# The effects of solar radio bursts on GNSS operations

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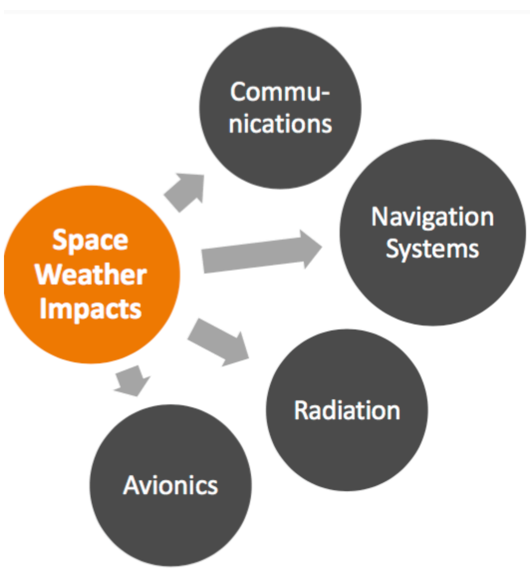
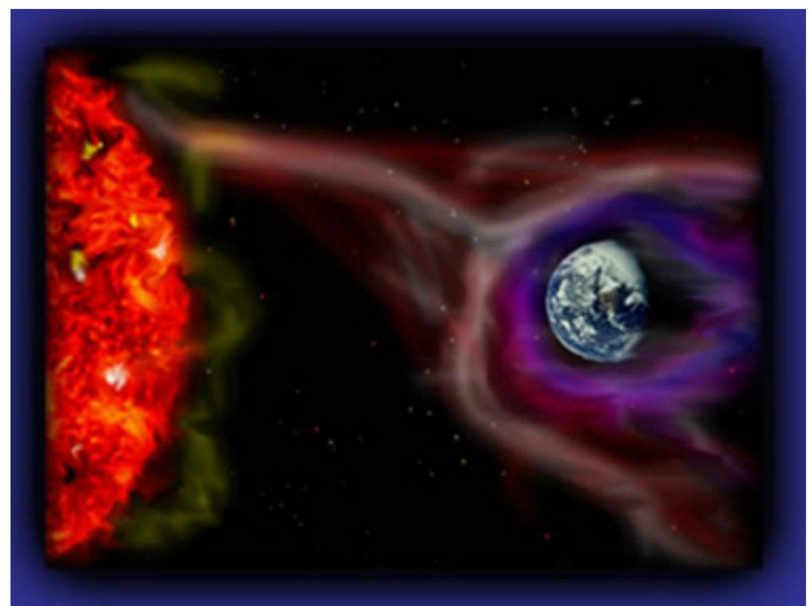
# Space Weather

The variations in the Sun energy emissions, solar wind, magnetosphere, ionosphere and thermosphere, which can influence the performance and reliability of a variety of space borne and ground-based technological systems and can also endanger human health and safety.



# Space Weather effects on GNSS Operations (1)

- GNSS signals suffer from a number of known vulnerabilities.
- A potential severe vulnerability is the effect of **Space Weather**.
- The importance of Space Weather effects on Aviation operations has been recognized by ICAO.
- A document called: "**Space Weather Effects in Regard to International Air Navigation**", including the effects on GNSS operations, is being prepared by ICAO on the matter.

# Space Weather effects on GNSS Operations (2)

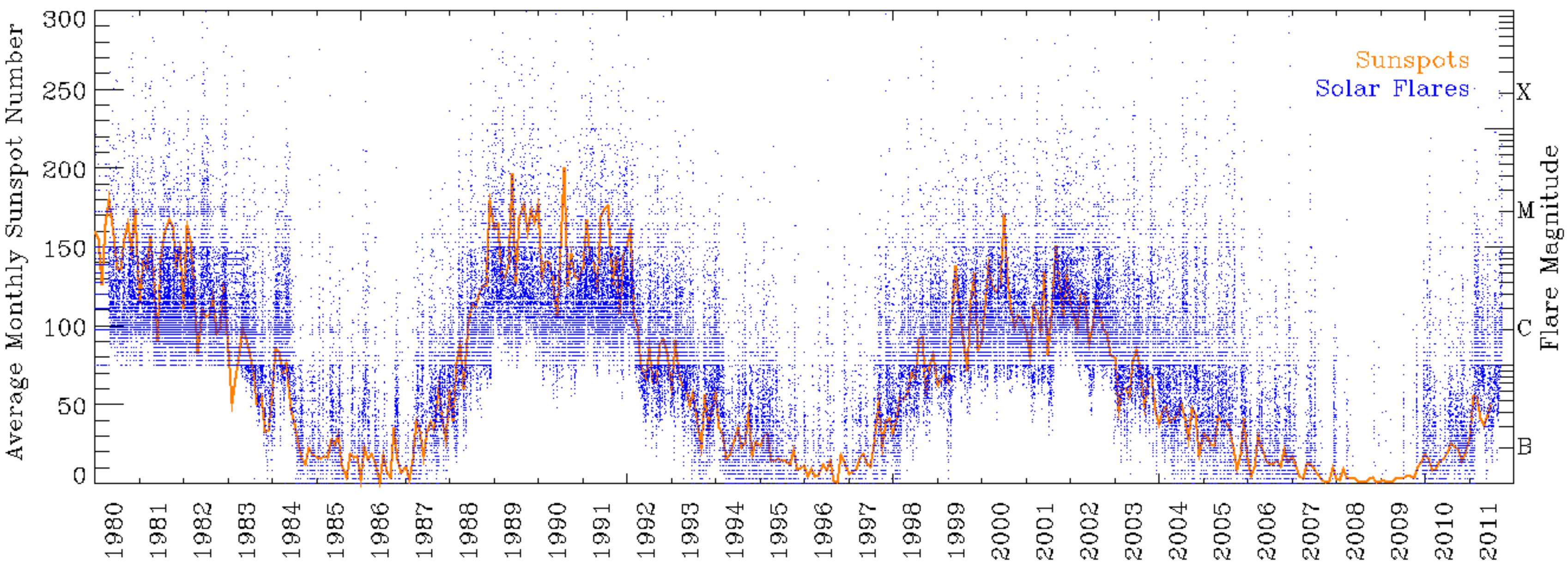
Space Weather influence on the GNSS signals includes the effect on the ionosphere and the direct effect of solar radio bursts.

**Of these two, the direct effect of solar radio bursts on GNSS signals has been the least investigated, and there is an important gap in understanding this space weather effect.**

# Sudden Solar electromagnetic emissions

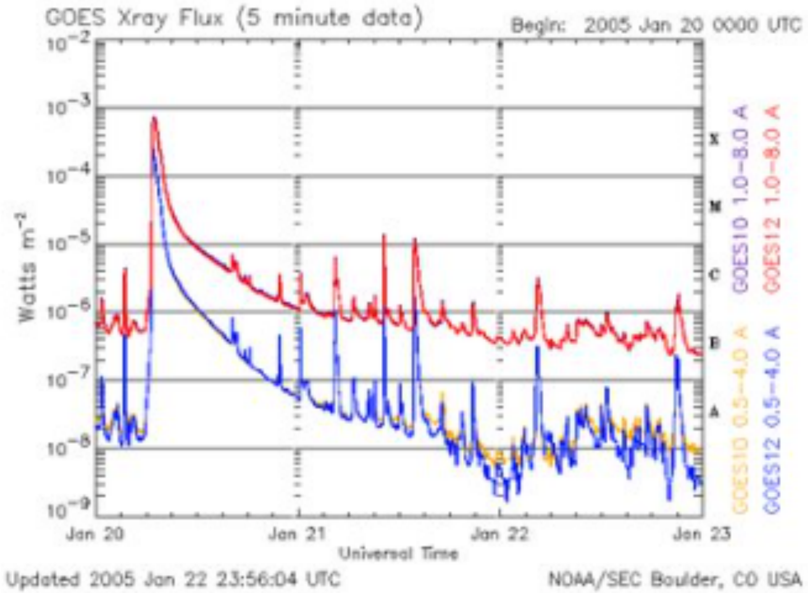
Sudden strong solar electromagnetic emissions are **Space Weather** events linked to the Solar Activity (Sunspot) cycle.

