OPERATIONAL CONSIDERATIONS FOR IMPROVED ACCURACY WITH AN IOC GALILEO CONSTELLATION

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ABSTRACT

When Galileo achieves its Initial Operating Capability (IOC), there will be 18 satellites in orbit, broadcasting navigation messages around the world. This set of satellites will achieve 100% coverage, given the three plane, six satellites per plane geometry. During the IOC phase, the Dilution of Precision (DOP) is not yet ideal and indeed may have severe spikes several times during the day globally.

Navigation accuracy during the IOC phase of Galileo is a function of many factors. This paper focuses on two components of navigation accuracy that the Galileo Control Center (GCC) can manipulate in operations to improve overall accuracy for the users of the system. Using the fundamental error equation, this paper shows that tuning operations at the GCC can reduce navigation errors from the IOC constellation on a global basis by selectively timing uploads of the orbital ephemeris and clock state predictions.

The GCC must refresh the satellite orbital position (ephemeris) and clock state predictions on a regular basis to keep the receiver's calculated positions accurate. These predictions are sent to the user's receiver, where it uses this data to calculate its position and velocity. Understanding how these predictions affect a user's accuracy and understanding how to manipulate these predictions will aid the GCC in delivering a lower average navigation error during the Galileo IOC period.

Even with very accurate clocks, individual satellite clock state predictions must be uploaded to the Galileo satellites on a regular basis – to keep the Galileo system accuracy at a desired level. For the same reason, the orbital ephemeris predictions must also be updated regularly. Since both of these data items are predictions, errors in these predictions result in errors at the user's receiver. Ideally, these orbit and clock predictions would be updated continuously, but that cannot be achieved operationally. This paper will show the results of manipulating the GCC operations upload tempo to deliver better navigation accuracy performance for Galileo.

Benefits of implementing these results include a smaller average navigation error for users of the IOC system, leading to increased user desire for system use. Additionally, early application developers will more readily adopt the system over GPS and more reliable safety-of-life use of Galileo may result.

INTRODUCTION

When Galileo reaches its Initial Operational Capability (IOC) in the next few years it will have 18 navigation satellites in orbit (1). Using the fundamental error equation (2), it's possible to see the errors inherent in a radio navigation system. Many different errors are described and can be classed into three separate groups; signal-in-space (SIS) errors, atmospheric errors and receiver errors. This paper focuses on the signal-in-space errors only and what the Galileo Control Center can do to minimize these. Galileo satellites will have clocks on board that provide unprecedented timing accuracy in space. These passive hydrogen maser clocks are capable of keeping time to 0.45 nanoseconds within a 12 hour period (3). With this level of timing accuracy, the SIS error is going to be dominated by the remaining piece: satellite ephemeris error. Understanding how the signal-in-space error can be managed, and the results of such management are the subject of this paper.

THE FUNDAMENTAL ERROR EQUATION

The fundamental error equation (2) shows how user positioning errors are related to errors in Galileo and the environment.

$$\mathbf{G} \cdot \Delta\vec{x} = \Delta\vec{\rho}_c \tag{1}$$

$$\Delta\vec{\rho}_c \equiv \mathbf{A} \cdot \mathbf{\Delta R} - c \cdot \Delta\vec{S} + \varepsilon \tag{2}$$

In equation 1, $\Delta\vec{x}$ is the user's positioning error vector and the vector $\Delta\vec{\rho}_c$ represents the errors in the corrected pseudorange for each tracked satellite. See reference (2) for details of how the pseudorange is corrected. Here, $\mathbf{G}$ is a geometry matrix defining the direction cosines to the user's receiver from the Galileo satellites. This matrix is also augmented with a column of 1's to assist in the determination of the receiver's timing error. In equation 2, $\mathbf{A}$ is a diagonal matrix of line-of-sight vectors to each satellite, c is the speed of light in a vacuum and ε represents remaining errors in the solution which this paper does not cover, including atmospheric and other environmental and receiver errors.

The values in equation 2 that we are particularly interested in are $\mathbf{A} \cdot \mathbf{\Delta R}$, the set of vectors representing the positioning errors for each satellite (also known as the ephemeris errors), along the line of sight vector from the satellite to the receiver and $\Delta\vec{S}$, the satellite clock error for each satellite. This line-of-sight mapping is important; for the ephemeris errors, only the radial component and the dot product of the cross-track and in-track components will be added to the user's error. The clock error ΔS is also fully along the line-of-sight vector.

$$\Delta\vec{x} = \left(\mathbf{G}^T\mathbf{G}\right)^{-1}\mathbf{G}^T \cdot \Delta\vec{\rho}_c \tag{3}$$

Equation 3 shows the solutions for equation 1. The residual errors for a user's positioning solution are the product of two factors, one based purely on geometry, the other based on SIS errors and other factors. Breaking equation 3 into a different form:

$$\Delta\vec{x} = \mathbf{K} \cdot \Delta\vec{\rho}_{c,comp} \tag{4}$$

$$\mathbf{K} = \left(\mathbf{G}^T\mathbf{G}\right)^{-1} \tag{5}$$

$$\Delta\vec{\rho}_{c,comp} = \mathbf{G}^T \cdot \Delta\vec{\rho}_c \tag{6}$$

The matrix **K** represents the Dilution of Precision of the solution – a pure geometric effect. Equation 6 shows that $\Delta\vec{\rho}_{c,comp}$ represents the corrected pseudorange errors mapped into the components of the reference frame of the solution. The value $\Delta\rho_{c,comp}$ is here after called the Signal-In-Space User Range Error (SISURE) – one for each satellite.

