# ORBIT RECONSTRUCTION FOR THE GAIA MISSION

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## ABSTRACT

Gaia is one of the European Space Agency's (ESA) science cornerstone missions with the scientific objective to create a precise three-dimensional map of about one billion stars aiming at visual magnitudes as faint as $V = 20$ throughout. The envisaged astrometric accuracy for stellar objects is 25 µas at $V = 15$, or 300 µas at $V = 20$ which can be compared with values achieved by ESA's Hipparcos mission of 1 mas. Moreover, Gaia will make - to lower but still unprecedented precision - astrometric measurements of solar system objects, mainly minor planets, for the purpose of improving the knowledge of their physical and orbital properties. Besides astrometry, Gaia will perform radial velocity determination at a 2–10 km $s^{-1}$ level for stars with $V < 17$, low resolution spectroscopy in the same brightness range, and spectrophotometry in 25 colours for $V < 20$. Gaia is due to be launched in 2013 on a Soyuz-Fregat from Kourou, French Guyana and it will spend its 5 years nominal mission lifetime in a Lissajous orbit around L2, the second Lagrange point in the Sun-Earth system.

In order for the Gaia science team to fulfil their scientific objectives the Gaia orbit has to be known *a posteriori* to a precision that is unprecedented for ESA's space observatories. The requirement on the reconstruction accuracy of the spacecraft position is 150 m in each component. The main driver for this requirement is the measurement of solar system object parallaxes for which the observer baseline needs to be known to high precision. The requirement on the reconstruction accuracy of the spacecraft velocity is 2.5 mm/s in each velocity component. The main driver for this requirement is the need to correct astronomical observations for relativistic aberration for which the observer velocity needs to be known to high precision.

For ESA missions to the Lagrange points the orbit is determined by using ESOC's interplanetary orbit determination system which relies mainly on 2-way range and Doppler tracking observables. With the existing tracking systems that are installed in ESA's deep-space stations in New Norcia and Cebreros and by using an X-band communication link an end-to-end measurement precision of better than 5 m and 0.1 mm/s for 2-way range and range-rate (derived from Doppler observables integrated over a 1 minute count time) respectively is achieved. With these measurements the Gaia orbit reconstruction requirements for the spacecraft state components along the line-of-sight are easily achievable. However, simulations have shown that this is not true for the plane-of-sky components of the spacecraft position and velocity and that

the conventional line-of-sight radiometric tracking data have to be augmented with direct measurements of the plane-of-sky components. Delta Differenced One-Way Range (Delta-DOR) measurements are normally used for that purpose in the domain of deep-space navigation but this type of measurement was considered being too resource demanding by needing at least 3 deep space stations for about 2 hours every night over the full duration of the Gaia mission lifetime. The solution to this problem came from the Gaia science team: they proposed the use of astrometric measurements of Gaia by ground based optical telescopes. The precision of these measurements depends on the quality of the star catalogue that is used to reduce the optical images to angular measurements. It is reckoned that with the best star catalogues that are available today the angular measurements have a precision of better than 50 mas (corresponds to 360 m at L2). Unfortunately, this is not precise enough to meet the Gaia requirements. More precise angular data can only be derived from optical images once better star catalogues are available. The only improved star catalogue that will be available in the near future will be the Gaia star catalogue itself and it is reckoned that with this an angular precision of better than 10 mas (corresponds to 70 m at L2) can be achieved. These measurements could therefore be used to meet the Gaia orbit reconstruction requirements and this has been confirmed by simulations provided that measurements are available approximately every night. But now there is the dilemma that the generation of the Gaia star catalogue depends on a precise Gaia orbit reconstruction and the precise Gaia orbit reconstruction depends on the availability of the Gaia star catalogue. This interdependency calls for an iterative process between Gaia orbit reconstruction and Gaia star catalogue generation which is now the baseline for the Gaia project.

This paper describes the usage of astrometric measurements within the orbit determination system of Gaia which to the knowledge of the authors have never been used before for the purpose of orbit determination of a spacecraft at the Sun-Earth Lagrange point. It explains the data interface and the Gaia specific iterative orbit reconstruction process as well as the requirements for modelling such precise astrometric measurements at low geocentric distances within the orbit determination algorithm. It moreover outlines the challenges to acquire them basically every night over a period of 5 years at ground based telescopes that are distributed around the Earth and that normally are not used to provide this kind of semi-operational service. Finally, it presents orbit determination results that have been achieved in the framework of a tracking campaign by using radiometric and astrometric tracking data of ESA’s Planck spacecraft that is currently in a similar Lissajous orbit around the Sun-Earth L2 point as Gaia will be.

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