They are ***solar flares*** and ***solar radio bursts***.



# Solar Flares

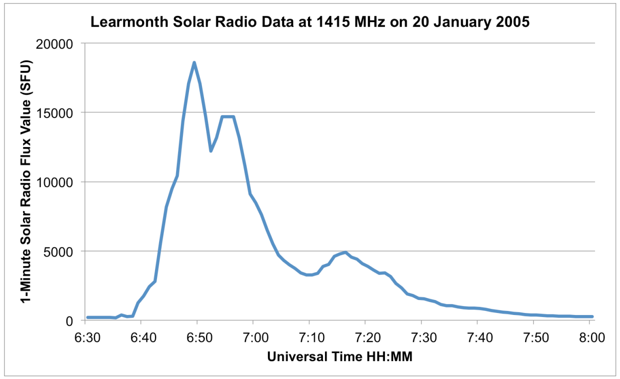
Solar flares are sudden giant flushs of electromagnetic radiation. X rays and UV radiation emitted in a flare can affect the Earth ionosphere almost instantaneously. Flares may produce also coronal mass ejections (CME) with effects on the ionosphere through geomagnetic storms.




Flares are classified by their strength being the M and X-classes the strongest. A X-class Solar Flare is 10 times stronger than a M-class Solar Flare and a X9 flare is 9 times stronger than a X1 flare.

# Radio Bursts

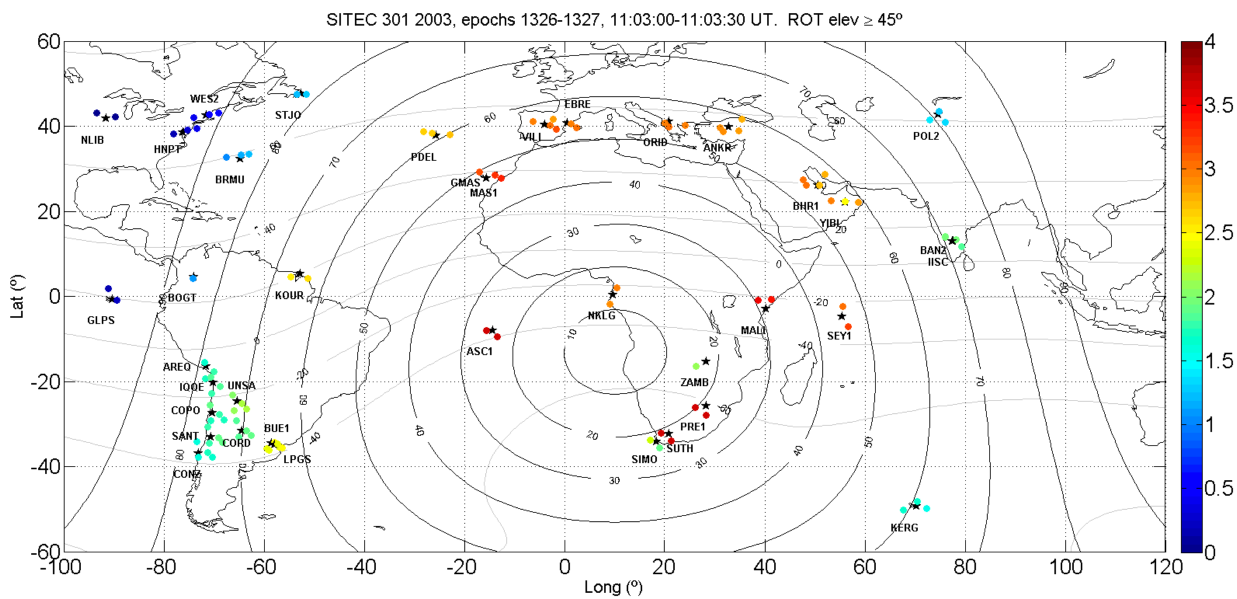
Solar radio bursts are intense radio emissions, mostly associated with strong flares, with durations from tens of seconds to a few hours. Radio bursts in the L-band can impact GNSS receivers located in the sunlit hemisphere of the Earth, with intermittent loss of signal lock, and complete loss of positioning information, that can persist for a significant period of time.




Solar radio burst at 1415 MHz that took place on January 20, 2005 associated with the solar flare of the previous slide.

# Solar Flares effect on the Earth Ionosphere

- ✓ The sudden increase in X-ray and EUV fluxes during solar flares causes extra ionization of the D, E and F regions of the earth's ionosphere in the sunlit hemisphere within short intervals of time.
- ✓ Solar flares may cause a sudden increase of total electron content (SITEC) strongly dependent on the solar zenith angle.




From: Rodriguez Bilbao et al.(2015)

# Solar Radio Burst effects on GNSS operations (1)

Solar burst effects on GNSS receivers were first described by Klobuchar et al. (1999). They suggested that bursts with power of 20000 SFU (1 SFU=$10^{-22}$W/$m^2$/Hz) all Right Hand Circularly Polarized (RHCP) or 40000 SFU half RHCP can produce 3 dB reduction of signal-to-noise ratio.

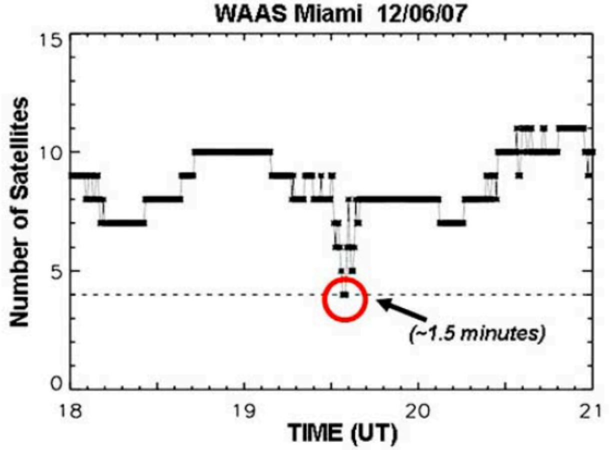
- ✓ Chen et al. (2005) showed that almost no GPS L2 signals were tracked by IGS receivers during the peak time of the intense X5 solar flare with associated strong solar radio burst of 28 October 2003.
- ✓ **However, the measured burst peak power was 12000 SFU indicating that the effects of radio bursts on GPS receivers is much more complex than what originally estimated by Klobuchar et al. (1999).**

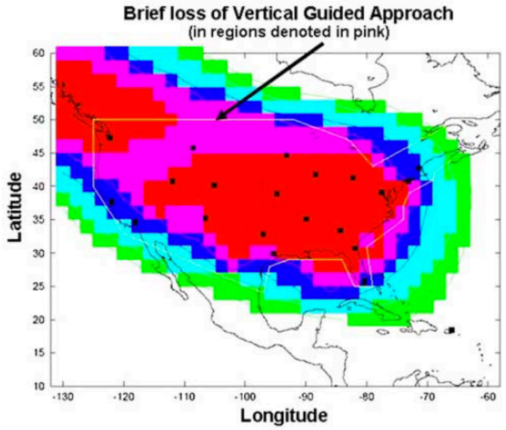
# Solar Radio Burst effects on GNSS operations (2)

- ✓ The strongest solar radio burst with a power of **1,000,000 SFU** occurred on **6 December 2006** and affected the operation of many GPS receivers (Cerruti et al. 2008; Carrano et al. 2009; Kintner et al. 2009 ).
- ✓ GPS receivers experienced problems in tracking leading to increased vertical dilution of precision and positioning errors of up to 60 m in the vertical direction (Carrano et al. 2009 ).
- ✓ **"Despite such relevant experimental evidence, not enough emphasis or research effort has been given to this phenomenon, which is characterised by a low probability of occurrence, and also by the high impact when it occurs.' (Sreeja, 2016)**

# Solar Radio Burst effects on SBAS

- ✓ The 6 December 2006 event marks the first time a Solar Radio Burst was detected on a SBAS (WAAS).
- ✓ The figure on the left shows that the number of satellites monitored by the WAAS receiver in Miami dropped to 4 for approximately 1.5 min in response to the solar burst. This is the minimum number of satellites required for GPS positioning.
- ✓ The figure on the right shows in pink the WAAS coverage area that lost use of the guided approach service. This loss of service lasted less than 15 min and did not challenge the integrity of the WAAS system.