By breaking the user's solution error equation into the form of equation 4 we can understand more clearly how to manipulate the Galileo system to optimize accuracy. By selecting orbital positions for the initial 18 satellites appropriately we can optimize the geometrical portion of the equation. The Galileo Control Center can also optimize the pseudorange errors by keeping $\mathbf{\Delta R}$ and $\Delta\vec{S}$ as small as desired. It should be noted that this mathematical formulation assumes that all of the errors in $\Delta\vec{\rho}_c$ are independent, have the same variance and zero mean.

An effect one can see from this equation is that irrespective of the DOP value, if the SISURE is small, the user's positioning accuracy will be correspondingly small. DOP can be a good indicator of a user's navigation accuracy, but this is not necessarily true in low SISURE situations.

UNDERSTANDING GPS EPHEMERIS AND CLOCK ERRORS

To understand how the SIS ephemeris and clock errors affect navigation accuracy, let's look at how these errors arise. The algorithms for radio navigation using a GNSS system demand that, for a receiver to determine its position, it must know where each of the satellites it is tracking are located and the precise time onboard each satellite. This information is delivered to the receiver by the GNSS satellite as data on the navigation timing signals. The data is fit to models the receiver uses to determine the satellite's position and time. For the GNSS satellite to send this data to receivers, the Control Center has to predict what these model values should be in advance. Once determined, the Control Center uploads these values to the individual satellites for broadcast to the users.

The Control Center can choose to derive and upload the ephemeris and clock predictions at any time, within the constraints of the system. Since these are predictions however, there are errors associated with them. The models used to predict satellite ephemerides always contain some level of unmodeled phenomenon and typically do not represent anomalies onboard the satellite which can affect the ephemeris. Similarly for satellite clocks – they are quantum mechanical devices governed by the laws of probability. We have made great strides in atomic clock stability but we are not able to predict the behavior of an atomic clock without some error. The predictions are best the moment the Galileo Control Center predicts the ephemeris and clock states. As time passes, the age of the predictions (known as *age of data* or AOD) increases, leading to increasing errors in calculated satellite position and clock states for the users. Striving to reach a balance between the amount of work required to predict new state data and upload it, against the amount of accuracy improvement gained, is a key concern in GNSS constellation management. In a perfect world, the AOD would always be zero and ephemeris and clock errors would vanish.

Some examples of GPS ephemeris and clock errors are plotted in Figures 1 and 2. Figure 1 shows the Root-Sum-Square (RSS) of the ephemeris error for a good and bad performing GPS satellite over five days. Figure 2 shows the clock errors (multiplied by the speed of light) for good and bad performing satellites over five days. Note how often the errors jump back to close to zero – this is when the GPS Control Center uploads a new set of predictions, effectively resetting the AOD.

