“Problème récurrent à étudier”
Lessons Learned from the Galileo programme

TRISMAC

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ESA-ESRIN | Frascati (RM), Italy

Introduction - The Galileo System

Galileo is Europe's own global navigation satellite system, providing a highly accurate, guaranteed global positioning service under civilian control. Galileo is interoperable with GPS and Glonass, the US and Russian global satellite navigation systems. By offering dual frequencies as standard, Galileo can deliver real-time positioning accuracy down to the metre range.

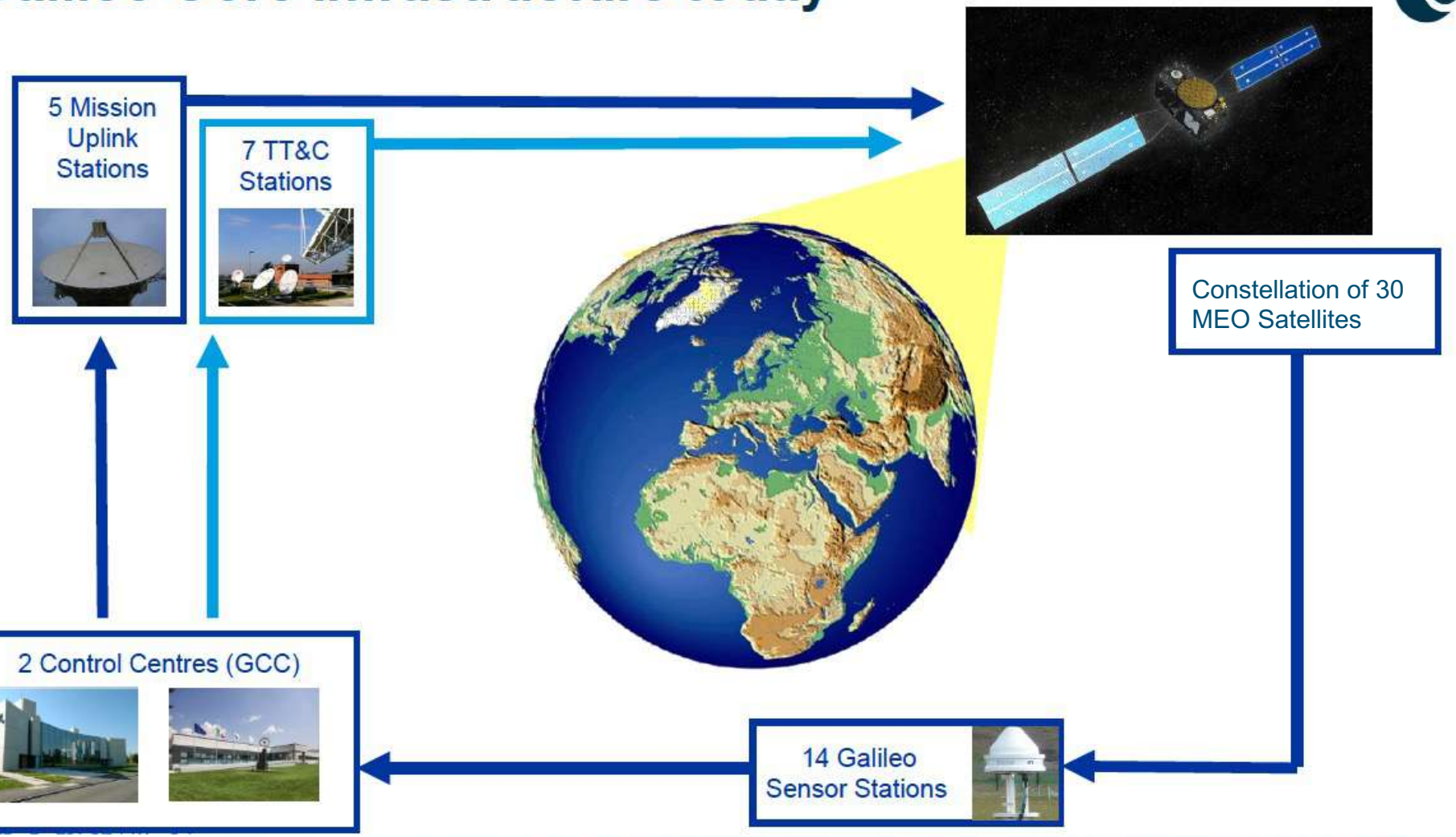
Galileo initial services became available on 15 December 2016. Then as the constellation is built-up beyond that, new services are being tested and made available.

