Space-Time Structure Explorer
Sub-microarcsecond astrometry for the 2030s

Response to the call for White Papers for the definition of
the L2 and L3 missions in the ESA Science Programme

24.05.2013

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Document code: GAIA-CG-TN-LEI-AB-039

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This white paper also benefited from contributions and comments by C. Turon and A. Helmi.

1 Motivation for a brief white paper on space astrometry

The call for white papers for the definition of the L2 and L3 missions in ESA's science programme asks for the development of science themes for these future large missions. With the launch of Gaia to occur later in 2013, it is appropriate to assess the full scientific potential of Gaia in the light of its actual in orbit performance, before embarking on a detailed road mapping exercise for the next leap in astrometry.

We anticipate the production of the final science data products from Gaia in 2021/22 and thus a range of new questions to emerge around 2025. This implies the need for the next leap in observational capability in the 2030+ time frame – consistent with an L3 astrometry mission around 2034.

Thus, in this short white paper we outline a few broad discovery themes that could be addressed by such a mission and stress the need to keep the ESA and European expertise on space astrometry up to date in order to make sure that in due time suitable proposals for the next space astrometry mission can be put forward.

2 Options for future space astrometry missions

Gaia will provide a jump of two orders of magnitude in accuracy and four orders of magnitude in number of stars with respect to Hipparcos. Needless to say that the impact of Gaia on the mapping and understanding of the Milky Way, stellar astrophysics, solar system science, extragalactic astrophysics, and fundamental physics, may even go much farther than what we now expect. In addition Gaia will surely uncover surprises which may point to entirely new directions in which to take astrophysics. Thus once the Gaia results are known the most interesting directions to take for future space astrometric missions will be much clearer.

These future directions will also have to be considered in the context of the state of astronomy and astrophysics when the large digital sky surveys (Pan-Starrs, LSST, spectroscopic surveys) and the Euclid mission have delivered their results. Data from the new astronomical mega-facilities ALMA, E-ELT, and SKA will further influence the global context. In addition developments in the area of exoplanet science should be taken into account. Nevertheless it is possible to identify a number of options for future astrometry missions that would cover capabilities not offered by Gaia. We list three options here, starting from the most ambitious.

2.1 Nano-arcsecond astrometry

We believe that the long term goal for space astrometry should be to make the next big breakthrough beyond Gaia and aim for the sub-micro-arcsecond (sub-μas) or even nano-arcsec (nas) regime, preferably using techniques that enable the 'global astrometry' delivered by Hipparcos and Gaia. The figure illustrates the power of sub-μas astrometry by translating the astrometric accuracies to accuracies achieved in direct distance and transverse motion measurements. We briefly list some of the science cases that would be enabled by sub-μas to nas astrometry:

Census of terrestrial planets around nearby stars This case was already developed briefly by M.A.C. Perryman for the 'Cosmic Vision: Space Science for Europe 2015–2025' report. He showed that a 10 nano-arcsec precision mission will be able to survey hundreds of thousands of stars out to 100 pc for the presence of earth-sized planets. This science case has been developed further in the context of the NEAT proposal, which aims at the 50 nano-arcsec level for small-field astrometry. Clearly the interest of this science case should be weighed against future developments in the field of exoplanets.

Geometric or real-time cosmology It was already noted in the Gaia Concept and Technology Study report that astrometric measurement accuracies much better than a micro-arcsec would allow the direct determination of the transverse motions of external galaxies and quasars, and thus measure their kinematic properties independently