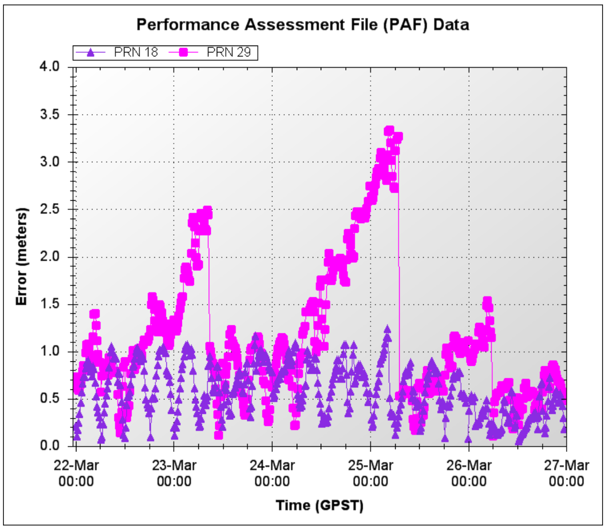

Figure 1- GPS Ephemeris Errors, PRNs 18 and 29

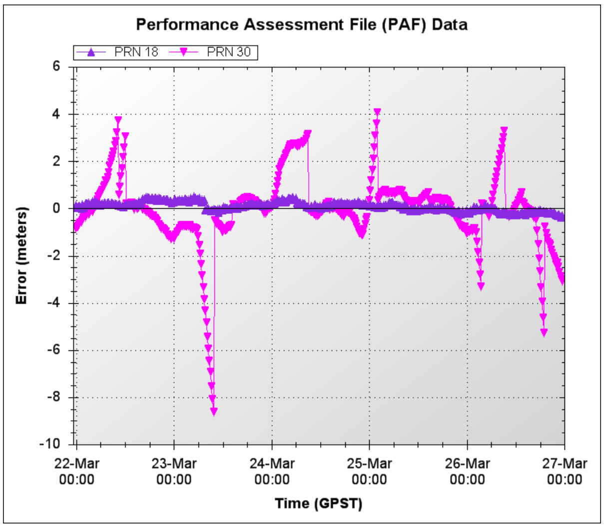

Figure 2 - GPS Clock Errors, PRNs 18 and 30

Because Galileo is using hydrogen maser clocks, the clock error ΔS is going to be small. In fact, it's reported (3) that the new clocks will only vary by 0.45 nanoseconds over a 12 hour period. This equates to roughly 13 cm of clock error in 12 hours. If this holds true in production, the clock error plots for Galileo will look similar to the plot for PRN 18 in Figure 2. Clock errors on Galileo satellites are not likely to drive the user's positioning error. The satellite's ephemeris prediction error will be the largest SIS error component which drives the user's positioning accuracy.

EPHEMERIS ERROR EFFECTS

We know that ephemeris predictions aren't perfect and as they degrade, a user's accuracy degrades. A few of the major causes of ephemeris degradation are listed here.

- *Mismodeling of the satellite's orbit*. Obviously if we could model all effects on an orbit, the predictions would be perfect. The better your ephemeris model however, the more it costs to run, in both time and resources. A trade-off is required to determine how much error you can stand for example, by modeling medium fidelity versus high fidelity. The ability to model solar radiation pressure correctly is also a challenge. Understanding the motion of all of the reflective surfaces on a satellite in a dynamic situation is a challenging undertaking.

- *Ephemeris perturbations.* Spacecraft momentum dumps can affect the orientation, which, coupled with the solar radiation pressure model in use, can affect the ephemeris. Solar storms can eject material from the Sun towards the satellite, causing a significant change in solar pressure. Additionally, if any magnetometer devices are used on the satellites, the changing magnetic fields surrounding Earth will have an effect on their readings. When the satellite enters eclipse season, solar radiation pressure will change abruptly causing ephemeris errors, unless modeled specifically.

- *Unknown perturbations*. The space environment is becoming increasingly populated and unfortunately, high-velocity collisions have occurred. Currently, about 20,000 orbiting objects are tracked and cataloged, but estimates show that there are 100,000 or more objects orbiting the Earth. Any type of collision, whether it's from a man-made object or not, will cause the ephemeris prediction to be incorrect. Devastating collisions will most likely cause the satellite to no longer function, but collisions from micro-meteorites or small debris may still leave a usable, if damaged satellite.

All of these effects make ephemeris errors a reality that must be dealt with. Reducing these errors can be achieved by uploading new ephemeris predictions. How often and to which satellites is determined by analyzing the performance of each satellite. As mentioned previously, the desire would be to drive the age of data for these predictions to zero, but zero age of data (ZAOD) is only a goal – it is not achievable operationally yet.

If the Galileo Control Center could change the upload tempo to drive the predictions AOD down, how much would be needed to have a significant effect on Galileo users? The next section explores the end result of managing the SISURE – answering the question: how do changes in SISURE affect changes in the end user's positioning accuracy?

EFFECTS OF MANAGING THE CONSTELLATION TOWARDS ZAOD

Here I show the effects of varying the SISURE for an 18 satellite Galileo constellation, and look at the global navigation accuracy results. I'll explore 3 different scenarios:

- *Scenario1*: An 18 satellite Galileo constellation modeled as a perfect walker constellation with equidistant plane spreading and equidistant satellite spreading within plane. With this constellation we'll look at a SISURE of 2 meters for each satellite.
- *Scenario 2*: An 18 satellite Galileo constellation modeled as in Scenario 1. Here I'll look at a SISURE of 0.5 meters for each satellite.
- *Scenario 3*: Finally, the results for a full 30 satellite Galileo constellation are shown. In this scenario, three planes each have ten satellites and the SISURE is fixed at 0.5 meters.

