EGNOS back-up integrity based on NLES autonomous integrity: the mini-GIC solution

Javier Ventura –Traveset, Isabel Neto, *European Space Agency (*)*
Manuel Toledo, *GMV, S.A. (**)*

* European Space Agency, GNSS-1 Project Office, 18 avenue Edouard Belin, 31401 Toulouse Cedex, France
** GMV, S.A., Isaac Newton 11, P.T.M. Tres Cantos, Madrid, Spain

Abstract:

The EGNOS (European Geostationary Navigation Overlay System) system is being developed in Europe to provide GPS (and GLONASS) regional augmentation services to aviation, maritime and land users ([3], [4]). The EGNOS System is being designed to serve the needs of all modes of transport in the European Region, namely: Civil Aviation; maritime and in-land water navigation and docking; and rail and road transport and traffic monitoring systems. For civil aviation, EGNOS Advanced Operational Capability (AOC) will provide a primary means service of navigation for en-route oceanic and continental, non-precision approach and CAT-I precision approach within the ECAC (European Civil aviation conference) area. EGNOS Full Operational Capability (FOC), which will follow the AOC phase, will ensure sole means operation.

The EGNOS AOC architecture is very robust and it is designed in such a way that integrity will always be guaranteed. For EGNOS AOC, though, under some very unlikely extreme failure conditions (e.g. in the case of SW common mode failure in all EGNOS Central Processing Facilities --CPFs--), although the system will be kept safe (integrity guaranteed), continuity of service may not be guaranteed. The probability of those outage situations is very low. Yet it is expected to remove those in EGNOS FOC (several solutions have been proposed by the EGNOS industrial consortia).

Aiming at contributing to the EGNOS FOC debate, this article introduces the concept of mini-GIC, as an elegant and very simple way of filling those unlikely outages, i.e. guarantying an operational service even under these extreme events. The EGNOS mini-GIC concept is based on the idea that, in extreme failure conditions of the EGNOS AOC System (e.g. a SW common mode failure in all EGNOS CPFs), and in order to ensure continuity of service, each navigation uplink GEO station (NLES) may autonomously assess on the integrity of visible GPS satellites. A rough integrity information may then be provided by combining that partial NLES information in a single message which is forwarded to the users (back-up integrity). This paper discusses the mini-GIC performance as well as some related architectural issues.[1]

1 - Introduction: The mini-GIC architecture: back-up to nominal EGNOS architecture

The EGNOS AOC architecture is designed to be robust against several sub-system HW and SW failures. The EGNOS design is such that integrity is always guaranteed. In some extreme failure conditions (e.g. in the case of SW common mode failure in all CPFs), though, continuity of service may not be kept in EGNOS AOC. In EGNOS FOC, where it is intended to use EGNOS as sole means of operation, the continuity of navigation service in such limiting conditions (e.g. SW common mode failure) is likely to be required.

Today, EGNOS industrial consortia has proposed as a possible FOC solution, a global diversification of the EGNOS AOC architecture (e.g. diversify the MCCs; redundant EWAN, etc). Diversification is certainly an expensive solution. In addition, some experienced voices seem to indicate that diversification is not always effective and some degree of correlation is always existing between the baseline and the diversified solution. This causes some safety concerns.

Suppose for instance the unlikely situation that a major SW common mode failure occurs at all EGNOS Central Processing Facilities (CPFs). Since the CPFs are the responsible of generating the EGNOS message, this will not be generated in this case. This situation has a very low probability to occur, and therefore, if EGNOS was able to provide a minimum service level under this odd outage case, this should be considered as adequate enough. In particular, let's assume that a minimum service level to be guaranteed is the provision of Non-Precision Approach. In terms of availability, let's assume that in this case, the back-up service should be able to guarantee a minimum operational availability, say in the range 95% to 99%, (if we consider that mini-GIC outages may be completed by RAIM implementation at user level, the resulting global availability may certainly be operationally adequate).

Having these objectives in mind, a simpler conceivable alternative to the complete diversified architecture solution is the EGNOS mini-GIC concept, which is discussed here. The basis of the mini-GIC generation and architecture are explained here below:

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1 The material presented here is only a technical discussion paper and does not reflect in any way EGNOS position for the implementation of EGNOS FOC nor the position of any of the institutions for which the authors work.

