

Improving distance estimates to nearby bright stars: Combining astrometric data from *Hipparcos*, *Nano-JASMINE* and *Gaia*

Daniel Michalik,¹ Lennart Lindegren,¹ David Hobbs,¹
Uwe Lammers,² and Yoshiyuki Yamada³

¹Lund Observatory, Lund University, Box 43, SE-22100 Lund, Sweden
e-mail: [daniel.michalik, lennart, david]@astro.lu.se

²European Space Agency (ESA/ESAC), P. O. Box 78, ES-28691 Villanueva de la Cañada,
Madrid, Spain
e-mail: uwe.lammers@sciops.esa.int

³Department of Physics, Kyoto University, Oiwake-cho Kita-Shirakaw Sakyo-ku, Kyoto,
606-8502 Japan
e-mail: yamada@amesh.org

Abstract. Starting in 2013, *Gaia* will deliver highly accurate astrometric data, which eventually will supersede most other stellar catalogues in accuracy and completeness. It is, however, limited to observations from magnitude 6 to 20 and will therefore not include the brightest stars. *Nano-JASMINE*, an ultrasmall Japanese astrometry satellite, will observe these bright stars, but with much lower accuracy. Hence, the *Hipparcos* catalogue from 1997 will likely remain the main source of accurate distances to bright nearby stars. We are investigating how this might be improved by optimally combining data from all three missions through a joint astrometric solution. This would take advantage of the unique features of each mission: the historic bright-star measurements of *Hipparcos*, the updated bright-star observations of *Nano-JASMINE*, and the very accurate reference frame of *Gaia*. The long temporal baseline between the missions provides additional benefits for the determination of proper motions and binary detection, which indirectly improve the parallax determination further. We present a quantitative analysis of the expected gains based on simulated data for all three missions.

Keywords. astrometry, catalogs, methods: data analysis, methods: statistical, reference systems

1. Introduction

The distance to a star can most directly be deduced from its trigonometric parallax. From the ground, this was only done for a few thousand very nearby stars, but with the advent of space astrometry this picture changed dramatically. *Hipparcos* (1989–1993) was the first satellite to determine astrometric parameters (stellar positions, parallaxes and proper motions) from space and yielded the distances to approximately 21,000 stars with an uncertainty of better than 10% (ESA 1997). Now, 25 years later, *Gaia* will further improve our knowledge of stellar astrometry significantly and provide millions of stellar parallaxes with unprecedented accuracy. *Gaia* is an ESA cornerstone mission which will be launched for its nominal five-year mission at the end of 2013. It will continuously scan the sky in a well-chosen pattern and observe up to a billion stars down to magnitude 20. However, because of CCD saturation it will not observe stars brighter than about magnitude 6. Hence the brightest ~ 5000 stars are not observed by *Gaia*, and for these *Hipparcos* will continue to be a main source of distance information.

In addition to these two astrometry missions, the third upcoming mission is the ultrasmall Japanese satellite *Nano-JASMINE*. Just like *Gaia*, this satellite is based on CCD

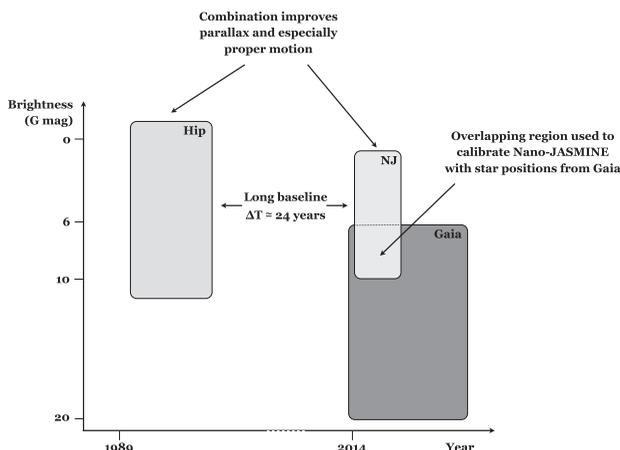


Figure 1. Magnitude range versus mission time for the three astrometry missions, *Hipparcos* ('Hip'), *Nano-JASMINE* ('NJ') and *Gaia*.

detections, and its scanning principle and observing strategy are derived from the *Gaia* pendants. This mission, however, is meant to be a technology demonstrator for larger follow-up missions and is therefore significantly smaller and less accurate. It is scheduled for launch by the end of 2013 and expected to provide astrometry for approximately one million stars in the visual magnitude range from ~ 1 to 10 with an accuracy of ~ 3 mas for objects of magnitude 7.5. *Gaia* data will be reduced using the Astrometric Global Iterative Solution (AGIS), developed by ESA and Lund Observatory (Lindgren *et al.* 2012). Thanks to a collaboration between the *Nano-JASMINE* Science Team and parts of the AGIS team, it is possible to use AGIS also for the core data reduction of *Nano-JASMINE*.