From: Cerruti et al. (2008)

# What we are going to report in this presentation

- ✓ The preliminary analysis of the potential effects on EGNOS performance of Solar Radio Bursts occurred during three Space Weather Events of the present Solar Cycle 24 including one of September 6, 2017.
- ✓ A series of open questions arising from the analysis will be presented.

## Parameters to be analysed

- Availability APV1 hourly maps evolution during the event.
- Time evolution of the number of IGPs monitored for each event.
- Time evolution of the carrier to noise density C/No at selected RIMS.
- Presence of SITEC associated with the Flare.

# The events

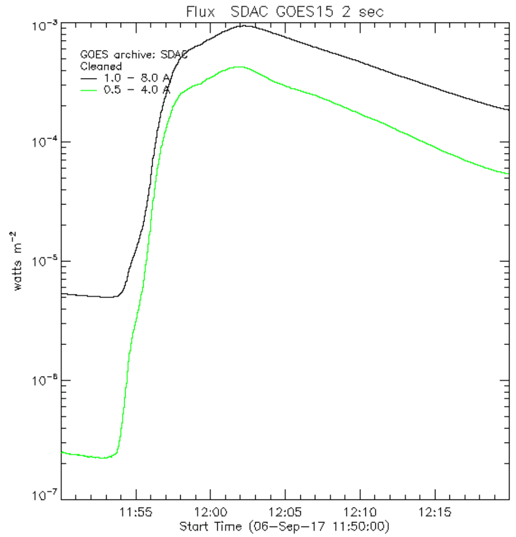
Particular attention will be paid to the one occurred

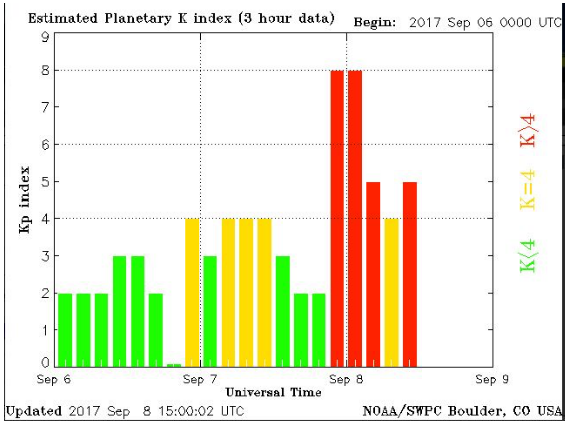
6 September 2017

```
=================================================
YYYY MM DD Start  Max   End   Peak Flux @ 1415 MHz
            UTC    UTC   UTC           SFU
=================================================
2012 03 04 10:29 10:52 12:16 XRA M2.0 AR 1429
           10:35 11:16 12:25 RBR    34000
-------------------------------------------------
2015 06 25 08:02 08:16 09:05 XRA M7.9 AR 2371
           08:12 09:19 09:36 RBR     17000
-------------------------------------------------
2017 09 06 11:53 12:02 12:10 XRA X9.3 AR 2673
           11:56 12:02 14:24 RBR    19000
=================================================
XRA: X-ray Flare; RBR: Radio Burst;
AR: Active Region
=================================================
```

# The Solar event of 6 September 2017

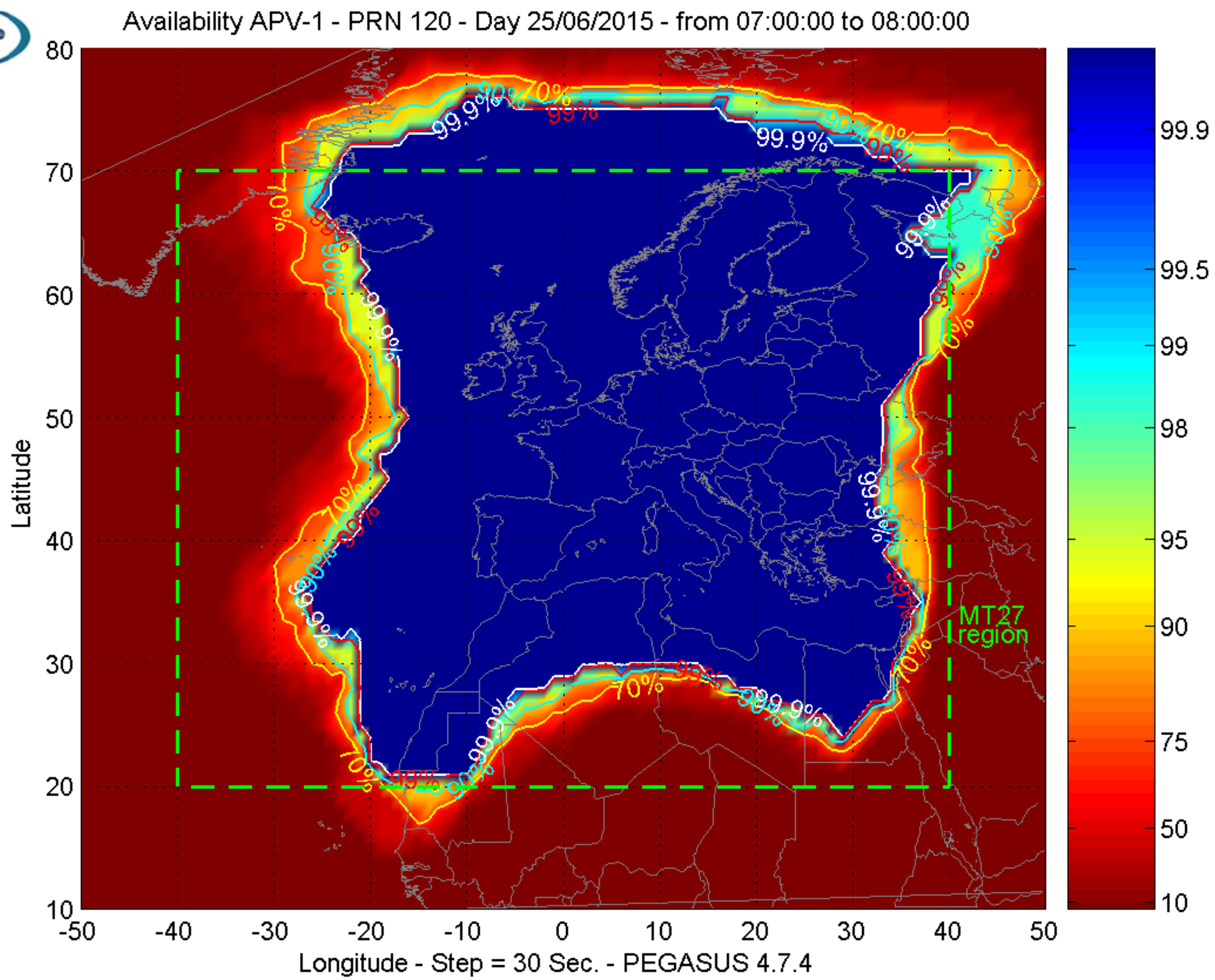
A major X-class solar flare erupted from geoeffective Active Region 2673 peaking as **X9.3** at 12:02 UTC on **September 6, 2017**. The event started at 11:53, peaked at 12:02 and ended at 12:10 UTC. It is also the strongest solar flare of the current solar cycle (Solar Cycle 24).
A Solar Radio Burst with peak intensity of **19000 SFU** at 12:02 UTC occurred in connection to the flare.
A **coronal mass ejection** (CME) was associated to the flare that reached the Earth on **8 September** generating a **Severe (Class G4) Geomagnetic storm** with **Kp = 8**.




