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Absolute time stamping with Athena

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ABSTRACT

Athena's mission requirement R-MIS-390 specifies that the mission shall perform all observations with an absolute photon timing accuracy better than 50 microseconds. This note proposes an absolute time accuracy budget – based on a one-way time-synchronisation (clock-calibration) scheme similar to the one currently successfully applied for XMM-Newton, Integral, and Gaia – that supports a much more stringent, microsecond-level requirement. The proposed allocation is presented in Section 5.5 and an executive summary is provided in Section 6.

1 INTRODUCTION

The Athena Mission Budgets Document (MBD) [RD 01] provides a preliminary absolute time accuracy budget, based on XMM-Newton and Integral experience, compatible with the 50-microsecond mission requirement. This note takes a fresh look at absolute timing of Athena data based on Gaia experience. For Gaia, the absolute time accuracy requirement at mission level is 2 microseconds (equally split between ground and space segment) and this requirement is routinely met with significant margin during nominal operations using a time-source-packet-based, one-way[1] clock synchronisation scheme [RD 02]. Since this scheme is based on standard ESA products and procedures in terms of ground stations, spacecraft tracking, mission operations, etc., there is *a priori* no reason why microsecond-level timing accuracy could not be reached for Athena. Pursuing this would make Athena an order of magnitude more accurate than XMM-Newton and would put Athena in the same, microsecond-level regime as RXTE and Chandra (see Section 2).

2 NOMENCLATURE

By absolute timing, we mean the datation of photon arrival times in a relativistically well-defined, reference time scale, for instance UTC (Universal Coordinated Time), TT (Terrestrial Time), or TCB (Barycentric Coordinate Time). Absolute timing is linked to accuracy. By relative timing, we mean the datation of photon arrival times with respect to each other (or between different instruments). Relative timing is linked to precision.

In X-ray terminology, the **relative** timing error is normally understood to be the difference between the period of the Crab pulsar measured in X-rays and the period measured at radio wavelengths evaluated at the epoch of the X-ray observations. For XMM-Newton, this is around 1E-9 [RD 03]. For the **absolute** timing analysis, one normally considers the

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[1] In the alternative, two-way synchronisation method, a signal generated at the ground station is sent to the remote clock, where it is received and, after some (calibrated, so known) delay, re-transmitted back to Earth, together with the time reading of the remote clock at which the signal was received. The advantage of this method is that tropospheric delays cancel out and that errors in the position of the remote clock do not deteriorate the accuracy. However, the hardware available at the ESA (ESTRACK) ground stations is currently not prepared for two-way clock synchronisation.

phase of the main peak of the X-ray profile and measures the phase difference[2] with respect to the corresponding peak of the radio profile. The (random) error with which this phase difference can be determined is known as the absolute timing error. For XMM-Newton, this is 48 microseconds [RD 06], while it is 40 microseconds for INTEGRAL [RD 06], 200 microseconds for XRT (SWIFT) [RD 10], 2 microseconds for RXTE, based on two-way clock synchronisation, after application of the so-called "fine clock correction" [RD 08][RD 09][RD 12], and 4 microseconds for Chandra, measured relative to RXTE [RD 11].

We finally define the time-stamp resolution as the smallest-possible difference in time stamps that can be discriminated in the coding that is employed in the datation. The resolution should be chosen to be (much) smaller than the required absolute timing accuracy (and the relative timing precision), for instance 100 ns or less for Athena, to avoid rounding / discretisation errors. Use of a 64-bit integer for on-board encoding of time stamps is recommended for Athena (in contrast to the 32-bit integer used on XMM-Newton).

3 OVERVIEW OF DATATION

Datation of photons detected by a space mission normally involves four steps: (1) time stamping the event arrival times in on-board time (OBT, generated by the spacecraft master clock) and transmitting this information to ground for all events, (2) during ground-station contacts, frequently generating dedicated, so-called "(standard spacecraft) time source packets" (also known as "time reports") on board, latched with OBT, and transmitting these to the ground station, where they are time tagged in UTC upon reception (this step also involves correcting for on-board delays, propagation delays, and ground-station delays), (3) deriving, based on the series of time source packets accumulated during ground-station contact (visibility[3]), an accurate, continuous relation between OBT and UTC (sometimes referred to as OBT-UTC time correlation or on-board-clock modelling), and (4) applying this relation to convert the OBT reception time of each event on board to UTC (after which it can be converted to any other time scale as/if needed). These four steps are discussed in more detail in the following subsections (see also [RD 02] for an overview of these steps).

Note for completeness: in addition to OBT, which is the high-accuracy time used for science-data time stamping at payload level, there is also a low-accuracy time called

[2] The Crab pulsar-monitoring programme at Jodrell Bank provides monthly timing ephemeris data, reduced to infinite frequency. These timing ephemerides represent fits to the daily time-of-arrival measurements with RMS residuals of the order of 20–50 microseconds. It is furthermore important to note that the radio data has systematic uncertainties at the level of a few dozen microseconds due to uncertainties in the variable amount of pulse delay due to interstellar scattering and imperfect instrument calibrations (e.g., unmodelled delays in filter banks).

[3] We use the words visibility and contact interchangeably although **visibility** formally refers to the possibility – from a geometrical perspective – of establishing a link between the spacecraft and the ground station whereas **contact** refers to the actual existence of such a link.

Spacecraft Elapsed Time (SCET). SCET is generated in the Central Data Management Unit (CDMU) and is used for housekeeping-data time stamping at platform level. SCET is not further discussed in this note but is also subject to correlation with UTC for operational purposes.

In Gaia, OBT is generated in the Clock Distribution Unit (CDU) in the payload, based on an atomic clock. SCET is continuously synchronised with OBT through a Pulse-Per-Second (PPS) mechanism. In Gaia, SCET is hence effectively enslaved to OBT, which is generated by the payload master clock. In Athena, a more logical solution would be to implement a stable master clock in the bus and distribute the time from there to the instruments through a PPS mechanism.

3.1 On-board time stamping

A precise and accurate datation of science data requires a careful design of the on-board time-distribution architecture and selection of a proper master clock, also known as frequency standard (or oscillator). Both of these aspects are beyond the scope of this document but we do mention that, in terms of the master clock, frequency stability and insensitivity to “environmental effects” are the most important aspects. Long-term frequency ageing and drifts[4] – at the level of months or years – are unavoidable but can be calibrated out; short-term frequency instabilities – at the level of hours to days – are more harmful since they hamper the clock calibration (time correlation) during periods without ground-station contact. In terms of “environmental effects”, care should be taken to place the master clock in a suitably shielded, stable, controlled environment. For instance, Gaia’s Rubidium Atomic Frequency Standard (RAFS) frequency-stability sensitivity is small [typical values are <5E-13 per degree Kelvin (temperature), <1E-12 per Volt (power supply), and <3E-13 per Gauss (magnetic-field sensitivity) [RD 05]] but JUICE’s Oven-Controlled Crystal Oscillator (OCXO) frequency-stability sensitivity is significantly larger [e.g., <1E-9 per degree Kelvin (temperature) [RD 04]]. XMM-Newton flies a Temperature Compensated Crystal Oscillator (TCXO) with a temperature sensitivity measured in orbit of ~3E-8 per degree Kelvin [RD 03].