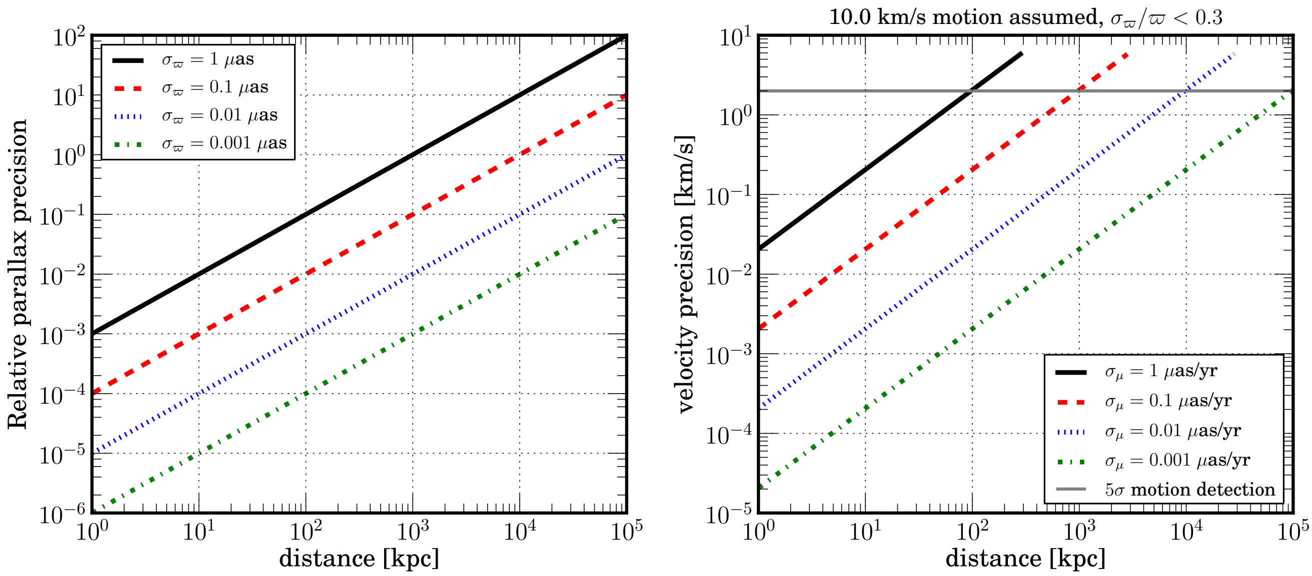

Figure 1: Illustration of the reach of a sub-μas astrometric mission. The right panel shows the relative parallax error achieved for individual sources as a function of distance for four levels of parallax accuracy. The right panel shows the transverse motion errors achieved for the same levels of accuracy on the proper motion measurements for sources moving at 10 km/s. For the calculations of the transverse motion errors the relative parallax error was assumed to be smaller than 30% and the ratio of parallax to proper motion measurement errors was assumed to be 2.

of a dynamical model of the universe. In addition several papers have been written in which the concept of 'real-time' cosmology is explored (Quercellini et al., 2012, 2009), in which very high accuracy astrometry permits the measurement of changes over time in the angular separation between sources at cosmic distances, providing a powerful consistency test of the assumed metric and independent constraints on cosmic anisotropy.

Fundamental physics A global astrometric mission at the nas level would allow much more stringent tests of General Relativity through light bending and would also enable the measurement of the energy density of stochastic gravitational wave background. In the narrow field regime one could for example weigh many neutron stars in binary systems in a model-independent way. In addition, reaching 1 μas or better for faint sources would allow the observation of pulsar-white dwarf systems and lead to tests of GR in the strong field regime.

Dark energy At the nano-arcsec level the quasar secular parallax shift due to the Solar system motion with respect to the CMB will be detectable and would lead to geometric constraints on dark energy (Ding & Croft, 2009).

Dark matter astrometry As laid out in Majewski et al. (2009) and Shaya et al. (2009) sub-micro-arcsec to nano-arcsec astrometry on a global scale (and to faint magnitudes) will allow the precise mapping of dark matter from the outer reaches of the Milky Way to beyond the local group.

Internal motions throughout the Local Group Gaia will not be able to directly measure internal motions of the nearby dwarf galaxies. Going to the sub-μas or nas regime would enable resolving 10 km/s motions out to 1–100 Mpc, thus opening up the tantalising possibility of measuring internal motions and thus astrometrically resolving the dynamics of Galaxies even beyond the Local Group and out to the nearest galaxy cluster.

