HIGH-ACCURACY TIMING FOR GAIA DATA FROM ONE-WAY TIME SYNCHRONIZATION

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ABSTRACT. This work contains a brief description of the algorithms behind the timing subsystem of the Gaia data processing. The reading of the free-running atomic clock on board of Gaia should be related to the widely used time scales like TCB. The accuracy requirements for the data timing for Gaia are summarized. To monitor the synchronization between TCB and the on-board clock Gaia implements the one-way clock synchronization scheme. The available data and the algorithms used for the time synchronization are discussed.

1. REQUIREMENTS FOR THE GAIA DATA TIMING

The second ESA astrometry mission Gaia launched on 19 December 2013 successfully passed the scrutiny of the commissioning phase and delivers scientific data since July 2014. This paper is devoted to one particular aspect of the Gaia data processing: expressing the Gaia-internal time tags of each observation in terms of widely-used time scales like TCB, which can be used e.g. to interrogate solar system ephemerides or to link Gaia observations with observations performed by other instruments.

Each observation of Gaia is internally tagged with the corresponding reading of the Gaia clock latched at some fiducial event defined within the time span taken by that individual observation. A free-running clock is installed on board of Gaia and produces time tags which are called On-Board Time (OBT). OBT is a technical time scale which reflects all the imperfections of the particular clock. OBT can also have jumps related to the resets of the clock (in some technical conditions the Gaia clock can be automatically switched off before being switched on again). In this way OBT remains a purely technical time scale with no a priori relation to the widely-used time scales like TCB that are realized by Earth-based ensembles of clocks via TAI or TT.

The timing requirements for Gaia are tricky and represent a source of confusion even within the Gaia Data Processing and Analysis Consortium (DPAC). As usual in the time science, one should carefully distinguish between *stability* and *accuracy* of the timing information.

All the digital electronics on board of Gaia (e.g., the CCDs) must be driven by some frequency standard. Many space missions use a sort of quartz (crystal) oscillator to drive the on-board electronics. A space-qualified crystal oscillator has a stability of typically 5×10^{-5} in a very large range of temperature. This stability can improve to about 5×10^{-7} in the thermally stable environment of Gaia, but it is still very far from the Gaia requirements. Indeed, Gaia rotates with angular velocity of $60''$/sec or 0.6 microarcsecond in 10 nanoseconds. The ultimate accuracy of centroiding for one observation is expected to be at the order of ten microarcseconds. No systematic errors over the rotational period (6 hours = 21600) should be introduced by the clock performance. This means that the timing error should be below 10 nanoseconds over the period of 21600 seconds, which implies the frequency stability of the on-board clock below 10^{-12}. For this reason Gaia spacecraft has got an atomic (Rb) clock with the stability reaching $\sim 10^{-13}$ over the Gaia rotational period of 21600 seconds.

The accuracy requirements for the OBT tags are very different in their nature and origin. A shift in the Gaia clock phase or in its frequency would be no problem in a purely Gaia-internal data processing (as long as the frequency stability remains at the level discussed above). The relation between the OBT readings and some Gaia-external time scales becomes important as soon as some auxiliary data are used in the data processing. Those auxiliary data (e.g. Gaia or solar system ephemerides) are usually parametrized using some TAI/TT-based time scale (TT, UTC, TCG, TCB, etc.) and the relation between OBT and, say, TCB is needed to interrogate the auxiliary data with the correct argument. Similarly, analyzing some time-dependent phenomena or predicting some astronomical events one wishes to express the analysis in terms of generally available time scales. One can think of several different sources of requirements coming from different types of time-dependent astronomical phenomena: variability of stars, motion of binary stars, motion of asteroids, etc. On the other hand, the *model* describing Gaia observations uses time-dependent positions and velocities of Gaia and massive solar system bodies and they should be computed at the correct moments of time. Taking into account all these applications, the official goal for the timing accuracy for Gaia was taken to be 1.7 microseconds. This number resulted from an assessment of the level of accuracy achievable without any upgrade of the timing hardware available at the ESA ground stations.

