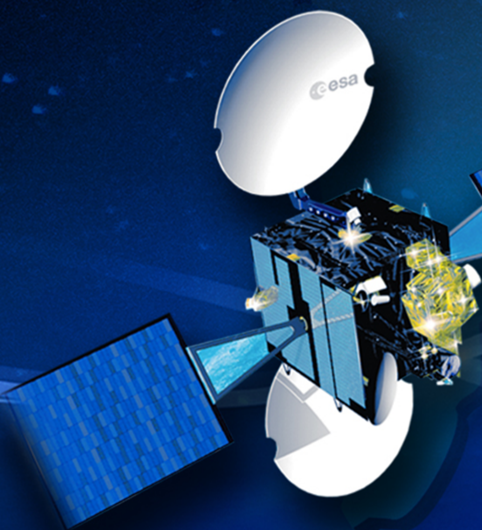
Latest SBAS Performances under Severe and Equatorial Ionosphere Conditions



ICAO Workshop

August 15th – 17th 2016

Lìma (Peru)

Franck HADDAD

ThalesAlenia Space

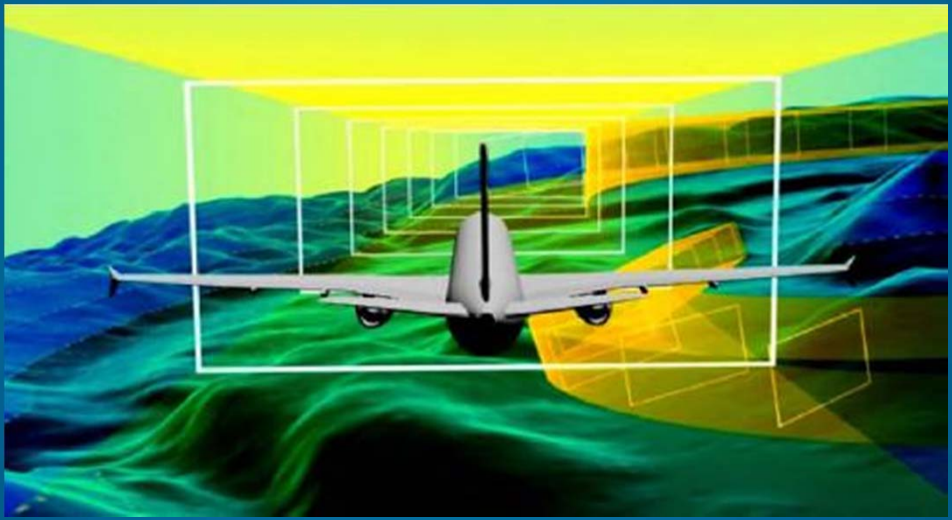
A Thales / Finmeccanica Company

Scope

- INTRODUCTION
- IONOSPHERE IMPACT ON GNSS-SBAS PERFORMANCES
- TAS-F R&D STUDIES ON EQUATORIAL IONOSPHERE IN AFRICA
- TAS-F EQUATORIAL ALGORITHMS DURING GEOMAGNETIC STORMS ON EGNOS NETWORK
- TASF-F EQUATORIAL ALGORITHMS IN BRAZIL
- CONCLUSIONS