- In nominal conditions the EGNOS message is generated at the CPF and broadcast through the GEO(s) by means of the Navigation Land Earth Stations (NLES). In case of a major global problem in the EGNOS architecture (e.g. SW common mode of failure) there is no possibility to generate the EGNOS message at the CPF and, therefore, no message may be broadcast. The NLESs receive the alarm information and the mini-GIC back-up is activated.

- For the mini-GIC back-up we assume the very worst case where the EGNOS network (EWAN) is down (thus also the reference stations –RIMS-- and CPFs). There is, therefore, no way to send a message to the NLESs through the EWAN to inform the users and to provide any integrity message. However, we still have the EGNOS GEOs. This is the key element of the mini-GIC concept. For the purpose of the mini-GIC we assume the extreme and conservative case that the only elements of the system which may be used are the NLESs and the GEOs.

- The NLESs, which are built upon RIMS, are equipped with GPS/GLONASS and GEO receivers. The NLESs are also perfectly surveyed. In addition, in the case of EGNOS, up to 7 NLESs are to be implemented in EGNOS AOC (although only 6 has been assumed in this study), widely spread through Europe main land (see Fig. 1 where 6 of the NLESs are indicated).

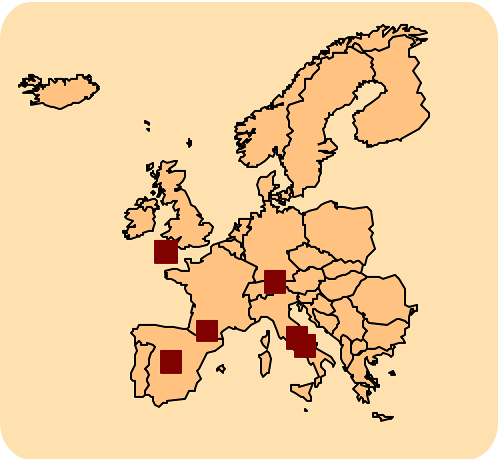

Fig 1 – NLES's location across Europe

- The mini-GIC principle is based on the idea that each NLESs may autonomously assess on the integrity of the GPS satellites that it has under visibility (say autonomous NLES integrity). Then, even assuming a limiting condition in which only the NLES and the GEOs are working a rough integrity information may be provided to the users by combining the partial NLES obtained GPS integrity information in a single integrity message.

- We may conceive that the integrity information obtained by the NLESs may be conveyed through the GEO transponders to a master NLESs. At the Master NLESs, then, having received all these information, a mini-GIC channel may be generated (essentially providing a reduced subset of the EGNOS message; e.g. UDRE integrity information and no corrections) and broadcast to the users using the traditional L1 link.

- The users receive the mini-GIC channel through L1 and will apply HPL on-board equation to determine their protection levels and availability conditions. For NPA, the Alert limit is 556 m and the HPL equation to be used is described in the RTCA MOPS [2]. If the resulting HPL is below the alert limit, the system will be available and navigation may be continued. We have therefore solved the continuity problem and provide a back-up integrity message.

Key points of the mini-GIC architecture are studied in the following sections.

2 – Improving RAIM availability using NLES surveillance

The integrity monitoring in each NLES station can be performed with algorithms of diverse complexity: from a simplified RAIM algorithm using the knowledge of the NLES exact position, to all the possibilities provided by concepts developed for local area differential stations. The level of complexity of this contingency integrity monitoring system should be defined through a trade-off considering the required integrity and availability performances. Hereafter a brief description and a first assessment of the possibilities of a simplified RAIM are developed.

The common RAIM techniques are usually based in the consistency check of overdetermined least squares snapshot solutions. In order to apply RAIM in user receiver navigation, since there are four unknowns (position and receiver clock bias), the visibility of at least five satellites is required to detect a satellite anomaly thanks to the redundant measurement. The identification of the failing satellite requires at least two redundant measurements, hence 6 satellites. This capability is called Fault Detection and Exclusion (FDE) and is required for GPS to be a primary navigation system (i.e. the user may not back-up to an alternative navigation system in case of detection of a satellite anomaly).