The current Galileo constellation consists of 30 satellites in all. All but two of these are positioned in three circular Medium Earth Orbit (MEO) planes at 23 222 km altitude above the Earth, and at an inclination of the orbital planes of 56 degrees to the equator.

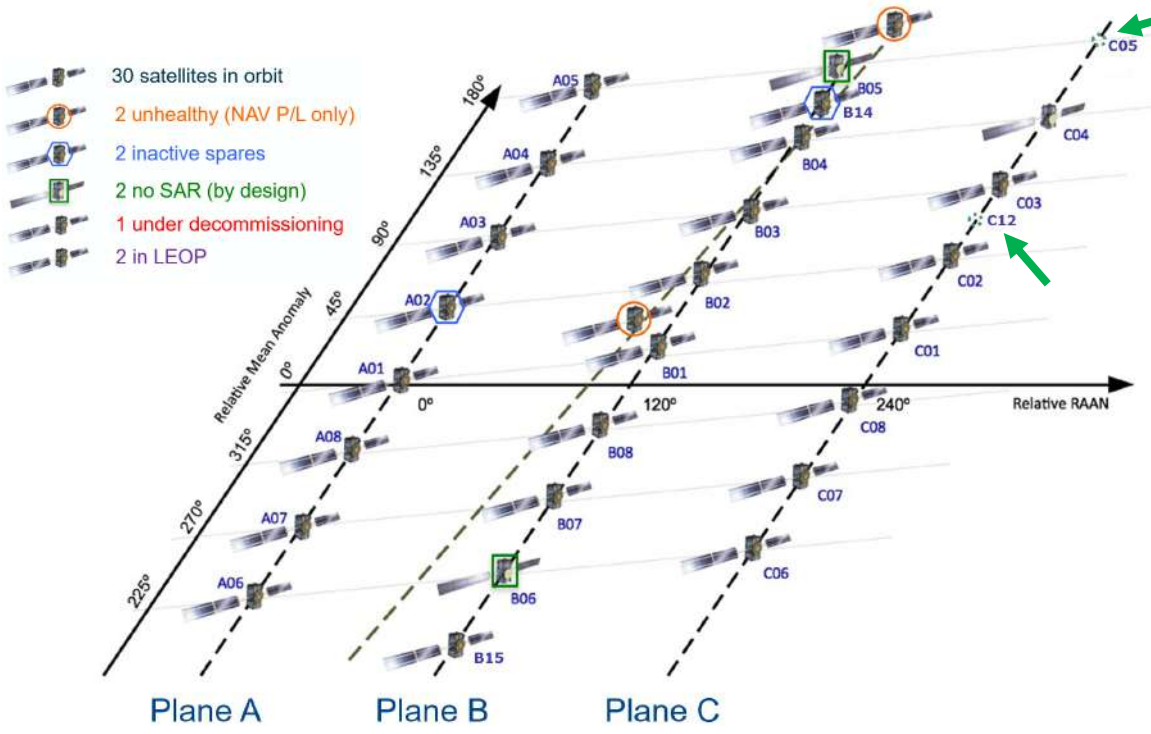
In this presentation we will introduce some of the most significant problems and failures we had to face while building the Galileo system.

The lessons we have learnt - which can help to avoid similar problems in the future - will be presented.