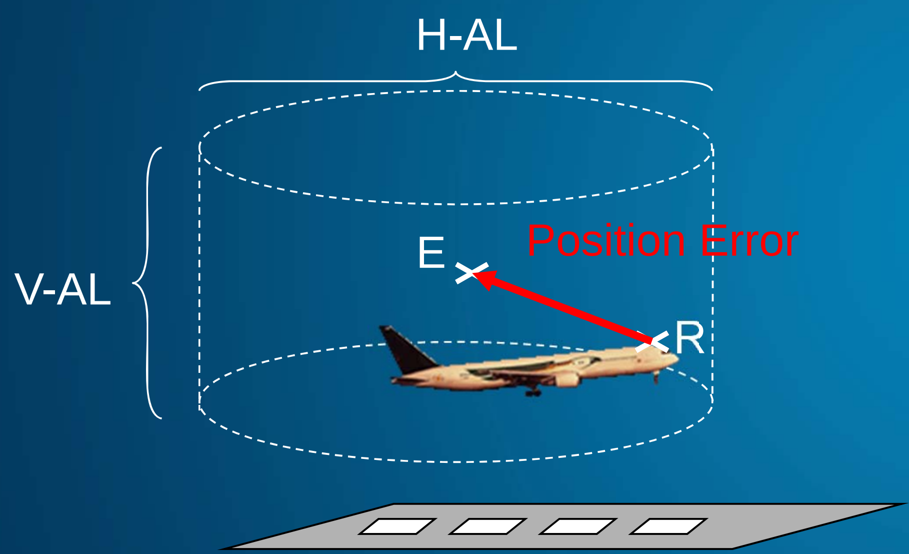
INTRODUCTION

THALES ALENIA SPACE AND SBAS



Introduction – SBAS Mission : integrity

Guarantee navigation system user that the positioning system does not endanger its physical integrity.



V-AL and H-AL
- depend on flight phase
- are fixed by the ICAO

The SBAS must provide the users with information so that
- Tolerated propability to be outside the box $P_{NonIntegrity} < 2\ 10^{-7}$ / 150 s
- If conditions of non-integrity, alert to be received within maximum 6 s

Introduction : Thales Alenia Space

- THALES ALENIA SPACE (TAS - France) is the prime contractor of EGNOS (European SBAS) since the 1998
- More than 17 years' experience of SBAS
- Leading role in EGNOS:
  - Specification / Development and Procurement,
  - EGNOS Performance and Integrity,
  - Integration / Verification / Qualification
  - EGNOS Operation preparations
  - Support to SBAS certification

