Performance Assessment of the Time Difference between EGNOS-Network-Time and UTC

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***Abstract*— The European SBAS (Satellite Based Augmentation System) EGNOS (European Geostationary Navigation Overlay Service) provides in its navigation message the time difference between EGNOS Network Time (ENT) and UTC. For that purpose, an EGNOS ground station was installed in the Observatoire de Paris (OP) and is connected to UTC(OP). Applying EGNOS corrections on GPS measurements provides a precise time and navigation solution referenced to ENT. Therefore the assessment of the time difference between ENT and UTC is a key issue for time users. A new EGNOS system release has been tested since the beginning of 2008, it includes some improvements in the timing functions. This paper deals with the evaluation of the performances obtained by these functions.**

First the paper recalls the timing aspects of EGNOS and describes the connection of ENT to UTC(OP). Then two methods of performance assessment are described.

The first method is based on the time difference between ENT and UTC obtained by the combination of broadcast information (EGNOS Message Type 12) and BIPM Circular T. The EGNOS Message Type 12 contains an estimation of ENT – UTC(OP) computed by the EGNOS ground segment, using the Observatoire de Paris ground station measurements. The BIPM Circular T provides UTC – UTC(OP).

The second method consists in an independent estimation of ENT at user level (in locations where EGNOS corrections are valid). In that case, we use the GPS measurements of a receiver connected to a UTC(k). We apply EGNOS corrections and station delays on these measurements so that we get ENT – UTC(k). With the BIPM Circular T, we have therefore access to an estimation of ENT – UTC.

The results of the two methods are checked with respect to EGNOS system requirements. Information is also given on the current status of EGNOS for the operational Open Service and on a daily model of ENT-UTC(OP) that is provided in the RINEX SBAS navigation files. To conclude, as EGNOS Network Time is by construction linked to UTC(OP) and not directly to UTC, the on-going improvements of UTC(OP) will have a positive impact on the prediction performance of UTC – UTC(OP) and are briefly discussed.

I. INTRODUCTION

The European Satellite Based Augmentation System, called EGNOS (European Geostationary Navigation Overlay Service), provides to users in Europe an augmentation of three pseudo-GPS signals plus corrections/integrity information about the available GPS constellation [1,2,3] enabling to compute a safe and precise position that can be dated in a legal time scale (UTC).

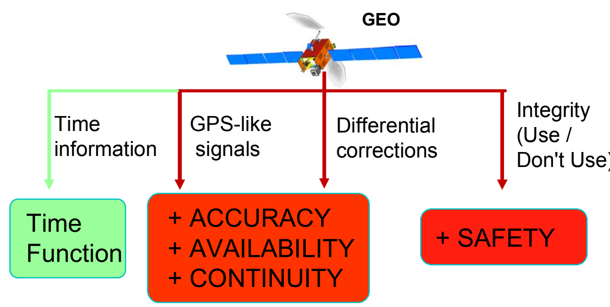

Figure 1. SBAS missions

EGNOS also broadcasts in its navigation message the time difference between EGNOS Network Time (ENT) and UTC. This requires connecting ENT to at least one UTC(k) in Europe. To this aim, an EGNOS Earth station of the Ground Segment, so-called Ranging and Integrity Monitoring Station (RIMS), was installed in Observatoire de Paris (OP) in July 2003. This connection has already been described in detail in [4], the major points will be recalled hereafter.

The aim of this paper is to evaluate the time difference between ENT and UTC (via its prediction UTC(OP) in Observatoire de Paris) by two completely independent methods. The first one simply uses the EGNOS message #12 that contains an evaluation of the time offset between ENT-UTC(OP) as seen by EGNOS system combined to the UTC-UTC(OP) as computed by the BIPM and available in the BIPM Circular T, while the second one uses a receiver in OP connected to a Hydrogen Maser which time difference with UTC(OP) is permanently measured

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II. TIME IN EGNOS

EGNOS provides with GPS regional augmentation services to aviation, maritime and land users by using transponder on board geostationary (GEO) satellites [1,2,3]. The EGNOS Ground Segment consists of Ranging and Integrity monitoring Stations (RIMS), which are connected to a set of redundant control and processing facilities (CPF), in order to determine the integrity, ephemeris and clock differential corrections for each monitored satellite, to compute the ionospheric delays, and to generate the GEO satellite ephemeris. The GEO satellite downlinks these data on the GPS L1 frequency with a modulation and a coding scheme similar to GPS.