Standard candles throughout the Local Group Sub-μas astrometry will enable the direct distance measurement (avoiding the problems caused by (patchy) extinction or metallicity effects) of various stellar standard candles all throughout the Local Group, and even up to the closest galaxy clusters for the brightest candles, i.e. in very different environments (galaxy type, metallicity) from the Milky Way.

More science cases have been developed in the context of the SIM mission (Unwin et al., 2008) and of course include applications to stellar physics. The latter will obviously benefit from the next level in parallax accuracy, bringing very rare and typically distant stellar types into the range of per cent level or better distance accuracy.

2.2 Global infrared astrometry at sub micro-arcsecond accuracy

An obvious complement to Gaia would be an infrared mission able to peer through the dust in the plane of the Milky Way. It should achieve at least the same astrometric accuracy as Gaia. This would enable a much better astrometric mapping of the inner disk, spiral arms, the bar, and the bulge of our galaxy. In addition one would have access to low-mass stars, brown dwarfs, and free floating planets over a large volume around the Sun.

We note that the Japanese community has plans for a near-infrared astrometric mission, JASMINE, which will be preceded by the nano-JASMINE and Small-JASMINE missions. JASMINE would only cover the inner disk and bulge and thus not be an all sky mission.

The interest and detailed requirements for an infrared astrometric mission will be much clearer once the Gaia results have been analyzed, especially through the combination of Gaia measurements with data from surveys probing the interstellar medium (such as Planck).

2.3 Repeat of Gaia

Although at first glance this option looks rather unambitious, it is nonetheless of significant interest, in particular in the area of extending the baseline of proper motion measurements. This will allow for more precise but also more accurate proper motions, especially for unresolved binary stars. In addition one would get better measurements of the motions of globular clusters and nearby dwarf galaxies. The repeat of Gaia would permit some of the real time cosmology experiments by making use of the secular parallax effect over the extended time baseline. Finally, a 'Gaia-2' in the 2030s would also improve the parallaxes from Gaia.

This option would possibly fit a lower cost envelope (a medium class mission perhaps) and one should of course consider to enhance the design, for example by going to fainter magnitudes at the same accuracies, and by optimizing the photometric and spectroscopic instrument designs. Note that at Gaia or better precision levels simultaneous photometry and spectroscopy are a must for the correct interpretation of the astrometric measurements.

2.4 Staying competitive

Gaia was first proposed 20 years ago and will deliver its final results 10 years from now. In the intervening 30 years observational astrophysics will have evolved a lot and many of the science cases for Gaia will have been addressed already to some extent. For example the RAVE and SDSS surveys have delivered many new results in the area of the Milky Way structure and formation history and the same will hold for the Gaia-ESO survey, Pan-Starrs and LSST.

However Gaia provides unique capabilities which will keep its results at the forefront of astrophysics over the coming decades:

- Global astrometry: absolute parallaxes and proper motions to unprecedented accuracies, simply not achievable from the ground.
- All sky, homogeneous, multi-epoch photometry and spectroscopy.
- Spectroscopy for numbers of objects out of reach of ground based efforts.
- Mapping of the full sky at HST-like angular resolution to 20th magnitude.

In fact Gaia would have remained competitive even if other astrometric missions such as SIM, DIVA and JASMINE would have flown already. The message is that any 'astrometric' science case and corresponding mission concept should remain competitive over the time scale from now to 2040–2060. Therefore we strongly believe that the most attractive option (as judged at this point in time) for a next large space astrometry mission is one that aims for the sub-μas to nano-arcsec regime over the full sky.

3 Challenges on the road to (global) sub-microarcsec astrometry

Although we do not present a mission concept here we do outline some of the challenges that need to be solved in order to achieve global sub-μas astrometry in the future.

3.1 Engineering

If we assume that the sub-μas astrometry mission will be done in the optical then basic considerations (e.g. Lindegren, 2005) show that astrometric precision scales as:

$$\sigma \propto \frac{\lambda}{B\sqrt{N}},$$

where λ refers to the effective wavelength of the measurements, N to the number of photons collected and B to the aperture size of the mirrors or the baseline of an interferometric system. In the optical the collection efficiency of photons by modern detection systems is almost 100%, meaning that gains in accuracy can only be achieved through increasing B.