It is clear that at the level of accuracy better than a few milliseconds the modeling of the Gaia clock must be relativistically meaningful. This means in turn that the atomic clock of Gaia could be used to test tentative violations of the Local Positional Invariance. From this point of view, it is useful to model the timing data as careful as possible to reach maximal possible accuracy. It should be stressed that further increase of the accuracy can be reached only by improving the data processing algorithms and careful assessment of the input data. No additional observational efforts are required.

2. ONE-WAY CLOCK SYNCHRONIZATION DATA

There are many technical ways to synchronize remote clocks (see, e.g. Klioner, 1992). In principle, for a microsecond accuracy with a pair of clocks separated by 1.5 million kilometers, one would think of the so-called two-way clock synchronization as the most appropriate method. In this method a special signal generated on a reference station is sent to the remote clock (to Gaia), where it is received and, after some well-calibrated delay, re-transmitted back to the reference station together with the time reading of the remote clock at which the signal was received. The well-known advantage of this method is that the errors in the position of the remote clock don't directly deteriorate the resulting accuracy. This is also true for the tropospheric delay: the delays on the way from the ground station to the remote clock and back largely cancel out.

However, the hardware readily available on the ESA Tracking Stations (ESTRACK) is not prepared for the two-way clock synchronization and this option was dropped early at the design stage of Gaia. A straightforward one-way clock synchronization scheme was implemented instead. In the application to Gaia this scheme can be summarized as follows:

(1) a signal is generated on board of Gaia that contains the momentary (latched) OBT value – we denote it by OBT_k – and initiates the process of transmission of a special data packet, called "time packet" to the ground station;
(2) after some on-board delay the time packet is emitted from Gaia to the ground station;
(3) the time packet propagates all the way from Gaia to the phase center of the ESTRACK station antenna;
(4) after some ground-station delay the content of the time packet (in particular, the value of OBT_k) is registered by the ESTRACK station hardware by assigning the corresponding value of UTC – we denote it by UTC_k – and storing the time couple $(\mathrm{OBT}_k, \mathrm{UTC}_k)$ in the database.

Thus the raw data for the time synchronization is a series of the time couples $(\mathrm{OBT}_k, \mathrm{UTC}_k)$. These time couples are obtained at irregular intervals of time with a typical interval of 1.5 sec between the subsequent time couples within the visibility periods, that is, the periods of time during which Gaia communicates with one of the ESTRACK stations. The visibility periods range between about 3 and 16 hours depending on the data volume that needs to be transmitted from Gaia to the ground.

3. LOW-ACCURACY TIME TRANSFORMATIONS

Beside the purely scientific use summarized above, the relation of OBT and, say, UTC is required for the technical control of the spacecraft. All the control commands to be sent from the European Space Operation Center (ESOC) to the Gaia spacecraft must be time-tagged in OBT since it is the only timing information that is available on board for the Gaia hardware and software. The required accuracy of this time transformation is at most 1 millisecond (even 0.1 sec can be often tolerated). The ESOC team generates this lower-accuracy time transformation between UTC and OBT independently of Gaia DPAC. This is termed "time correlation" and is done by fitting a straight line to the moment $\mathrm{UTC}_k^{\mathrm{em}}$ as function of OBT_k using some selected number of time couples. Here $\mathrm{UTC}_k^{\mathrm{em}}$ is the computed UTC moment of emission of the signal, which was received at the moment UTC_k. The moment $\mathrm{UTC}_k^{\mathrm{em}}$ is computed by subtracting the light travel time from UTC_k. The light travel time is computed used a predicted orbit of Gaia and neglecting tropospheric delay. The deviation of newly coming time couple data from the last computed linear relation between UTC and OBT is automatically checked. As soon as the deviation exceeds some limit, the operator is supposed to initiate the computation of the new linear relation. In this way one gets a piecewise linear relation between UTC and OBT. The validity intervals of individual linear functions range from a few hours to several weeks. The overall accuracy of the OBT synchronization obtained in this way reaches a few milliseconds.