A. *EGNOS time requirements*

All measurements and data are referred to an internal EGNOS Network Time (ENT) which performance requirements were derived exclusively from navigation accuracy performance requirements. The European Space Agency (ESA) requires ENT to be steered within 50 ns (5σ) to GPS Time (GPST). This requirement is mostly specified to keep compatibility with the maximum capacity of the message used to correct the GPS satellite clocks. It will allow the user to combine in its navigation solution GPS and EGNOS signals.

The [ENT - GEO Time] transfer error is specified to be less than 10 ns (3σ), after offset and frequency corrections provided in EGNOS GEO message #9. This particular requirement is of special interest to a precise time broadcast function in real time. Table 1 below summarizes the EGNOS time requirements:

TABLE I. EGNOS TIME REQUIREMENTS [6]

1	[ENT - GPS time] offset ≤ 50 ns (5σ)
2	[GEO Time - GPS time] offset ≤ 50 ns (5σ)
3	[GEO Time – ENT] accuracy ≤ 10 ns (3σ)
4	[ENT - UTC(OP)] accuracy ≤ 10 ns (3σ)

We will check this requirement #4 in this paper. As required in SIS (Signal in Space) specification, EGNOS provides in its message #12 the time difference between ENT and UTC. Since UTC is a deferred-time paper time scale, the time difference [ENT – UTC] will be computed using a physical clock signal of a European National Metrology Institute, taking into account or not the prediction of the difference between this UTC(k) and UTC.

B. *RIMS clock synchronization, ENT generation*

RIMS clock synchronization is performed using the composite clock technique [5] in which ENT is defined as the implicit ensemble mean of a set of RIMS clocks and the synchronization process generates estimates of the time and frequency offsets of each RIMS clock relative to it. ENT is then steered to GPST using a second order, low-pass digital filter. The steering input signal is an instantaneous estimate of the [ENT - GPS Time] offset. The latter is computed from the estimated satellite clock offsets with respect to ENT and the GPS broadcast satellite clock corrections.

C. *Relationship between ENT and UTC*

To synchronize ENT and UTC, it was decided to put a special RIMS called "RIMS-UTC" or PARA in the EGNOS system. A block diagram of this RIMS can be found in [7]. The time difference [ENT – UTC] is computed by CPF using simply :

$$ENT – UTC = [ENT – UTC(OP)] + [UTC(OP) – UTC]$$

where [ENT – UTC(OP)] is determined by the CPF as an output of its ENT composite clock algorithm, and [UTC(OP) – UTC] is computed by CPF using a prediction algorithm. Currently this prediction is not implemented and therefore EGNOS broadcasts in its message #12 the time offset [ENT – UTC(OP)] for the real time synchronization to UTC in compliance to [11].

The message type #12 (MT12) contains an estimation of ENT – UTC(OP) expressed in the form of a linear model (offset A0, drift A1 and reference time t_{ot}), assumed to be valid for 86400 s, that can be extrapolated at any current time from its reception to the reception of a new set of such parameters or its validity time. The maximum broadcast interval of MT12 is 300 s [11].

D. *EGNOS releases*

Some improvements have been implemented in a new EGNOS release called ESR2.2 over the last months in order to provide among other objectives, a more efficient content in its message #12. This ESR2.2 release has been on air for test purposes through the PRN124 (Artemis) GEO frame from beginning of February 2008 and was deployed and used in the EGNOS operational chain since the 6th of October 2008 for the PRN120 (INMARSAT AOR-E) and PRN126 (INMARSAT IOR-W) GEO frame elaboration. To know the current status of each EGNOS GEO frame, a web server is available [9].

