GAIA FIRST LOOK

S. Jordan[1], U. Bastian[1], H. Lenhardt[1], H.-H. Bernstein[1], S. Hirte[1], M. Biermann[2]

[1]Astronomisches Rechen-Institut, Mönchhofstr. 12-14, 69120 Heidelberg, Germany
[2]Landessternwarte Königstuhl, 69117 Heidelberg, Germany

ABSTRACT

A complicated and ambitious space mission like Gaia needs a careful monitoring and evaluation of the functioning of all components of the satellite. This has to be performed on different time scales, by different methods, and on different levels of precision. On the basis of housekeeping data a Quick Look will be performed by the ground segment. A first analyses of the science data quality and consistency will be done by a Science Quick Look. However, due to the nominal scanning law a full self-consistent calibration of the satellite, and a determination of astrometric and global parameters, is not possible before about half a year has elapsed, imposing a serious danger to lose valuable observing time if something goes wrong. Therefore, it is absolutely necessary to perform a Detailed First Look on a daily basis on the μas accuracy level. We describe two different methods, a block iterative procedure and a direct solution, to monitor all satellite parameters that in principle can be evaluated within a short amount of time, particularly those that can be measured in along-scan direction. This first astrometric analysis would greatly benefit from a modified scanning law (Zero-nu-dot mode) for some time during the commissioning phase.

Key words: Gaia; First Look.

1. INTRODUCTION

The First-Look task aims at a rapid health monitoring of the Gaia spacecraft and payload at the targeted level of astrometric precision. This is difficult to achieve because Gaia needs a global, coherent, interleaved reduction and calibration of about six months of measurements to reach that level of precision. It is intended to be done by means of a Global Iterative Solution (ESA 2004; Lindegren 2001), abbreviated as GIS. Since the GIS simultaneously solves for astrometric, attitude, calibration, and global parameters (including relativistic effects) one can call Gaia a self calibrating instrument, but this can only be achieved after measurements from several months have been gathered. It is, on the other hand, of utmost importance to quickly get a handle on the inherent quality of the elementary measurements. Learning only from the primary science reduction that some subtle effect has degraded the measurements would effectively mean the loss of many months of data and mission time. It is the goal of the First-Look task to perform an analysis of Gaia's data on a daily basis in order to perform the best possible monitoring of the satellite status during the whole mission. This would allow counter-measurements if serious problems should arise.

2. FIRST LOOK = QL, SCQL, FLP, & DFL

The monitoring of the satellite health and the quality of its data is performed on different levels of accuracy, executed under different responsibilities, and with somewhat different objectives (see Figure 1).

The Quick Look (QL) task comprises all ground segment activities concerning satellite (i.e., bus and instrument) health. It generates telecommanding via the ground segment if necessary. QL is performed in real-time or in quasi real-time and uses only housekeeping and attitude control system data.

The Science Quick Look (ScQL) task comprises all activities concerning scientific data health and either generates telecommanding or alerts the scientific Gaia consortium if necessary. The Science Quick Look task will be some less precise and simplified version of the Detailed First-Look task, intended to immediately react on obvious deviations from what is expected for the scientific data, such as empty windows or a very high background in the windows. Such deficiencies are easy to detect and should quickly be handled / removed to safe observation time. ScQL is performed immediately after data reception on ground. It seems reasonable to perform it at the same location where the QL task will be executed.

The Detailed First Look (DFL) is the in-depth scientific assessment of the quality of the Gaia observations within about 24 hours after its reception at the Data and Processing Centre (DPC). At first sight this seems only possible on the basis of high-precision knowledge of Gaia's attitude and geometric calibration, and of the positions of at least some of the observed stars. However, as already mentioned in the introduction, a full self-calibration of