2. Catalogue combination by joint solution

While *Nano-JASMINE*'s uncertainties are not better than the uncertainties in the *Hipparcos* results, significant improvements for bright-star astrometry can be made by combining the results of *Hipparcos* and *Nano-JASMINE*, thanks to the long time baseline between the missions. The combination is done by incorporating the *Hipparcos* information directly in the astrometric solution for the *Nano-JASMINE* data. This is done using the *Hipparcos* data and the inverse of its covariances as starting values when accumulating the normal equations for the astrometric solution. In contrast to a *posteriori* catalogue combination, this 'joint solution' combines the data sets in a statistically optimal way (Michalik *et al.* 2012), taking into account the correlations between the different astrometric parameters.

In addition to the astrometric improvement facilitated by the combination described above, further improvement can be gained by incorporating (preliminary) results from *Gaia* during the *Nano-JASMINE* data processing: *Gaia* and *Nano-JASMINE* will both observe stars between magnitude 6 and 10. Since the astrometry of these stars is well-determined by *Gaia*, a joint solution can be used to determine the attitude and geometry deviations of *Nano-JASMINE* with better accuracy and therefore improve all *Nano-JASMINE* results. This includes calibrating the basic angle (the nominally fixed angle between the two fields of view of the satellite) which may be affected by thermal variations originating in the low-earth-orbit of the satellite. The basic angle stability is particularly critical to avoid zero-point errors thus allowing the determination of absolute parallaxes. Additionally, the *Nano-JASMINE* results are aligned with the *Gaia* reference frame.

Therefore, optimal results for bright stars are obtained by reducing the *Nano-JASMINE* data together with preliminary *Gaia* results and by combination of these with the historic *Hipparcos* measurements during data analysis (see Fig. 1). We quantify the expected improvements in parallax and proper-motion determination by simulating this scenario.

3. Simulations

Simulations are carried out using AGISLAB, a software package developed at Lund Observatory to aid the development of algorithms for *Gaia* data processing (Holl *et al.* 2012). It is used to simulate *Nano-JASMINE* observations and process these data in the same manner as done for the real mission, i.e., by employing the AGIS algorithms. AGIS is an iterative scheme that implements a block-wise least-squares solution on very large data sets, i.e., as required to reduce data from large astrometry missions such as *Gaia*. *Nano-JASMINE* simulations are based on a realistic scanning law featuring a triangular spin-axis precession motion (see Fig. 2). The observation accuracy model assumes a (somewhat optimistic) centroiding uncertainty of $1/300^{\text{th}}$ of a pixel (~ 7 mas) for stars brighter than magnitude 7, with additional photon noise for fainter stars (~ 30 mas at magnitude 10).

The simulation data set consists of two parts. The first is composed of the 5026 brightest *Hipparcos* stars ($\text{mag} < 6$), with astrometric parameters and uncertainties taken from the *Hipparcos* Catalogue. They are used to evaluate the improvement in the uncertainties of the astrometric parameters of the bright stars. To these, we add 330,000 randomly distributed stars of magnitude 10 that represent stars observed in the overlapping magnitude range which were not included in the *Hipparcos* Catalogue. They represent the stars that will be seen by *Gaia* as well as by *Nano-JASMINE*, and for which the well-determined *Gaia* positions help to better constrain the solution.

First, we simulate the errors in the *Hipparcos* Catalogue, providing a reference case for the bright stars and initial values for the solutions (Cases B and C below), which incorporate the *Hipparcos* data. This is followed by three simulations.

Case A: We simulate *Nano-JASMINE* observations with the two data sets mentioned above and process the data without additional information, i.e. *Nano-JASMINE* only.

Case B: In a second run, we incorporate the information from *Hipparcos* into the data processing of *Nano-JASMINE* using the method described in Michalik *et al.* (2012).

