A catalog of reference stars for long baseline stellar interferometry*

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ABSTRACT

The calibration process of long baseline stellar interferometers requires the use of reference stars with accurately determined angular diameters. We present a catalog of 374 carefully chosen stars among the all-sky network of infrared sources provided by Ref. 1. The catalog benefits from a very good sky coverage and a median formal error on the angular diameters of only 1.2%. Besides, its groups together in a homogeneous handy set stellar coordinates, uniform and limb-darkened angular diameters, photometric measurements, and other parameters relevant to optical interferometry. In this paper, we describe the selection criteria applied to qualify stars as reference sources. Then, we discuss the catalog's statistical properties such as the sky coverage or the distributions of magnitudes and angular diameters. We study the number of available reference stars as a function of the baseline and the precision needed on the visibility measurements. Finally, we compare the angular diameters predicted in Ref. 1 with existing determinations in the literature, and find a very good agreement.

Keywords: catalogs, stars: fundamental parameters, instrumentation: interferometers, techniques: interferometric

1. INTRODUCTION

Astronomical optical interferometers need to be calibrated not only against long term drifts but also against short term effects due to the atmospheric turbulence. The usually adopted solution consists in interleaving observations of scientific targets and reference sources. A reference source is an astronomical source for which the theoretical fringe contrast, or visibility, can be predicted with a high accuracy. The visibility of the scientific target can then be deduced from the equation

$$V_{\mathrm{target}} = \frac{\mu_{\mathrm{target}}}{\mu_{\mathrm{ref}}} V_{\mathrm{ref}}, \tag{1}$$

where μ denotes a measured fringe contrast and V a visibility. The reference sources that have the most simple model are non-resolved or almost non-resolved single stars with compact atmospheres, and will be called reference stars or calibrators in the following. They can be correctly described by a uniform disk (UD) model whose visibility is

$$V_{\mathrm{UD}} = \frac{2J_1(x)}{x} \quad \text{with} \quad x = \pi\sigma_{\mathrm{eff}} B\,\theta_{\mathrm{UD}}, \tag{2}$$

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where σ_{eff} is the effective wavenumber (see Sect. 3.4), B the interferometric baseline projected on the sky, and θ_{UD} the stellar angular diameter. As many instrumental effects depend on the direction aimed at the sky, it is preferable that the reference star be close to the target. Hence arises the need for a grid of such stars with a good sky coverage. In this paper, we describe the catalog of reference stars that was made up for that purpose by the FLUOR[2] team (more details will be available in a forthcoming paper[3]).

In Sect. 2, we explain the selection process of our reference stars. Section 3 describes the catalog's content and Sect. 4 its statistical properties. Finally, we compare the angular diameters of our reference stars to other existing determinations in Sect. 5.

2. SELECTION OF REFERENCE STARS

As explained in the introduction, reference stars have to be non-variable single stars with compact atmospheres and accurately known angular diameters. In order to build there all-sky network of absolutely calibrated stellar spectra, Martin Cohen and collaborators[1] have used criteria that match quite well are requirements. Moreover, they have derived angular diameters with formal errors by fitting Kurucz's atmosphere models to stellar spectra of some prototype stars. By making the fundamental assumption that every K0–M0 giant has a spectrum identical to its prototype, they have extended their collection of spectra to 422 well chosen stars by rescaling them in flux thanks to photometric measurements. Angular diameters are then derived using the scaling factor. In the following, this method will referred to as the spectro-photometric method (SPM).

We have taken advantage of this existing network by extracting a subset of reference stars suitable for the calibration of stellar interferometers. Our extra requirements are essentially the absence of significantly variable (> 0.01 mag) and close binary stars that would both necessitate a model more elaborate than Eq. (2). The initial network is then cross-checked with the Simbad database[†], the Batten catalog of spectroscopic binaries,[4] and the catalog of visual double stars observed by Hipparcos.[5] We choose to discard all double stars with separations less than $4''$, and to avoid pointing confusion, we keep double stars with separations between $4''$ and $30''$ only when the companion is five magnitudes fainter than the primary. Companions' magnitudes and separations are notified in the comments. As a result of this more stringent selection, our catalog is left wih 374 entries.

3. CATALOG'S CONTENT

Table 1. Summary of the catalog's content.