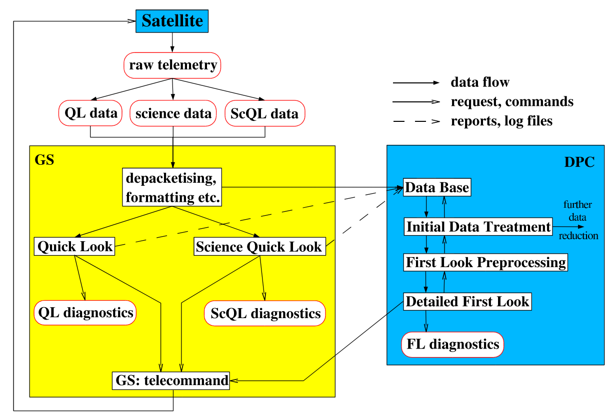

Figure 1. Sketch to illustrate the proposed logic of the different 'Look' tasks. The raw telemetry consists of different kinds of data (QL, ScQL and science data) organised in different virtual channels for a simpler handling on ground. This data is prepared for injection into the data base at the Data and Processing Centre (DPC) and for further processing. Each of the subsequent tasks (QL, ScQL and DFL) carry out their own diagnostics to judge the bus, instrument and science data health and (possibly) generate telecommanding and alert the scientific Gaia consortium, respectively. Initial Data Treatment and FLP are preparatory steps to enable the DFL task.

Gaia can only be achieved by collecting many months of measurements. Some compromise must thus be found to solve this apparent contradiction.

The goal of such a compromise must be a restricted astrometric calibration sufficient to judge the quality of the measurements but not necessarily giving absolute astrometric and calibration parameters. We call this task First-Look Preprocessing (FLP). It is the most complicated process in the chain. In the case of Hipparcos it was the strictly one-dimensional Great-Circle Reduction (ESA 1997).

After FLP has been performed DFL will produce diagnostics of the status of the satellite and instrument in a more sophisticated manner than can be performed within QL and ScQL. The diagnostic output will be accessible in the data base. If modifications to the satellite operations appear necessary, this will be communicated to the ground segment. The overall First-Look task thus consists of the sub-tasks QL, ScQL, FLP, and DFL.

First Look tasks also exist for Gaia's photometry and radial velocity measurements. For these measurements numerous *a priori* calibration objects exist in the sky on the accuracy level of Gaia. The details of these tasks are not described in this paper.

3. BASIC GAIA DATA REDUCTION

Gaia's scanning astrometric telescope forms optical images of celestial light sources (mostly stars) that are detected by TDI-operated CCDs in the focal plane. With

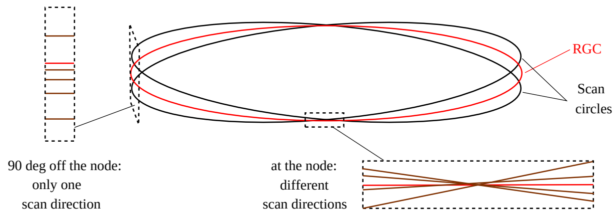

Figure 2. The RGC is defined by the scan plane in the middle of our one-day time interval. During this period the scan plane changes by only about 4°. Stars 90° away from the node are moving practically parallely, therefore providing no information about the r coordinate perpendicular to the RGC. In the region around the nodes r can be measured with limited precision.

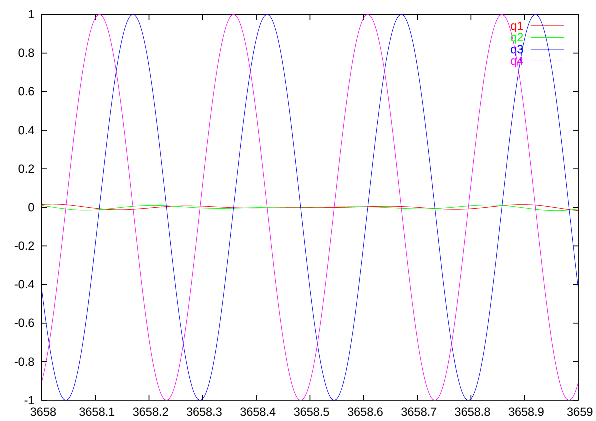

Figure 3. In the RGC system two of the quaternion components, usually called q_3 and q_4, have large amplitude and describe the orientation in υ direction, while the other two components, q_1 and q_2, oscillate closely around zero and describe the slow tilt during one day.