G1 Galileo Core Infrastructure today



Galileo Constellation Status



L12 target slots on Plane C: C05, C12

30 Satellites | 23 set USABLE

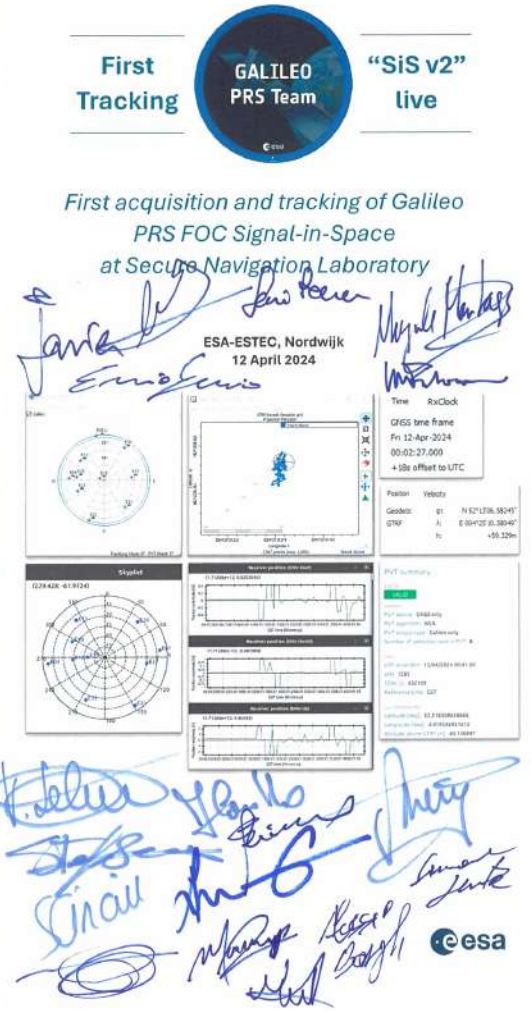
Satellite Family	S/C in orbit	S/C set USABLE	Average Age (years)	Oldest S/C (years)
IOV	4 →	3 →	12.0	12.5
FOC WO1/WO2	22 →	18 →	7.5	9.7
FOC Batch#3	4 ↑	2 →	1.2	2.4
TOTAL	*30* ↑	*23* →	*7.3*	*12.5*

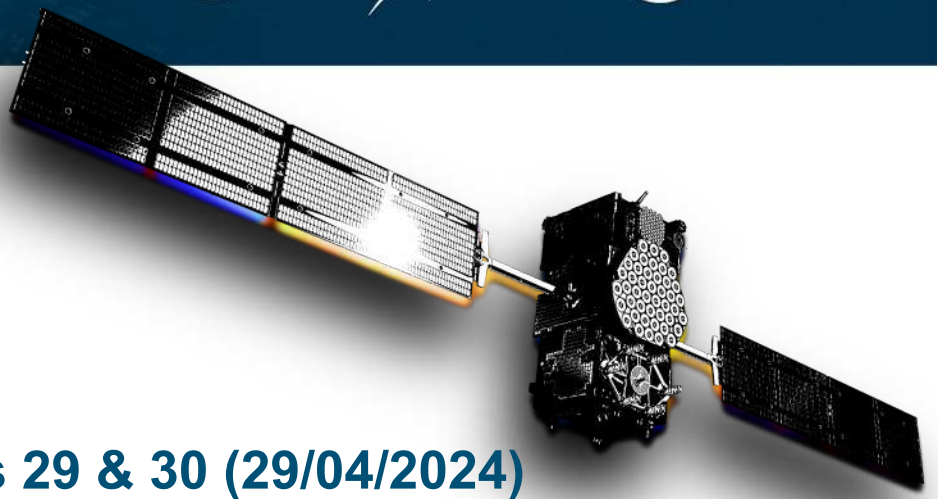
As of 30th Apr 2024

↓ → ↑ : *trend wrt previous reporting period*

Galileo Big Achievements in April 2024!

PRS SiS V2.0 – First acquisition (12/04/2024)





Galileo Launch of satellites 29 & 30 (29/04/2024)

What we will present

1. Galileo Satellites – Rubidium clock failures
2. Galileo Satellites – Maser Clock problems
3. In-Orbit Failure of Galileo NAVIGATION Antenna (NAVANT)
4. Galileo Solar Array failure during 1st FOC launch
5. July 2019: Galileo Service Incident
6. Galileo Service Incident in November 2018