III. ASSESSMENT OF [ENT – UTC] USING MESSAGE TYPE #12

A. *IMAT - Independent MT#12 Analysis Tool*

Several indicators have been defined to monitor the EGNOS time offset to UTC on a daily or mid term (monthly) basis [10]. A tool (IMAT) has been developed to support these indicators.

The received messages are first decoded according to the SBAS standard [11]. The ENT – UTC(OP) information can then be computed in two different ways:

- for each valid MT12, extrapolation of the broadcast linear model at one second sampling, until a new valid MT12 is received (referred to as the "broadcast model")
- computation of a linear regression using all the valid MT12 models estimated at their first reception time (referred to as the "daily model").

IMAT is then producing daily indicators and comparisons between these two computations of ENT – UTC(OP) in textual and graphical forms, especially the daily average and the daily standard deviation of ENT-UTC(OP) obtained by the "broadcast model", as well as the ENT-UTC(OP) computed at noon from the last valid MT12 received before noon.

Figure 2 below shows ENT – UTC(OP) for one day using the "broadcast model" and the "daily model" :

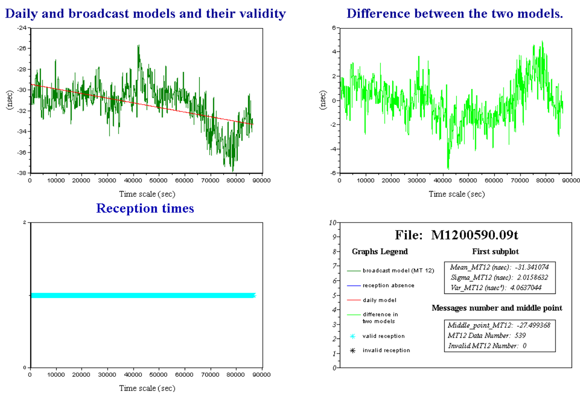

Figure 2. IMAT daily graphic output

B. Comparison of information broadcast by both operational EGNOS GEO/PRN

The EGNOS operational system is composed of 2 navigation chains and has evolved recently (on the 17th of February 2009), the navigation chain using PRN124 moving from the TEST part to the operational one and PRN126 moving in the other way (from operational part to TEST one). So, in the plots below, PRNOP2 information means a combination of PRN126 until the 17th of February and of PRN124 after this date.

A first comparison based on the daily mean value of the "broadcast model" for each PRN has been carried out from the 6th of October 2008 until end of February 2009 when the two operational navigation chains were broadcasting the ESR2.2. The results for both PRN are very close as depicted hereafter, the interruption from the 12th of January to the 18th of February 2009 being due to an impossibility to configure PARA. All Figures below are expressed in nanoseconds, unless otherwise stated.

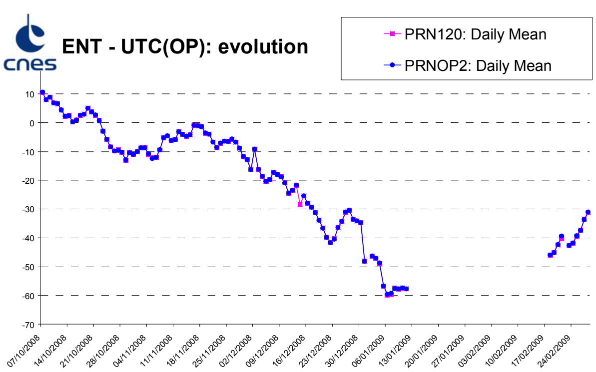

Figure 3. ENT-UTC(OP) evolution - daily mean comparison

A second comparison based on the daily value computed at noon using also the "broadcast model" for each PRN is performed. Figure 4 shows the difference between the two estimations of ENT – UTC(OP) coming from the two PRN :