**The analysis will be concentrated on the effects occured during 6 September 2017**

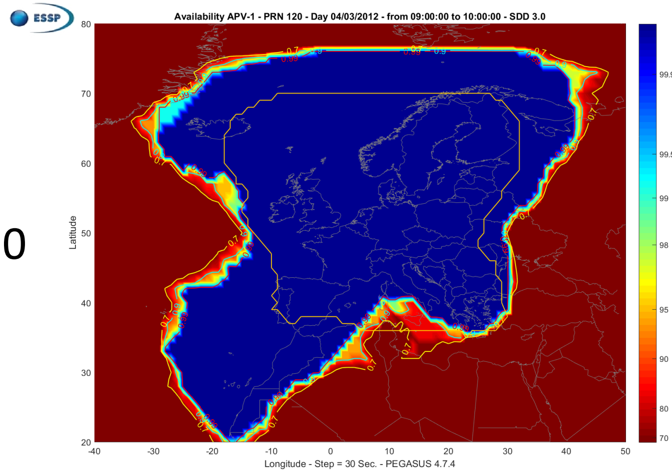
# Availability APV1 maps

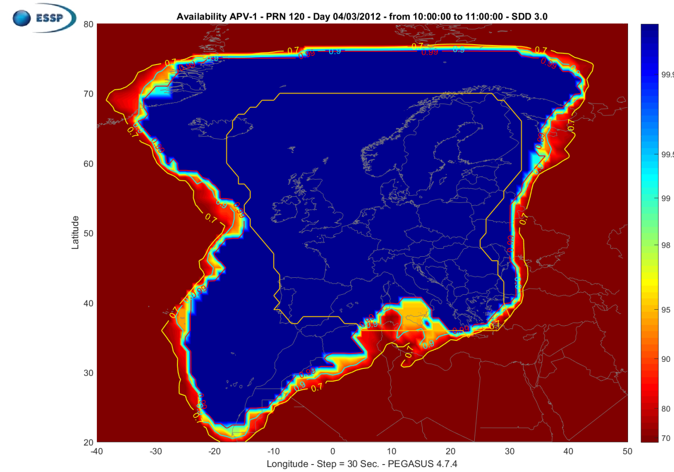



Approach operations with vertical guidance (APV1) availability (%). One hour step.