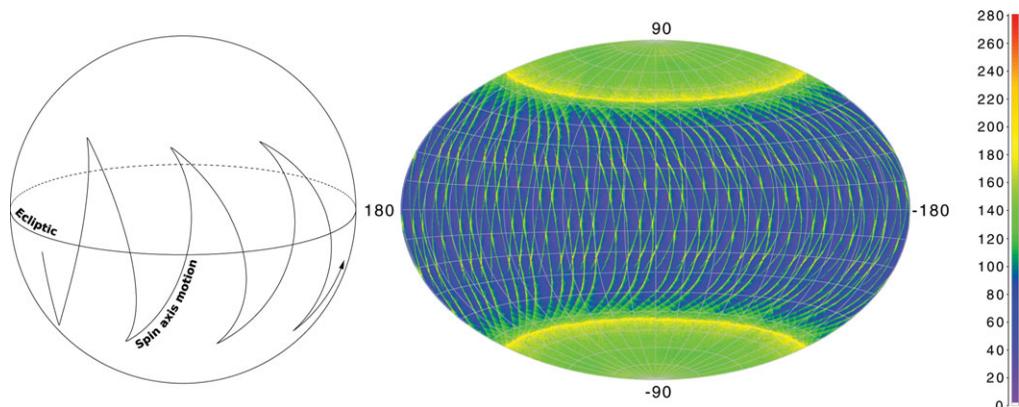


Figure 2. (left) 130 days of spin-axis motion. (right) Number of observations per star (ecliptical sky map), based on simulations of two years of the baseline *Nano-JASMINE* scanning law.

Table 1. Average uncertainties (RSE[†]) of 5026 *Hipparcos* stars between magnitude 1 and 6.

		Parallax (μas)	Proper motion ($\mu\text{as yr}^{-1}$)
Reference	<i>Hipparcos</i> only (<i>Hip</i>)	740	673
Case A	<i>Nano-JASMINE</i> only (<i>NJ</i>)	1282	1844
Case B	<i>Hip</i> + <i>NJ</i>	595	50
Case C	<i>Hip</i> + <i>NJ</i> + <i>Gaia</i>	588	43

Case C: In a third run, we simulate the astrometric parameters with *Gaia* accuracy and fold expected *Gaia* covariances (de Bruijne 2012) into the *Nano-JASMINE* data processing. This is done by setting up the covariances of these sources with a σ according to the expected *Gaia* uncertainties and using it in a joint solution scheme. Under the optimistic assumption of uncorrelated parameters, the covariance is set up with zeros in all off-diagonal positions.

4. Results

We compare the three cases and our current knowledge of the bright-star astrometric uncertainties with the results in Table 1. Our current knowledge is represented by the *Hipparcos* Catalogue. The results of the *Nano-JASMINE* observations alone are less precise, but combined with *Hipparcos* they lead to a significant improvement with respect to our current knowledge. Including provisional *Gaia* results yields a further improvement thanks to the improved calibration of the geometry and attitude of *Nano-JASMINE*. This improvement is fairly small, but it needs to be emphasized that there is a second and very important advantage of the *Nano-JASMINE* joint solution with *Gaia* results, i.e. alignment of the *Nano-JASMINE* results with the *Gaia* reference frame.

5. Conclusions

Nano-JASMINE offers an opportunity to significantly improve the *Hipparcos* parallaxes and proper motions of the brightest ~ 5000 stars which will not be observed by *Gaia*. In addition, a combined solution with *Gaia* data ensures that the results are in the same reference frame as the *Gaia* catalogue and that the parallaxes are absolute.

References

- de Bruijne, J. H. J. 2012, *Ap&SS*, 341, 31
 ESA 1997, *The Hipparcos and Tycho Catalogues*, ESA SP-1200
 Holl, B., Lindegren, L., & Hobbs, D. 2012, *A&A*, 543, A15
 Lindegren, L., Lammers, U., Hobbs, D., O’Mullane, W., Bastian, U., & Hernández, J. 2012, *A&A*, 538, A78
 Michalik, D., Lindegren, L., Hobbs, D., Lammers, U., & Yamada, Y. 2012, *Astron. Soc. Pac. Conf. Ser.*, 461, 549

[†] “The Robust Scatter Estimate (RSE) is defined as 0.390152 times the difference between the 90th and 10th percentiles of the distribution of the variable. For a Gaussian distribution, it equals the standard deviation. The RSE is used as a standardized, robust measure of dispersion [within the *Gaia* core processing unit].” (Lindegren *et al.* 2012)