As the NLES shall be perfectly surveyed, the RAIM least squares snapshot solution on them can be reduced to only one unknown, the receiver clock bias. Then the FDE capability can be used since two satellites to detect the presence of a satellite anomaly, and since three satellites to identify and remove the satellite anomaly.

The problem of the estimation by least squares of the receiver clock bias of the NLES receiver is straightforward, from the problem elements:

State vector	Observable	Observation matrix	Weight matrix
Receiver clock bias	Vector of differences between real and estimated pseudoranges	Dependence of the measurements with the state vector. (In this case with independence from the geometry)	Measurements are weighed with the pseudorange measurement noise σ
$\hat{x} = \hat{B}$	**Error! Objects cannot be created from editing field codes.**	$H = \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix}$	$P = \begin{bmatrix} \frac{1}{\sigma_1^2} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \frac{1}{\sigma_N^2} \end{bmatrix}$

In the estimation problem, formulated as $\tilde{Z} = H\hat{x} + \vec{\varepsilon}$ the estimated receiver clock bias solution is:

$$\hat{B} = H^* \tilde{Z} = \frac{\sum_i^N \frac{\Delta PR_i}{\sigma_i^2}}{\sum_i^N \frac{1}{\sigma_i^2}}$$

$\vec{\varepsilon}$ is the vector of "a posteriori" measurements residuals, used as input to the Chi-squared test (χ_{N-1}^2) for failure detection in RAIM. The components of the residual vector are given by:

$$\varepsilon_i = \left\lfloor \left(I - HH^* \right) \right\rfloor_i \tilde{Z} = \Delta PR_i - \frac{\sum_{j=1}^N \frac{\Delta PR_j}{\sigma_j^2}}{\sum_{j=1}^N \frac{1}{\sigma_j^2}}$$

with the corresponding variance:

$$\left(C_e \right)_{ii} = \left\lfloor \left(I - HH^* \right) \right\rfloor_i \left\{ P^{-1} \right\}_i = \sigma_i^2 - \frac{1}{\sum_{j=1}^N \frac{1}{\sigma_j^2}} = \sigma_i^2 \left(1 - \frac{1}{\sum_{j=1}^N \frac{\sigma_i^2}{\sigma_j^2}} \right)$$

In these expressions there is no dependence on the geometry of the in view satellites, but only on their number and the dependence of the measurement noise σ with the elevation. The NLES receivers shall work with the uncorrected raw pseudorange measurements, as any absolute user receiver. The measurements noises σ are dominated by the Selective Availability and the residuals of the ionospheric correction using the Klobuchar parameters broadcast in the GPS navigation message. In these conditions the measurement noise σ is basically the same for all the measurements, the dependence with the elevation disappears and the above expressions can be simplified.

This independence from the satellites geometry is a very important and powerful feature simplifying the design of this special NLES RAIM test. All the RAIM algorithm characteristics shall always be the same depending only on the pseudorange noise σ parameter and the number of in view satellites. In particular, assuming that there is only one anomalous satellite, the Minimum Detectable Bias (MDB) shall depend only on these two parameters and shall be the same for all the in view satellites. The MDB is defined in the case of satellite failure from the obtained non central Chi-squared distribution that meets the missed (?) detection probability in the detection threshold defined from the false alarm RAIM requirements. The non-central Chi-squared has a non-centrality parameter λ given in general by $\lambda = \vec{b}^T P \left(I - HH^* \right) \vec{b}$ where $\vec{b}$ is the vector of measurement biases. The MDB is the measurement bias b_i corresponding to the λ value of the non-central Chi-squared distribution that meets the above requirements. In this particular case the non-centrality parameter λ, assuming bias only in one measurement, is given by:

$$l = \frac{b_i^2}{s_i^2}\left(1 - \frac{\frac{1}{s_i^2}}{\sum_{j=1}^{N}\frac{1}{s_j^2}}\right)$$

The measurement noise s parameter and an appropriate bound to the MDB can be used to build UDRE values, to be broadcast to the user receiver or even directly computed in by the user. The user receiver shall be aware of the unhealthy satellites detected by the NLES RAIM and which UDRE to use for the healthy satellites, except in the worst to detect satellite for which an UDRE derived from the MDB is more appropriate. With the broadcast information each user receiver can autonomously determine for its EGNOS healthy in view satellites the worst case of satellite with MDB for the computation of the HPL until the NPA phase.