Star identification	HD and HR numbers, Bayer/Flamsteed name
Coordinates	Right ascension, declination, proper motions, parallax
Physical properties	Spectral type, effective temperature, surface gravity, linear limb-darkening coefficients in the J, H, and K bands
Angular diameters	LD diameters, UD diameters in the J, H, and K bands
Cross-properties	Effective wavenumber and shape factor in the K' band
Photometry	B, V, J, H, K, L, M, and N Johnson's magnitudes
Comments	Simbad classification, companions' magnitudes and separations if any

3.1. Star identification

The catalog is meant to group together all useful information in the context of long baseline stellar interferometry (LBSI). The Henry Draper (HD) number has been chosen as the main identifier in the catalog (the Bright Star

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[†] http://simbad.u-strasbg.fr/Simbad

Catalog number, denoted HR, is also provided for convenience). As the knowledge of these stars is likely to be improved in the future, it is very important to keep track of the calibrator(s) used for a given scientific observation, so that any data could be reduced again if necessary. Additionally, it makes easier the search for observations that used the same calibrator(s) and that are thus correlated.[6] Identifiers (HD, HR, and Bayer or Flamsteed name) are followed by the stellar coordinates, some physical properties, angular diameters in different bands, some cross-properties of the star and FLUOR, the photometry, and some comments (Table 1).

3.2. Angular diameters

Limb-darkened angular diameters have been computed in Ref. 1 for every star. This diameter corresponds to the physical diameter of the star, *i.e.* the one that appears in the Stefan-Boltzmann law

$$F_{\text{bol}} = \frac{1}{4}\,\theta_{\text{LD}}^2\,\sigma_{\text{S}}\,T_{\text{eff}}^4, \tag{3}$$

where F_{bol} is the bolometric flux (W/m^2) emitted by the star and σ_{S} denotes Stefan-Boltzmann constant. As such, θ_{LD} is independent of the observational wavelength. This diameter can be converted into the UD angular diameter of Eq. (2), usually used by interferometrists. However, the latter depends on the wavelength, so a spectral band has to be specified. The following formula[7] provides an efficient way to perform the conversion using linear limb-darkening coefficients u_λ:

$$\frac{\theta_{\text{LD}}}{\theta_{\text{UD}}} = \sqrt{\frac{1 - u_\lambda/3}{1 - 7u_\lambda/15}}. \tag{4}$$

For every star, we interpolate u_λ into the tables computed in Ref. 8 using the effective temperature T_{eff} and the surface gravity $\log(g)$ derived from the spectral type.[9, 10] Then, Eq. 4 yields UD angular diameters in the J, H, and K bands. As the conversion process introduces an additional although very small error, the catalog states the new uncertainty for every UD diameter.

3.3. Photometry

For every star, the catalog features the B and V magnitudes drawn from the Simbad database, and the J to N infrared magnitudes taken from Ref. 1, or estimated from the spectral type using the tables in Refs. 11 and 12. A boolean flag indicates whether the quoted value is a measurement or not.

3.4. Effective wavenumber and shape factor

The effective wavenumber and the shape factor are cross-properties of the star's spectrum and of the instrument. In the case of FLUOR, observations are carried out in the K' band (2.0–2.3 µm) and these quantities have been computed in this band only. The effective wavenumber is the wavenumber at which the monochromatic visibility defined by Eq. (2) is equal to the measured wide-band visibility. If $\mathcal{S}$ denotes the star's spectrum multiplied by the filter's transmission profile, the effective wavenumber is

$$\sigma_{\text{eff}} \equiv \frac{\int_0^\infty \sigma\,\mathcal{S}^2(\sigma)\text{d}\sigma}{\int_0^\infty \mathcal{S}^2(\sigma)\,\text{d}\sigma}. \tag{5}$$

As explained in Ref. 13, the wide-band fringe contrast measured by FLUOR is weighted by the squared stellar spectrum:

$$\overline{\mu^2} = \frac{1}{SF}\int_0^\infty \mu^2(\sigma)\mathcal{S}^2(\sigma)\,\text{d}\sigma \quad \text{with} \quad SF \equiv \int_0^\infty \mathcal{S}^2(\sigma)\,\text{d}\sigma. \tag{6}$$

The shape factor *SF* allows for a correct calibration when the spectral types of the target and its reference stars are different. Effective wavenumbers and shape factors should be mostly considered as relative information between stars of different spectral types. Their typical values are respectively 4685 cm^{-1} and 13.19 µm, and vary very little from one spectral type to another.

