Impact of HPC on the Global Astrometric Sphere Reconstruction from space in the Gaia era and beyond

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Abstract

We give a brief account of the problem of the Global Astrometric Sphere Reconstruction in Astrometry, with particular reference to the Gaia and Gaia-like astrometric missions. In particular, we stress the need for HPC to solve the linearized equation system of the size that is brought about by modern space astrometry missions. The difference between the two different implementation of the Gaia mission is illustrated, with specific reference to the problems of the covariance estimation, and we show how the latter have recently been implemented in the GSR pipeline of Gaia.

The Gaia mission

Building on the legacy of the Hipparcos satellite, Gaia implements an approach to global and absolute astrometry via a two-way telescope doing measurements in scanning mode. The entire celestial sphere is observed every 6 months thanks to a scanning law that combines three independent motions: the spin of the satellite, the precession of the spin axis around the Sun-Earth direction, and the orbital motion of the satellite. The CCDs on the focal plane operate in TDI mode.

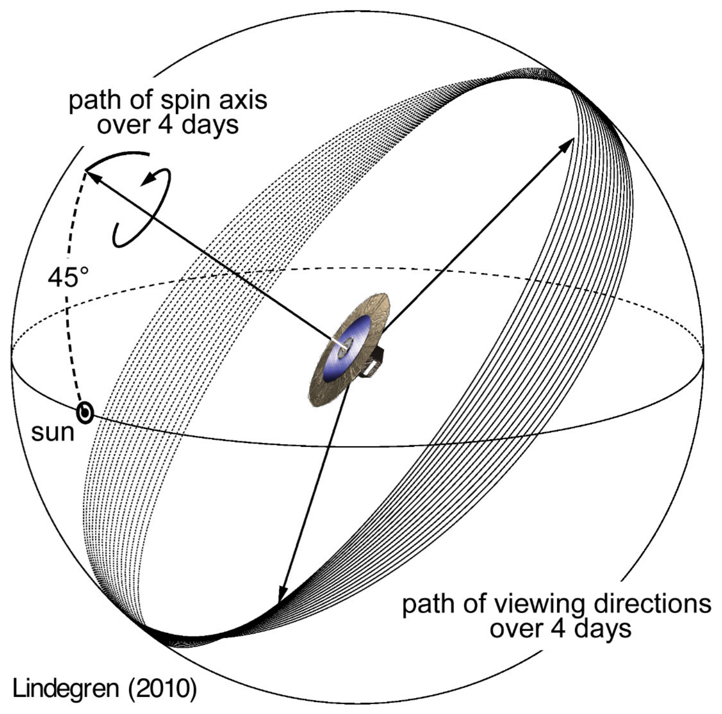

Figure 1. The Gaia scanning strategy.

The linearized equation system

Each star is observed in one of the two fields of view (FoV1 or 2) separated by a large Basic Angle (Γ). This observation is modelled into a linearized equation, function of up to 24 unknowns pertaining to different classes: Source, Attitude, Calibration, and Global.

$$-\sin\phi_{\rm calc}\,\delta\phi = \sum_{\rm Source}\left.\frac{\partial F(\mathbf{x})}{\partial \mathbf{x}^{\rm S}}\right|_{\mathbf{x}_0}\delta\mathbf{x}^{\rm S} + \sum_{\rm Attitude}\left.\frac{\partial F(\mathbf{x})}{\partial \mathbf{x}^{\rm A}}\right|_{\mathbf{x}_0}\delta\mathbf{x}^{\rm A} + \sum_{\rm Cal}\left.\frac{\partial F(\mathbf{x})}{\partial \mathbf{x}^{\rm C}}\right|_{\mathbf{x}_0}\delta\mathbf{x}^{\rm C} + \sum_{\rm Global}\left.\frac{\partial F(\mathbf{x})}{\partial \mathbf{x}^{\rm G}}\right|_{\mathbf{x}_0}\delta\mathbf{x}^{\rm G}$$

Gaia collects a few 0^9 observations of up to 10^8 primary sources over a mission duration of about 10 years. Each source brings 5 astrometric unknowns, while the those of the other classes can be up to a few 10^7. This produces a sparse and overdetermined linear equation system $\mathbf{b} = A\mathbf{x}$ whose design matrix A has $m \sim 10^9 - 10^{10}$ rows and $n \sim 5\times10^8$ columns. Such a size calls for a parallelized implementation of the solution algorithm, and an adequate HPC machine.