3.2 Time source packet generation

During ground-station contact, dedicated time source packets are frequently generated on board to obtain a series of (OBT, UTC) time couples that form the basis for the clock calibration (time correlation) described in Section 3.3. Following ECSS standards [RD 14], this process of time-strobe-induced time source packet generation is filtered on board, so that the OBT-latch process is only triggered once every N^{th} telemetry transfer frame of virtual channel 0 (VC0), N (a configurable parameter defined in the CDMU) being one of the following: 1, 2, 4, 8, 16, 32, 64, 128, or 256. The ECSS default time-strobe rate is once per 256 VC0 telemetry transfer frames (i.e., N = 256). Since the time source packet

[4] Ageing is normally defined as the change in the oscillator frequency over time due to changes in the oscillator mechanism, such as outgassing. Drift is normally defined as the change in oscillator frequency due to external influences, for example thermal and power cycling.

generation is linked to the VC0 rate – with VC0 containing the real-time essential housekeeping data from the CDMU – it is not constant in time. For instance, VC0 traffic is partly generated by uploaded telecommands, which are acknowledged by the spacecraft on VC0: if telecommands come in bursts, VC0 traffic will peak. Time source packets are generated only during visibility, i.e., during ground-station contact. The clock calibration (time correlation) discussed in Section 3.3 is essentially meant to allow "interpolating" the OBT-UTC relation "defined" during ground-station contacts to non-visibility periods between subsequent ground-station contacts.

Upon arrival of the time source packets at the ground station, their reception time in UTC is determined using the GPS-linked, atomic clock at the ground station. Clearly, "included" in these (OBT, UTC) time couples are (1) on-board delays between latching and transmission, (2) propagation delays between transmission on board and reception at the antenna[5], and (3) ground-station delays between reception at the antenna and recording in the Intermediate Frequency and Modem System (IFMS) at the ground station. Determination of propagation delays involves a geometric delay (the distance between the spacecraft and the antenna, defined in a relativistic sense in the Barycentric Coordinate Reference System, BCRS), the relativistic Shapiro light-propagation delay, and tropospheric delays. Correcting for these delays hence requires auxiliary data, in particular the (reconstructed) spacecraft orbit, Solar-system ephemerides (e.g., Intégration Numérique Planétaire de l'Observatoire de Paris, INPOP), coordinates of the ground stations in the International Terrestrial Reference System (ITRS), International Earth-Orientation Service (IERS) Earth-orientation parameters (i.e., the UT1-UTC difference, the offset of the Celestial Intermediate Pole [CIP – the fictitious axis of the adopted, IAU-2000 precession-nutation model], and motion of the CIP with respect to the terrestrial crust [polar motion]), and a tropospheric-delay model for wet and dry zenith components (plus an elevation mapping function), requiring in turn regularly-sampled meteorological data (temperature, humidity, and pressure) collected at the ground stations during contact periods with the spacecraft.

3.3 Clock calibration (time correlation)

The basic idea behind the time synchronisation based on time source packets is depicted in **Figure 1**. One starts with a time series of time source packets collected during visibility (ground-station contact). These time source packets link OBT of the latch moment on board to the UTC reception time at the ground station.

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5 The CCSDS definition of the ground reception time is the UTC time at which the signal event corresponding to the leading edge of the first bit of the Attached Synchronisation Marker (ASM) that immediately preceded the subject telemetry transfer frame was presented at the antenna phase centre, which is normally defined as the intersection point of the azimuth and elevation axes of the antenna. The first bit of the frame is the first bit following the attached synchronisation marker.

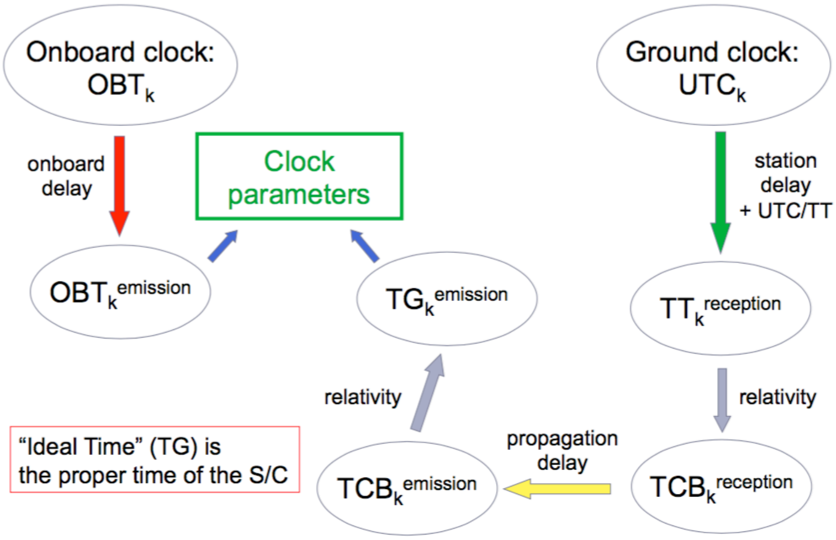

Figure 1 *Basic idea of the clock calibration. A series of time source packets (indexed with subscript k) received during ground-station contact links OBT of the on-board clock to UTC of the ground-station clock. After applying the various delay corrections and (relativistic) time transformations, one can compare OBT with TG (proper spacecraft time). The difference between these quantities reveals the behaviour / errors of the on-board master clock, which can be fitted with a model. Figure courtesy Sergei Klioner.*

First, "on the left", one re-computes OBT of the latch moment into $OBT^{emission}$ by correcting for (known, measured) on-board delays. Second, "on the right", one re-computes UTC into $TG^{emission}$, where TG denotes the proper time of the spacecraft. In other words: TG is an ideal form of OBT, or: an ideal master clock on the spacecraft would show TG, or: OBT is a realisation of TG with all real-life imperfections included (drift, ageing, jumps, etc.). The conversion from UTC to $TG^{emission}$ contains several steps:

- UTC into $TT^{reception}$: (known, measured) station delays plus UTC/TT transformation;
- $TT^{reception}$ into $TCB^{reception}$: TT/TCB transformation at the ground station;
- $TCB^{reception}$ into $TCB^{emission}$: propagation delay (distance, Shapiro, troposphere);
- $TCB^{emission}$ into $TG^{emission}$: TG/TCB transformation at the location of the spacecraft.

The differences $OBT^{emission}$ - $TG^{emission}$ give the best estimate of the on-board-clock errors. Parameters of a model of the clock are therefore finally fitted to obtain the calibration of OBT for arbitrary moments in time, i.e., also covering non-visibility periods. The precise form of the clock model to be used depends on the properties and environment of the on-board clock. One could, for instance, start with a simple model of the form $OBT(TG) = a + b\ TG + c\ TG^2$, where parameter a denotes the phase offset, b denotes the phase drift (i.e., frequency offset), and c denotes the frequency drift. If needed, further terms could be added, for instance to model the clock sensitivity to supply voltage, temperature, etc.

3.4 From OBT to UTC

The last step in the process is to apply the OBT-UTC relation derived above to all events collected and time-stamped on board in OBT. A final challenge awaits: the OBT-UTC relation is only valid for the visibility period it is based on, so the OBT-UTC relation is not continuous yet but consists of N_v-hour visibility stretches followed by (24-N_v)-hour non-visibility periods. More generally, the task is to glue one visibility period to the previous one as well as to the next one. In practice, a fit employing piece-wise-continuous polynomials or quadratic splines could be used.