This quickly leads to the argument for an interferometric mission with collecting areas of a few m^2 and baselines of 100–1000 meter (as argued by Perryman in his Cosmic Vision proposal, see also Lindegren, 2007). Thus precision formation flying will have to be developed and a concept to do global astrometry with such a configuration.

An important challenge is that the (thermo-)mechanical stability of the entire spacecraft down to the level required for a smooth motion of the telescope is far from trivial. For stability at measurement levels below 1 μas internal movements well below a micron over the entire body of the spacecraft will become critical. Experience with Gaia so far has shown that this is well beyond (3 orders of magnitude) anything engineers can estimate or predict in a large structure. Gaia will teach us a lot in this respect.

Similar considerations hold for the requirements on attitude control and knowledge of the barycentric velocity of the spacecraft.

Alternatively one would develop technology that could break the scaling relation above in such a way as to enable sub-μas astrometry at much lower cost (in terms of engineering).

Further developments that should be pursued:

- Detectors that allow for photon collection in a way not sensitive to radiation damage effects. Already for Gaia dealing with these effects will be very challenging. It is not likely that ‘software solutions’ can be made to work for the sub-μas regime.
- If the infrared option is pursued the challenge of developing IR-sensitive detectors that could be operated in Time-Delayed Integration (TDI) mode would have to be tackled in addition to issues of cooling the payload sufficiently without disturbing the astrometric measurements.

3.2 Data processing

Data processing to achieve sub-μas precisions will be complicated by (among others) the following:

- Relativistic modelling of astrometric measurements will have to be pushed to the nano-arcsec level in order to correctly interpret the raw data. It is believed that 100 nas precision in relativistic modelling can be achieved already. Going further would require research and improvements in our knowledge of the solar system (asteroid masses for example).

- System calibration at this level will have to be much better than (by an order of magnitude) than the astrometric accuracy aimed for and will thus be extremely challenging. The design of the instruments and mission concept will have to incorporate the data processing demands from the start. That is, any future ‘concept and technology study’ as well as subsequent development phases should treat engineering and data processing on an equal footing.
- Approaching nas levels it is not obvious that simple models of the time dependence of source coordinates will be sufficient. In addition research into sources of astrometric jitter (such as star spots or microlensing in crowded regions) and their effect on the interpretation of image locations in the data stream is required.
- Another conceptual problem when approaching the nas regime is that for parallax measurements small (< 1 AU) sources which are sufficiently bright (hot) are required in large numbers (for global astrometry). It is not clear that at cosmological distances this requirement is fulfilled (Lindegren, 2007).

For the first two elements above a lot will be learned from the data processing for the Gaia mission.

4 Conclusions

Gaia will soon provide a detailed view of our Milky Way enabled through astrometry at the micro arcsec level. European leadership in the delivery of this advanced astrometric mission will ensure that the European astronomical community is at the forefront of a range of research furthering our understanding of a wide domain of key astrophysical topics. However, Gaia is likely to throw up new questions which will demand the next level of data in order to fully understand the nature of Dark Matter, and how it fundamentally drives the formation and evolution of galaxies, large and small. These questions will only be answered through detailed precision mapping of not only our Milky Way, but neighbouring galaxies in our local group. This in turn will demand the leap to sub-μas or even nano-arcsecond astrometry.

Over the coming years the Gaia science community will embark on an intense series of workshops to develop the key science themes which will scope the requirements for a future ’Space-Time Structure Explorer’ mission. This will culminate in a detailed white paper which will be published to coincide with the first releases of Gaia data. This will allow for a simultaneous exposure of not only the early science yield of Gaia but also set our European led programme in motion to ensure continued momentum in the development of the required new technologies and eventual mission to deliver the next leap in our understanding of the fundamental interplay of matter (dark and light) and energy shaping our cosmos.

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