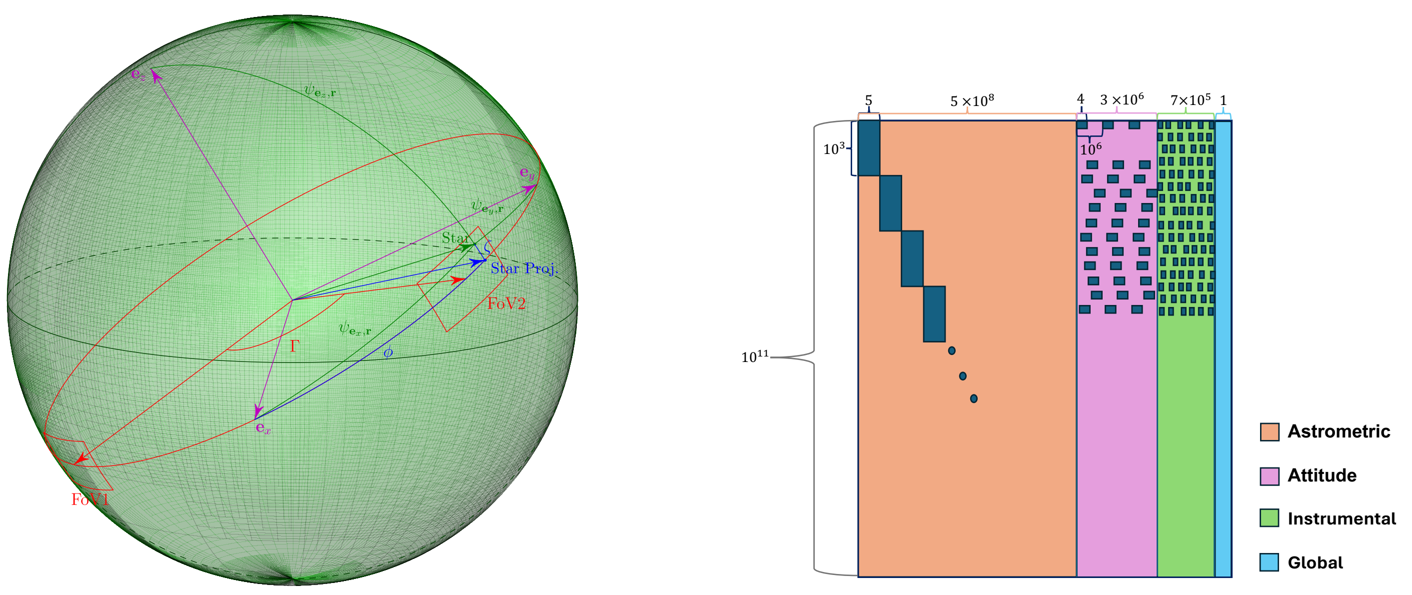

Figure 2. The Gaia observables and the structure of the matrix A of the linearized equation system.

Algorithms for the solution of the equation system

A typical system of equations for the full mission will require about 40 TB RAM and, if solved with direct methods $10^2$6 FLOPs, a task unfeasible even with the largest supercomputers available. The problem of the Global Astrometric Sphere Reconstruction thus resorts to iterative algorithms. Gaia currently uses two different approaches: a block-iterative algorithm, implemented in the AGIS pipeline (Lindegren et al., 2012) and a fully iterative algorithm based on a customized version of LSQR (Paige and Saunders, 1982) implemented in the GSR pipeline.