3.5. Comments

This field is used to provide additional information about the source: the object type[14] as it is given by Simbad, the separations and the magnitudes of the companions when the source is a double or a multiple star.

4. CATALOG'S STATISTICAL PROPERTIES

4.1. Global statistics

A major feature of our catalog is its excellent sky coverage (Fig. 1): whatever the point on the sky, its distance to the closest reference star is less than 16.4° and the median distance is 5.2°. Most stars (91%) are class III giants with a spectral type K (82%) or M0 (18%). Also most stars (72%) have a visual magnitude between 4 and 6, and almost all of them (95%) between 3 and 7, with a median value of 5.0. As for K magnitude, most stars (95%) lie in the interval K=0–3 with a median value of 1.8. Limb-darkened angular diameters range from 1 to 10 mas (Fig. 2a) with a median value of 2.3 mas. The median error on the diameter is only 1.2% (Fig. 2b), which brings a significant gain (Fig. 2c) compared to the classical 5–10% (*e.g.* Ref. 15) encountered when little is known about the calibrator.

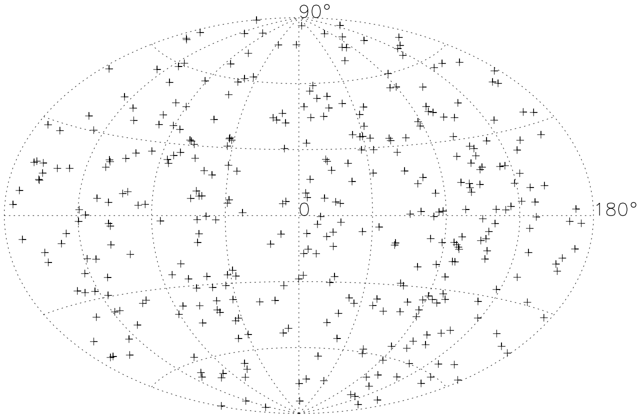

Figure 1. Catalog's sky coverage in the Hammer-Aitoff equal-area projection.

4.2. Catalog's effective size

In the framework of a UD model, the relative error on the visibility reads

$$\frac{\Delta V_{\mathrm{UD}}}{V_{\mathrm{UD}}} = x\frac{J_2(x)}{J_1(x)}\frac{\Delta\theta_{\mathrm{UD}}}{\theta_{\mathrm{UD}}} \quad \text{with} \quad x = \pi\sigma_{\mathrm{eff}} B\,\theta_{\mathrm{UD}}, \tag{7}$$

assuming negligeable errors on the effective wavenumber and on the interferometric baseline. Figure 2c represents the visibility and the error on the visibility as a function of the reduced variable x. Equation (7) implies that the catalog's reference stars have not all diameter estimates accurate enough to allow a given precision on the visibility, whatever the wavenumber and the baseline. For example, the number of stars whose error on the angular diameter is small enough to be used for a given accuracy on the visibility in the K band and at a given baseline is given in Table 2, as well as displayed on Fig. 2d.

5. COMPARISON WITH OTHER DIAMETER DETERMINATIONS

We have searched the literature by the way of CHARM[‡] catalog[16] for other angular diameter determinations of the stars in our catalog. Angular diameters can either be estimated by photometric means or directly measured by LBSI or during a lunar occultation. In the following sections, we will examine two photometric methods and direct measurements performed by two interferometers.