Introduction to EGNOS

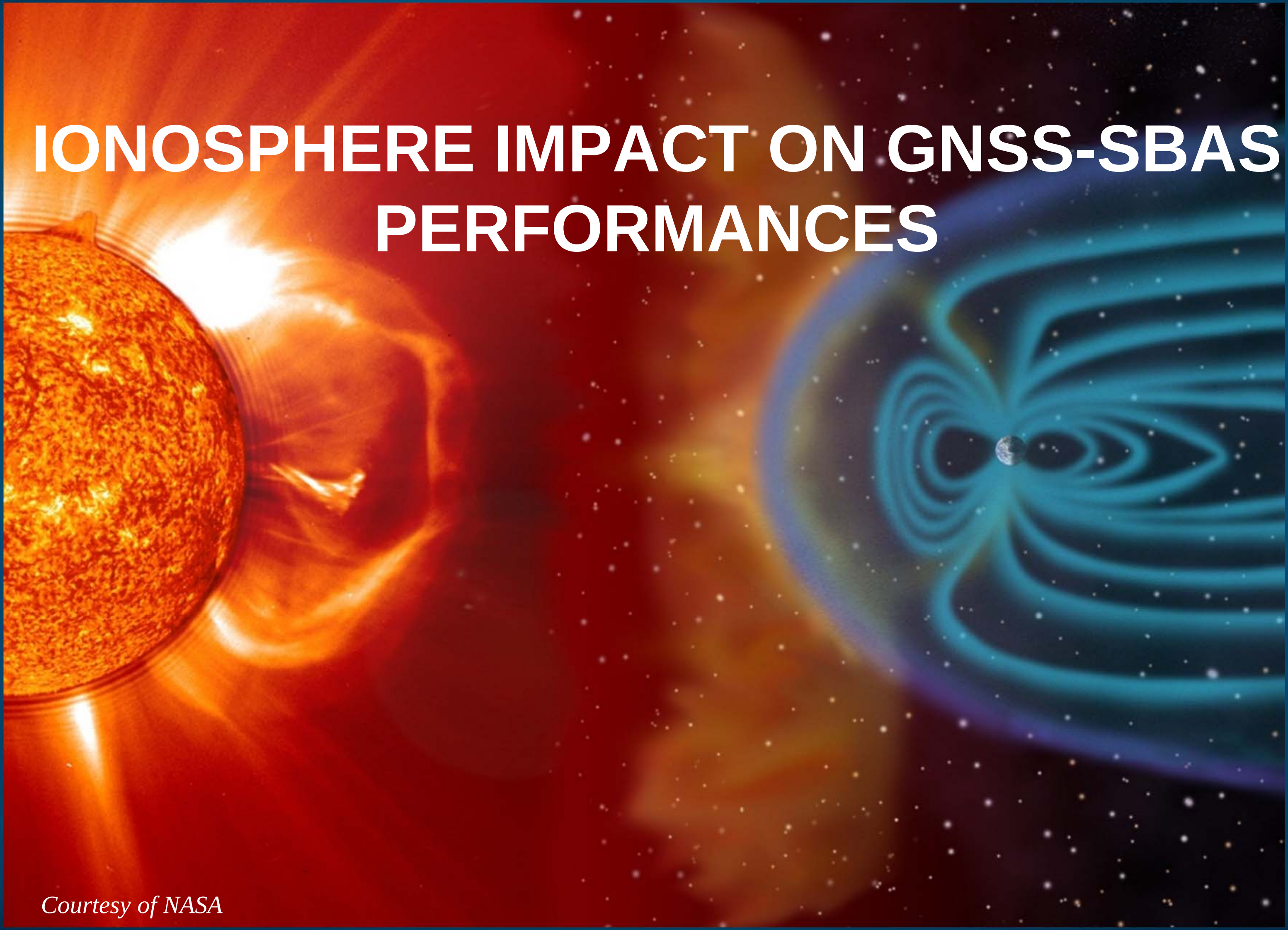
- EGNOS services

Service	Service coverage	Availability	Continuity	Time to alarm	Accuracy (xNSE)		Integrity		
					Hor. [m]	Vert. [m]	Hor. [m]	Vert. [m]	Risk
SL2/NPA	FIR of ECAC member States	99,9%	1E-5/hour	8 s	100	NA	556	-	1E-7/h
SL3/Open service	ECAC Landmasses	99,0%	-	-	3.0	4.0	-	-	-
SL3/APV-I	ECAC Landmasses	99,0%	8E-6/15 s	6 s	16.0	20.0	40.0	50.0	2E-7/150 s
SL3/LPV200	ECAC Landmasses	99,0%	8E-6/15 s	6 s	16.0	4.0	40.0	35.0	2E-7/150 s

Precision Approaches

Part I

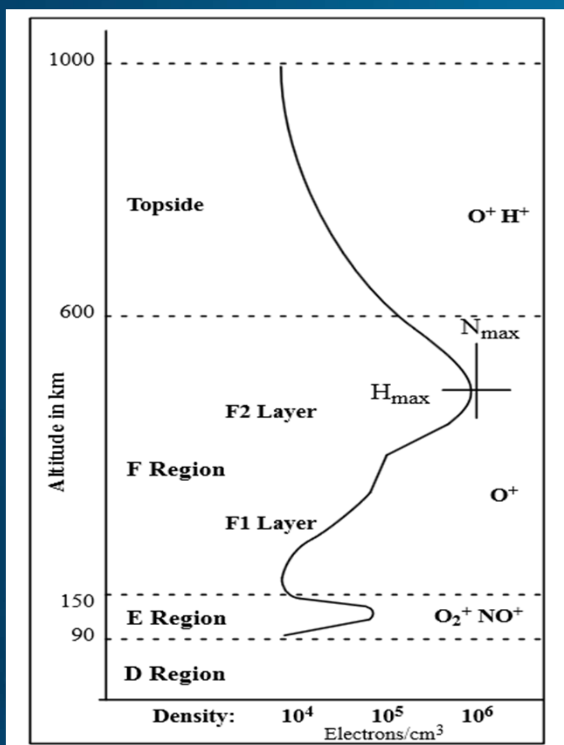
IONOSPHERE IMPACT ON GNSS-SBAS PERFORMANCES