The issues are NOT presented in chronological order

1. Galileo Satellites – Rubidium clock failures

- From March 2016 onward a significant number of rubidium clocks experienced a hard failure in orbit or showed instabilities
- Extensive root cause investigations were performed, and the root cause was identified in a faulty component that could cause a short circuit
- The component was not high-rel and had not been declared by the manufacturer in their declared EEE components list so it skipped the ESA review and approval loop
- The supplier had declared to never have had issues of a similar nature. To identify the problem, an extensive review of the logbooks of all failed units was performed at the supplier's premises. The finding of a copy of an internal NCR reporting in the closeout box **"Problème récurrent à étudier"** (recurring problem to be studied) was fundamental to decide to dig further in the investigation which led to the identification of the root cause.
- All rubidium clocks still on ground were refurbished to correct the problem
- According to the new operational procedures the clocks are tested in orbit after launch and then switched off to preserve their lifetime.

2. Galileo Satellites – Maser Clock problems

- Since the first IOV satellite launch in 2011, several Galileo Maser clocks have shown problems which may impact performance and lifetime or have failed in orbit.
- The problems are of different types:
  - Plasma ignition failures: difficulty in starting or restarting the clocks in orbit once they have been switched off. For this reason all masers in orbit are now kept ON (with only one fully active) →LESSON LEARNED
  - Dissociation Bulbs manufacturing
  - Bad plasma
  - Too high hydrogen consumption
- The Maser clock is a very complex equipment and ESA and industry are putting all efforts in place to try and understand better its behaviour and improve the clock reliability. A crucial role is played by the product assurance team in introducing a very analytical and rigorous problem-solving approach.

3. In-Orbit Failure of Galileo NAVIGATION Antenna

On 27 May 2014 an in-orbit corona event caused a severe damage of the the Galileo IOV Satellite GSAT104 Navigation Antenna (NAVANT).

As a consequence, the L1 signal beam showed a deformed radiation pattern, and the E5/E6 beam was completely lost with no measurable transmission in the channel. The affected satellite has not been able to broadcast the navigation message since then and is only able to provide the search and rescue service.

Root causes and Lessons Learned:

- *Qualification by similarity:* the IOV antenna qualification was based on heritage and thermal cycling life tests were not performed
- *Schedule Pressure:* this may have resulted in some short cuts being taken in testing and analysis activities.
- *ESA Monitoring at a distance:* ESA did not participate directly to the IOV NAVANT qualification review and monitoring was reduced to a minimum.
- *FMECA:* The FMECA did not assess well the specific failure propagation mode.
- *Similar anomalies experienced in the past:* During the GIOVE-B mission and on another IOV satellite, anomalies that could today be linked to the same root cause were not properly followed up.
- *Fault Detection Isolation and Recovery (FDIR):* The FDIR implemented in the Avionics Software did not actively intervene in the event of NAVANT failures.

4. Galileo Solar Array failure during 1st FOC launch

- After separation of Galileo FOC FM01 and FM02 satellites from the launcher, the satellites initialised and commenced the solar array deployment sequence to deploy the wings.
- Both satellites managed to deploy only 1 wing, the other still being stowed, with the deployment sequence reported failed for the stowed sides.
- Analysis of the telemetry from both satellites confirmed the anomaly and that some thermal knives were not correctly powered long enough during the automated sequence; both un-deployed wings were on the cold side of the respective satellites.
- The root cause of the anomaly was identified in the thermal knifes in-rush current, at cold activation temperature, triggering the power conditioning unit overcurrent protection.

Corrective actions:

- The 2 satellites were rotated to put the undeployed SAW facing the sun: the higher temperature allowed the deployment.
- Design modifications were introduced and implemented to all satellites still on ground to eliminate the design flaw.

Lesson Learned

- The issue was visible in the qualification test reports, but due to schedule pressure the problem was overlooked.