(at least approximately) known geometric calibration of the telescope and focal plane, the pixel coordinates of the centroid can be transformed into spherical longitude and latitude coordinates. These coordinates are called 'field angles', more specifically 'observed field angles', and denoted η (along scan) and ζ (across scan). For a given instant of time they depend on the astrometric parameters of the source (i.e., barycentric celestial position at some reference epoch, proper motion, parallax and maybe radial velocity) and Gaia's attitude with respect to astronomy's inertial space, defined by the International Celestial Reference System.

In the GIS the differences between the observed field angles and the ones computed from approximate parameters are used to determine corrections in a linearized least-squares adjustment process. This is the basic principle of the self-calibrating astrometric reduction of Gaia's measurements.

4. FIRST-LOOK PREPROCESSING

The main astrometric instrument measures only along scan (i.e., only η). The astrometric sky mapper (ASM) measures in two dimensions, but with a significantly lower precision across scan (1–3 mas, but only, if the across-scan instrument calibration is known, which is not the case at the beginning of the mission). Within 24 hours the scan plane tilts by only about 4° degrees. A Reference Great Circle (RGC) can be defined by the great circle perpendicular to the direction of the rotational axis in the middle of the one-day time interval (see Figure 2). The coordinate along the RGC is called υ, the perpendicular coordinate r. 90° away from the nodes all scans are approximately parallel to the RGC, providing only one-dimensional (υ) information from the main instrument. Only in the region around the nodes the slow tilt leads to regions where sources are measured in slightly different directions resulting in low-precision determinations of r from multiple η measurements.

A Hipparcos-style great-circle reduction won't do the First-Look job in the case of Gaia since the across-scan position of the stars is not known with sufficient accuracy until the first GIS has been performed. The great-circle reduction could work if the ASM were calibrated.

Whatever method we use, we cannot expect a full astrometric solution because the problem is degenerate. Nevertheless, our goal must be to monitor the accuracy of the measurement on the μas level of those parameters where it is possible. There are some aspects of the instrument and of nature that just cannot be tackled with one day of one-dimensional measurements, which, however, do not significantly disturb the FLP output data. Examples are a possible along-scan 'astrometric chromaticity' of the instrument, stellar proper motions and parallaxes, and a possible deviation of gravitational light bending from the predictions of General Relativity.

We have begun to work on two different ways to tackle the problem of FLP:

- A One-Day Iterative Solution (ODIS)[1], which is a reduced variant of GIS, i.e., a block-iterative method in the spirit of GIS, but somehow identifying and omitting the degenerate dimensions of the adjustment problem.

- A direct setup and solution of the full least-squares adjustment problem of FLP, using a direct elimination of the source unknowns before inverting the remaining normal-equation matrix. Using eigenvector decomposition of the space of unknowns allows to identify the degenerate dimensions. This (already quite mature) method is called 'ring solution' for the time being.