4 APPLICATION OF THE SCHEME TO GAIA

In this section, we describe how the scheme that is conceptually described in Section 3 is in practice being applied to Gaia (in Section 5, we describe the projected application of the scheme to Athena). The same subsection titles are applied, which means Section 4.1 refers back to Section 3.1, Section 4.2 refers back to Section 3.2, etc. Section 4.5 contains the final, end-to-end Gaia absolute OBT-UTC time-correlation budget.

4.1 On-board time stamping

The Gaia on-board clock is a Rubidium Atomic Frequency Standard (RAFS) from Spectratime, also used in ESA's Galileo spacecraft. Its specified frequency stability (Allan deviation σ_y) is better than 8E-14 over τ = 10,000 s after drift removal. Gaia's flight RAFSs (nominal and redundant) have both been subject to eight-week, ground-based performance campaigns in vacuum to measure their frequency performance over longer time scales, confirming that requirements are met with a measured Allen deviation of σ_y = 7E-14 over τ = 10,000 s. The intrinsic RAFS Allan deviation – ignoring environmental effects – equals σ_y = 3.0E-12 $\tau^{-1/2}$ up to the flicker floor, which sets in around τ = 20,000 s and amounts to σ_y ~ 6E-14; for τ = 120,000 s (~33 h), the measurements indicate σ_y ~ 3E-13. See **Figure 5**.

An alternative way to specify timing requirements is through the Maximum Time Interval Error (MTIE), which is defined as the worst-case phase variation of a signal with respect to a perfect signal over a given period of time. The MTIE is required to be better than 10 ns over 6 hours = 21,600 s [RD 05]; the measured MTIE is less than 3 ns over 21,600 s. For Gaia, the MTIE (95% confidence level) can roughly be approximated by the relation MTIE ~ 2.5 σ_y τ. This gives MTIE = 3 ns for σ_y = 6E-14 and τ = 20,000 s, and MTIE = 90 ns with σ_y = 3E-13 and τ = 120,000 s.

In-orbit experience shows that ageing is negligibly small over non-visibility periods, around -3E-16 per day. Random walk, of the order of at most 100 ns over a few weeks, is also negligible over time scales of a few dozen hours. In addition to drift, ageing, and random walk, the Gaia clock is also subject to frequency jumps. These jumps, typically with Δf ~ 5E-12 and occurring less frequently than once a week, are observed for all atomic clocks in space; their origin is not fully understood, although some jumps are correlated with Rubidium-lamp light-level changes and others may be related to stress relief.

4.2 Time source packet generation

For Gaia, N = 1 is being used to receive as many time source packets as possible on ground, whereas N = 16 is being used for XMM-Newton. For XMM-Newton, the typical time source packet rate is one packet per 20 seconds [RD 03], whereas for Gaia, the typical time source packet rate is one packet per 1.5 seconds [RD 02]. The typical contact period for Gaia is 8–12 hours per visibility period. Contacts are scheduled daily, occasionally (at times of high data rates) involving two ground stations consecutively. In Gaia budgets and timing assessments, it is normally (conservatively) assumed that the single-packet time stamping standard error at the ground station with respect to UTC is 1.0 microsecond (formally, the requirement is 1.1 microsecond); this is the rounded, worst-case (i.e., peak-to-peak) value when linearly summing all contributors (965 ns, see Section 4.5).

4.3 Clock calibration (time correlation)

Two separate aspects need to be discussed: (i) the modelling of the on-board, propagation, and ground-station delays, and (ii) the predictability of the on-board clock over the non-visibility period.

4.3.1 Modelling of delays

For Gaia, the overall modelling accuracy of all delays (and transformations) discussed in Section 3.3 is better than 30 nanoseconds [RD 02]. This error is limited by the knowledge error in the distance between the reconstructed orbit of the spacecraft and the ground station(s), which can reach 10 m (**Figure 4**). This uncertainty essentially reflects the error of an instantaneous range measurement and not the "full, three-dimensional" error of the reconstructed orbit, which is typically smaller than 150 m, but (significantly) larger when the spacecraft is at low declinations, say $|\delta| < 15°$ [RD 17]. Since Gaia's near-Earth-asteroid science case requires the reconstructed-orbit error to be always less than 150 m, special, optical "plane-of-sky" measurement of the spacecraft location with respect to the stars are routinely being collected from ground through the so-called Ground-Based Optical Tracking (GBOT) programme [RD 15]. These data will be processed at MOC, together with the nominal, standard daily ranging and Doppler data (plus occasional Delta-DOR data) as well as the forthcoming Gaia-catalogue positions of the "background stars", in a special effort to improve the accuracy of the reconstructed orbit in the plane of the sky. This better orbit, however, which will be delivered bi-annually by MOC to SOC after the first Gaia Catalogue has been constructed, is of **no** relevance to time correlation since the optical measurements make no significant difference to the accuracy of the spacecraft range determination and spacecraft-orbit reconstruction in the radial, line-of-sight direction. For time correlation, therefore, the **standard** reconstructed orbit derived from **standard** radiometric (Doppler and range) data, which is delivered weekly by MOC to SOC with a six-week delay, is sufficient input.

Besides the high-accuracy, "scientific" time correlation described in this document, which is not achieved instantaneously since the reconstructed orbit is delivered only weekly to SOC with an unavoidable, six-week delay, there is a second time-correlation product, usually referred to as the daily, or operational, or rapid, or instantaneous, or low-accuracy service. This correlation is not performed by SOC but by MOC, "on the fly" inside the Mission Control System (MCS, which is based on SCOS-2000 / S2K), based on the spacecraft predicted orbit and using simplified algorithms (for instance using a linear relation between OBT and UTC and ignoring subtle yet relevant relativistic effects). This time correlation is used for spacecraft operations and also for initial (first-look) science data processing at SOC. The formal (required) accuracy of this product is 1 millisecond, but the typical accuracy in practice is 50–100 microseconds.

4.3.2 Predictability of the on-board clock over the non-visibility period

Based on data extracted from the on-ground tests mentioned in Section 4.1, Monte Carlo simulations have been done to estimate how well the clock behaviour during the non-visibility period can be reconstructed. The following, conservative assumptions have been made:

1. The model of the phase of the on-board clock is quadratic, which means it covers "only" a frequency offset and a frequency drift (temperature-, magnetic field-, voltage-, and radiation-induced variations are ignored).
2. For each Monte-Carlo simulation, the "real" frequency offset is randomly chosen between -5E-10 and +5E-10; the "real" frequency drift is randomly chosen between -5E-12/86,400 and +5E-12/86,400 s^{-1}.
3. The generation and reception rate of standard spacecraft time source packets is one packet per 2.2 seconds during visibility (cf. one packet every ~1.5 seconds in reality).
4. The single-time-packet timing error at the ground station is 1.0 microsecond in the form of white Gaussian noise (the formal requirement is 1.1 microseconds).
5. The daily ground-station visibility period equals 3 hours – which is the minimum contact duration – and is scheduled at the same time each day. In other words: the non-visibility period equals 24 - 3 = 21 hours.
6. The knowledge error of all delay corrections and the modelling error of all timing transformations are negligibly small compared to the 2-microsecond requirement.

In 1000 Monte-Carlo experiments, two subsequent three-hour visibility periods have been used to fit the clock-model parameters – using a quadratic model covering both periods simultaneously – and the resulting model has been used for the timing during the 21-hour non-visibility interval.