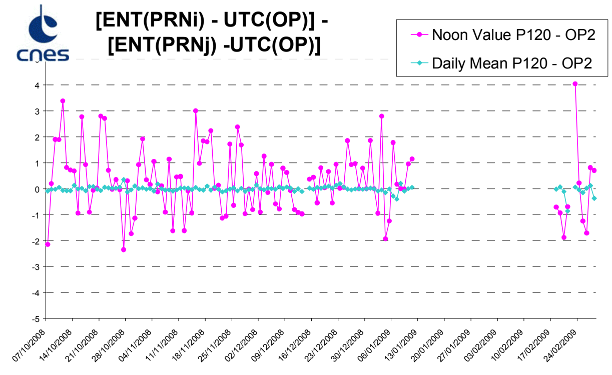

Figure 4. $[ENT - UTC(OP)]_{PRN120} - [ENT - UTC(OP)]_{PRNOP2}$

If the differences between the ENT - UTC(OP) information broadcast by each operational navigation chain are negligible for the daily mean, this is not the case for the noon value where differences of several nanoseconds are observed. This is currently explained by the slope that is included in each model of MT12 that is not representative of the expected one. This observation is under investigation at EGNOS level.

C. Comparison of ENT-UTC(OP) from broadcast information to UTC-UTC(OP) from BIPM Circular T

The daily mean (computed as explained before) has been compared to UTC-UTC(OP) obtained from BIPM Circular T. As in BIPM Circular T, the sampling is one point every five days, in order to have a maximum number of points for this comparison, the information coming from the ESR2.2 test phase have also been taken into account in this analysis. This is possible because we have demonstrated previously that the difference between the different EGNOS GEO is negligible for the daily mean of [ENT-UTC(OP)].

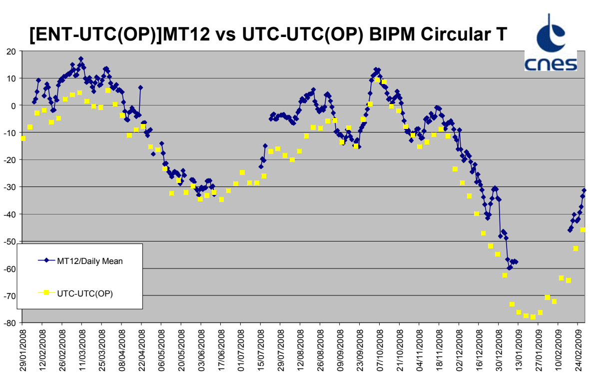

Figure 5. $[ENT - UTC(OP)]_{MT\#12}$ compared to $[UTC - UTC(OP)]_{BIPM}$

The two time differences are close, it has to be noted once again that only the information coming from MT#12 is available in real time, the BIPM circular T being a differed time information.

Using the decomposition of [UTC – ENT](t) in [UTC – UTC(OP)]$_{BIPM}$ (t) - [ENT - UTC(OP)]$_{MT12}$(t) and by assuming [ENT-UTC(OP)]$_{MT12}$(daily mean) is close to [ENT-UTC(OP)]$_{MT12}$(0h00:00), we are able to provide an estimation of UTC – ENT, called UTC – ENT via UTC(OP). The uncertainty on this result is in the range of a few ns (quadratic sum of the uncertainties in our process and in the BIPM Circular T).

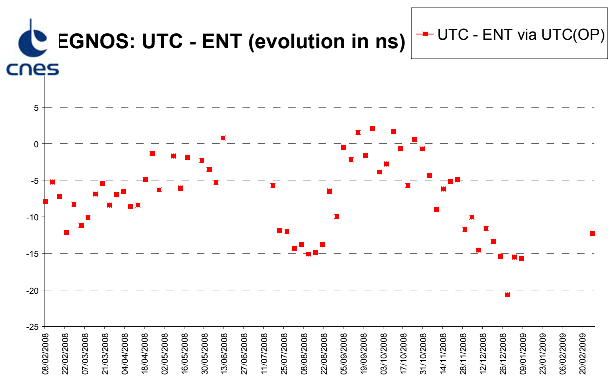

Figure 6. UTC - ENT evolution

From this chart covering the period from the 30th of February, 2008 to the 27th of February 2009 (61 samples), we deduce that the average of UTC-ENT is -7.3 ns, the minimum and maximum values are -20.7 ns and 2.1 ns, respectively, and the standard deviation is 5.3 ns.

