCG+03-40-009 | Sy2 | 15 35 52.6 | +14 31 04 | 12.9 | 9.6 | 12.5 |
| J154025.1+030640 | Sy2 | 15 40 25.1 | +03 06 40 | 15.0 | 9.4 | 11.3 |
| ESO 137-34 | Sy2 | 16 35 14.2 | -58 04 41 | 11.4 | 7.3 | 9.2 |
| LEDA 2829294 | QSO | 17 33 02.6 | -13 04 50 | 14.2 | 7.4 | 14.8 |
| J173728.3-290802 | Sy1 | 17 37 28.3 | -29 08 02 | 11.1 | 8.7 | 11.0 |
| IGR J18027-1455 | Sy1 | 18 02 47.3 | -14 54 54 | 10.9 | 8.6 | 15.2 |
| LEDA 86291 | Sy1 | 18 51 59.5 | +11 52 33 | 11.0 | 9.9 | 14.2 |
| J193109.5+093713 | BLL | 19 31 09.8 | +09 37 04 | 14.4 | 8.9 | 13.5 |
| LEDA 65714 | Sy1 | 20 55 22.3 | +02 21 17 | 12.5 | 9.6 | 12.7 |
| 1H 2107-097 | Sy1 | 21 09 09.9 | -09 40 15 | 10.9 | 8.8 | 12.1 |
| J211837.3-010537 | AGN | 21 18 37.3 | -01 05 37 | 8.14 | 8.1 | 12.3 |
| J220555.0-000755 | Sy2 | 22 05 55.0 | -00 07 55 | 14.8 | 8.9 | 11.6 |
| J223013.4-292554 | QSO | 22 30 13.4 | -29 25 54 | 14.9 | 9.8 | 11.0 |
| MCG+01-57-007 | Sy1 | 22 32 30.8 | +08 12 27 | 11.8 | 9.3 | 10.7 |

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Table 8. Science target list with a bright star (0<K<11) in their isoplanetic patch (i.e., star separation < 30 arcsec). These nearby stars are suitable for fringe tracking.

| Reference                | Science Targets                          | Total Number of Targets in the Catalog | Total Number of Targets with Phase Ref. Sources |
|--------------------------|------------------------------------------|---------------------------------------|-----------------------------------------------|
| de Winter et al.          | Herbig Ae/Be, LBV & T Tauri              | 162                                   | 62                                            |
| Egret                    | supergiants                              | 5073                                  | 1253                                          |
| Fracassini et al.         | stars with d<10 mas                       | 143                                   | 8                                             |
| Ramos-Larios & Phillips   | planetary nebulae                        | 325                                   | 68                                            |
| Herbig & Bell             | pre-main sequence stars                  | 763                                   | 217                                           |
| Muench et al.             | pre-main sequence stars                  | 1 010                                 | 875                                           |
| Véron-Cetty & Véron       | AGN, BL Lacs & QSOs                      | 108 080                               | 133                                           |

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