The worst-case/RMS clock-calibration performance among the 1000 Monte-Carlo realisations is 0.23/0.05 microseconds over the 21 hours non-visibility (when introducing a missed visibility period, the worst-case/RMS performance degrades to 0.52/0.10 microseconds over the 45 hours non-visibility). It should be realised, however, that the covariance properties of the time-packet reception errors are not known (and will never be known: quantification is deemed unfeasible by MOC). In particular, the assumption of uncorrelated Gaussian noise is violated in practice due to systematic synchronisation errors of ground(-station) clocks (see Section 4.4). In the most extreme case, with full error correlation between all packets in a visibility period, the clock-calibration performance does not improve with the number of time source packets so that the worst-case clock-calibration performance would be 1.0 microsecond. In reality, the true worst-case performance is expected to be somewhere between the two extreme cases, i.e., the 0.23 microseconds Gaussian results on the one hand and the constant 1.0 microsecond on the other hand.

The above assessment, which is based on pre-launch test data and simulations, has recently been confirmed based on in-flight experience: the assessment presented in [RD 13] demonstrates that the residuals of the clock calibration are below 1 microsecond (**Figure 2**).

4.4 From OBT to UTC

The task of gluing the clock calibration of one visibility period to the previous one as well as to the next one is achieved in practice for Gaia using a quadratic spline. Four issues require special attention:

1. Leap seconds: UTC is discontinuous at the introduction of leap seconds.
2. Frequency jumps of the on-board clock: as mentioned in Section 4.1, Gaia's RAFS undergoes occasional frequency jumps at the level of 5E-12 (equivalent to ~400 ns over 21 h non-visibility).
3. Discontinuities in the reconstructed orbit [RD 16]: the reconstructed orbit has a block structure and does contain discontinuous (in position, velocity, and acceleration) at block boundaries, for instance at times of orbit-maintenance manoeuvres. The typical/maximum positional discontinuity along the line of sight equals ~20/200 m (corresponding to ~70/700 ns – see **Figure 3**).
4. Synchronisation errors of the ground(-station) clocks: the UTC time stamping at ESA's 35-m deep space antennae (Malargüe, Cebreros, and New Norcia) is a three-step process involving (see Section 4.5):
    a. The IFMS (IRIG, Inter-Range Instrumentation Group) to System-1PPS (One Pulse Per Second) synchronisation (typical/worst-case error ~10/100 ns),
    b. The System-1PPS to station GPS receiver synchronisation (typical/worst-case error ~50/200 ns), and
    c. The station GPS receiver to GPS master clock synchronisation (typical/worst-case error ~20/50 ns).

    The total, worst-case synchronisation error is hence ~350 ns. This is a systematic error, shared between all time source packets received over extended periods of time (up to weeks).

It is difficult, if not impossible, to track and correct for these three (systematic) effects which means that absolute time correlation at sub-microsecond levels is not within easy reach.

4.5 Gaia time-correlation budget

The final Gaia OBT-UTC time-correlation budget is as follows.

Contributor	Allocation [ns]	Actual RMS [ns]	Actual peak-to-peak [ns]	Comment
Payload time stamp error	50	7	25	[RD 18]
Platform time stamp error	950	111	210	[RD 18]
Error in correction for vacuum propagation delay	250	30	30	MOC requirement SRD-159 states: "*The position accuracy of the restituted orbit of both the first and the second iteration shall be 75 m along the direction operating ground station to spacecraft*". Explanation: 75 m translates into a propagation delay accuracy of 250 ns, which is required for the reconstructed time correlation. The actual performance is better than 10 m (30 ns) [RD 17]
Error in tropospheric-delay correction	100	1	1	The maximum error of the correction is less than 10 cm (0.3 ns) at low elevations [RD 23]
Ionospheric and solar-plasma delays (not corrected for)	10	10	10	The X-band ionospheric delay at night time at low elevations is less than 1 m (3 ns) [RD 21]; solar-plasma delays for probes at L2 are less than 2 m (7 ns) [RD 22]
Error in ground station delay (from the intersection of the elevation and azimuth axes of the antenna to the IFMS input)	250	1	1	Residual error after daily pre-pass calibration of the medium ranging loop [RD 19]
Long-term stability of ground station delay	1	1	1	Error introduced from medium loop conversion delay variations [RD 19]
Error in the IFMS correction for the delay separating the strobe that triggers the latching of OBT to the falling edge of the clock defining the first symbol of the first bit of the Attached Synchronisation Marker (ASM) in the transmitted telemetry transfer frame	50	50	50	The spacecraft timestamps are generated on the first bit of the ASM. The IFMS detects the time of the first bit of the frame **following** the ASM. For some of the GMSK punctured-coding rates, there are two solutions for the delay correction depending on the phasing between the frame data and the encoding. This will in most cases result in a 50 ns jitter but in one case (2/3 encoding) in a 50 ns systematic offset [RD 24]
IFMS measurement quantisation	57	16	57	The IFMS has a 17.5 MHz clock, i.e., a 57 ns clock cycle. This leads to a quantisation error of 16 ns RMS (57 ns peak-to-peak) [RD 18]
Offset IFMS versus station clock (IFMS IRIG-B 5 MHz to System-1PPS synchronisation)	100	10	100	Synchronisation between the IFMS (IRIG Generator Version 1) and the System 1PPS, which is derived from the station atomic clock. The "actual numbers" are 6.25 ns for IRIG Generator Version 3 [RD 20]
Offset station clock versus GPS receiver (System 1PPS to station GPS receiver synchronisation)	200	50	200	Synchronisation between the System 1PPS and the station GPS receiver clock. The station clock is monitored against GPS time, which has almost perfect long-term stability. Once the offset to GPS time exceeds 200 ns, an alarm goes off after which the station operator corrects the offset by one IRIG clock cycle (200 ns) to zero [RD 20]

Offset GPS receiver versus GPS master clock (station GPS receiver to GPS master clock synchronisation)	50	20	50	Synchronisation between the GPS receiver clock and the GPS master clock. The station UTC time is maintained by reference to the GPS time of the GPS receiver at the ground station [RD 20]
On-board clock error outside visibility	1300	50	230	For a non-visibility period of 21 hours; Section 4.3
Total Linear [ns]	3368	357	965	
Total RSS [ns]	1670	147	396	

The following remarks can be made:

1. IRIG Generator Version 3 is deployed at Malargüe: the associated peak-to-peak offset of the IFMS versus the station clock is 6.25 ns (instead of 100 ns).
2. For Cebreros, the 50 ns allocation for the offset between the GPS receiver and the GPS master clock has been violated in the past (measurements in May 2015 indicated an offset of 369 ns for the nominal chain and 529 ns for the redundant chain). It is well possible that similar violations exist(ed) for New Norcia and Malargüe; this is under investigation. A yearly recalibration of the offsets is now being considered, which should allow to reach 20 ns RMS and 50 ns peak-to-peak.
3. The 50 ns (RSS) and 230 ns (peak-to-peak) on-board clock error outside visibility (Section 4.3.2) is based on the best-case assumption for the covariance properties of the timing errors of the time source packets (uncorrelated, white noise) and a worst-case time-stamp error of 1 microsecond for an individual time source packet.
4. The budget above is for nominal conditions, for instance availability of GPS (and without Selective Availability), daily ground-station contacts, etc. For contingency situations (missed contact, GPS unavailability, ...), the actual performances can be worse.