From Figure 6, we conclude that EGNOS broadcasts in real time a time scale ENT that is close to UTC as near as UTC(OP) is.

Figure 7 shows the stability of ENT – UTC :

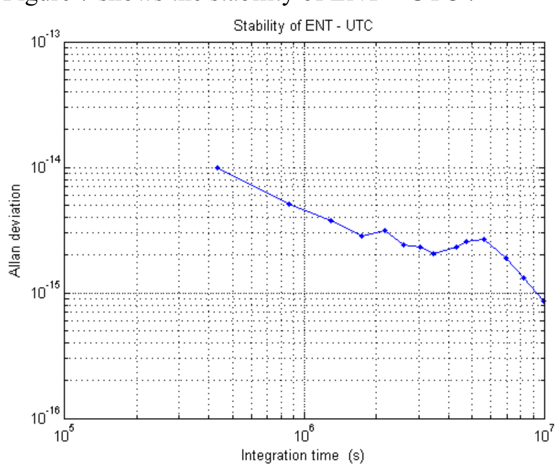

Figure 7. Allan Deviation of ENT-UTC

IV. Independent Assessment of [ENT – UTC(OP)]

A. *Method*

The method consists in an independent estimation of ENT at user level. In that case, we use the GPS measurements of a receiver connected to a UTC(k). We apply EGNOS corrections and station delays on these measurements, so that we get ENT – UTC(k). We use here UTC(OP) and we can therefore compare [ENT$_{user}$ - UTC(OP)]$_{OPMT}$ to [ENT - UTC(OP)]$_{MT12}$.

The general model for EGNOS measurements uses the C/A pseudo-range observable (C1 observable in the RINEX files). The reference orbit and clocks come from the GPS broadcast ephemeris.

The following formulation is used (one epoch and one GPS):

$$C_1 = D^{EGNOS} + e + \left(h_{rec}^{EGNOS} - h_{GPS}^{EGNOS}\right)$$

- C_1 is the C/A pseudo-range measurement.
- D^{EGNOS} is the geometrical distance between the transmitter and the receiver L_1 centres of phase, including the troposphere delay.
- e is the ionosphere propagation delay on the L1 GPS frequency.
- h_{rec}^{EGNOS} and h_{GPS}^{EGNOS} are respectively the receiver and transmitter clock offsets expressed in the EGNOS reference time.

D^{EGNOS} is computed using the GPS broadcast ephemeris corrected with the data from the EGNOS messages. The tropo delay is estimated with a standard mapping function and a fixed zenith troposphere delay of 2.37 m. The receiver centre of phase is obtained using the IGS station log for OPMT station and the ITRF solution for the corresponding marker coordinates. e is estimated using the EGNOS ionosphere message. h_{GPS}^{EGNOS} is computed using the slow and fast corrections obtained from the EGNOS messages applied on the GPS broadcast clock value corresponding to a single frequency user (use of the broadcast TGD values).

Then, at a given epoch and for each GPS in view we obtain an estimation of h_{rec}^{EGNOS} from the above equation. All these estimates are averaged (median value robust estimation) over a 15 minutes interval to minimize the pseudo-range measurement noise effects. This produces an estimation of the offset between the receiver clock and the EGNOS time defined by the EGNOS messages.

B. *EPO_ENT : EGNOS Performance Observatory*

An independent calibrated GPS Time receiver “OPMT” is used for this analysis and its GPS raw measurements are collected through the IGS network (OPMT station). This receiver is not directly connected to UTC(OP), but is connected to a Hydrogen Maser which time offset is monitored versus UTC(OP) on an hourly basis. These time offset values are given in so-called LZOP files. These values can be interpolated by a simple linear model over one day for down sampling. The values of the different time propagation delays of OPMT station are extracted from the clock daily file (GZOP file).