5. July 2019: Galileo Service Incident

ZDNet

EU's GPS satellites have been down for four days in mysterious outage

EU's Galileo global navigation satellite system nears 100 hours of downtime

What happened when Galileo experienced a week-long service outage

July 23, 2019 - By Alex Minetto, Fabio Dovis, Andrea Nardin, Emanuela Falletti, Davide Margaria, Mario Nicola and Matteo Vannucchi

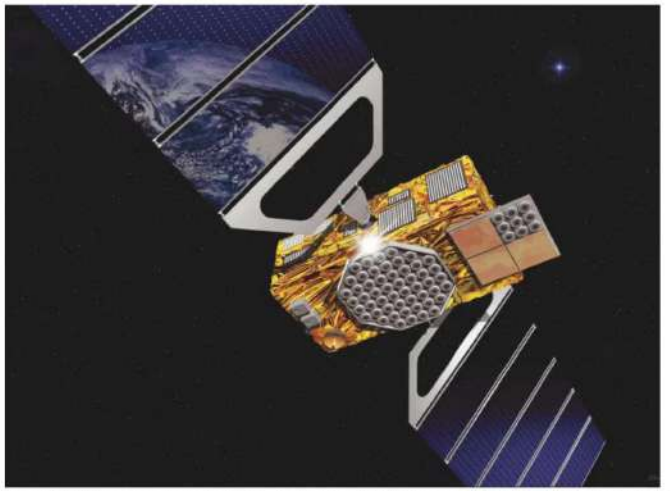
Est. reading time: 3 minutes

0 Comments

Lessons to be Learned from Galileo Signal Outage

IG Inside GNSS

October 1, 2019



With or Without You? – Analysis of a Galileo Outage - 31/07/2019

Huibert-Jan Lekkerkerk

"On Tuesday, 18 July 2019, technical weather is forecast as I get into my car on my way to an important GNSS verification test. Yesterday I received a short e-mail from the local reseller, informing me that Galileo is off air. Should the verification go ahead or not?" In this new column for 'GIM International', Huibert-Jan Lekkerkerk reflects on the two main lessons he learned during the recent Galileo outage.

Part of the purpose of the verification test was

Galileo Service Incident in July 2019

- One of the requirements for reaching full operational capability of the Galileo System was to upgrade the Galileo global ground infrastructure to boost the robustness of Galileo services
- In February 2019, a major upgrade of the Galileo operational infrastructure started.
- In July 2019, an exercise of a sequential upgrade of the Galileo ground control centers was ongoing.
- Due to this exercise, there was a temporary reduced redundancy of the control centers

Galileo Service Incident in July 2019
WHAT HAPPENED

- On 10 July 2019, during the system upgrade, a service incident occurred in the Galileo ground infrastructure. Despite intense recovery efforts, it resulted in a six-day interruption of the Galileo initial navigation and timing services.
- No single or double combination of failures would have resulted in a service interruption
- The complex failure propagation mechanism was the result of **three** independent events, which occurred in a short time sequence:
  1. Mishandling on a temporary equipment installed for the sequential upgrade exercise,
  2. Technical anomaly on an important equipment to establish the Galileo reference time,
  3. Non-nominal configuration of the equipment that was subject to the anomaly
- This resulted in system losing capability of generating navigation messages on July 11, 0:50 UTC.

Galileo Service Incident in July 2019
SERVICE RECOVERY

- Normal rapid recovery actions based on switching to redundant facilities were not successful due to the configuration operated at the time of the event and the complexity of the failure mechanism
- A comprehensive analysis of system data logs was necessary to understand this failure mechanism
- Once the root cause of the incident was understood, any capacity of rapid system convergence had already elapsed
- The system restart and convergence was therefore long. The reduced redundancy of the Galileo control centers during the sequential upgrade exercise also reduced fast recovery capabilities.
- Longer convergence time was also built-in by design to ensure quality of service upon recovery.

Galileo Service Incident in July 2019 Recommendations & Lessons Learned

Recommendations

Service continuity is Galileo's primary driving force, and needs to be guaranteed

An independent enquiry board set up by EC recommended the following:

- review Galileo's operational management to better meet the needs of a service-driven exploitation phase and parallel evolution, while ensuring service continuity, integrating an oversight function;
- improve service continuity, system stability and system resilience, including operability;
- enhance operation, maintenance and configuration management, including training;
- ensure prompt and structured institutional communication towards users and Member States in crisis situations.