5 APPLICATION OF THE SCHEME TO ATHENA

In this section, we describe how the scheme that is conceptually laid out in Section 3 could be applied to Athena. Again, the same subsection titles are used, which means Section 5.1 refers back to Sections 4.1 and 3.1, Section 5.2 refers back to Sections 4.2 and 3.2, etc. Section 5.5 contains a draft end-to-end Athena absolute OBT-UTC time-correlation breakdown with proposed allocations to meet an end-to-end performance of 2 microseconds with margin.

5.1 On-board time stamping

In order for Athena to achieve microsecond-level timing performance, key is to have a stable on-board master clock, such that its behaviour over non-visibility periods can be modelled / interpolated, plus a proper architecture for the on-board time distribution (including 50-100 ns resolution, i.e., a 10-20 MHz clock, 64-bit encoding of OBT, and well-calibrated delays). With a daily visibility (ground-station-contact-duration) requirement of 3 hours, the non-visibility period is not necessarily 21 hours since the ground-station contacts do not necessarily take place at the same time each night (the deep-space antennae are shared with other missions which [may] have non-regular demands). A worst-case situation is hence a long winter night with 16-hour spacecraft visibility in which Athena is allocated 3 hours at the beginning of the night and subsequently allocated 3 hours at the end of the following night. The effective, worst-case visibility gap is then 34 hours (~120,000 s). Assuming that the requirement is MTIE < 1000 ns (Section 5.5), it follows that $\sigma_y \sim$ 1E-11 is needed for τ = 120,000 s. This seems compatible with an Oven-Controlled Crystal Oscillator (OCXO) frequency standard (for instance a Rakon RK 410 has an Allen deviation of 5E-13 at 10 s and hence ~2E-11 at 120,000 s assuming a $\tau^{1/2}$ degradation beyond 100 s representative of random walk). This conclusion as well as the flight-model clock selection, however, requires a careful industrial evaluation, which is considered normal work.

5.2 Time source packet generation

Another key for Athena to reach microsecond timing accuracy is to generate on board and transmit to ground as many standard spacecraft time source packets as possible, i.e., one packet for each VC0 telemetry transfer frame (N = 1). Depending on housekeeping traffic, this would generate typically one packet every few seconds (Gaia sees one packet every 1.5 seconds with N = 1 whereas XMM-Newton sees one packet every 20 seconds with N = 16, so it would see one packet every 1.3 seconds with N = 1). We can conservatively set, based on Gaia experience, the requirement that individual time source packets shall be time stamped at the ground station with peak-to-peak error less than 300 ns (Section 4.5).

5.3 Clock calibration (time correlation)

Gaia experience shows that, with a proper relativistic formulation, the overall modelling accuracy of all delays (and transformations) discussed in Section 3.3 is better than 30 nanoseconds. This error is limited by the knowledge error in the distance between the (reconstructed orbit of the) spacecraft and the ground station(s), which can reach 10 m (**Figure 4**). Recall: this performance is based on the **standard** reconstructed orbit derived from **standard** radiometric (Doppler and range) data, which is delivered weekly by MOC to SOC with a six-week delay.

For Athena, the following scheme is hence proposed:

1. Daily, operational, low-accuracy time correlation is performed at MOC with a formal peak-to-peak requirement of 1 millisecond. This product is based on the predicted orbit and historical pass data and is hence available (semi-)instantaneously. This product is used for spacecraft operations and for science Quick-Look Analysis (QLA) at SOC and/or the Instrument Control Centres (ICCs). Note: although the formal requirement is 1 millisecond, the typical accuracy in practice is 50–100 microseconds – [RD 03] mentions 30 microseconds for XMM-Newton.
2. MOC performs standard, daily Doppler and ranging and standard, weekly orbit reconstruction. The reconstructed orbit is delivered to SOC on a weekly basis with an unavoidable six-week delay.
3. SOC performs a high-accuracy time correlation (on-board clock calibration) for scientific purposes, in line with the budget in Section 5.5. This product is subsequently distributed to the ICCs.

This scheme is robust against actual spacecraft operations, including unplanned events such as Targets of Opportunity (ToOs) and/or Spacecraft Safe Modes (SSMs). It does mean, however, that science products with high-accuracy time stamping can only be made available ~8 weeks after acquisition on board (assuming step 3 above takes two weeks).

5.4 From OBT to UTC

The same caveats as for Gaia will apply to Athena:

1. Leap seconds: UTC is discontinuous at the introduction of leap seconds.
2. Frequency jumps of the on-board clock: jumps are a reality for both atomic clocks and crystal oscillators (typical levels for crystal oscillators are 1E-9 to 1E-11, compared to ~5E-12 for Gaia's Rubidium clock);
3. Discontinuities in the reconstructed orbit: discontinuities at block boundaries at the level of a few dozen m (~100 ns) should be expected;
4. Synchronisation errors of the ground(-station) clocks: synchronisation errors at the level of several hundred ns should be expected.

The same conclusion as for Gaia applies: it is difficult, if not impossible, to track and correct for these three (systematic) effects which means that absolute time correlation at sub-microsecond levels is not within easy reach.

5.5 Athena time-correlation budget

Taking the above into account, the following budget and allocation are proposed for Athena. Since there is no golden rule on how to sum individual contributors in the budget (RSS or linear), or on whether to provide RMS or peak-to-peak errors for individual contributors, we arbitrarily chose – still having some kind of worst-case situation in mind – to add the contributors in an RSS sense, under the assumption of no correlation, with each contributor reflecting a peak-to-peak error. One may add, on a cynical note, that if it matters greatly how contributors are summed, then one is up to not much good to start with.

	Contributor	**Allocation [peak-to-peak error, ns]**	**RSS sum [ns]**	**Justification**
Payload	Payload time stamp error	500	500	See the discussion in Section 6
SC	Platform time stamp error	500	500	Gaia = 210 ns
OGS	Error in correction for vacuum propagation delay	100	300	Line-of-sight error of the standard reconstructed orbit is less than 10 m (30 ns)
	Error in tropospheric-delay correction	10		The maximum error of the correction is less than 10 cm (0.3 ns) at low elevations
	Ionospheric and solar-plasma delays (not corrected for)	10		The X-band ionospheric delay at night time at low elevations is less than 1 m (3 ns); solar-plasma delays for probes at L2 are less than 2 m (7 ns)

	Error in ground station delay, including long-term stability (from the intersection of the elevation and azimuth axes of the antenna to the IFMS input)	10		Residual error after standard, daily pre-pass calibration of the medium ranging loop is better than 1 ns; long-term stability is better than 1 ns
	Error in the IFMS correction for the delay separating the strobe that triggers the latching of OBT to the falling edge of the clock defining the first symbol of the first bit of the Attached Synchronisation Marker (ASM) in the transmitted telemetry transfer frame	100		For some of the GMSK punctured-coding rates, there are two solutions for the delay correction depending on the phasing between the frame data and the encoding. This will in most cases result in a 50 ns jitter but in one case (2/3 encoding) in a 50 ns systematic offset
	IFMS measurement quantisation	100		The IFMS has a 17.5 MHz clock, i.e., a 57 ns clock cycle
	Offset IFMS versus station clock (IFMS IRIG-B 5 MHz to System-1PPS synchronisation)	100		Synchronisation between the IFMS (IRIG Generator Version 1) and the System 1PPS, which is derived from the station atomic clock
	Offset station clock versus GPS receiver (System 1PPS to station GPS receiver synchronisation)	200		Synchronisation between the System 1PPS and the station GPS receiver clock. The station clock is monitored against GPS time. Once the offset to GPS time exceeds 200 ns, an alarm goes off after which the station operator corrects the offset by one IRIG clock cycle (200 ns) to zero
	Offset GPS receiver versus GPS master clock (station GPS receiver to GPS master clock synchronisation)	100		Synchronisation between the GPS receiver clock and the GPS master clock. The station UTC time is maintained by reference to the GPS time of the GPS receiver at the ground station
SGS	On-board clock error outside visibility	1000	1000	For a non-visibility period of 34 hours; Section 5.1
System margin	System margin	1552	1552	
	Total RSS [ns]	2000	2000	

*SC = SpaceCraft = service module, or bus, or platform;
*OGS = Operational Ground Segment = ground stations + MOC;
*SGS = Science Ground Segment = SOC + ICCs.