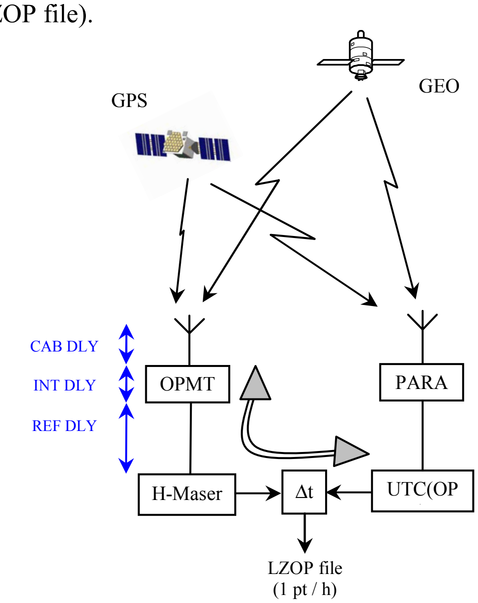

Figure 8. Independent assessment chain (OPMT), EGNOS RIMS (PARA) and their connections to UTC(OP)

Basically, the method implemented in CNES EPO tool is to determine first ENT_{user} - UTC(OP), this time difference being obtained by :

- applying the EGNOS corrections on the GPS measurements collected at OPMT (using the previously described method)
- relating ENT to UTC(OP) using the internal delays of the station OPMT

More details on this technique are given in [8], the only difference is that the computation is carried out for a L1 user/data (like EGNOS users) and no more based on an ionosphere free user/combined data. This time difference is then compared to the broadcast information at each reception time of a new valid model of MT12 ("broadcast model").

Finally, we obtain the difference $[ENT_{user} - UTC(OP)]_{OPMT}$ – $[ENT - UTC(OP)]_{MT12}$ which is expected to be close to zero if the different calibrations of equipments and cables in the EGNOS PARA RIMS and in the independent assessment chain are correct. $[ENT\text{-}UTC(OP)]_{MT12}$ is computed using the « broadcast model ». This analysis is automatically performed on a daily and a monthly basis.

C. Results

It has to be noted that our tool has been developed to assess the performances of ESR2.2 during the EGNOS qualification campaign (March-April 2008) then integrated and qualified in last 2008 quarter for the continuous assessment of EGNOS operational service, and was not used from April 2008 to November 2008 included. So the following results are the concatenation of different periods where some equipments were changed or restarted (receiver), especially in OP (maser change).

Figure 9 shows the daily average and median values of the difference between the two estimations of ENT – UTC(OP) :

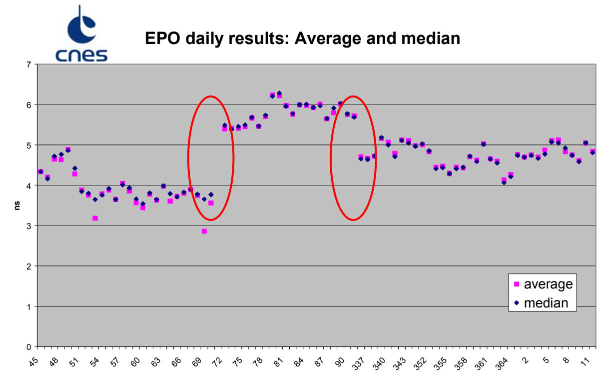

Figure 9. Daily average and median value of $[ENTuser - UTC(OP)]_{OPMT} – [ENT - UTC(OP)]_{MT12}$

There are clearly three periods. Between the first and the second period, a Maser change occurred. Between the second and the third period, several changes occurred in OPMT configuration.

Considering these 3 periods, the daily difference stays under a bias of about 6.3 ns that can be at least partly explained by :

- the uncertainty in the calibration of IGS station OPMT
- the uncertainty in the calibration of RIMS PARA and equipment used to connect it to UTC(OP)
- the difference between ENT and $ENT_{user.}$

It shall be noticed for instance that the uncertainty in the OPMT calibration itself is of the order 3.3 ns (1 σ).