Scenario 1

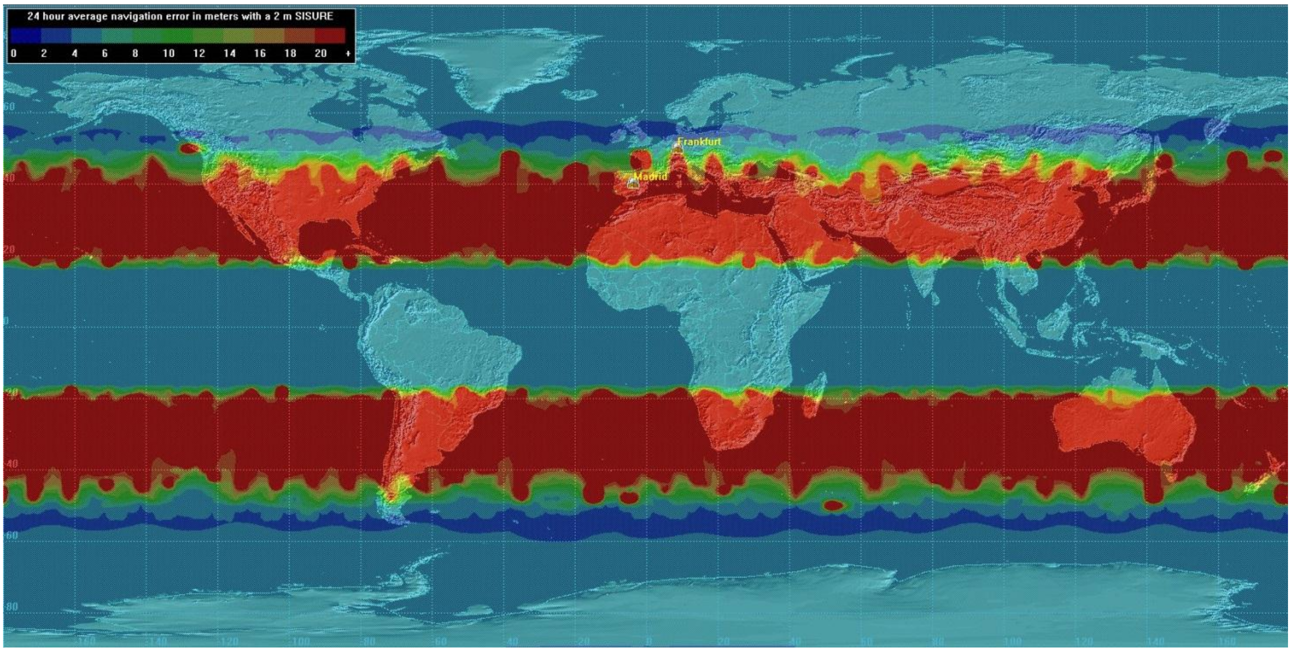

Figure 3 – Scenario 1: 24 hour average navigation error using a 2 m SISURE

Figure 3 shows the 24 hour average navigation error results when a 2 meter SISURE is used on each Galileo satellite. Because there are only 18 satellites in the IOC constellation, there are large mid-latitude bands that do not have good DOP coverage for portions of the day. Note that there are small dark blue bands above and below these that do have good DOP all day long. To understand how the navigation errors vary over a day, Figures 4, 5, 6 and 7 show a plot of navigation errors over 24 hours in Frankfurt, Germany and Madrid, Spain. There are severe DOP spikes in these plots which denote Galileo outages for the duration of the spike. Figures 5 and 7 both show the navigation errors on a smaller scale to highlight the nominal navigation error. We can see that both Frankfurt and Madrid experience navigation errors on the order of 4 meters over the day, excluding the values from the DOP spikes.