Exploiting the reduction in the minimum number of satellites which need to be monitored simultaneously in view of a NLES for FDE capability, is a key issue in improving the final user availability with the mini-GIC principle. This is analysed in some detail in Section 4.

3 – Communication between NLESs and Master and generation of the mini-GIC message

Once each NLES has determined the integrity of the different GPS under its visibility, they need to convey this information to the master NLES for the generation of the mini-GIC channel to the EGNOS users. Although it is not the intention of this document to analyze this issue in detail some ideas are proposed through this section.

As indicated in Section 1, we assume the following architectural constraints:

1. There is only one Master NLES which collects the GPS health information to generate the integrity message to the users;
2. The EWAN connection is not working anymore; we assume, therefore, that the EGNOS Wide Area Network (EWAN) may no be used for NLES to master-NLES connection;
3. All GEOS and NLES are working and all NLES may accessed the GEO satellites.

Considering that assumptions it comes clear that the NLES need to transmit the GPS status information through the GEO satellites. We may envisage two different strategies:

- NLES transmit to the master NLES using the EGNOS available GEOS and using dedicated pre-defined standard mobile communication channels. This is possible since all EGNOS GEOS (Inmarsat AOR-E, Inmarsat IOR and Artemis) do provide mobile communication services that may be accessed through the same up-link antennas used to access the Navigation payloads. Dedicated VSAT type connections are then needed at each NLES. The advantage of this approach is that the communication NLES-master NLES may be of high quality (e.g. protection codes may be used) and it may be kept continuous.

- NLES transmit to the master NLES using the Navigation transponder and the L1 down-link. This approach has the advantage that it may be readily provided since all NLES are prepared to transmit in this mode. In this case, though, since the number of GEOS is lower than the number of NLES to transmit a network protocol need to be followed (e.g. each NLES has particular window time assigned to transmit; or one NLES transmit after another and only after it has received acknowledge that the preceding NLES message was sent; etc). In addition since this message may reach the user a new message type needs to be defined such that the user knows it does not need to be used.

Once the Master NLES has received the GPS integrity information conveyed by the different NLESs, a global integrity message (the mini-GIC back-up message) need to be generated to be transmitted to the users. A dedicated SW is therefore needed to be installed at the master NLES for this message generation. The level of this SW should therefore be according to the integrity service provided (likely SW level B may be required). Again, no analysis has been performed on this message generation, but it may anticipated that this should be a rather simple SW which after decoding the different NLES messages, generates the UDRE GPS integrity information.

4 – Simulation Results

In order to analyze the performances that can be obtained by the mini-GIC solution, some GIC - HPL simulations for a HAL=556m have been performed. Following the previous section, the main idea is that the system provides integrity messages to the user which will compute its position with healthy satellites only.

This concept implies the following NLES *filtering* criteria:

- In order to compute its position the user needs to have at least 4 *'valid'* satellites. An NLES will be able to provide integrity messages referring to one satellite if it monitors say X satellites at the same time: meaning that there are more than ***X*** satellites in visibility, with an elevation angle bigger than a certain mask angle. We define ***X*** as being the NLES filtering number, referred to throughout this paper. In fact, the NLESs compute RAIM, and so, for FDE, X should be 6. However, there is the particularity that the NLESs' positions are perfectly surveyed, and so, for FDE, a value of 3 should be enough (see section 2). (For that reason, values between 6 and 3 are considered). If a satellite belongs to a group of more than ***X*** monitored satellites in at least one of the considered NLESs, then it is considered monitored, and 'valid'.

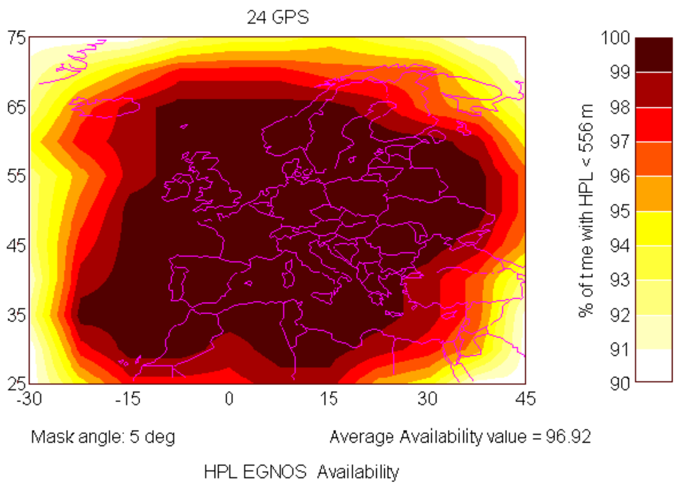

Fig 2 – Example of mini-GIC Performance result

The simulations have been performed in the ECAC region, using combinations of:

