Functional description of the Astrometric Global Iterative Solution (AGIS)

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ABSTRACT. A top-level functional description of the Astrometric Global Iterative Solution (AGIS) is given. It focuses on the expected functionality and level of complexity that AGIS should have one year prior to launch.

1 Introduction

This top-level functional description of AGIS is intended as a starting point for defining the requirements for AGIS, from which in turn the work breakdown structure and development schedule follow. The focus here is on describing the expected functionality and level of complexity of the major AGIS components at a point roughly one year prior to launch. The interfaces with other parts of the data processing are not covered here (refer to the ICD for this), although they are to a large extent implied by the description of AGIS.

2 Purpose of AGIS

The purpose of AGIS is to determine

1. accurate astrometric parameters for a subset of ‘primary’ sources, and provisional values of the same parameters for all ‘secondary’ sources;
2. the three-axis attitude of the Astro instrument axes as function of time;
3. the geometric calibration of the Astro instrument as function of time and photometric characteristics of the sources; and
4. an optional set of ‘global’ parameters describing the transformation from astrometric parameters and time to observed source directions.

Moreover, these data must be determined in an internally consistent celestial reference frame (see Sect. 3.1).

The subset of primary sources is iteratively selected as part of the AGIS processing. The selection is based on the observed astrometric, photometric, spectroscopic and imaging characteristics of the sources, as well as the need for an adequate sampling versus position, magnitude and colour. Sources for which there is some indication that they may be non-single or otherwise deviating from the standard astrometric model are excluded from the primary set. AGIS should be able to handle at least $10^8$ primary sources.
3 Main components of the Global Iterative Solution

The consistent estimation of source, attitude, calibration and global parameters will be done according to a variant of the Global Iterative Solution (GIS) scheme, modified for efficient implementation (e.g., by allowing any or all of these processes to use the same residuals and downweights in a given GIS iteration, rather than being executed in a specified sequence). The AGIS system should allow a sufficient number of GIS iterations to be run even in the final outer iteration (i.e., when data from the whole mission are taken into account), targeting an overall convergence to within 0.1 μas in the astrometric parameters. However, in view of the still unknown convergence properties of the full GIS, we will for present design purposes assume that five GIS iterations are sufficient.

3.1 Reference frame and source model

The data sets listed in Sect. 2 must be determined in an internally consistent celestial reference frame, linked to the International Celestial Reference System (ICRS) by means of a subset of extragalactic primary sources. This link will determine and take into account the acceleration of the solar-system barycentre in the cosmological frame (cf. Sect. 3.5).

The astrometric source model used by AGIS is based on the assumption that the source is a point object moving with uniform space velocity relative to the solar system barycentre, with known radial velocity at a specified epoch. This ‘standard astrometric model’ is applicable (to some degree of accuracy) to all non-solar system objects. Hence five astrometric parameters - representing their position, parallax and proper motion at a specified epoch - are determined as part of AGIS for every non-solar system source, even if the fit in many cases will be very poor.

The formulation of the standard astrometric model and the transformation to the observed direction in the instrument frame is based on General Relativity (GR). A modelisation accuracy of 0.1 μas is targeted, i.e., all known effects greater than this should be taken into account when calculating the observed source directions from given model parameters. Barycentric Coordinate Time (TCB) will be the primary time scale for the astrometric processing: the astrometric parameters (including reference epochs etc) will exclusively refer to TCB. The use of other time scales (such as TT, TAI, UTC, proper time at Gaia, or an ad-hoc on-board time) will be restricted to the necessary minimum (if any).

Deviations from GR are considered only in terms of global parameters that may either be estimated by AGIS or fixed to their values according to GR.

3.2 Attitude model

The attitude model uses a spline representation of the quaternion of the Astro instruments axes expressed directly in the celestial reference frame. (In view of the expected high-frequency attitude noise from the micro-propulsion system, it is not likely that a more sophisticated modelling of the overall spacecraft dynamics would improve the attitude, except in special circumstances; see below.) The selection of knot interval will be made adaptively in order to achieve local optimisation, i.e., balancing observation noise against
modelisation errors. This will take into account the estimated spectrum of perturbations and the changing density of primary sources. The processing will include post-analysis of residuals to identify localised events (micrometeoroid impacts, excitation of vibrational modes) which may require a modification of the model (e.g., by inserting additional knots at the time of impact, or superposing dynamically constrained vibrational components).

3.3 Calibration model

The calibration model describes the relation between the quasi-field angles \((\phi, \zeta)\) (where \(\phi = \eta \pm \gamma/2\) is the AL angle reckoned from the \(x\) axis, and \(\zeta\) the AC field angle) of the centroid of a source image and its position among the CCD pixels at a specified time. This relation depends on many things, e.g.: the basic angle; the optical distortions of the Astro fields; the physical positions, dimensions and photometric characteristics of the CCDs and of their individual pixels; the gating used during the CCD transit; the spectral energy distribution (SED) of the source and the spectral throughput of the instrument (through chromaticity effects); the magnitude of the star, background level and charge injection (through CTI effects); the LSF model used for the centroiding; the definition of centroid as implemented in the centroiding algorithm; and time (through the variability of most of the other items). However, for many of these effects it is not possible (nor desirable) to separate their physical origins; only their combined effect is of interest. For example, the optical distortion and the physical positions of the CCDs cannot (and need not) be separated in the AGIS calibration model.