# Solar event of 4 March 2012: Availability APV1 maps

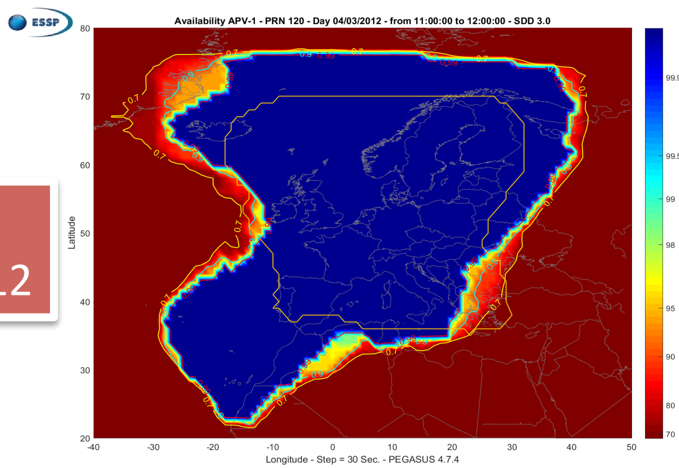
from
09 to 10

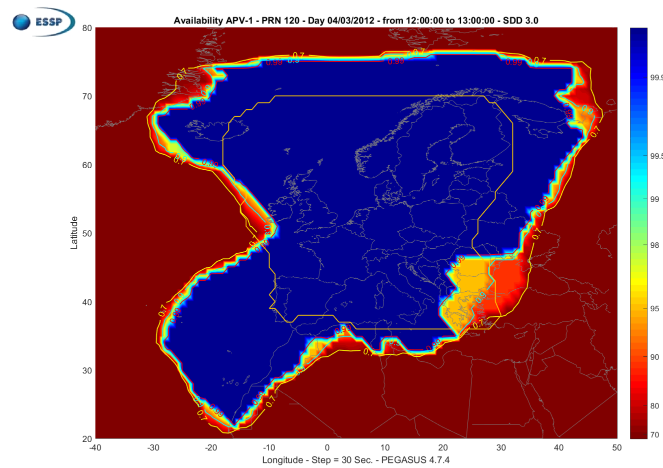



from
10 to 11

from
11 to 12



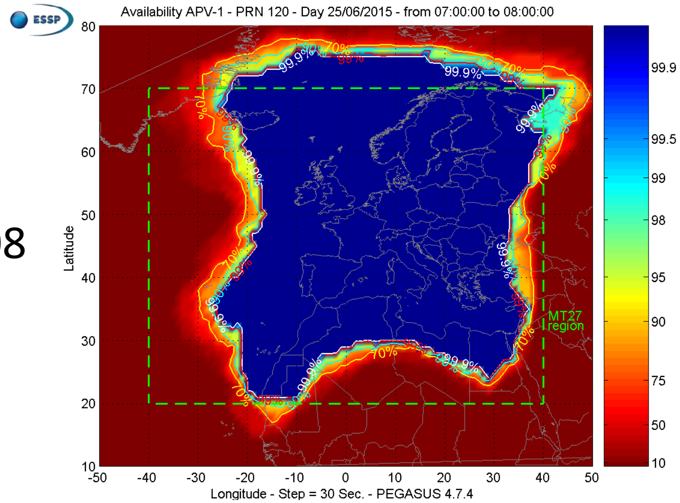



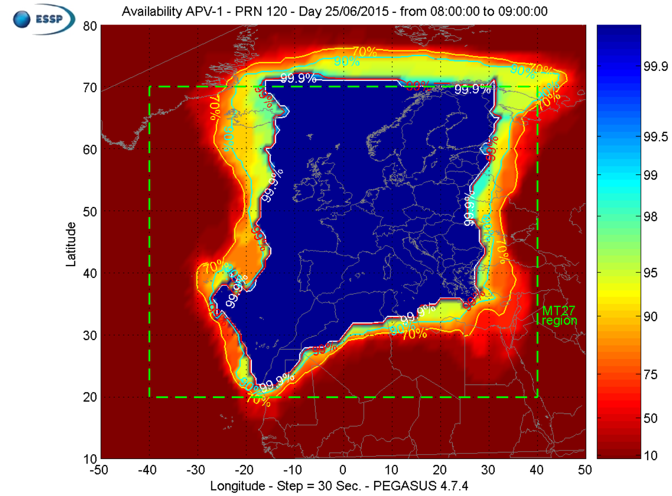

from
12 to 13

No major effect on APV1 availability

# Solar event of 25 June 2015: Availability APV1 maps

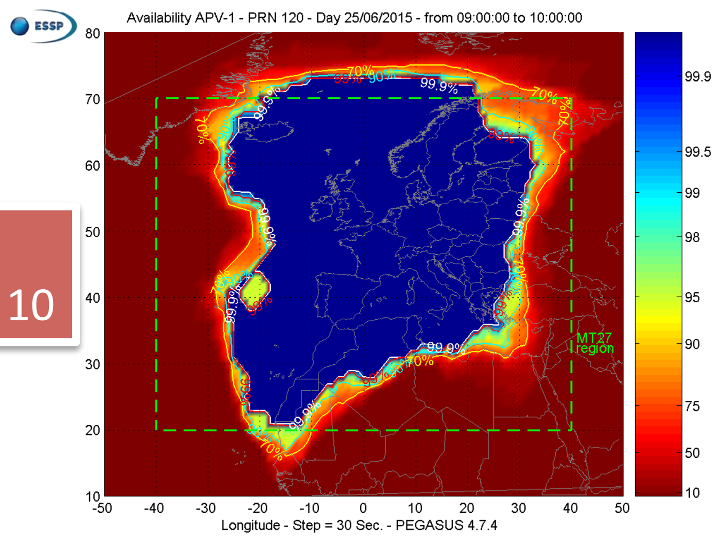
from
07 to 08

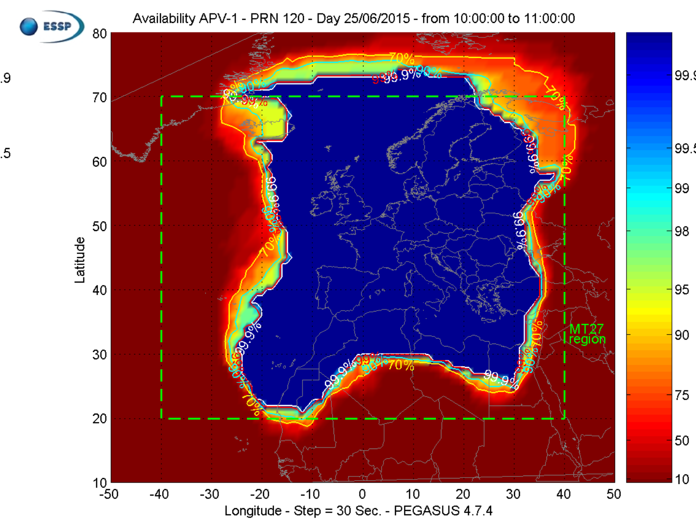



from
08 to 09

from
09 to 10

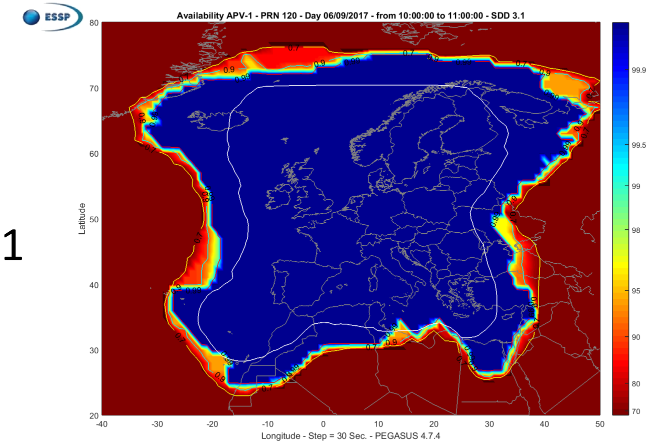


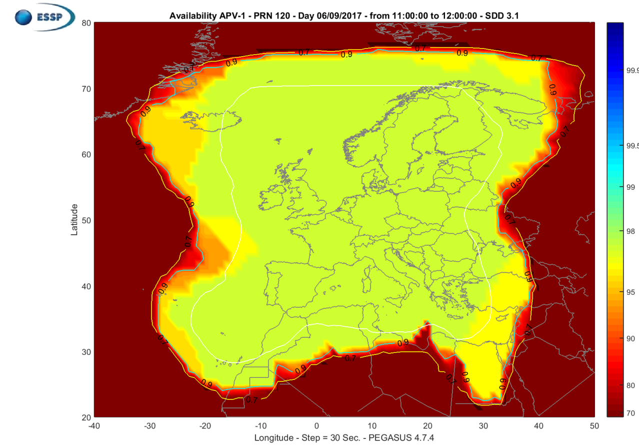

from
10 to 11

## Slight effect on APV1 availability

# Solar event of 6 September 2017: Availability APV1 maps

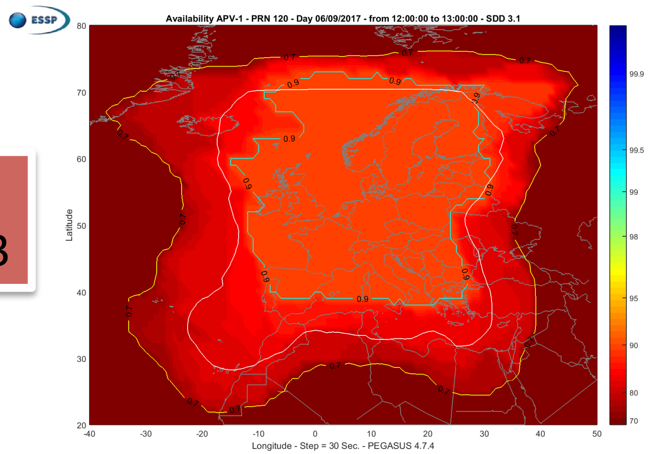


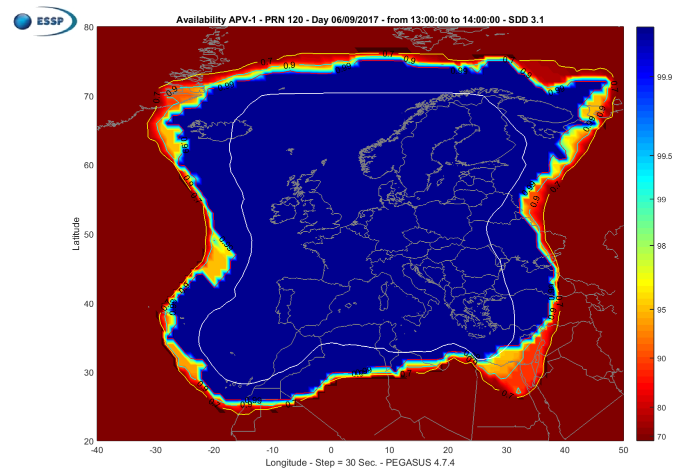

from
10 to 11




from
11 to 12

from
12 to 13

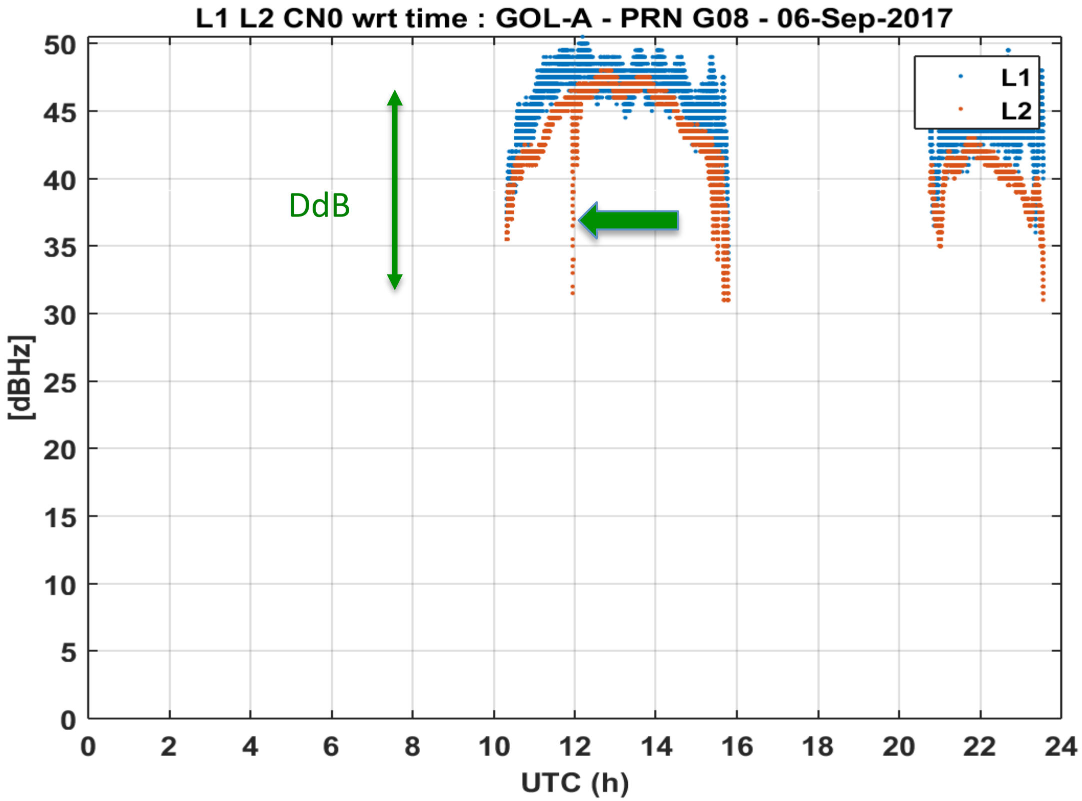