- GPS constellation (RTCA standard for simulation purposes [2]);
- GEO (IOR and AOR-E) and ESA's Artemis satellite [6].
- GLONASS (GLONASS ICD [7] considering the situation that one of each two satellites has failed, i.e. the even ones).

A mask angle of 5 degrees has been used for the users, which are uniformly distributed over the considered area with a 5-degree grid step. Satellite orbits are sampled every 5 minutes during 24 hours. The NLES considered are the ones in Fig. 1.

The resulting sensitivity of changing some input parameters has been studied: constellation used (GPS only, GPS and GLONASS, GPS + GEOs), mask angle for NLES (15, 10 or 5 degrees) and NLES filtering number (6, 5, 4 or 3). We have assumed that GEO, GPS and GLONASS have an UDRE equal to 33 m and that the receiver is based on a worst case MOPS receiver Class-2 [2]),

Table 1 summarizes the simulations performed, indicating which input parameters were used in each one of them. The last column states the availability of GIC-HPL, HAL=556m, for ECAC.

From these basic simulations, several system availability sensitivity studies have been carried out. (availability versus NLES masking angle, versus NLES filtering number, versus use of GLONASS, and, finally, use of GEO ranging). When using Glonass, availability is not dependent on NLES filtering numbers since the number of satellites in view is such, that there are always enough 'valid' satellites. Comments on those results and conclusions are presented in the following section

Table 1 - List of Simulations performed and corresponding input parameters

Simulation number	Constellation	Protection Error Budget UDRE (in meters) [5]	Mask angle for NLES	NLES Filt. No.	Avail for ECAC (%)
1	24 GPS	33	15	6	92.11
2, 3, 4	24 GPS	33	15	5, 4, 3	96.92
5	24 GPS	33	10	4	98.68
6	24 GPS	33	5	4	99.74
7, 8, 9, 10	24 GPS + 12 GLO	33	15	6, 5, 4, 3	99.35
11	24 GPS + 3 GEOs	33	15	4	99.63
12	24 GPS + 3 GEOs	33	10	4	99.88
13	24 GPS + 3 GEOs	33	5	4	99.97

5 – Comments on the Simulation results and Conclusions

For the readers' advantage, it has been decided to express the conclusion to this small study in form of answers to the key questions concerning the implementation of the EGNOS mini-GIC solution.

- *May the mini-GIC solution provide a back-up to the EGNOS nominal operational mode so that the combined architecture is robust against SW common mode failures in the CPF or EWAN major interruption problems?*

  Considering that the mini-GIC message generation is completely independent of the way the standard EGNOS message generation is generated, it is clear that a common SW mode in all EGNOS CPFs would be transparent to the mini-GIC architecture. This independence makes the mini-GIC approach very attractive. Based on the preliminary study presented in this document, it seems that with the mini-GIC channel an adequate back-up operational service level could be achieved. As a consequence of these two considerations, it may be concluded that the resulting architecture EGNOS + mini-GIC should be robust against major EGNOS architectural failures (such as SW common mode failure or a global problem in the EWAN network).

- *Assuming operation in the mini-GIC back-up mode, will the level of back-up operation of interest in an operational scenario perspective?*

  Assuming as the minimum acceptable operational performance a level equivalent to NPA with an associated availability larger than 95%, the mini-GIC approach provides this level of service. The level of service ranges between 95 and more than 99.9% depending on the assumptions considered (including NLES minimum elevation angle, use or not of GEO autonomous ranging, degrees of freedom considered for the RAIM NLES autonomous generation, use or not of GLONASS.) If in addition we consider that mini-GIC outages may be completed by RAIM implementation at user level, the resulting global availability may certainly be operationally adequate.

