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Parsec's astrometry direct approaches

A.H. Andrei[1,2,3,4]

[1] Observatório Nacional/MCTI, R. Gal. José Cristino 76, Rio de Janeiro, RJ, CEP20921-400, Brasil
[2] Osservatorio Astronomico di Torino/INAF, Strada Osservatorio 20, 10025, Pino Torinese (TO), Italy
[3] SYRTE/Observatoire de Paris, 61 Avenue de l'Observatoire, 75014, Paris, France
[4] Observatório do Valongo/UFRJ, Ladeira do Pedro Antônio 43, Rio de Janeiro, RJ, CEP 20080-090, Brasil e-mail: `oat1@ov.ufrj.br`

Abstract. Parallaxes - and hence the fundamental establishment of stellar distances - rank among the oldest, keyest, and hardest of astronomical determinations. Arguably amongst the most essential too. The direct approach to obtain trigonometric parallaxes, using a constrained set of equations to derive positions, proper motions, and parallaxes, has been labeled as risky. Properly so, because the axis of the parallactic apparent ellipse is smaller than one arcsec even for the nearest stars, and just a fraction of its perimeter can be followed. Thus the classical approach is of linearizing the description by locking the solution to a set of precise positions of the Earth at the instants of observation, rather than to the dynamics of its orbit, and of adopting a close examination of the never many points available. In the PARSEC program the parallaxes of 143 brown dwarfs were aimed at. Five years of observation of the fields were taken with the WIFI camera at the ESO 2.2m telescope, in Chile. The goal is to provide a statistically significant number of trigonometric parallaxes to BD sub-classes from L0 to T7. Taking advantage of the large, regularly spaced, quantity of observations, here we take the risky approach to fit an ellipse in ecliptical observed coordinates and derive the parallaxes. We also combine the solutions from different centroiding methods, widely proven in prior astrometric investigations. As each of those methods assess diverse properties of the PSFs, they are taken as independent measurements, and combined into a weighted least-square general solution.

Key words. Stars: brown dwarfs – Stars: Gaia – Astrometry: Parallaxes

1. Introduction

Brown dwarfs (BD) masses are insufficient to sustain the core hydrogen fusion reactions that balance radiative energy losses. Supported from further gravitational contraction by electron degeneracy pressure, evolved brown dwarfs continually cool and dim over time as they radiate away their initial contraction energy, ultimately achieving photospheric conditions that can be similar to those of giant planets (Burningham et al. 2013). Since they cool over time, their spectral properties are inherently time dependent. However, spectral type, as well as temperature and luminosity, besides age, also depend on mass (and weakly on metallicity). This degeneracy complicates characterizations of individual sources and mixed populations and requires absolute distances to calibrate the chain (**?**).

With trigonometric parallaxes the distances are determined independently of any model, and the photometric and spectroscopic parallaxes can be calibrated for the classes and sub-classes of brown dwarfs. The absolute luminosity becomes more accurate for a large number of objects, what leads to the derivation of the luminosity function. Determining the distance and the luminosity enables the spectral features be used to derive the surface gravity, and to relate radius to temperature. Additionally, with known distance an excess of luminosity indicates binaries. And combining also proper motion, then either large velocities and/or low luminosities point out to subdwarfs. Membership can be assigned and the 3D and evolution map of the Solar neighborhood is traced (Smith et al. 2014).

2. Program features

The PARSEC (Parallaxes of Southern Extremely Cool stars) was established to redress the lack of absolute distances in many of the BD sub-classes. It measured trigonometric parallaxes of 122 L and 28 T dwarfs brighter than z=20 in the southern hemisphere. This represented doubling the number of L dwarfs with trigonometric parallaxes. And, in conjunction with the existing results, it left no spectral sub-class up to L9 with less than 10 elements (Bucciarelli et al. 2011).

The PARSEC program started in 2007 and ended in early 2011 (currently complementary proper motion observations are on the run), entailing 4 to 6 observation epochs (2 to 3 nights) per year. All the observations were taken using the WFI camera of the 2.2m Telescope of ESO, in Chile. The poses were made in the z band as a compromise between optimal quantum efficiency in I band and target typical brightness (I-z≈2). Though the WFI has important distortions at *mas* level, stability and repeatability are the crucial requirements for relative astrometry and those were kept throughout the program, enforcing a move-to-pixel telescope facility to attain pose repeatability. For parallax determinations always only the top third of CCD#7 is used. It is a zone of minimal distortions, and the smaller size further minimizes the differential color refraction, which is already negligible in the z band. A full account of the program set up and procedures is in (Andrei et al. 2012).

The image treatment starts with standard IRAF routines for bias and flat, but fringing removal uses a tailored approach. It is build from the short images plus a few (usually four) science frames, aligned and combined by the mode to get rid of stellar ghosts.