The SC contribution above is meant to cover on-board delays and time stamping errors at platform level (e.g., CDMU, transponder, ...). The above allocation is ambiguous when it comes to the SGS contribution: the 1-microsecond error of the on-board clock resulting from a 34-hour non-visibility period has been assigned to the SGS whereas it could be argued that it actually belongs to the spacecraft: only if the on-board master clock is sufficiently stable over 34 hours, including all time variations (environmental effects), then the SGS will be able to model the clock behaviour over the visibility gap based on the standard spacecraft time source packets received in the adjacent ground-station contact periods. In this sense, the SGS would not contribute at all to the end-to-end time absolute timing budget.

6 DISCUSSION AND CONCLUSIONS

Based on proven XMM-Newton, Integral, and foremost Gaia experience, which routinely achieves sub-microsecond absolute time stamping using a one-way time-synchronisation (clock-calibration) scheme – based on standard spacecraft time source packets – using standard ESA facilities (deep-space antennae), a standard ESA spacecraft tracking strategy (daily Doppler and range acquisitions), a standard ESA orbit reconstruction, standard ESA spacecraft operations (based on SCOS-2000), and standard ESA time calibration procedures of the ground stations (daily pre-pass calibration), we recommend to adopt a similar scheme for Athena. With proposed allocations of 500 ns for the payload (but see the discussion below), 500 ns for the spacecraft (SC), 300 ns for the operational ground segment (OGS), and 1000 ns for the science ground segment (SGS), an end-to-end performance of 2 microseconds is reachable with 1.5 microseconds system margin (Section 5.5). For Athena timing budgets, it is proposed to add uncorrelated contributors in a root-sum-square sense with each contributor reflecting a peak-to-peak error (or, if more desirable, an error with 99.7% [3σ] confidence level).

For what regards the payload allocation of 500 ns, we do recognise that:

1. For WFI, there is limited interest in microsecond-accuracy timing: the large-area detector has a requirement of 5 milliseconds (and a goal of 1.3 milliseconds) while the small-area, fast DEPFET chip has a full-frame resolution of 80 microseconds.
2. For X-IFU, on the other hand, there are science cases benefiting from microsecond-level timing accuracy. The current resolution of the time stamping is 10 microseconds and, obviously, if a tightening of the mission-level requirement from the current 50 microseconds is pursued, then also the X-IFU time resolution (and timing architecture, including delay-calibration aspects) should be revisited. Possibly, for instance, the proposed 500 ns allocation turns out to be prohibitively small in view of residual, energy-dependent calibration errors linked to the delay-corrections necessitated by the (sampling of the) pulse profile.

The proposed strategy is based on a detailed modeling / calibration of the on-board clock, taking place at the SOC, based on time-source packets regularly (~0.5 Hz) received during ground-station-contact periods with the spacecraft. By applying the resulting model to periods without ground-station contact, it is possible to time tag **all** events in UTC with an accuracy of 2 microseconds. Clearly, a proper relativistic treatment is required for the various transformations between different time scales (OBT, TG, TT, TAI, UTC, TCB) and different locations (Athena, ground station, solar-system barycentre). To correct for propagation delays, the model uses the reconstructed spacecraft orbit, which is made available to SOC by MOC on a weekly basis but with a six-week delay. This unavoidable delay necessitates a two-step approach:

1. Spacecraft operations at the MOC, as well as the scientific Quick-Look Analysis (QLA) at SOC (or the ICCs), necessarily have to use the standard ESA, daily, instantaneous, low-accuracy time-correlation product, which has a formal accuracy requirement of 1 millisecond but has an accuracy between 50 and 100 microseconds in practice;

2. The time stamps in the final scientific data products – including ToOs – are corrected ~8 weeks after acquisition, based on the high-accuracy time correlation produced by SOC and subsequently distributed to the ICCs.

It should be noted in particular that the transformation from UTC to TCB at the solar-system barycentre, as required for pulsar timing, is also impacted by errors in the reconstructed orbit in the "non-radial", i.e., plane-of-sky component. So, for absolute timing of events **at the solar-system barycentre**, an associated extra error term should be added to the budget presented in Section 5.5. The size of this error depends on the source direction (and Athena's position with respect to L2) and cannot be larger than the reconstructed-orbit error in the plane of the sky. **Figure 4** suggests this error is ~300 m at most, which bounds this extra error term to 1000 ns (1 microsecond). It could be considered to reformulate the mission requirement to explicitly include this error term.

In order to achieve microsecond-level datation, the on-board timing architecture needs to be properly designed and the spacecraft and payload timing chains properly calibrated on ground. In particular, we recommend:

1. To select a crystal oscillator with 1E-11 Allen deviation over 34 hours (the worst-case non-visibility period between adjacent ground-station contacts). Care should be taken to minimise frequency changes over a few dozen hours resulting from environmental effects, i.e., changes in clock temperature, supply voltage, magnetic field, and radiation;
2. To select a 10-20 MHz on-board master clock such that the time stamps have 50-100 ns intrinsic resolution;
3. To apply a 64-bit encoding of OBT;
4. To generate and transmit to ground as many standard spacecraft time source packets ("time reports") as possible, i.e., one packet for each VC0 telemetry transfer frame (CDMU parameter N = 1);
5. To conduct an integrated-system time correlation test (IST) to confirm that measured delays are in line with predictions and budgets (for Gaia, this test was most useful, allowing verification at 50-ns level).

Once launched, we recommend:

6. To perform occasional two-station tests during which two ground stations receive time source packets transmitted by the spacecraft simultaneously. Such tests allow monitoring the desynchronisation of the ground stations (which, from Gaia experience, can be at the level of several hundred ns) and allow verifying (i) that the high-accuracy model for the timing data is physically adequate and correctly interprets the input data, and (ii) that the timing data delivered by MOC have satisfactory quality. Clearly, such experiments cannot reveal problems with the on-board clock or on-board delays since such errors influence the data at both stations in the same way;
7. To perform occasional observing campaigns of suitable, celestial calibration targets possibly contemporary with other facilities, albeit we note that source-intrinsic limitations may limit the usefulness of these campaigns for microsecond-level

verification (e.g., the broad pulse profile of the Crab pulsar combined with dispersion variations limit the accuracy of absolute timing to ~40 microseconds).