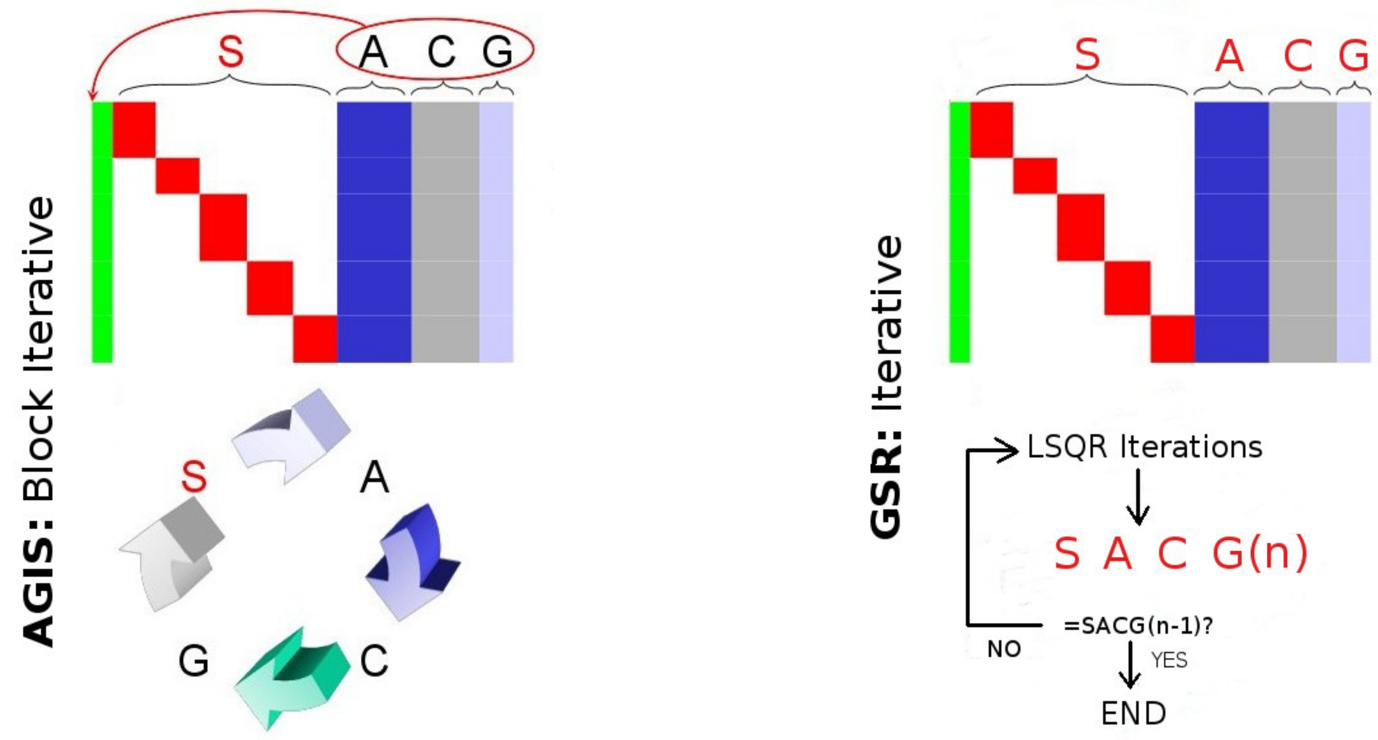

Figure 3. The two approaches adopted for solving the linear equation system.

The block-iterative approach adopted by AGIS allows a simpler implementation, which is essentially embarassingly parallel. This is not possible for the fully iterative algorithm, which requires a more sophisticated approach (Becciani et al., 2014) but, on the other side, allows the estimation of the full variance-covariance matrix (Kostina et al., 2009).

Estimation of the variance-covariance matrix in GSR

The covariances are iteratively computed with the LSQR algorithm (Kostina et al., 2009):

$$Cov^{itn}[j] += factor^{itn}\cdot x^{itn}[j_1]\cdot x^{itn}[j_2],$$

where itn is the index of the LSQR iteration, $\vec{Cov}$ is the 1D double-precision array of the covariances, j is an index that goes from 0 to $N_{\rm cov}-1$, and (j_1,j_2) are the couples of indexes of the unknowns $\vec{x}$ between which we have to compute the covariances.

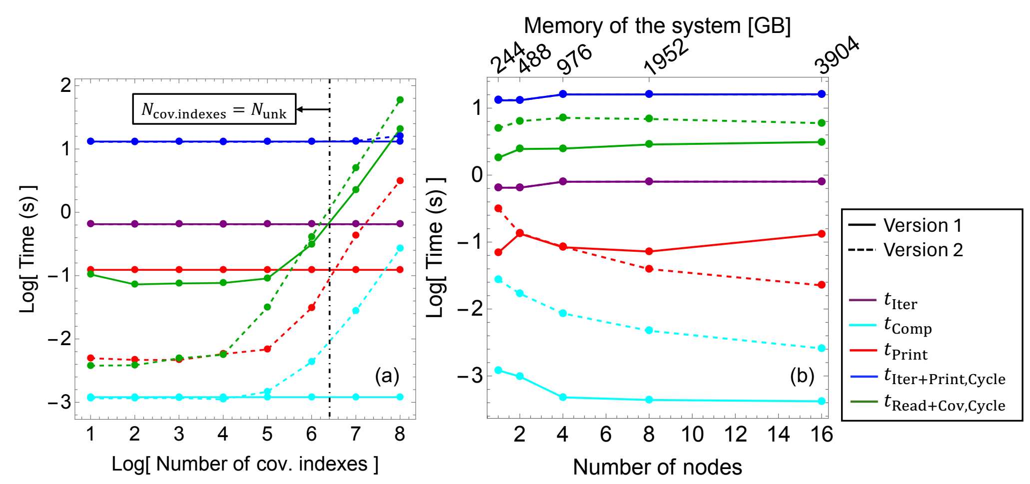

Figure 4. Tests to measure the performance of the different sections of the LSQR + covariances pipeline.

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