A detailed specification of the calibration model is one of the most difficult parts of AGIS. Probably it cannot be completely achieved until well into the mission, in close interaction with a careful analysis of the actual data. The pre-launch model implemented in AGIS should however include a reasonable approximation of all the effects identified during the next several years. As a minimum, it will include the effective large-scale AL and AC position of each ASM and AF CCD expressed as a low-order polynomial of the pixel column number and separately for each viewing direction and gate (implicitly, this also defines the basic angle); additional small-scale AL and AC distortion at the level of individual pixel columns; chromaticity expressed as a simple function of the effective SED, field position and viewing direction; and CTI displacement expressed as a simple function of flux, CCD and pixel column. All parameters are regarded as variable on some timescale; any time variability may however be modelled as a spline of degree zero (constant between knots).

3.4 Global model

The global model will as a minimum contain the PPN parameter \(\gamma\). However, this component of AGIS should be flexible enough to include a much larger number of parameters (up to a few hundred), assuming that the relevant partial derivatives can be computed from readily available data (such as time, ephemerides, and the astrometric parameters or observed direction).
3.5 Link to ICRS

The link to ICRS is based on a separate analysis of the astrometric parameters determined by AGIS for the full subset of identified quasars, including the objects used to define the positional system of ICRS (see Sect. 4.1). The analysis, which is optionally run in between two outer iterations of the AGIS, is based on a model with 9 degrees of freedom (6 degrees for the uniform rotation of the provisional reference frame of AGIS with respect to the ICRS, and 3 degrees from the cosmological acceleration of the solar system barycentre\(^1\)).

Having completed this analysis, there is a separate process to be (optionally) executed before the start of the next outer AGIS iteration. This will adjust the astrometric parameters for all sources (primaries and secondaries), as well as all the attitude quaternions, according to the indicated change of reference frame.

It is envisaged that the link to ICRS will only be executed a small number of times during the Gaia data analysis, and not during its early stages. It will always involve a high degree of manual inspection and interaction, and the planning of the outer iteration cycles must therefore allow sufficient time for this analysis.

4 Other considerations

4.1 Input data and initial parameter values

The input to AGIS consists of the the elementary Astro observations for every detection of a non-solar system source, with associated information such as the photometric fluxes used to compute the LSF. These are provided by the IDT per sky region and after cross-matching and including references to the astrometric input catalogue (see below). The IDT also provides the initial estimates of attitude and calibration for the AGIS.

AGIS will need an astrometric input catalogue, containing the best ground-based positions and proper motions for a subset of the sources. This must include an identified subset being part of the definition of the ICRS, and (in the later stages of the processing) a subset of identified quasars.

4.2 Robustness

The processes described above (source, attitude, calibration and global updating) will be based on the weighted least-squares method for computational efficiency. However, the implementations will be extremely robust in the following two senses. First, they should provide sensible (if not useful) results in all situations that can reasonably be encountered during the real mission, e.g. when the problem is underdetermined because of a lack of data or too many parameters. This may for example happen with the attitude determination if too few primary stars are encountered in some region. These situations should always be handled gracefully (no floating exception due to a singular matrix, for example) and

\(^1\)Note that the cosmological acceleration is only used to model the (apparent) proper motion of quasars; for stars the corresponding effect is already included in the usual definition of their proper motion (TBC).
generate appropriate warning messages. Secondly, the processes should be able to handle a
significant fraction of outliers among the observations and still achieve solutions that are
nearly optimal from the accuracy viewpoint (given the quality of the data). Both mild
outliers (indicating longer tails than a gaussian but still what you often expect in a
real data set) and the occasional corrupt data item (clearly and utterly wrong) should be
appropriately handled. In practice this requires the consistent use of adaptive and
robust solution methods. These will iteratively estimate the normal range of residuals
while identifying and taking care of outliers (e.g. by rejection or downweighting).

4.3 Monitoring and analysis tools

The AGIS will include a number of graphical and interactive tools to monitor, analyse
and control the individual processes as well as the overall convergence of the GIS. It will
be possible to select subsets of data (parameter values, updates and residuals) in
terms of specified ranges for a number of control variables (such as time, position on sky,
and position in the FOV), calculate their statistics and make various plots (histogram,
scatter/density plots, time evolution, etc).

5 Acronyms

The following table has been generated from the on-line Gaia acronym list:

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>AC</td>
<td>ACross scan (direction)</td>
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<tr>
<td>AF</td>
<td>Astrometric Field (in Astro)</td>
</tr>
<tr>
<td>AGIS</td>
<td>Astrometric Global Iterative Solution</td>
</tr>
<tr>
<td>AL</td>
<td>ALong scan (direction)</td>
</tr>
<tr>
<td>ASM</td>
<td>Astrometric Sky Mapper (obsolete)</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge-Coupled Device</td>
</tr>
<tr>
<td>CTI</td>
<td>Charge Transfer Inefficiency</td>
</tr>
<tr>
<td>FOV</td>
<td>Field of View (also denoted FOV)</td>
</tr>
<tr>
<td>GIS</td>
<td>(Astrometric) Global Iterative Solution</td>
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<tr>
<td>GR</td>
<td>General Relativity</td>
</tr>
<tr>
<td>ICD</td>
<td>Interface Control Document</td>
</tr>
<tr>
<td>ICRS</td>
<td>International Celestial Reference System</td>
</tr>
<tr>
<td>IDT</td>
<td>Initial Data Treatment</td>
</tr>
<tr>
<td>LSF</td>
<td>Line-Spread Function</td>
</tr>
<tr>
<td>PPN</td>
<td>Parametrised Post-Newtonian (formalism in General Relativity)</td>
</tr>
<tr>
<td>SED</td>
<td>Spectral Energy Distribution</td>
</tr>
<tr>
<td>TAI</td>
<td>International Atomic Time</td>
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<tr>
<td>TCB</td>
<td>Barycentric Coordinate Time</td>
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<tr>
<td>TT</td>
<td>Terrestrial Time</td>
</tr>
<tr>
<td>UTC</td>
<td>Coordinated Universal Time</td>
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