from
13 to 14

Strong effect on APV1 availability

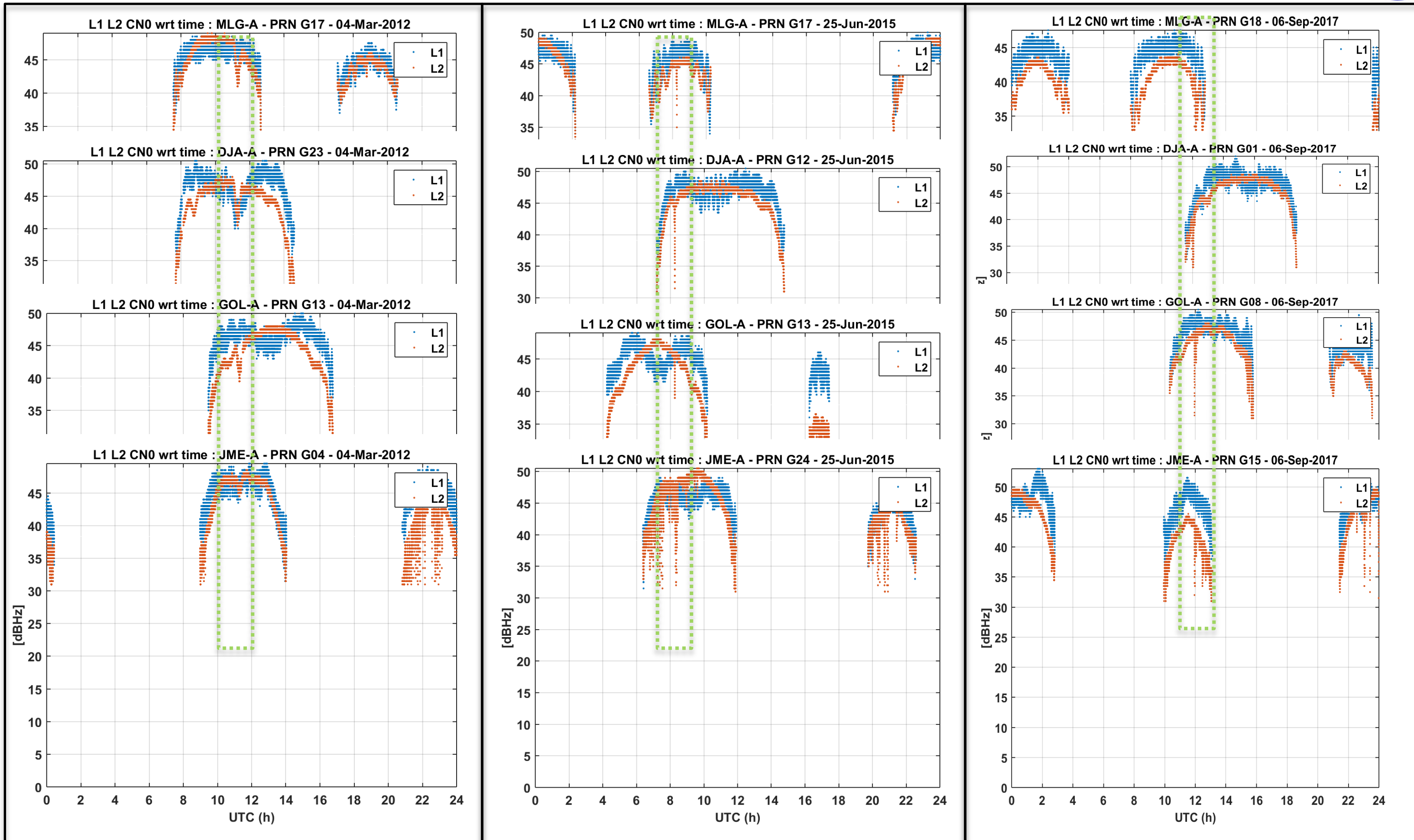
# L1 and L2 C/No vs. time




**Arrow indicates degrated C/No**

- ✓ **$C/N_0$ (carrier-to-noise density) is the ratio of received carrier (i.e., signal) power to noise density.**
- ✓ **$C/N_0$ provides a metric that is more useful for comparing one GNSS receiver to another.**
- ✓ **C/No will vary in relation to the satellite elevation angle.**
- ✓ **DdB is the depth of the fade related to the solar event.**

# L1 L2 C/No vs. time




MLG

DJA

GOL

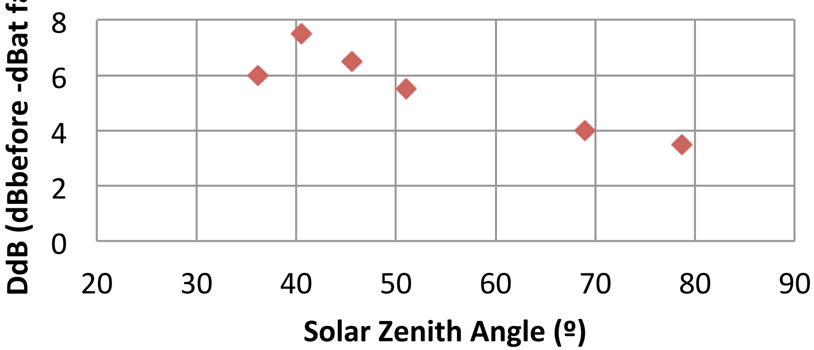
JME

**4th March 2012** **25th June 2015** **6th September 2017**

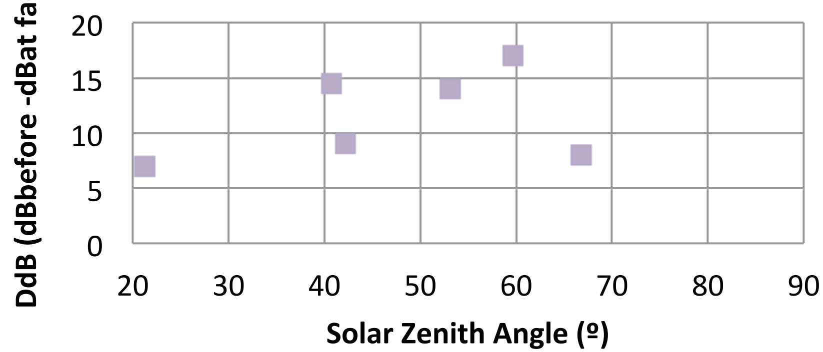
Evident degradation in C/No for L2 during the 3 Solar Events

# However…

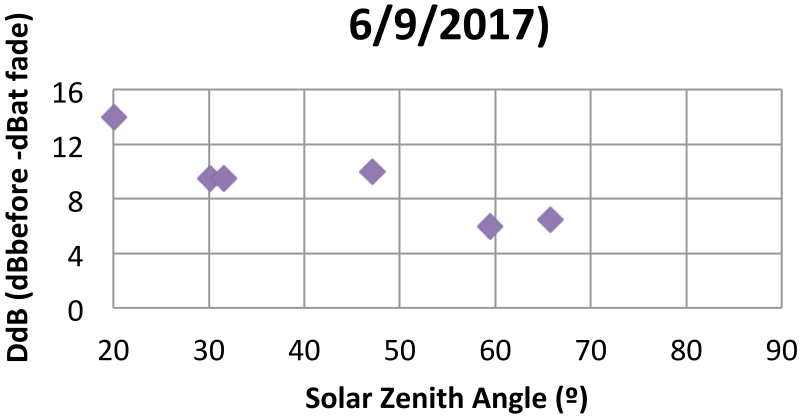
**C/No DdB vs. Solar Zenth angle at different locations (Event 4/3/2012)**