Each daily average of $[ENT_{user} - UTC(OP)]_{OPMT}$ – $[ENT - UTC(OP)]_{MT12}$ is determined with an associated standard deviation that is depicted on Figure 10 :

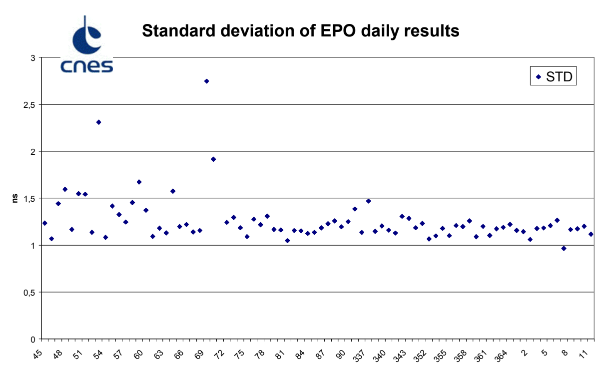

Figure 10. Daily standard deviation of $[ENTuser - UTC(OP)]_{OPMT} – [ENT - UTC(OP)]_{MT12}$

When considering only the last part of the plot, we see that the daily standard deviations stay very stable and remain below 1.5 ns (k = 1) hence 4.5 ns (k = 3).

As the EGNOS computation chain is different from the independent one, we can derive the following relation in a pessimistic approach:

Uncertainty ($[ENT-UTC(OP)]_{MT12}$) < Uncertainty ($[ENT-UTC(OP)]_{MT12} - [ENT_{user} -UTC(OP)]_{OPMT}$)

An uncertainty budget for the right part of this relationship can be built, taking into account the bias maximum value in a simple sum. Considering comprehensively the bias for a coverage factor k = 3, the following Table shows our computation :

TABLE II. UNCERTAINTY BUDGET FOR $[ENT-UTC(OP)]_{MT12} - [ENT_{USER} -UTC(OP)]_{OPMT}$

	k = 3 (ns)
Daily standard deviation	4.5
Bias maximum value	6.3
Simple sum	10.8

The information broadcast in EGNOS MT12 has to be in line with the specification #4 of Table 1: [ENT - UTC(OP)] accuracy ≤ 10 ns (3 σ). It is clear that most of the uncertainty reported in Table II comes from the OPMT internal delay uncertainty, we can conclude here that the EGNOS MT12 accuracy requirement is met.

V. UTC-UTC(OP) EVOLUTION

A modernisation of the French time scales TA(F) and UTC(OP) is on-going [14]. The goal is to produce a new UTC(OP) signal, based on a Hydrogen Maser signal for short term stability. This H-Maser signal will be steered first on an ensemble clock computed from Caesium Standards and second on the Primary Frequency Standards of the laboratory, for the middle and long term stability as for the accuracy of the signal with respect to the SI second. It is expected that this new UTC(OP) will stay closer to UTC with respect to what is currently achieved. With such improvements, the EGNOS time scale being put in relation in real time with UTC(OP) will be synchronized closer to UTC.

CONCLUSION

EGNOS is now broadcasting the information allowing any user to compute its own PVT in a reference time scale that is currently UTC(OP) by using the offset that is included in each EGNOS Message Type #12.

The synchronization in real time to this reference has proven to be very efficient: we provide here an independent method which assesses the accuracy of the broadcast offset to be less than 10 ns for a coverage factor k = 3. The broadcast offset of ENT to UTC in real time is now totally depending on the current quality of UTC(OP). But even without the implementation of the modernization of UTC(OP), the performances of this synchronization are already very good: the prediction performance of UTC – UTC(OP) over one month is estimated from its standard deviation over a long period of time to be about 20-25 ns. With the modernized French time scales, we can expect this prediction performance to be in the range of a few nanoseconds, making ENT an excellent real-time approximation of UTC available all over EGNOS service area.

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