Matching is central on a long term program, not only to keep tracking of the several measurements of a same object, but also to select the best objects to use at combining images. The probability of correct matching of one object in two frames is P=1/(ΦS), where Φ is the stellar density and S is the frame size. Usual cone search strategies run into trouble for long time intervals. We avoid such pitfalls by adopting the following strategy:

(1) the matching goes hand in hand with the fitting process;
(2) assigning high order in the matching process to objects with no proper motion between consecutive images, and low order to objects unpaired;
(3) using relative astrometry precise to better than 100mas, under those conditions P > 0.99 already when the third night is added even for $\Phi=1000/\mathrm{deg}^2$;
(4) removing the stars matched in the previous step Φ drops dramatically, and the process re-starts taking stars with smallest proper motions;
(5) finally the objects unpaired in the first step, and cases of suspicious magnitude or position matching are considered, now allowing for periodical jitter.

A catalog of proper motion was build for the 2MASS stars presented in the PARSEC program fields (Andrei et al. 2012). The proper motion catalogue samples 42.3° of the southern hemisphere with the exception of the lowest galactic latitudes where the number of known L/T dwarfs is significantly reduced. It covers the first 18 months of observations, reducing independently each of the

8 CCDs of the WFI mosaic using UCAC2 stars. Depending on the number of reference stars the polynomial degree was 2 or 3 and cross terms have been included. The matching criterion was of nearest neighbor to 2MASS point sources, with proper motions determined for each observation pair and later averaged while removing deviant values. The rms error is 5mas/year and the correlation to UCAC2 is higher than 0.95. The catalogue contains 195,700 entries. Combined with the z-observed and the 2MASS magnitudes, the catalog enabled to obtain reduced proper motions with which were selected new targets for spectroscopic follow up (Marocco et al. 2013).

3. Centroiding

The determination of parallaxes for the brown dwarfs targets is the center of the PARSEC program. To reach the precision of 5mas or better, that translates to a distance incertitude of 10% or less, factors of key importance are the covering of the parallax ellipse, the centroiding method, the astrometric solution (Andrei et al. 2013), and the solution algorithm (Bucciarelli et al. 2012).

The centroid algorithm was improved for the parallax determination, by using independent centroid determinations. They have been all used in several prior investigations, so there is abundant literature on them (Wang et al. 2014). Here we state the features of the centroid determination which distinguish one from another.

PHOT is the IRAF enhanced centroid task, with several embedded adjustments for the sky, image, and centroid determination. We use the GAUSS algorithm for two independent Gaussian and iterative mode, thus obtaining best adjustment for well exposed images.

PR3 is the GBOT (Gaia Groundbased optical Tracking) astrometry driven package. In it wings and skewness are taken into account through an initial determination of the centroid by marginal X,Y projections, and a baricenter is performed on a tight rectangular window. It is well suit for faint objects.

RWF from CASU (Cambridge Astronomy Survey Unit). It starts by two sequential steps of local background removal, and an initial clipping run to unweight pixels with discrepant counts. The final baricenter is applied on the 2D regular, linear fitting-apt components of the image, leading to quasi-Gaussian fwhm and ellipticity determinations. It is photometry driven aimed to both compact and extended objects.

RR5 from TOPP (Torino Observatory Parallax Program). Here it is used fitting a unweighted bi-dimensional Gaussian to the stellar profile, although assign zero weight to pixels which count approached the CCD nominal saturation limit. It is astrometry driven, dominated by a psf model on the field.

SE2 from SEXTRACTOR, the successful source extractor largely used on online applications. It has several features for sky subtraction and centroiding. We use the baricenter (as opposed to windowed parameters) performed over a Gaussian defined window. The summation is performed relatively to the spatial minima, skewness and large wings are assumed constant over the astrometry field or of minor importance. In this case the peak is particularly well determined.

The comparison between the centroiding methods made when of the preparation of the proper motion catalogue has shown negligible differences for well imaged stars, with averages ranging from 4.9mas to 7.5mas. However when all stars are include larger differences appear, the average error ranging from 7.1mas, for RWF, to 27.6mas, for RR5. Now taking a different, larger sample spread over the entire PARSEC's period, and including fields for 143 targets, the variety between the methods is reasserted. Table 1 shows the differences, that are detailed in the plots of figure 1.

The plots in figure 2 shed some light on the origin of the different results from the different centroid methods. The complete explanation being that the methods are independent from each other, exploiting diverse aspects of the photon count distribution, elaborated on different platforms leading to different numeric strategies, and developed at their onset aiming to particular objectives. Arguably the forefather of statistics, Rene Descartes asserted that the mean value should be taken when

Table 1. Observed-minus-calculated (O-C) averages. Notice that there is no loss for the astrometric solution by adopting the PPMXL. All values in mas.