Within the Gaia DPAC this ESOC product is used to generate the so-called Low Accuracy Time Transformation (LATT), which still uses a piecewise-linear fit between OBT and UTC, but is optimized in a number of ways to minimize the deviation from the timing data (time couples). The generation of the LATT is done immediately after the end of each visibility period of Gaia. The accuracy of the LATT is usually about 0.5 millisecond, but can vary depending on the operational circumstances. This level of accuracy is enough for the daily operations of Gaia (for all the tasks in the Gaia data processing chain that are performed immediately after receiving the next potion of the data). Since the LATT can also be generated immediately after the data become available, the LATT is used by the Gaia DPAC for daily operations.

However, the accuracy of LATT is not sufficient for the final data processing where a substantially higher accuracy is required. To improve the accuracy further, one needs to improve the model used to interpret the timing data. The deficiencies of the LATT modeling are obvious. The idea to directly correlate "UTC of emission" and OBT ignores all relativistic effects and mixes the errors of the Gaia clock with the relativistic effects between the proper time of Gaia and UTC. The latter effects are substantially non-linear and directly deteriorate the validity intervals and accuracy of the LATT.

For this reasons, a more rigorous high-accuracy approach for the Gaia clock synchronization was developed. This approach is called High Accuracy Time Transformation (HATT) The accuracy of HATT is supposed to reach the level of about 1 microsecond matching the accuracy requirements discussed above.

4. HIGH-ACCURACY TIME TRANSFORMATIONS

The HATT algorithm is a rigorous and straightforward relativistic model for the one-way clock synchronization data described in Section 2 above. The algorithm explicitly introduces the proper time of Gaia, which is denoted TG and represents an ideal clock located at the Gaia center of mass. The displacement of the Gaia's atomic clock from the Gaia center of mass is fully negligible in the current context. This means that the deviation between OBT and TG solely reflects the errors of the Gaia Rb clock.

TG can be computed as function of TCB using the ephemerides of Gaia and massive solar system bodies. The relation between the proper time of Gaia $\tau = \mathrm{TG}$ and $t = \mathrm{TCB}$ is given by the basic relation of metric gravity theories:

$$\frac{\tau}{dt} = 1 + f(t), \tag{1}$$

$$f = \frac{1}{c^2}\,\alpha(t) + \frac{1}{c^4}\,\beta(t) + \mathcal{O}(c^{-5}), \tag{2}$$

where $\alpha(t)$ and $\beta(t)$ are defined by the metric tensor of the BCRS and the usual relations of General Relativity:

$$\alpha(t) = -\frac{1}{2}\,v_o^2 - \sum_A \frac{GM_A}{r_{oA}}, \tag{3}$$

$$\begin{aligned}\beta(t) = {} & -\frac{1}{8}\,v_o^4 + \left(\beta - \frac{1}{2}\right)\left(\sum_A \frac{GM_A}{r_{oA}}\right)^2 + (2\beta - 1)\sum_A \left(\frac{GM_A}{r_{oA}} \sum_{B\neq A} \frac{GM_B}{r_{AB}}\right) \\ & + \sum_A \frac{GM_A}{r_{oA}} \Bigg(2(1+\gamma) v_A^i v_o^i - \left(\gamma + \frac{1}{2}\right) v_o^2 - (1+\gamma) v_A^2 + \frac{1}{2} a_A^i r_{oA}^i \\ & + \frac{1}{2} (v_A^i r_{oA}^i / r_{oA})^2 \Bigg).\end{aligned} \tag{4}$$