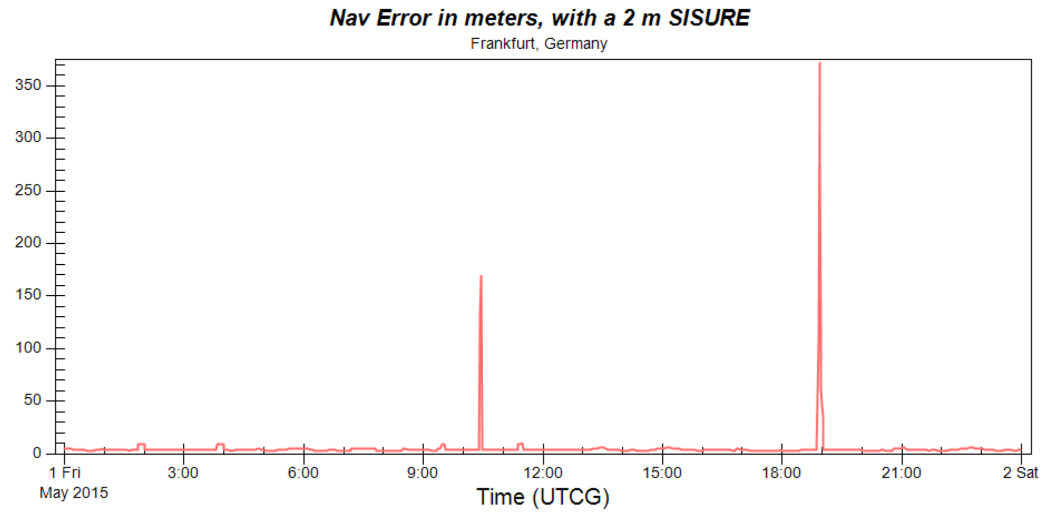

Figure 4 - Scenario 1: Navigation error in Frankfurt

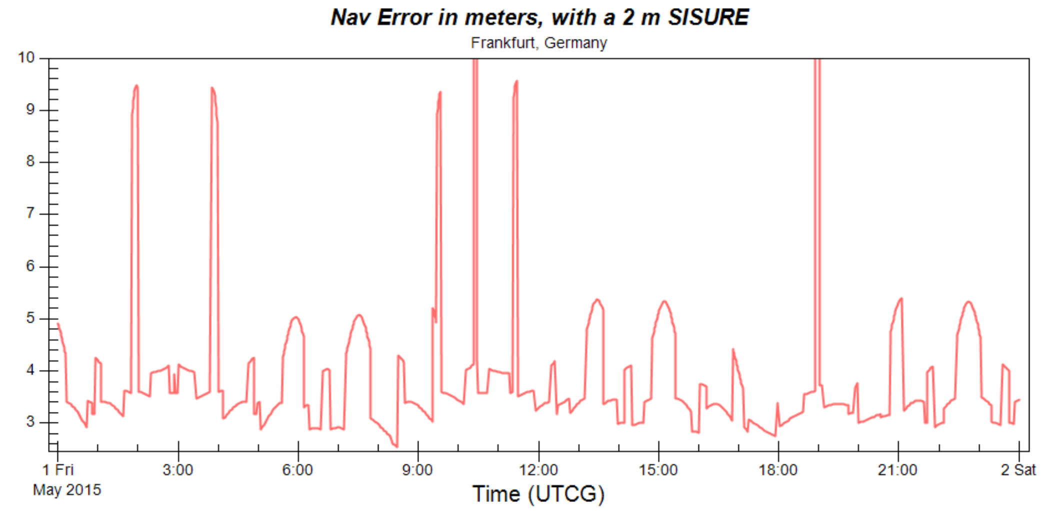

Figure 5 - Scenario 1: Navigation error in Frankfurt using a smaller scale

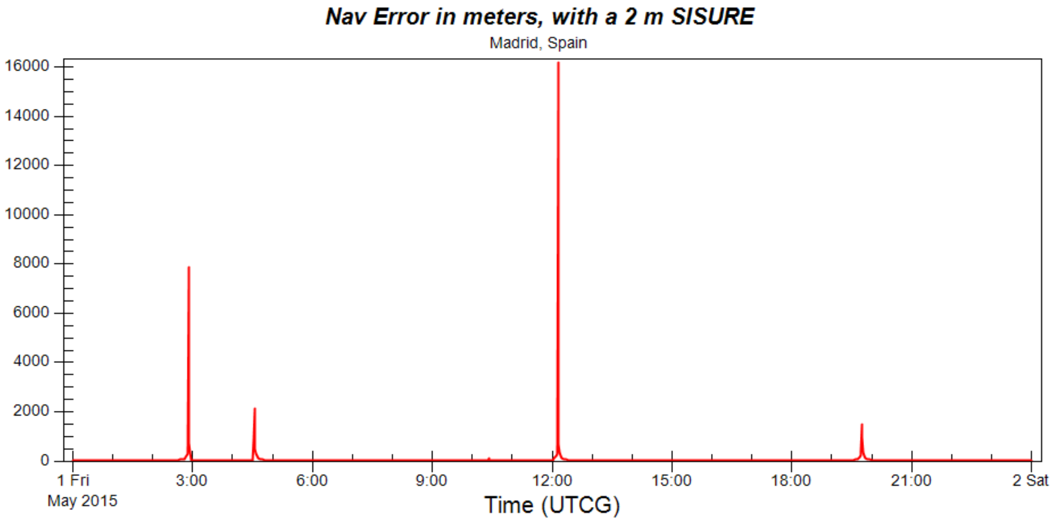

Figure 6 – Scenario 1: Navigation error in Madrid

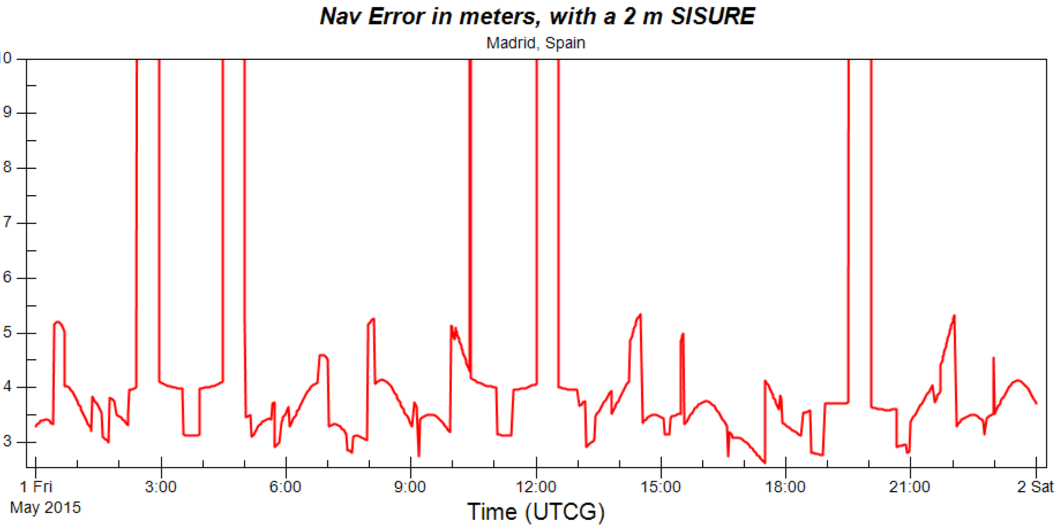

Figure 7 - Scenario 1: Navigation error in Madrid using a smaller scale

Scenario 2

Figure 8 shows the 24 hour average navigation error using a SISURE of 0.5 meters for each Galileo satellite. A marked reduction in global navigation error is seen – even in the mid-latitude bands. There are still areas of high average error – realistically this can only be fixed by adding more satellites to the constellation.