[1] formerly called 1-day GIS, which we renamed because it is not global at all

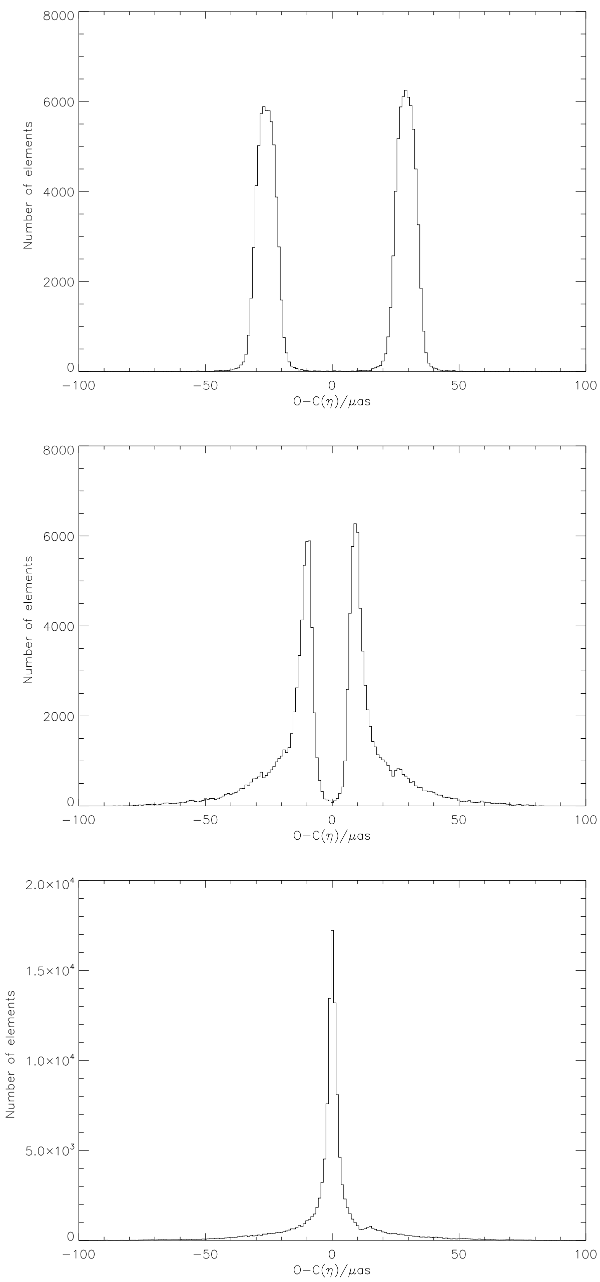

Figure 4. Observed – calculated along-scan angles before the ODIS iterations (top), after one iteration (centre), and after 50 iterations (below). The double distribution originates from an assumed wrong calibration angle between the two FoVs. Note that for this test data without any noise were used in order to test the validity of the simulated data and the ODIS program.

4.1. The One-Day Iterative Solution

In contrast to the GIS the ODIS will not be able to solve the full astrometric and calibrational problem due to the limitations in scan directions. The satellite attitude will – as in the GIS – be described by four quaternions. If converted to the RGC system, two quaternion components describe the orientation of the satellite in υ direc-

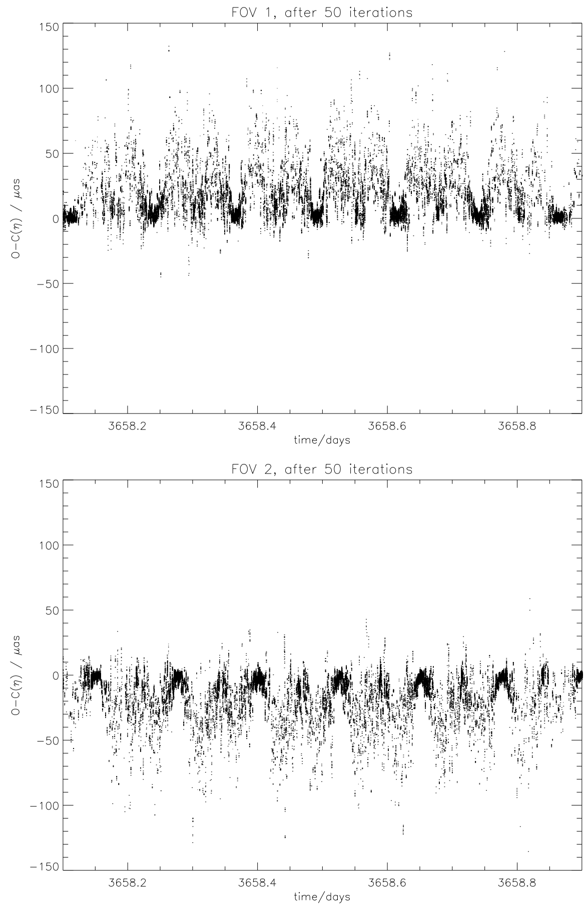

Figure 5. Observed – calculated along-scan angles vs. time for FoV1 (top) and FoV2 (bottom) after 50 ODIS iterations. Note the unequal density of our observations leading to strong correlations between the two FoVs.