- *For the efficient implementation of the mini-GIC solution, is the GEO autonomous ranging required to be kept at the level of NLES?*

  If we consider that the acceptable availability of interest is 95% NPA for the mini-GIC solution, the provision of GEO ranging may not be necessary since with only GPS satellites this availability may be achieved. The impact of the additional GEO ranging sources is remarkable if NLES are limited in visibility to 15 degrees elevation (96% to 99.6%). Instead if low elevations could be implemented at NLES sites (say between 5 and 10 degrees), the impact of the extra GEO ranging sources is much more limited.

- *Considering the performance that may be obtained with the mini-GIC solution. Is it needed to provide GLONASS integrity? Assuming a degraded GLONASS constellation what is the system performance impact of monitoring in addition to GPS the Glonass satellites?*

  If we consider that the acceptable availability of interest is 95% NPA for the mini-GIC solution, the provision of Glonass integrity may not be necessary since with only GPS satellites this availability may be achieved. The impact in the availability is remarkable if NLES are limited in visibility to 15 degrees elevation (96% to 99.3% for a degraded GLONASS constellation). Instead if low elevations could be implemented at NLES sites (say between 5 and 10 degrees), the benefit of Glonass is lowered. Yet since the provision of autonomous GEO ranging for long terms may be quite difficult to achieve, the use of GLONASS sources and the provision of integrity to those may be a good simpler alternative.

- *If no back-up solution were to be implemented, what is the availability of service that could be achieved with GPS and RAIM only? Would this be enough?*

  The mini-GIC solution provides a service with continuity in which satellite failures are detected and in which the user may continuous navigation as far as at least 4 satellites in visibility are monitored. Thus, we should consider for the sake of comparison, the achievable level of service of RAIM Fault detection and exclusion for Non-Precision Approach level of service. Considering the results published in [8], the RAIM FDE (NPA) availability achievable with GPS only would be below 60%. Therefore, the benefit of the mini-GIC solution is quite apparent.

- *May the EGNOS AOC architecture be updated to include the mini-GIC back-up solution as an integral part?*

  The architectural considerations of the mini-GIC solution made through this study are rather limited to answer properly to this question. The mini-GIC concept presented in this document is considered in any case rather simple, requiring essentially the implementation of four main functions:

  - The activation of the mini-GIC back-up mode in the limiting failure mode conditions;
  - Generation of NLES autonomous integrity of GPS satellites;
  - An efficient NLES-to-master NLES communication through the existing EGNOS GEO satellites;
  - The generation at the master NLES of a user integrity message;

  It is believed that the mini-GIC architectural concept may be included as a functionality of the EGNOS FOC solution in top of the existing EGNOS AOC architecture.

❑ *Which are the main open issues requiring further work after this preliminary analysis?*

This study has concentrated on the system availability of the resulting service that could be achieved is the mini-GIC solution was to be implemented. The architectural considerations of the mini-GIC solution made through this study are therefore, again, rather limited and should be where further studies should concentrate. Some of the specific issues that would need to be further assessed include:

- The possibility of proving NLES autonomous RAIM exploiting the fact that NLES are surveyed (see Section 2);
- The effective way of establishing communications between the different NLES and the master NLES (see Section 3);
- The generation of the mini-GIC channel at the master NLES using the different NLES integrity information (see Section 3);
- The mini-GIC message structure to be send to the users and the possibility to use existing MOPS DO229A message (e.g. message type 6);
- The robustness of this architecture in terms of safety.

Acronyms

AOC – Auxiliary Operational Capability
CPF – Central Processing Facility
ECAC – European Civil Aviation Conference
EGNOS – European Geostationary Navigation Overlay System
ESPADA – EGNOS Simulation Performance Assessment and Design Analysis
EWAN – EGNOS Wide Area Network
FDE – Fault Detection and Exclusion
FOC – Full Operational Capability
GEO – Geostationary satellite
GIC – Ground Integrity Channel
GPS – Global Positioning System
HAL – Horizontal Alarm Limit
HPL – Horizontal Protection Level
HW - Hardware
MCC – Master Control Station
MDB – Minimum Detectable Bias
NLES – Navigation Land-Earth Station
RAIM – Receiver Autonomous Integrity Ranging
RIMS – Ranging and Integrity Monitoring Stations
SW - Software
UDRE – User Differential Range Error

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