In terms of (possible) future developments / points of attention, we mention in particular:

1. Herschel versus Gaia: this document assumes the orbit reconstruction performance of Gaia will also apply to Athena. What remains to be verified is whether the Herschel and Planck orbit reconstruction errors are similar in magnitude. Herschel, for instance, was a pointing observatory, which means that the influence of solar-radiation pressure might have been more erratic than it is for Gaia, with possibly associated degraded orbit-reconstruction performance.
2. L1 versus L2: there is *a priori* no reason why the proposed scheme would not work for an L1 Lissajous orbit although, obviously, the solar-plasma delay would become several dozen meters (~100 nanoseconds) [RD 22] and possibly worth correcting for.
3. NASA's DSN: it is currently unclear whether, with the proposed scheme, it will be possible to include antennae from NASA's Deep Space Network (DSN) in the nominal ground segment; for Gaia, at least, this is impossible since NASA stations neither support punctured coding, nor GMSK encoding, nor the proper CCSDS Space-Link-Extension (SLE) protocol allowing picosecond-resolution time tagging.
4. Galileo: the proposed scheme is based on GPS receivers and assumes GPS availability. In the early 2020's, Galileo's Full Operational Capability (FOC) should allow reaching similar (if not better) and, more importantly, independent synchronisation capabilities of the ground(-station) clocks.
5. IRIG Generator Version 3: Version 3 is currently implemented only at Malargüe. Once implemented also at Cebreros and New Norcia, the allocation of 100 ns for the offset of the IFMS versus the ground-station clock can be safely reduced to 10 ns.
6. Two-way synchronisation: should ESA deep-space ground stations start supporting two-way time synchronisation, then it could be employed for Athena too. There would, however, be no real gain since Athena's absolute time stamping performance will foremost be limited by the performance of the on-board clock combined with systematic timing offsets in the ground stations, and not by errors in delay corrections.

ACKNOWLEDGEMENTS

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ACRONYMS

A(n incomplete) list of Athena acronyms is available from http://sci2.esa.int/cosmic-vision/AthenaYB_v4-2_final.pdf.

APPENDIX A: SELECTED GAIA PERFORMANCE PLOTS

This Annex shows a few selected Gaia time-correlation(-related) performance plots.

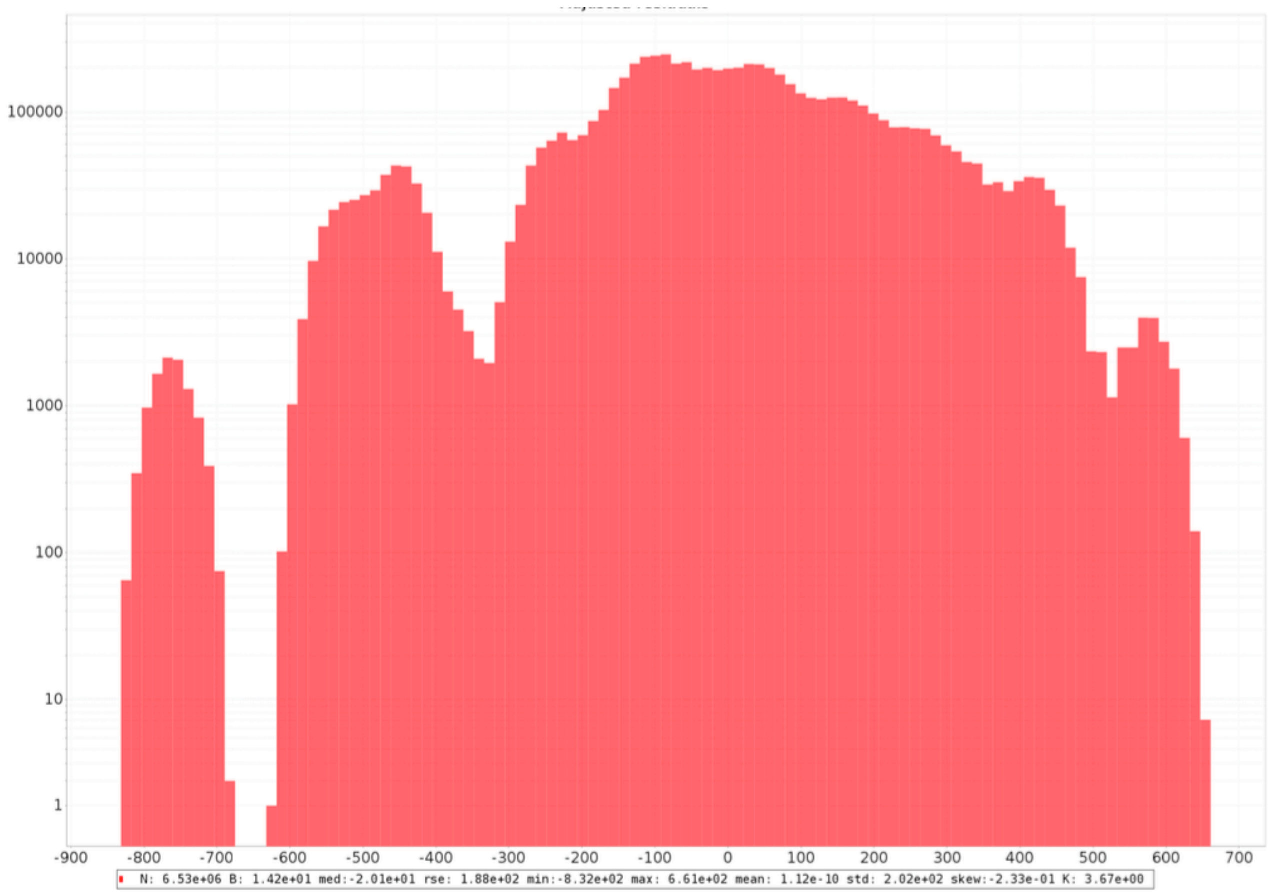

Figure 2 *OBT-minus-model residuals, in nanoseconds, of 6.53E6 time source packets received during the first year of nominal Gaia operations. The structure in the residuals is primarily caused by systematic timing offsets at the ground stations. All in all, sub-microsecond accuracy is achieved. Extracted from [RD 13].*