Catalog	Centroid	$\|\|\Delta\alpha cos\delta\|\|$	$\epsilon(\alpha)$	$\|\|\Delta\delta\|\|$	$\epsilon(\delta)$	$\|\|\Delta\|\|$	$\epsilon(\Delta)$
UCAC4	PHOT	152.5	16.1	151.2	15.9	151.9	16.0
PPMXL	PR3	91.9	10.3	109.3	10.9	100.6	10.7
PPMXL	RWF	148.0	15.6	178.4	17.8	163.1	17.2
PPMXL	RR5	196.8	18.4	189.7	18.0	193.3	18.2
PPMXL	SE2	134.8	14.3	139.7	14.3	137.3	14.3

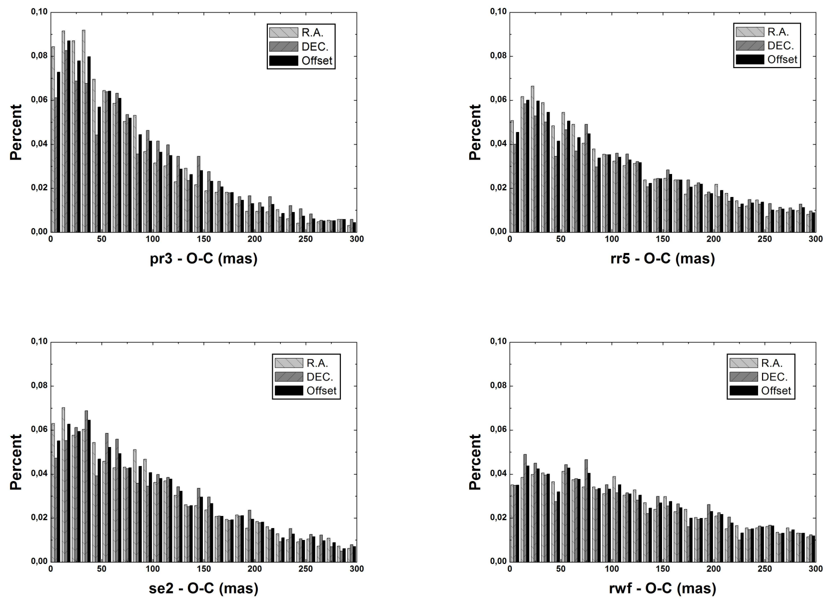

Fig. 1. Histogram of (O-C) for the centroidings used with the PPMXL catalog.

there are several measures of a same quantity. Though the meaning of mean was subsequently refined to encompass other possibilities for multi-modal distributions, the fundamental concept is so rooted in modern thought to become a truism. Much in opposition to choosing the most favoured value, or to dismiss measurements arbitrarily. As obvious as taking a few measurements of the one desired sofa before buying it, the scientific method ascribes measurements as independent, different, and statistically equivalent as possible to define the best value for a single quantity. Taking identical measurements of different quantities, hoping to be able to define the mean property of the mean quantity, is just a second choice, although many times used for practicality, econ-

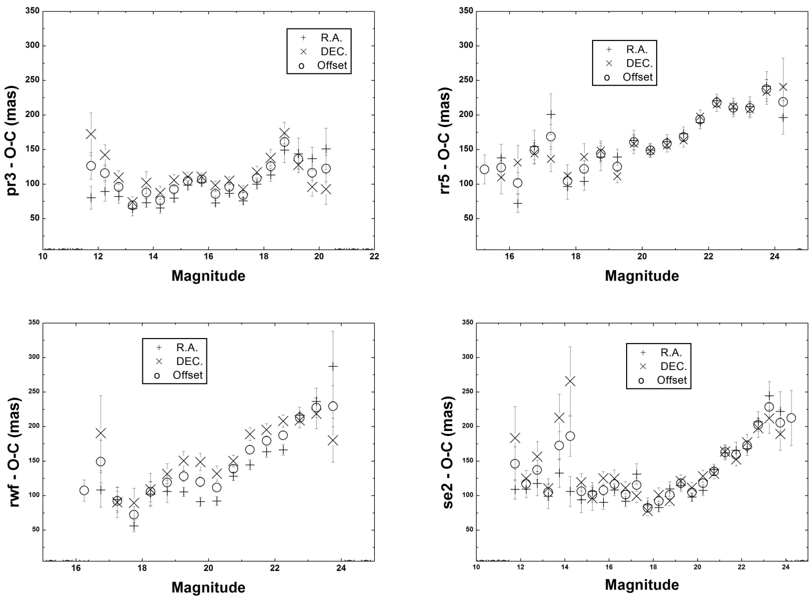

Fig. 2. Magnitude functional of the (O-C) for the different centroidings.

omy, and availability of independent measuring apparatus.

Since the available centroiding methods are described as independent by the authors, and are ascribed as equivalent in the literature, and are shown to give rise to different functionals over our universe of objects, we take the prime statistical assumption and use the average results from the several centroiding methods at hand.

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