Lessons Learned

- The large number of recommendations from the independent enquiry board (of which the above is a summary) were translated in a lessons learned check list which the Galileo project (ESA) systematically uses for all reviews since the occurrence of the incident, to make sure that past mistakes are not repeated again
- Moreover, significant additional system robustness was introduced

6. Galileo Service Incident in November 2018

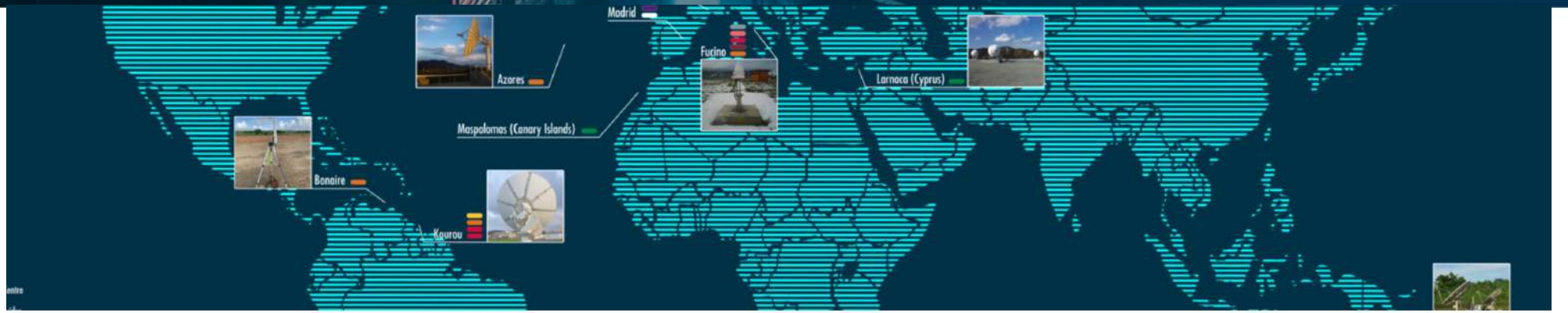
- On 6 November 2018, a malfunction occurred in a Galileo Sensor Station Precision Time Facility on ground. Its clock was set to a date in 1994 after a reboot. A swap to the redundant facility led to the same malfunction. Due to this double failure, all Orbit determination and Synchronization Processing Facilities lost the time reference needed to generate the navigation message. They went all on red on 7 November 2018.
- It was soon discovered that the incident resulted from an integer overflow, which occurred inside an equation from the Simple Network Time Protocol (SNTP)
- The problem was quickly corrected and resulted in only a few hours downtime
- However it clearly highlighted the insufficient SW testing coverage, which did not allow to spot this SW fault.
- As a result of this lesson, ESA has introduced a systematic static analysis of all Galileo ground segment SW.

CONCLUSIONS - 1 of 2

- Galileo is Europe's own global navigation satellite system, and has been designed, developed and built by ESA on behalf and in cooperation with the European Union.
- This was a very challenging endeavour which involved, in addition to the institutional organisations, a large portion of the European space industry.
- The challenge is still ahead of us – while we are busy bringing at completion the Galileo System of 1st generation and at the same time designing and building the Galileo System of 2nd generation
- The problems we have experienced in orbit (and on ground) with some of the critical Galileo satellite equipment have been instrumental in identifying several preventive measures and improvements

CONCLUSIONS - 2 of 2

- The Galileo satellite timing subsystem is a core element of the constellation and Galileo make use of a forefront technology which present several challenges to be closely monitored. ESA has taken direct control of the production of the Clocks and together with the EU has initiated various R&D activities to further develop new technologies for high precision timing systems.
- The Galileo Service Incident of July 2019 triggered a massive introduction of system robustness improvements and the lessons we learned are now systematically checked for implementation at each major system milestone.
- There were no other major service interruptions like the one in 2019 and even minor ones have no longer occurred in the last 3 years.
- A massive ground system upgrade was deployed in April this year and thanks to the lessons we learned in 2019 it was flawless, and the service continuity was guaranteed throughout the process.



APPLICATIONS

Europe's largest ground segment updated with no user impact

https://www.esa.int/Applications/Satellite_navigation/Galileo/Europe_s_largest_ground_segment_updated_with_no_user_impact


THANK YOU