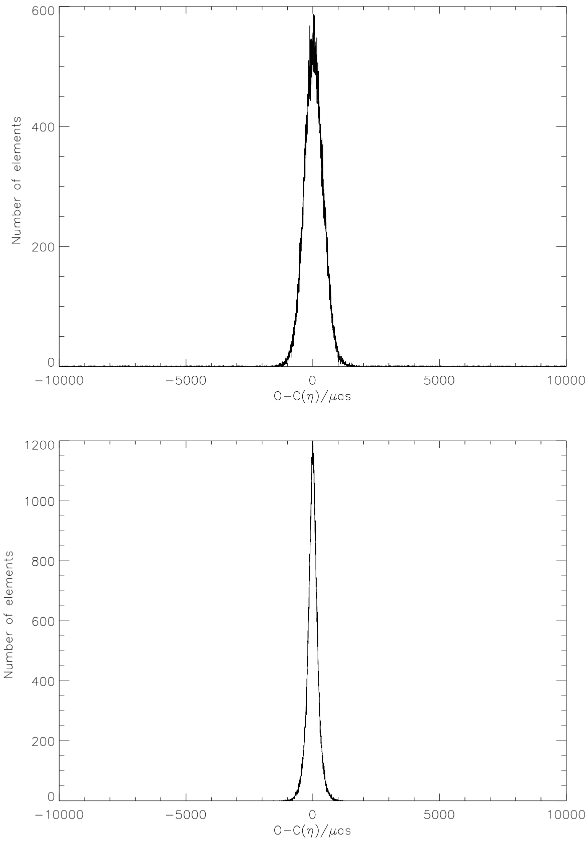

Figure 6. Observed – calculated along-scan angles before the ODIS iterations (top), and after 25 iterations (below). In this case simulated data with noise were used.

tion, while the other two account for the slow tilt during the 24 hour time interval (see Figure 3), see Jordan et al. (2004). In the current version the fitting parameters for the attitude are 1440 quaternion (for 24 hours) B-spline coefficients for the quaternions at equidistant nodes every 60 seconds; it may be necessary to use a higher density of nodes. 1440 quaternions translate into 5760 unknowns for the four components of which one quarter is redundant due to the constraint that the quaternions have length unity. This constraint is accounted for by pseudo observing equations.

The CCD calibration can be described by 3 along-scan unknowns per CCD (e.g., 'shift', 'rotation' and 'distortion') leading to 510 unknowns. We estimate the number of observed sources during one day to be about 3 million on average. Since we cannot try to measure more than v and a lower number of r coordinates, the number of source unknowns is less than 6 million. This number will be further reduced if we consider only those sources observed at least 2 times. The number of elementary measurements of η and ζ is of the order of 50 million.

For our software development and first tests we use 24 hours of data provided to us by the Gaia Simulation Working Group, calculated in the framework of the Gaia-1 instrument model – which is no important restriction for our tests and will be adapted to the current model in the future.

For a first consistency test we used the 'true' data, i.e., without any noise in attitude, source positions, and elementary measurements. For the latter we assumed that we can also precisely measure the across-scan angle ζ. Furthermore, we limited ourselves to 4% of the measurements from only one of the 16 strips of CCDs and took into account only those sources observed at least three times. This amounted to 140 000 measurements of 30 000 sources. While we began with 'correct' starting values for all other unknowns, we assumed a somewhat wrong along-scan calibration of the CCDs. The top panel of Figure 4 shows the distribution of the observed minus calculated along-scan angles η before the first ODIS iteration. It is clearly visible that the observations from both fields of view (FoVs) do not fit together and result in a bimodal distribution. After the first iteration (centre panel), both distributions came closer together, and after 50 iterations we have a single distribution with a sharp peak of only 3 μas width (bottom). However, besides the sharp peak we also find a broad background of strongly deviating η values. In Figure 5 we plot the observed minus calculated η vs. time for both FoVs and see that the strongest deviations from zero occur where the density of elementary measurements is small. This reflects the varying density with galactic latitude amplified by our negligence of those stars which have been observed less than three times. Therefore, while one FoV may be in a region of low density of considered sources the other may be in a high density region, giving very unequal weight. This makes it impossible for the attitude parameters to converge and leads to the broad background in Figure 4. We expect that this effect is strongly reduced if a higher number of observations are taken into account and if we require only one repeated observation of every source.

However, our simulation clearly shows that the vast majority of the ηs is concentrated around zero in the observed minus computed diagram after the iterations so that we conclude that our software works properly.