Here $\mathbf{r}_{oA} = \mathbf{x}_o - \mathbf{x}_A$, $\mathbf{x}_o$ and $\mathbf{v}_o$ are the BCRS position and velocity of Gaia, index A enumerated gravitating bodies of the solar system, $\mathbf{x}_A$ and $\mathbf{v}_A$ are the BCRS position and velocity of body A, and GM_A is the mass parameter of that body. Similar to the treatment in (Klioner et al. 2010) we introduce here functions $\delta t(t)$ and $\delta\tau(\tau)$ as

$$\tau = t + \delta t(t), \tag{5}$$
$$t = \tau - \delta\tau(\tau). \tag{6}$$

Substituting these definitions in (1) one gets

$$\frac{d\delta t}{dt} = f(t), \tag{7}$$
$$\frac{d\delta\tau}{d\tau} = \frac{f(\tau - \delta\tau(\tau))}{1 + f(\tau - \delta\tau(\tau))}. \tag{8}$$

These relations are exact. The expression for $f(t)$ given above is approximate. The initial conditions for these differential equations come from the condition that τ = TG is numerically equal to t = TCB at some moment $t = t_0$: $\tau(t_0) = \tau_0 = t_0$. This condition is equivalent to

$$\delta t(t_0) = 0, \tag{9}$$
$$\delta\tau(\tau_0) = 0. \tag{10}$$

The initial condition for TG is in principle arbitrary and is fixed as $\tau_0 = t_0$ =JD2457023.5 TCB (2015 January 01 00:00:00.0 TCB). With these initial conditions, Eqs. (7)–(8) are integrated numerically using the solar system and Gaia ephemerides. The results of numerical integration are represented as Chebyshev polynomials (Newhall, 1989; Klioner, 2010) thus giving time ephemerides for the transformations between TG and TCB in both directions. As solar system ephemeris a special TCB-based ephemeris INPOP10e is used. Gaia ephemeris is updated once per week by the flight dynamics team of ESOC. The TG–TCB transformation is updated as soon as a new version of Gaia ephemeris is received. All time transformations relevant for Gaia data processing and the details of their implementation are summarized in (Klioner, 2010).

The overall idea of the HATT modeling is to construct a smooth relation between OBT and TG. As it was already pointed out, this relation reflects only the imperfection of the Gaia Rb clock. Since the Rb clock is of very high quality one can expect a simple relation between OBT and TG. On the other hand, the OBT–TG relation represents physical model of the Gaia clock as if the clock would be monitored in a laboratory. In this way the health status of the clock and its performance can be directly assessed.

As a mathematical model for the relation between OBT and TG one can choose piecewise linear or piecewise quadratic function to account for frequency offset and frequency drift that are typical for a Rb clock. Because of the rotation of Gaia, one should expect certain temperature variations in the service module of Gaia, where the clock is located. Those temperature variations can lead to periodic variations of the clock frequency. If the data show periodic variations of OBT with respect to TG with a period of 6 hours, this variation can be easily fitted in the model together with the quadratic or linear polynomial.

Before the clock model between TG and OBT can be constructed, one needs to recompute the raw time couples $(\mathrm{OBT}_k, \mathrm{UTC}_k)$ into the couples of OBT and TG corresponding to one and the same physical event. Various physical events can be chosen, but the most natural choice seems to be the event of the emission of the signal corresponding to the time couple $(\mathrm{OBT}_k, \mathrm{UTC}_k)$. The HATT modeling scheme is depicted on Fig. 1. The scheme can be summarized as follows:

(A) The on-board delay $\Delta_{\mathrm{on-board}}$ is added to the latched OBT value OBT_k to get the OBT moment of emission:

$$\mathrm{OBT}_k^{\mathrm{emission}} = \mathrm{OBT}_k + \Delta_{\mathrm{on-board}}\,. \tag{11}$$

The on-board delay $\Delta_{\mathrm{on-board}}$ depends on the particular telemetry mode used at the moment of observation.