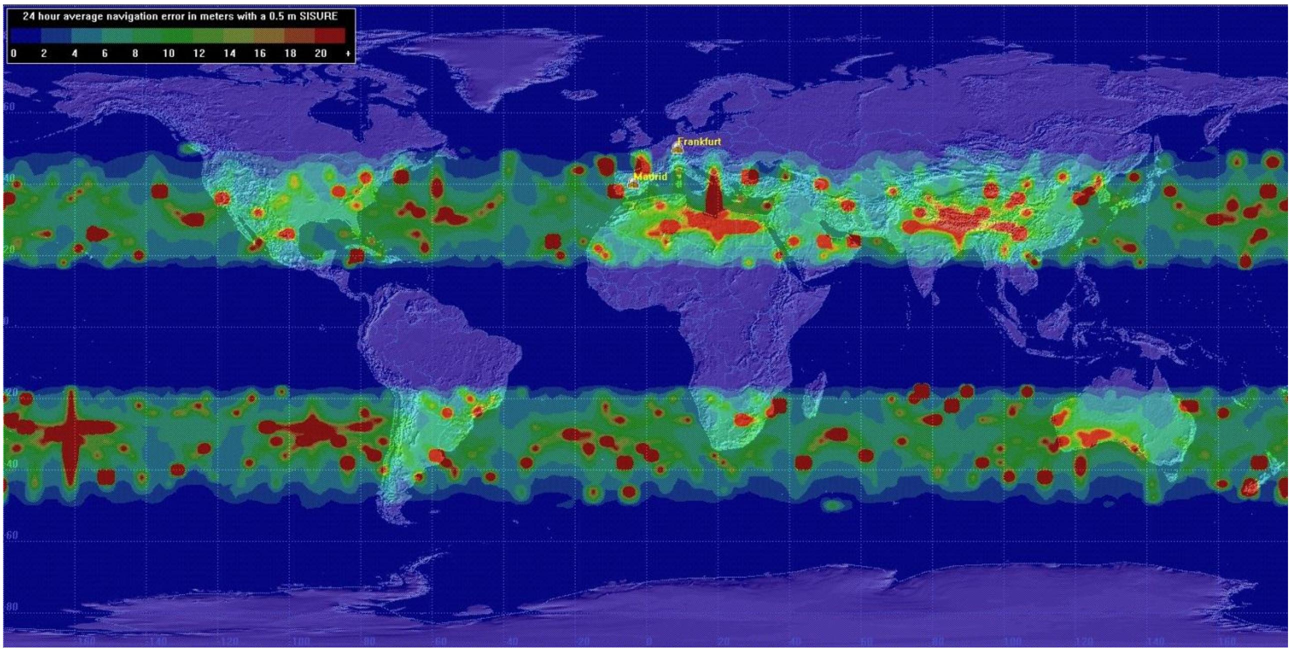

Figure 8 – Scenario 2: 24 hour average navigation error using a 0.5 m SISURE

Table 1 compares the global average navigation error values as a function of average SISURE used.

Table 1 - Comparison of Global Navigation Errors

Average SISURE Value meters	**Average Global Navigation Error Statistics** meters (Excluding errors over 100 m)
2.0	minimum: **3.89**, average: **5.68**, maximum: **9.84**
0.5	minimum: **0.98**, average: **1.88**, maximum: **4.18**

Figures 9 and 10 revisit the cities of Frankfurt and Madrid. Notice how their daily average navigation errors have dropped from roughly 4 meters to approximately 1 meter. This is a large improvement and is the result of just keeping the average SISURE managed to a value of 0.5 meters.