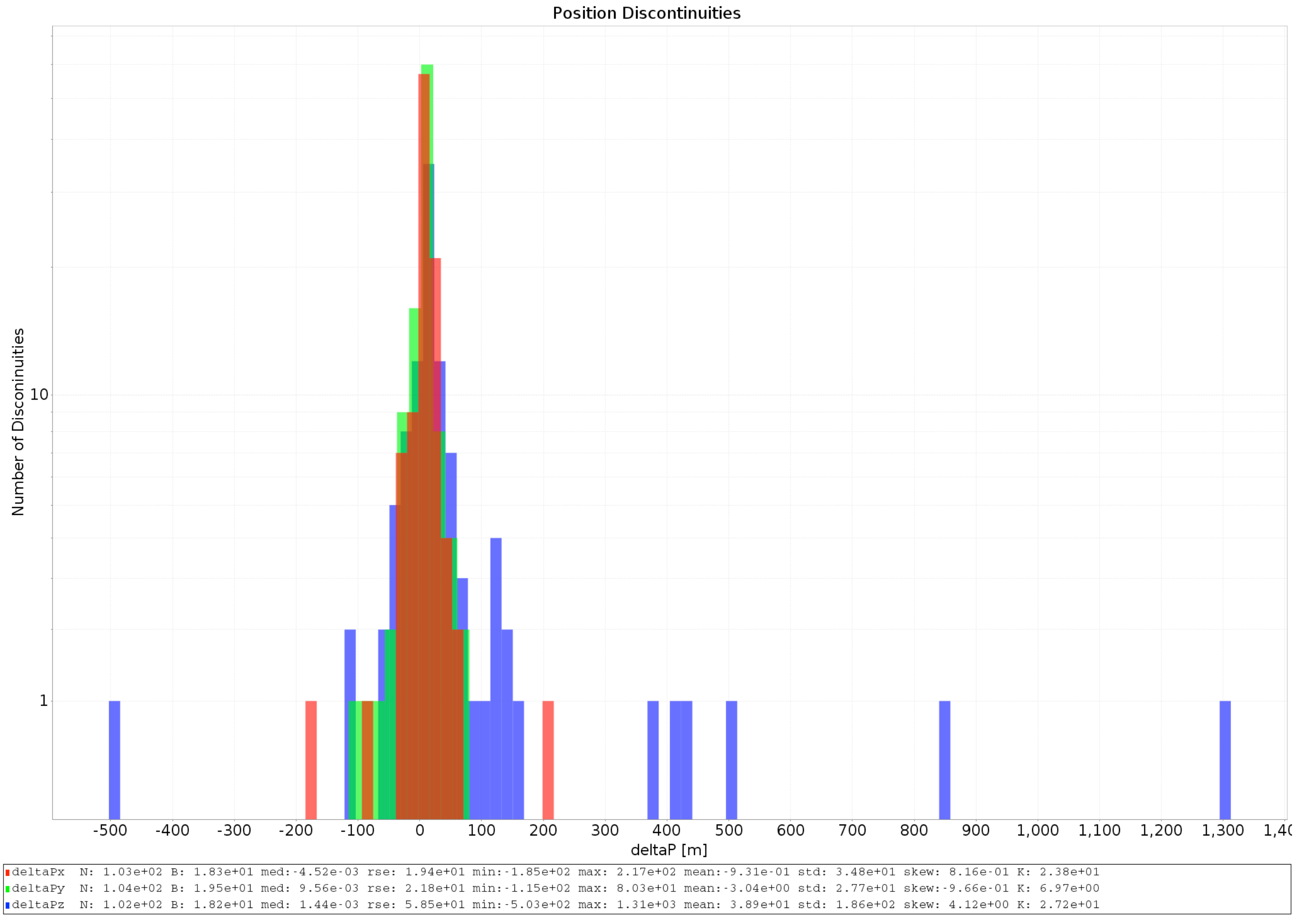

Figure 3 *Distribution of ~100 position discontinuities in the reconstructed orbit covering launch (December 2013) till October 2015. Red ("deltaPx") refers to the radial, line-of-sight coordinate between the ground station and Gaia. The maximum discontinuity is +217 m. A more typical value is ~20 m. Extracted from [RD 16].*

Figure 4 *Estimated accuracy of the reconstructed orbit of Gaia as function of time. The black data ("pX-rotated") refers to the radial, line-of-sight coordinate between the ground station and Gaia. The error is less than 10 m. Extracted from [RD 17].*

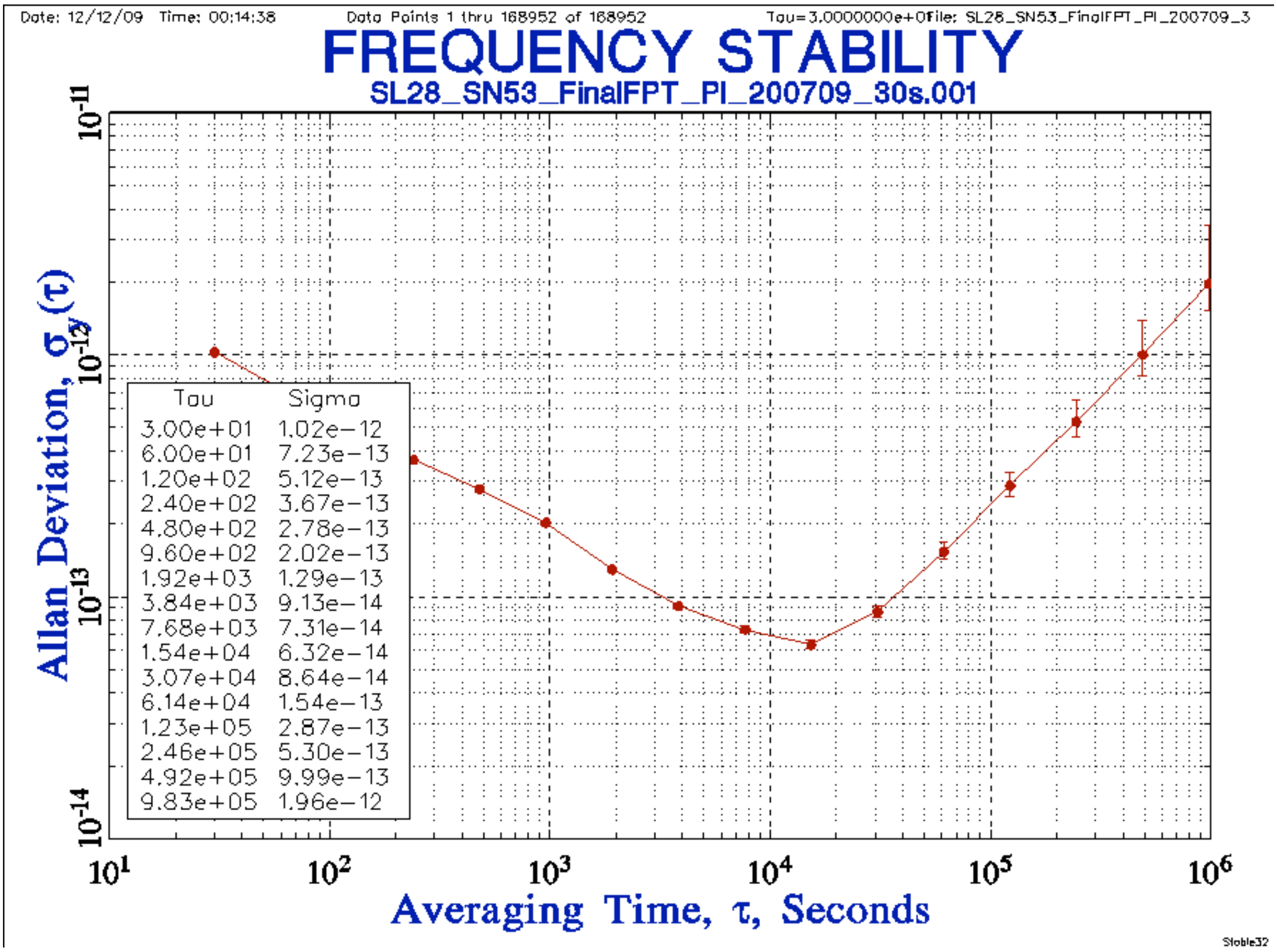

Figure 5 *Allen deviation σ_y of Gaia's redundant Rubidium Atomic Frequency Standard (RAFS; Serial Number 53), derived from data collected during the eight-week, ground-based performance test. The nominal flight model has roughly two times better performances. Figure courtesy Sergei Klioner, based on the raw test data delivered by Spectratime.*