(B) The corresponding value of TG at the moment of emission $\mathrm{TG}_k^{\mathrm{emission}}$ is computed from the registered UTC value UTC_k in several steps:

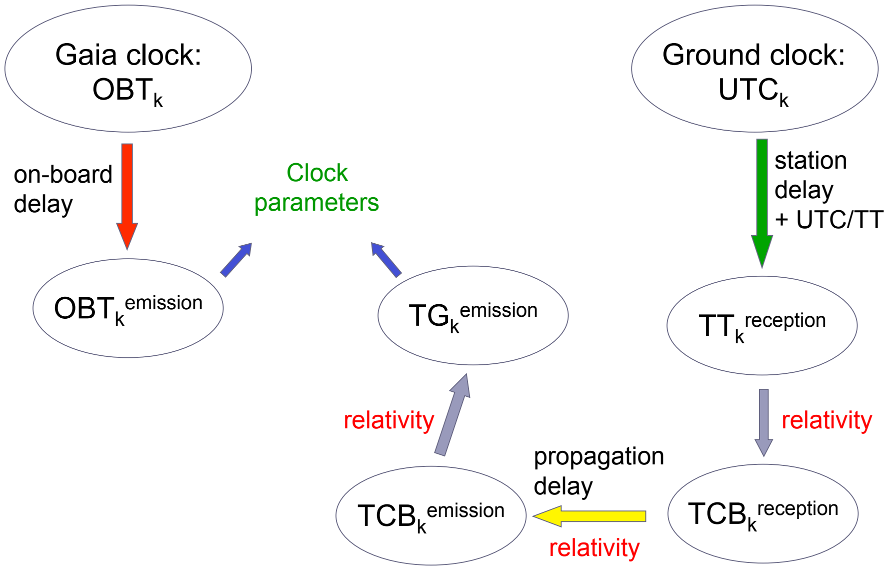

Figure 1: The HATT modeling scheme (see text for further details)

(a) The ground-station delay $\Delta_{\rm gs}$ is subtracted from the recorded UTC value UTC_k to get the UTC moment of reception:

$$\mathrm{UTC}_k^{\rm reception} = \mathrm{UTC}_k - \Delta_{\rm gs}\,. \tag{12}$$

The ground-station delay $\Delta_{\rm gs}$ again depends on the particular telemetry mode used at the moment of observation.

(b) The moment of reception in $\mathrm{TCB}_k^{\rm reception}$ is computed using the relativistic time transformations (Klioner, 2010):

$$\mathrm{UTC}_k^{\rm reception} \longrightarrow \mathrm{TAI}_k^{\rm reception} \longrightarrow \mathrm{TT}_k^{\rm reception} \longrightarrow \mathrm{TDB}_k^{\rm reception} \longrightarrow \mathrm{TCB}_k^{\rm reception} \tag{13}$$

Note that the transformation between TT and TDB is 4-dimensional and requires the position of the ground station in BCRS (this implies the use of the Earth orientation in space).

(c) The TCB moment of reception $\mathrm{TCB}_k^{\rm reception}$ is used to compute the TCB moment of emission of the corresponding signal by Gaia $\mathrm{TCB}_k^{\rm emission}$. Here one should account for the tropospheric delay $\Delta_{\rm tropo}$ and compute the TCB time interval that the signal needs to propagate from Gaia to the ground station in BCRS. This includes an solution of the implicit equation:

$$\mathrm{TCB}_k^{\rm emission} - \mathrm{TCB}_k^{\rm vacuum} = c^{-1}\,R + \Delta_{\rm pN}\,, \tag{14}$$

$$\mathrm{TCB}_k^{\rm vacuum} = \mathrm{TCB}_k^{\rm reception} - \Delta_{\rm tropo}\,, \tag{15}$$

$$R = \left|\mathbf{x}_o(\mathrm{TCB}_k^{\rm emission}) - \mathbf{x}_{\rm gs}(\mathrm{TCB}_k^{\rm vacuum})\right|\,, \tag{16}$$

$$\Delta_{\rm pN} = \sum_A \frac{2GM_A}{c^3}\,\log\frac{r_A + r_{A0} + R}{r_A + r_{A0} - R}\,, \tag{17}$$