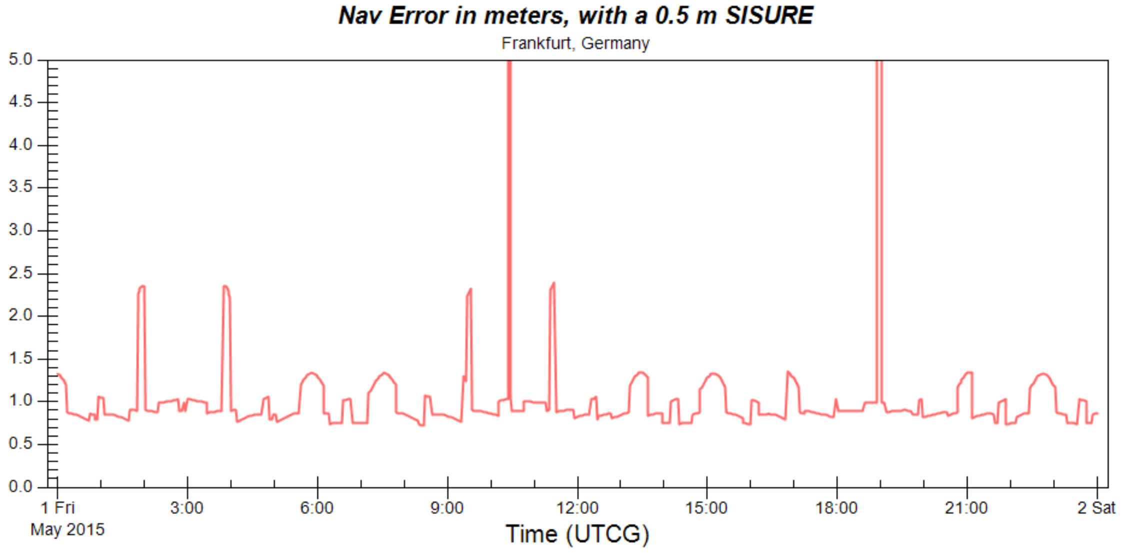

Figure 9 – Scenario 2: Navigation error in Frankfurt using a 0.5 meter SISURE

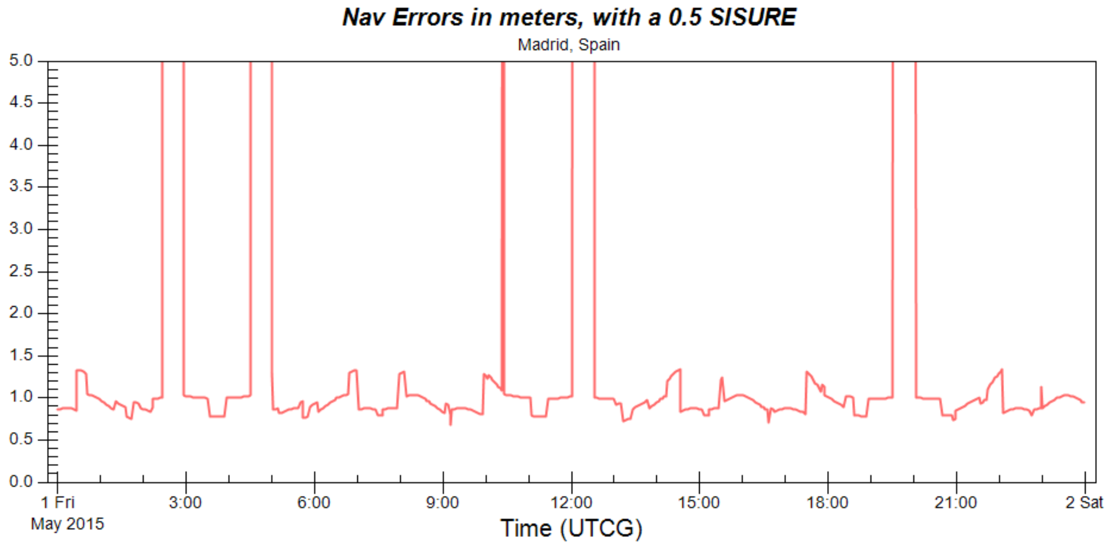

Figure 10 - Scenario 2: Navigation error in Madrid using a 0.5 meter SISURE

Scenario 3

Figure 11 shows the effects of a managed SISURE of 0.5 meters on global navigation error when the Galileo system reaches FOC. This picture was created using a three plane Galileo constellation, with ten satellites in each plane. The 24 hour average navigation error, due solely to the SISURE, is amazingly low: 0.92 meters. This figure shows that if a managed upload tempo can be achieved, Galileo will be the preeminent GNSS system.