In a next step we repeated the same procedure with Gaussian noise of 0.1 mas in along-scan and 2 mas in across-scan direction. Noise was also present in the initial approximation of the attitude. The latter value would be a realistic error estimation if we had a relatively precise calibration of the ASMs. Note, that this sort of calibration cannot be performed within the ODIS but would – before the first GIS – need a separate calibration step (see Section 6). Differently from the case of our simulation with the 'true' data, we started with the 'correct' CCD calibration. The top panel of Figure 6 shows the deviations of the observed from the calculated ηs before the first iteration, the lower panel the distribution after 26 iterations. The width of distribution is consistent with the assumed accuracy of the data and an average number of observations per source of 4. Due to the large total number of observations, even small deviations of this width from the expected one will allow a diagnosis of possible problems in calibration and attitude, particularly if further investigated in time (as Figure 5).

The ODIS by itself will not directly show the degeneracy of the problem. Another disadvantage is that there is no guarantee that the block-iterative scheme will converge to the correct solution.

By investigating a simple partially degenerate problem, Jordan & Bastian (2004) could show that the convergence behavior strongly depends on the block sequence, on block size, and on the block composition. It turned out that it would be an advantage to split up all three blocks (for attitude, sources, calibration; global parameters cannot be taken into account in ODIS so that the global block is omitted) into six blocks solving for along and across-scan, or more precisely, in direction of the RGC and perpendicular direction, separately. This would extremely accelerate the convergence and minimize the contamination of the solution of the well defined along-scan unknowns by the ill-conditioned across-scan unknowns. The attitude block, i.e., will be split up into a block for the quaternion components q_1 and q_2 for the across-scan directions, while the block for q_3 and q_4 would solve for the along-scan direction.

The next steps will be to test what kind of information can be gathered if we assume that no across-scan information from the ASMs is available (which would be the case if no across-scan calibration of the CCD is possible). We will also make use of the full data set of simulated data.

By assuming that the CPU time scales linearly with the number of elementary measurements we can already estimate the amount of data and the computational time for such a longer run with 300 times more observations: Each iteration will need about 10 hours on a 2 GHz Pentium III. When optimized, four ODIS iterations should be sufficient. Since the solutions for the astrometric parameters for each star are independent from each other the major part of the ODIS can easily be parallelized. Thus ODIS seems easily feasible computationally.

4.2. The Ring Solution

The limited number of unknowns during one day makes it possible to try a direct solution of the problem rather than an iterative solution. Such an approach makes it possible to further analyze the degeneracy of the problem in more detail and allow diagnostics which are not available in the case of iterative methods.

After initializing counters, matrices, *a priori* approximations of attitude and calibration, the process starts a loop over the relevant observations, in a source-by-source sequence. All available observation equations of a given source are set up and accumulated into normal equations (i.e., normal-equation matrix and right-hand side vector).

Next we analyze every submatrix for the source unknowns separately in order to find out whether it is degenerate due to insufficient across-scan information. If this is the case, only the along-scan unknowns are retained. We will also investigate analytically whether all sources having only one field-of-view transit must be eliminated.

The remaining non-degenerate source part is then directly eliminated from the entire normal-equation contribution of this source, using a Gauss elimination scheme. This leaves a reduced system of normal equations for the calibration and attitude unknowns only.

These reduced equations are accumulated in a source-by-source fashion, until the complete normal equations for the reduced problem (calibration and attitude unknowns only) have been set up.

The well-known, obvious degeneracies of any global astrometric adjustment (rigid rotation of the adjusted system with respect to inertial, astronomical space) are eliminated by adding simple, well-demonstrated constraints.

The eigenvalue spectrum allows to judge the condition of the system and restrict it to the non-degenerate dimensions. The restricted system is solved, using a Moore-Penrose pseudo-inverse of the normal-equation matrix.

Afterwards, the reduced solution is back-substituted into the source parts, yielding the source unknowns and — finally — the residues of the individual measurements.