[‡] Catalog of High Angular Resolution Measurements

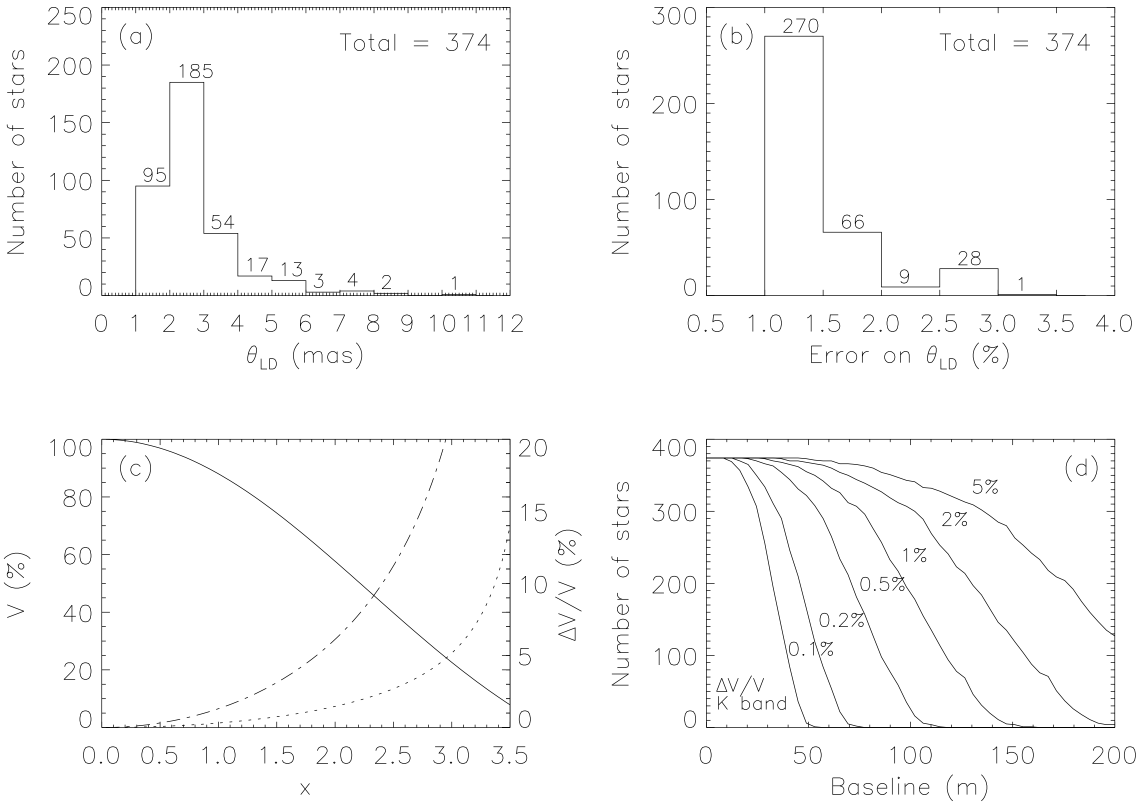

Figure 2. (a) Histograms of limb-darkened (LD) diameters and (b) their associate errors. (c) Visibility of a uniform disk (UD) and relative error on the visibility due to an error on the UD diameter of respectively 1.2% (dotted line) and 5% (dash-dotted line). (d) Catalog's effective size in the K band: number of stars whose formal errors on the UD diameter in the K band make them suitable reference stars at the labeled relative precision on the visibility.

Table 2. Catalog's effective size in the K band: number of stars whose error on the angular diameter is small enough to be used for a given accuracy on the visibility.

	$\Delta V/V$			
Baseline	$\leq 0.5\%$	$\leq 1\%$	$\leq 2\%$	$\leq 5\%$
50 m	316	354	366	372
100 m	24	186	305	341
150 m	0	4	126	266
200 m	0	0	4	127

5.1. Photometric methods

The angular LD diameters of 29 stars belonging to our catalog have been computed with the infrared flux method (IRFM) and are reported either in Ref. 17 or 18. As can be seen on Fig. 3a, the agreement with the spectro-photometric method[1] (SPM) is excellent: a linear least-square fit to the data yields $\theta_{\rm IRFM} = (0.99 \pm 0.02) \times \theta_{\rm SPM} + (0.02 \pm 0.07)$.

The surface-brightness method[19] (SBM) provides another way to derive the angular diameter:

$$\frac{\theta_{\rm SBM}\,({\rm mas})}{9.306 \times 10^{-0.2\,(V-A_V)}} = 10^{0.2\,S_V} \quad \text{with} \quad S_V = 2.536 + 1.493\,(V-K)_0 - 0.046(V-K)_0^2, \tag{8}$$

where S_V is the surface brightness in the V band. We have plotted on Fig. 3b the right-hand side of Eq. 8 vs. V−K. The superimposed values for our reference stars (crosses) match the curve nicely.

These two results demonstrate that the spectro-photometric method is completely consistent with other indirect methods.

5.2. Interferometric measurements

The NPOI and Mark III interferometers have measured the angular diameters of 21 stars belonging to our catalog.[20] We compare here the LD diameters deduced from the UD diameters measured in the visible, using a procedure very similar to the conversion process described in Sect. 3.2. Again, the agreement is very good (Fig. 3a): a linear least-square fit to the data yields $\theta_{\rm LBSI} = (1.03 \pm 0.01) \times \theta_{\rm SPM} + (-0.15 \pm 0.03)$. The average precisions of the NPOI and Mark III data are respectively 1.9% and 1.6%. A chi-square analysis of the difference $\theta_{\rm SPM} - \theta_{\rm LBSI}$ shows a good compatibility of the error bars since χ^2 equals respectively 3.0 and 2.4.