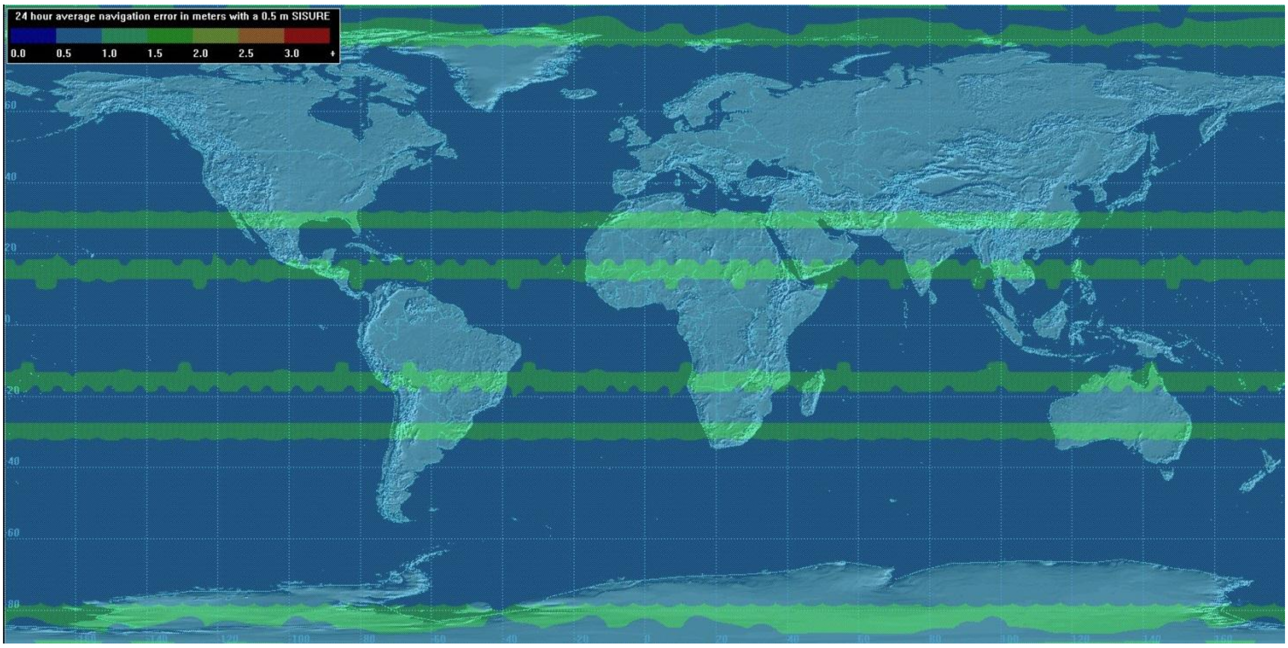

Figure 11– Scenario 3: 24 hour average navigation error, FOC constellation, using a 0.5 m SISURE

DESIRED ACCURACY VERSUS OPERATIONS COMPLEXITY

Managing an upload schedule that drives the ephemeris and clock prediction errors towards ZAOD is subject to many constraints. A full itemization is not listed here, but several key areas are addressed.

- *Availability of Galileo measurements*. There must be a sufficient number of monitor stations and measurements delivered into the GCC processing filter to allow for an ephemeris prediction covariance that is small enough to be acceptable to the operators. An additional concern is the processing filter update rate. It may take several measurement updates to acquire an acceptable prediction covariance.

- *Availability of ground stations to execute the data upload*. Regardless of how often you want to upload the satellites, ground resource constraints may prohibit uploads faster than a certain rate. Given that all satellites have to be uploaded at the desired rate, too few ground stations may prohibit that from happening. Scheduling these assets is complex and may require a great deal of planning, including outage times due to maintenance, etc. This holds for monitoring stations as well.

- *Availability of computing and personnel resources.* Computers are ubiquitous these days, but resource constraints may still exist in a complex control center. Additionally, to have a true desired upload rate met; personnel must be available to perform upload operations 24 hours a day, seven days a week.

BENEFITS OF LOWER AVERAGE NAVIGATION ERRORS

The main benefit of lowering the average navigation error is the trust engendered in the people using the system. Users of all levels; paid, free, civil or government will benefit from a more accurate Galileo constellation. Those with critical, safety-of-life needs will benefit dearly from a more accurate navigation system.

With a greater trust of the system, location-based application developers will develop applications that work better from the day IOC is declared, improving their businesses early on. This trust in Galileo also acts as a positive marketing message and will garner new paid users of the commercial Galileo signals – a true sign of success.

CONCLUSION

Through the use of the fundamental navigation error equation, I've shown how the Signal-In-Space User Range Error, if properly controlled by the Galileo Control Center, can yield a lower average navigation error worldwide. With only 18 satellites in the Galileo IOC system there will still be Dilution of Precision spikes, causing Galileo outages from slight to severe – especially in the mid-latitude bands. DOP spikes are to be expected in the IOC system; there are simply not enough satellites to eliminate them completely during this phase. Because of the lower number of satellites in the IOC system, navigation errors on average are larger than they will be in the FOC system. It is possible for the GCC to lower the average navigation error during IOC by manipulating the ephemeris and clock state prediction upload tempo. Driving the upload tempo towards a zero age of data was shown to decrease the global average navigation error from 5.68 meters using a 2.0 meter SISURE, to 1.88 meters with a 0.5 meter SISURE. This improved level of accuracy in the IOC system will attract more users to Galileo initially, leading to improved safety-of-life missions and a better economic outlook derived from navigation based business and commercial Galileo signal purchases.

Improving Galileo's IOC accuracy will come with challenges; worldwide monitor station and ground station resource management, GCC processing filter details and personnel management all must be considered and managed effectively to bring this improvement to fruition.

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