The whole procedure can be iterated a few times, for various purposes:

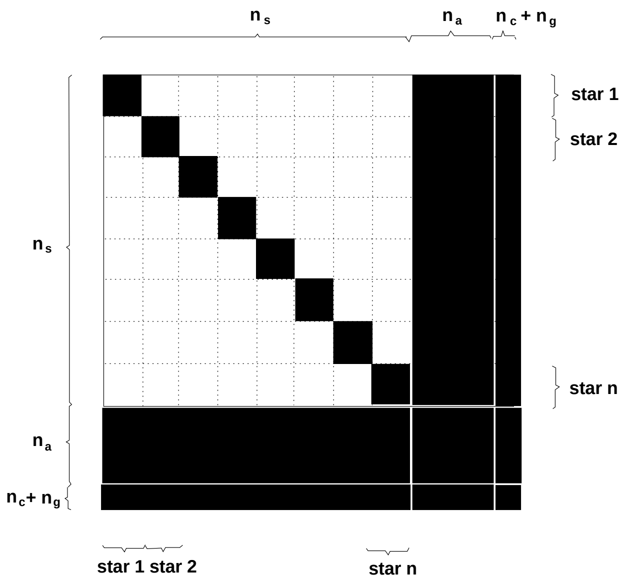

Figure 7. Structure of the normal equation matrix. n_a, n_s, n_c, and n_g denote the number of attitude, source, calibrational, and global unknowns. The submatrix for the source unknowns can be divided into small independent blocks allowing a star-by-star solution after the large blocks for the attitude, and calibration parameters has been evaluated. n_g is zero for FLP.

- to get rid of the (small) non-linearities in the problem
- to omit discordant individual measurements ('outliers')
- to omit disturbed sources (unresolved doubles, variables, extended objects, ...)

The basic structure of the normal equations is seen in Figure 7. The largest block that has to be solved as one block is a matrix containing a few thousand attitude B-spline coefficients and a few hundred calibration parameters.

In the near future we will begin numerical tests with the Ring Solution with the same input data that we used for the ODIS. We can then compare the strengths and shortcomings of both methods in terms of computing time, memory demand, and possibilities to build up First-Look monitoring tools for the DFL. We expect that ODIS will be much faster, but particularly a detailed study of the rank deficiencies should be possible only with the Ring Solution. Nevertheless, the two methods will complement each other so that both paths should be followed.

Our current estimate on a 2 GHz Pentium III system is that about 800 hours of CPU time are needed if the procedure is iterated two times for the whole 24 hour data set. This number is actually not alarmingly high because we believe that several optimizations in the numerical scheme and the applied methods are possible. Moreover, at the time of Gaia much faster computers will be available. Many parts of the Ring Solution can also be parallelized.

More details of the Ring Solution can be found in Bernstein & Bastian (2004).

In principle one could consider a direct method similar to the Ring Solution as an alternative to the GIS. It has, however, to be analyzed whether the much larger number of attitude unknowns will allow such a solution with reasonable computational effort. Since we do not expect degeneracy problems as serious as in the Ring Solution for a single day, one would not so much depend on the knowledge of the inverse of the normal equations. Therefore, more efficient mathematical methods to solve such equations without inversion, like Krylov subspace methods may allow the application of direct methods for the astrometric solution of the Gaia data.

5. THE DETAILED FIRST LOOK

The goal of both FLP methods is to find out whether the measurements lie within the predicted error range so that the mission's objectives can be reached. The basic procedure to achieve this goal is an in-depth investigation of the astrometric residuals after FLP, and of the astrometric unknowns derived from FLP and their variances and covariances, respectively. A careful analysis of the time dependence of the residuals by means of power spectra, wavelet analysis, or filtering is important. If periodic or other correlated oscillations occur, they can be used to test or update the mechanical model of the satellite. It is also planned to search for a dependence of the residuals on object classes with the help of auto-correlation functions, e.g., with respect to brightness and colour. In order to understand the details (e.g., mean, variance, and kurtosis of χ^2 distribution functions, auto-correlations) of the observed data, simulations under various physical hypotheses will be performed. Sophisticated hypothesis testing methods will then allow a detailed diagnostic of the behaviour of the satellite.

6. CALIBRATION AND ZERO-NU-DOT MODE

A basic problem of any kind of 24-hour astrometric solution is the lack of across-scan information. Even a limited knowledge in r direction would extremely reduce the degeneracy of the problem.

Prerequisite for such a measurement would be an accurate calibration of the ASMs. Since no ground-based calibration would be exact enough this has to be done in space. Ideally one would use a large number of observations of the same stars with well known positions in as many as possible scan directions.