6. CONCLUSION

We have presented a catalog of 374 carefully chosen reference stars for optical interferometry. Depending on the needed precision on the visibility, it is well suited for interferometers with baselines up to 200 m. Although this catalog has proven to be fully satisfactory since its first use by the FLUOR team in october 1999, most stars have not yet been observed by any interferometer and still need to be checked. More work lies ahead to extend this catalog to reference stars suitable for longer baselines, such as the baselines of CHARA[21] (330 m) and 'OHANA[22] (800 m), or to instruments with very high accuracies like AMBER.[23]

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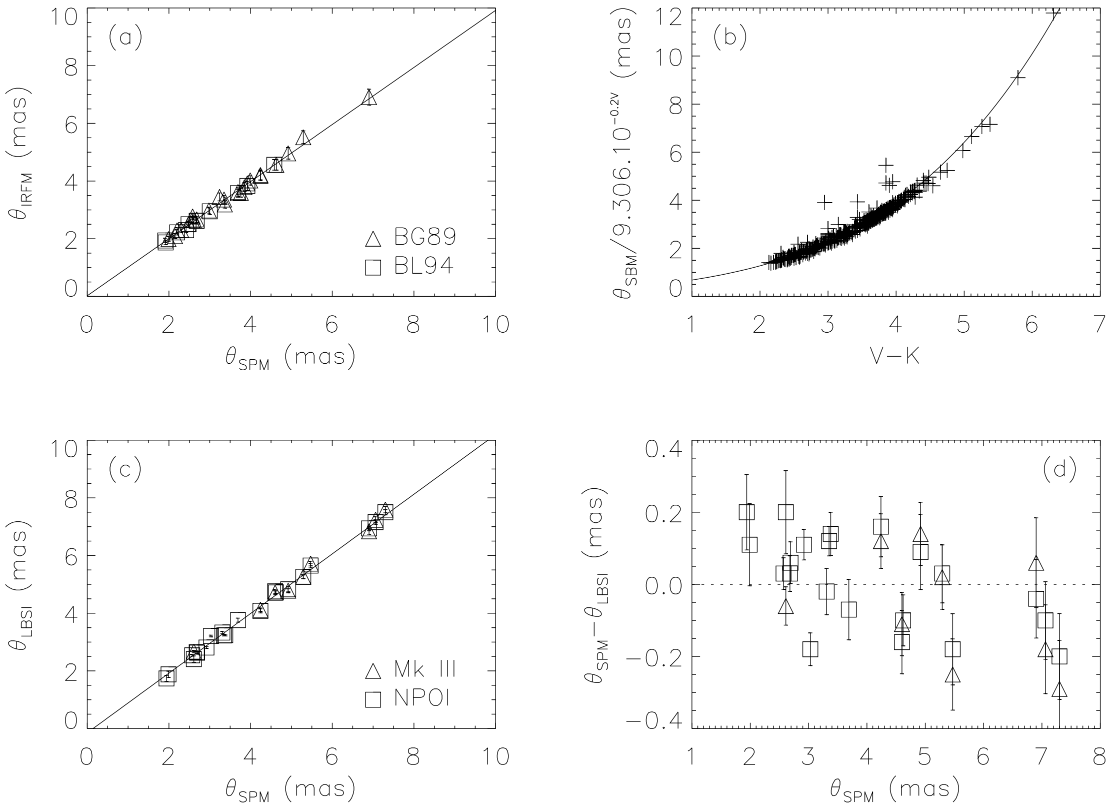

Figure 3. (a) LD angular diameters determined by the infrared flux method (IRFM) vs. those determined by the spectro-photometric method (SPM). The solid line represents the least-square linear fit to the data. (b) Comparison between SPM angular diameters (crosses) and those (solid line) predicted by the surface brightness method (SBM) as a function of V−K. (c) LD angular diameters determined by long baseline stellar interferometry (LBSI) vs. those determined by the SPM. The solid line represents the least-square linear fit to the data. (d) Difference between SPM and LBSI diameters vs. SPM diameters.

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