$$r_A = \left|\mathbf{x}_o(\mathrm{TCB}_k^{\rm emission}) - \mathbf{x}_A(t_A^*)\right|\,, \tag{18}$$

$$r_{A0} = \left|\mathbf{x}_{\rm gs}(\mathrm{TCB}_k^{\rm vacuum}) - \mathbf{x}_A(t_A^*)\right|\,, \tag{19}$$

where $\mathbf{x}_o(t)$ is again the BCRS position of Gaia, $\mathbf{x}_{\rm gs}(t)$ is the BCRS position of the relevant ESTRACK station (both are computed as functions of TCB), and $\Delta_{\rm pN}$ is the relativistic (Shapiro) light propagation delay in BCRS. In (17) at least the Sun must be taken into account here, but the Earth and Jupiter may also play a role. The TCB moment t_A^* is given by the implicit equation

$$c\,(\mathrm{TCB}_k^{\rm vacuum} - t_A^*) = \mathbf{r}_{A0}\,. \tag{20}$$

The latter equation can be solved by iterations (one Newton-like iteration is sufficient here).

(d) The TCB moment of emission $\mathrm{TCB}_k^{\mathrm{emission}}$ is recomputed into the corresponding moment of the Gaia proper time TG_k:

$$\mathrm{TCB}_k^{\mathrm{emission}} \longrightarrow \mathrm{TG}_k \tag{21}$$

This is done using the TG–TCB time ephemeris described above (Klioner, 2010).

From this description, it is obvious that the HATT data processing requires a number of additional data. First, four sorts of constants are required for each ESTRACK station:

(i) the ITRS coordinates (this includes the Cartesian coordinates as well as the height above the horizon);
(ii) the coefficients of the mapping function for the tropospheric delay (the dry and wet Niell mapping functions are used; a total of 9 coefficients per station);
(iii) the adjustment of the dry delay due to the altitude difference of the barometer and the intersection of the azimuth and elevation axis of the antenna (used to compute the zenith delay from the Saastamoinen model);
(iv) the ground-station delays Δ_{gs} for each telemetry mode.

All these constants were provided by ESOC. They were known previously (from the data processing of previous missions) or determined specially for Gaia using dedicated measurements. The manufacturer of the Gaia spacecraft (Airbus DS) has provided another type of constants:

(v) the on-board delays $\Delta_{\mathrm{on-board}}$ for each telemetry mode.

In addition to these constants the following data series are needed:

(vi) Gaia orbit (updated once per week by the ESOC flight dynamics team);
(vii) meteorological data – temperature, pressure and humidity – at the relevant ESTRACK station sampled once per minute (used to compute dry and wet tropospheric delays at zenith);
(viii) information on the telemetry modes used at the time of transmission of each time couple;
(ix) the Earth orientation parameters from the IERS (C04 series from `http://datacenter.iers.org/eop/-/somos/5Rgv/latest/214`; used to compute the BCRS positions of the ground stations).

The overall modeling accuracy of this algorithm is better than 30 nanoseconds and is limited by the error of the distance between Gaia and ground stations. This error can reach 10 meters. This accuracy is more than enough for all tasks in Gaia processing. The HATT data can be updated as soon as a new potion of the timing data and the auxiliary data becomes available. Typically, the auxiliary data are updated with a delay of about one month.

As it was announced earlier, all Gaia products will be parametrized by TCB, which is the most natural coordinate time for both stellar motions and solar system dynamics and does not require any ad-hoc re-scaling of astronomical constants and coordinates.

Let us stress that UTC in its current definition plays a negative role for Gaia. UTC is traditionally used in the ESA ground segment (e.g. as master time on the ground stations) and it is hardly possible to change this tradition. However, non-physical nature of UTC (its unpredictable discontinuity because of the leap seconds) directly implies a loss of precious observational data in a significant interval of time around the newly introduced leap seconds. One can only hope that the definition of UTC will be changed and no further leap seconds will be introduced starting from some time in the future.

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