The normal Gaia scanning law is quite inappropriate for this purpose since the nodes of the scanning law are moving too fast to allow multi-direction measurement of the

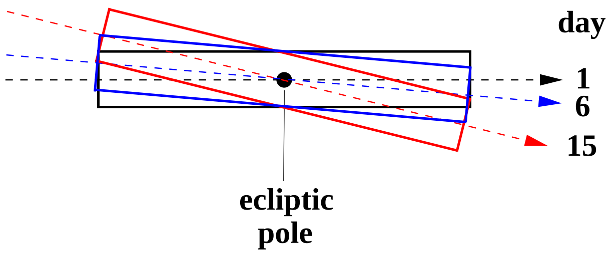

Figure 8. In the zero-nu-dot mode the satellite axis remains on the ecliptic 50° away from the Sun. Therefore, the ecliptic poles are the nodes of this scanning law. The scan direction changes by about 1° per day so that the stars around the ecliptic pole are measured in increasingly different directions.

same ensemble of stars in a short time interval. For this reason, a somewhat modified scanning law would help for the initial calibration: We propose that at the beginning of the mission or during the commissioning phase on the transfer to L2 the scan axis should remain on the ecliptic preceding or following the Sun at the nominal $50°$ angle. The precessing revolving angle ν of the nominal scanning law will remain constant in this phase. This is why we call this the zero-nu-dot ($\dot{\nu}$) mode. ν itself would be either $0°$ or $180°$. The nodes of this scanning law are the two ecliptic poles. Since the Sun moves by about $1°$ per day, the stars directly at the poles will be observed under increasingly different scan directions. Within 15 days we have already measurements differing up to $15°$ (see Figure 8).

This mode could be prepared and augmented complemented by high-precision ground-based observations of a few thousand stars around each of the ecliptic poles, aiming at *relative* astrometry with a precision of a few mas, performed shortly (a year or so) before the launch of Gaia. This would give an instant in-orbit astrometric across-scan calibration of Gaia at the mas level, even without FLP, i.e., on the ScQL level. If we limit the prelaunch astrometry to two circles of $1°$ radius around each pole we expect about 8000 stars with $V < 16$ at this galactic latitude (Allen 1973). This is the minimum, an optimum would be twice the radius, i.e., four times as many stars. Besides an improved calibration we would also obtain a first small ensemble of stars at the ecliptic poles with positional improvement from Gaia.

CONCLUSIONS

We have demonstrated the need of a First Look task for the Gaia mission. In particular the DFL on an astrometric level performed on a daily basis will significantly reduce the risk of losing valuable observing time due to problems which would otherwise become apparent after about half a year of data collection. The necessary FLP is by no means trivial due to much larger accuracy of the measurement along the RGC compared to the perpendicular direction. This drawback can partially be reduced when an in-flight calibration of the ASMs during the commissioning phase can be performed, e.g., with the help of a zero-nu-dot scanning mode.

The major and most complicated part of the First-Look task consists of the FLP which can be performed either by a block-iterative procedure (ODIS) or a direct (Ring) solution. Our first computational tests show that the ODIS will be computationally easy. With the help of the Ring solution we expect to develop more sophisticated diagnostic tools and have estimated that this method – although more CPU time demanding than the ODIS – will also be feasible with affordable computational effort.

ACKNOWLEDGMENTS

We are grateful to Lennart Lindegren for providing us FORTRAN routines for the GIS (LL37.f). We also thank Eduard Masana and his collaborators for producing the tailor-made simulated data for a 24-hour period.

REFERENCES

Allen, C.W. 1973, Astrophysical Quantities, third edition, Athlone Press, London, p. 244

Bernstein, H.-H., Bastian U., 2004, Gaia Technical Report Gaia-ARI-BST-001

ESA, 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200, Vol. 3

ESA, 2004, Gaia — Composition, Formation and Evolution of the Galaxy, Concept and Technology Study Report, ESA-SCI(2000)4

Jordan, S., Bastian, U., 2004, Gaia Technical Report Gaia-ARI-SJ-001

Jordan, S., Lenhardt, H., & Bastian, U. 2004, Gaia Technical Report Gaia-ARI-SJ-002

Lindegren, L. 2001, Gaia Technical Report Gaia-LL-34