**C/No DdB vs. Solar Zenth angle at different locations (Event 25/6/2015)**

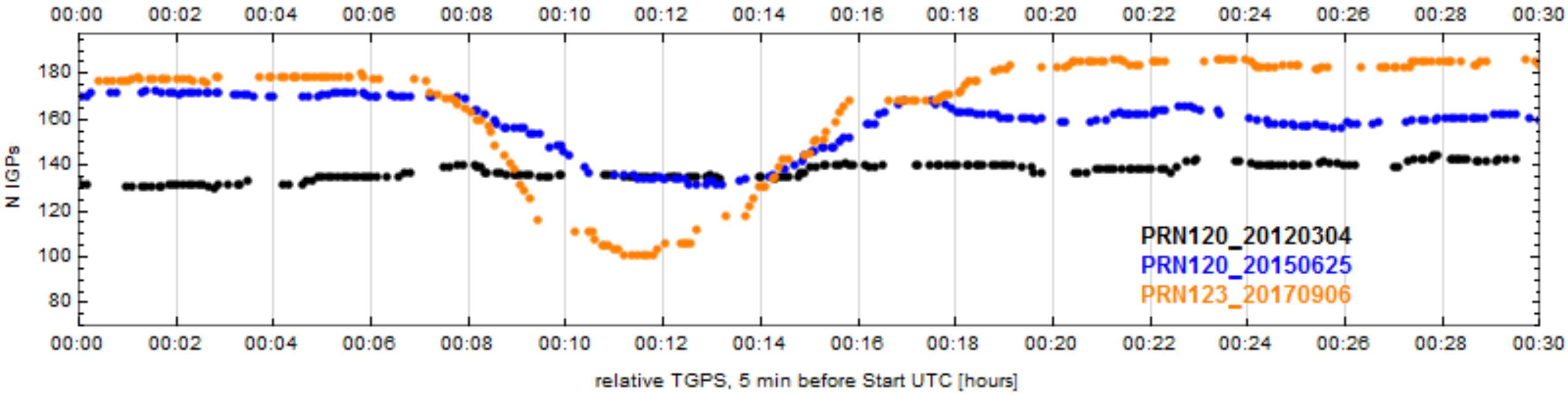



**C/No DdB vs. Solar Zenth angle at different locations (Event 6/9/2017)**




**The depth of the fades (DdB) observed for the events of 2012 and 2017 show a clear correlation with decresing Solar Zenith Angle.**
**This is not the case of the event of 2015.**

# Number of monitored IGPs by Event




- The event of 2012 did not affect the number of monitored IGPs.
- The two events of 2015 and 2017 have affected such number reaching the lowest value at the time of the intensity peak of the Solar Radio Burst, 7 and 6 minutes after the start of the burst respectively .
- The lowest value of monitored IGPs corresponds to the event of 2017.

# A word about EGNOS response to the Solar Events

EGNOS response to the lack of valid GNSS measurements and observables was to set some of IGPs as "not monitored". The IGPs influenced where actually located in the area surrounding affected ground stations.

EGNOS system reaction is justified by the fact that the amount of remaining measurements was considered as insufficient to monitor IGP while preserving service integrity.

**It has to be stressed that in all the three events, no integrity issue either on pseudorange or in the user domains have been observed nor reported.**

# The SITEC of 6 September 2017 (1)

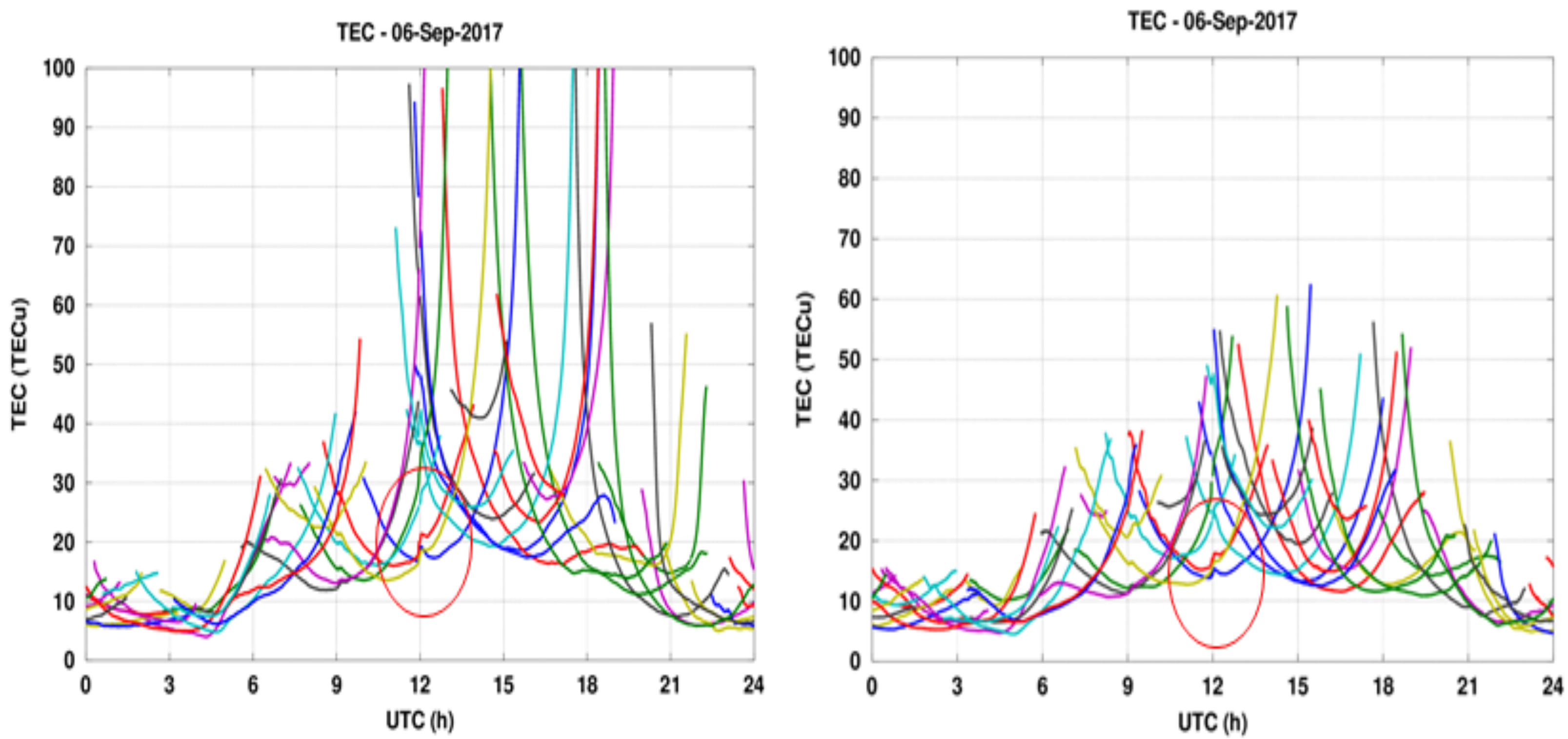
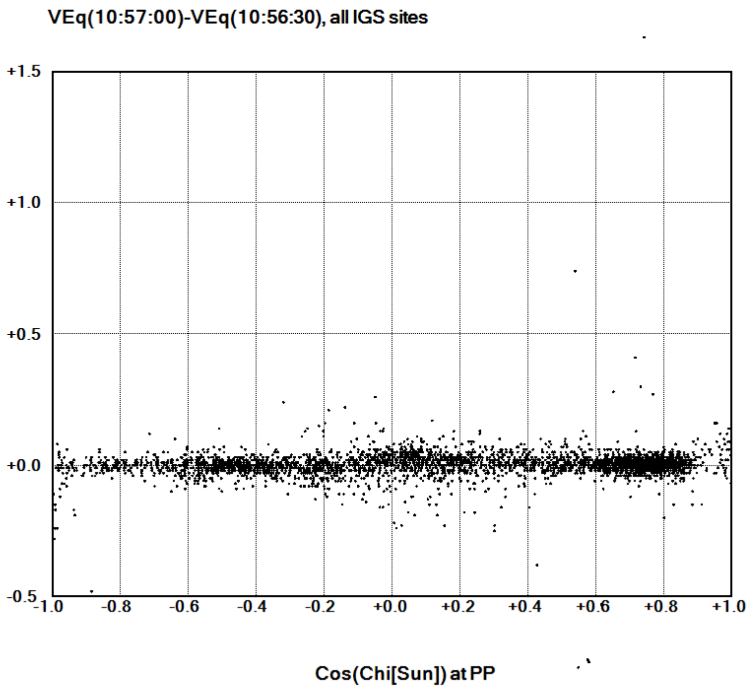
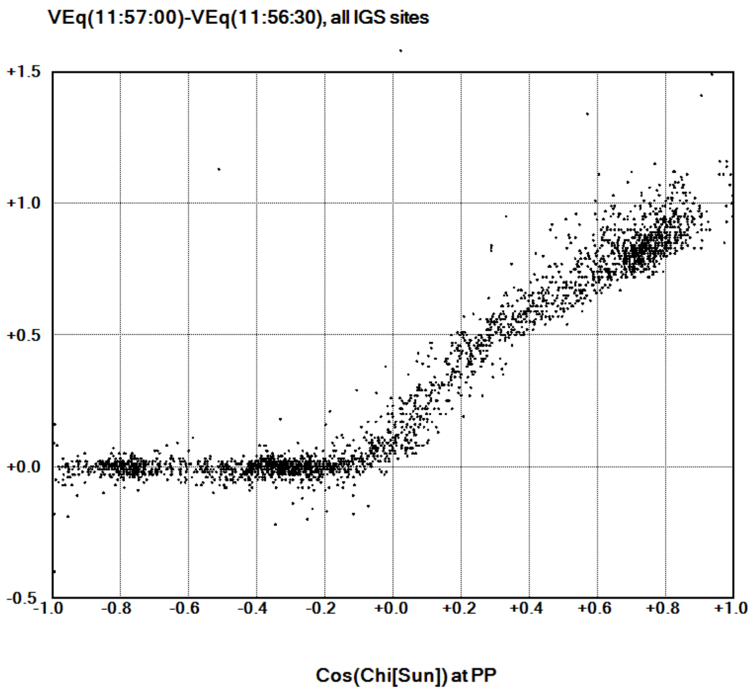



Figure 9: TEC behaviour on 06/09/2017 for Djerba (left) and Toulouse (right) RIMS

**The red ovals show the presence of SITEC in the slant TEC arcs of satellites in view at the EGNOS RIMS of DJERBA and TOULOUSE**

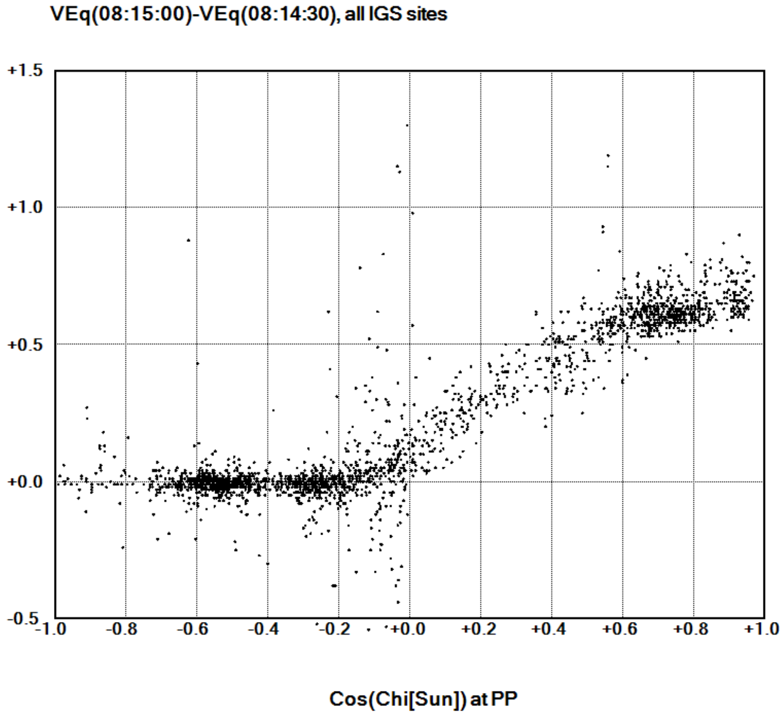
# The SITEC of 6 September 2017 (2)




The plots are the differences of Vertical Equivalent TEC for all the PP of the available satellites in view at the time of occurrence of the SITEC (right) and one hour before (left), for all the IGS stations available online, as a function of the Solar Zenith Angle.
All the stations in the sunlit hemisphere (Cos Chi > 0) have been affected depending on the Solar Zenith Angle.

# The SITEC of 25 June 2015 (for comparison)




The plots are the differences of Vertical Equivalent TEC for all the PP of the available satellites in view at the time of occurrence of the SITEC (right) and one hour before (left), for all the IGS stations available online, as a function of the Solar Zenith Angle.

All the stations in the sunlight hemisphere (Cos Chi > 0) have been affected depending on the Solar Zenith Angle but to a  lesser extent that the case of 2017 as expected considering the Flare intensity.

# Summary (1)

## Characteristics of the Solar Events

**The event of 3/4/12** had a **M2-class Flare** and a **34000 SFU peak intensity Radio Burst** of approximately the same duration.

**The event of 6/25/15** had a **M7.9-class Flare** and a **17000 SFU peak intensity Radio Burst** of approximately the same duration but with peak intensities shifted by one hour in time.

**The event of 9/6/17** had a **X9.3-class Flare** (the most intense in 12 years) and **19000 SFU peak intensity Radio Burst** that lasted more than two hours longer than the Flare but with simultaneous peak intensities of Flare and Radio Burst.

# Summary (2)

**Effects of the Solar Events on EGNOS**

**The event of 3/4/12**

In spite of being the strongest Radio Burst of the three, but associated with the weakest Flare, the AVP1 availability and the number of IGPs monitored was not affected. Only a  relatively small degradation C/No at L2 frequency was seen in several RIMS receivers with values that are correlated with the Solar Zenith Angle of the receiver location.

No SITEC associated with the weak flare was observed.

# Summary (3)

## Effects of the Solar Events on EGNOS

**The event of 6/25/15**

The Radio Burst of substantially lower intensity than the previous event associated with a 6 times stronger Flare had a partial effect on the APV1 availability, a noticeable effect on the number of IGPs monitored and also a clear degradation of C/No at L2 frequency. This effect did not correlate with the Solar Zenith Angle of the receiver location.

A SITEC associated with a strong Flare was observed over all the sunlight hemisphere.

# Summary (4)

## Effects of the Solar Events on EGNOS

**The event of 9/6/17**

The Radio Burst of almost the same intensity of the one of 25/6/15, but associated with a very powerful Flare more than 10 times stronger than the one of 2015 had a very strong effect on the APV1 availability, a strong effect on the number of IGPs monitored and also a strong degradation of C/No at L2 frequency. This effect was correlated to the Solar Zenith Angle of the receiver locations.

A SITEC associated to the powerful flare was observed over all the sunlit hemisphere.

# Open questions

The results summarized in the previous slides force to ask few questions. The answers to these questions would explain the effects described above.

1. If the effects observed are related only to the presence of the Radio Burst, why the strongest one of the three (4/3/12) shows the weakest effect?
2. Why the weakest Radio Burst, but associated with the strongest Flare, shows the strongest effect?
3. Are the effects on EGNOS related in some way to the presence of Sudden Increase of TEC (SITEC) observed during the Radio Bursts of 2015 and 2017 produced by strong and very intense Flares?
4. Are the effects due to only the presence of the interference introduced by the Radio Burst in the satellite signals or to this process plus the ionospheric disturbance introduced by the X and UV radiation of the Flare (SITEC)?

# Final comments

**The preliminary results of this work confirm that the effects of Solar Radio Bursts on GNSS operations are more complex than originally thought.**

**It confirm also that more research efforts should be given to this phenomenon that is poorly predictable but potentially of high impact on the GNSS operations.**

**Our group intend to study in deep this problem.**

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# THANK YOU FOR YOUR ATTENTION