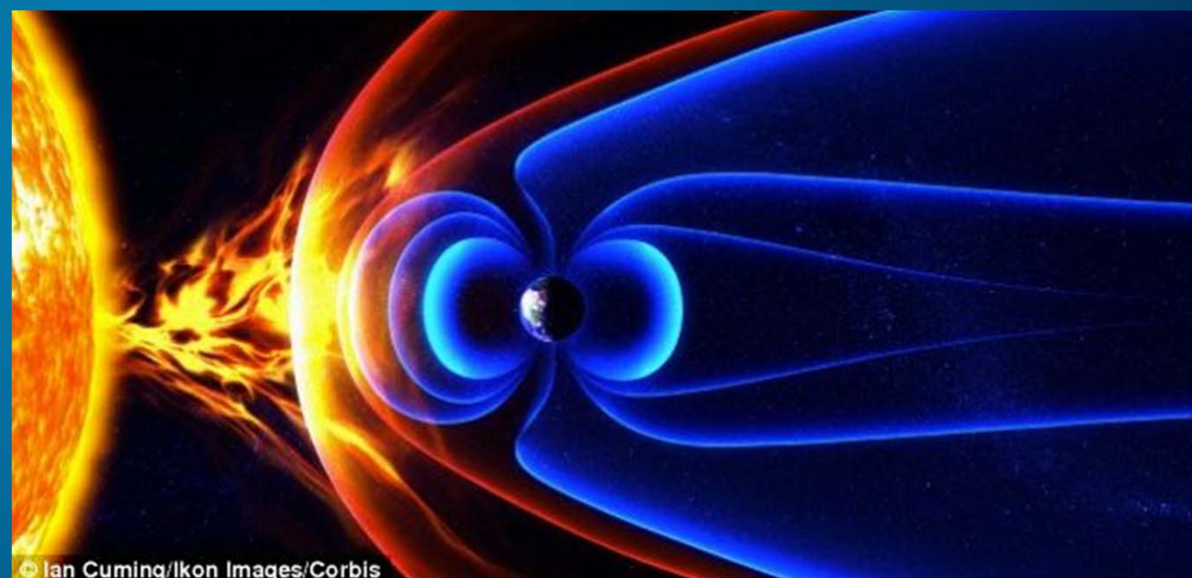
Courtesy of NASA

Ionosphere definition

- The ionosphere is that region of the upper atmosphere where charged particles (electrons and ions) energy are present.
- Results of the ionization of the neutral atmosphere constituents by the solar radiation and particle injection.



Daytime ionosphere electrons density profile



Interaction between solar wind and Earth magnetic field

Geomagnetic storm classification

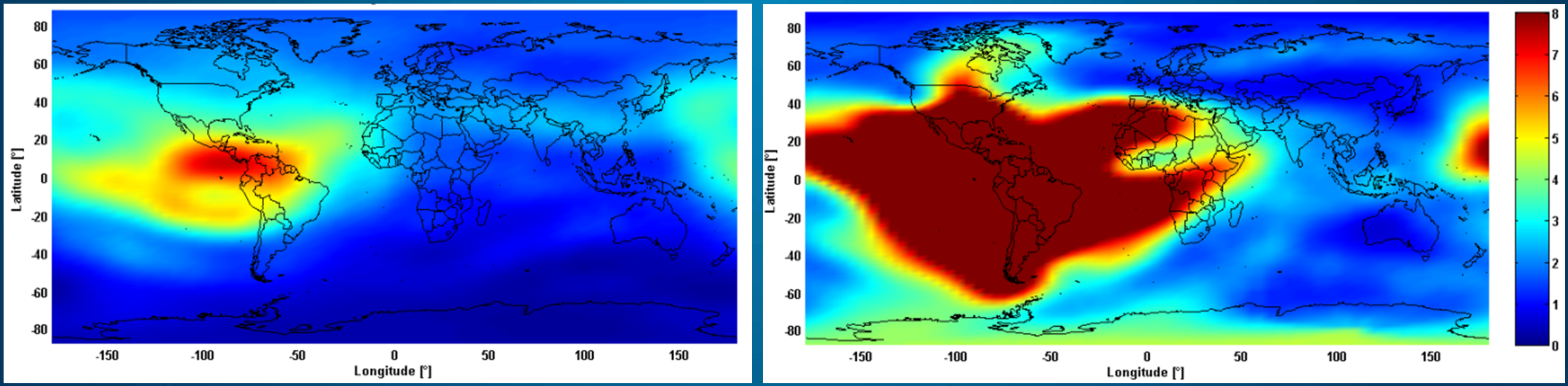
- Since the ionisation level of ionosphere is correlated with solar activity, geomagnetic storms occur mainly around solar cycle maximum activity (high solar flares level), and especially during equinoxes.
- K indices are used to classify geomagnetic storms level:

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	**Power systems:** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** May experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	**Power systems:** Voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate	**Power systems:** High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor	**Power systems:** Weak power grid fluctuations can occur. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5	1700 per cycle (900 days per cycle)

Impact of ionosphere on GNSS measurements

- ❑ Due to the high ionisation level present in the ionosphere, the refraction of radio waves causes non negligible delays on GNSS measurements.
- ❑ Not well corrected the ionosphere delays can degrade GNSS positioning accuracy of several dozen meters especially on vertical direction.

Ionosphere vertical delay (in meter)

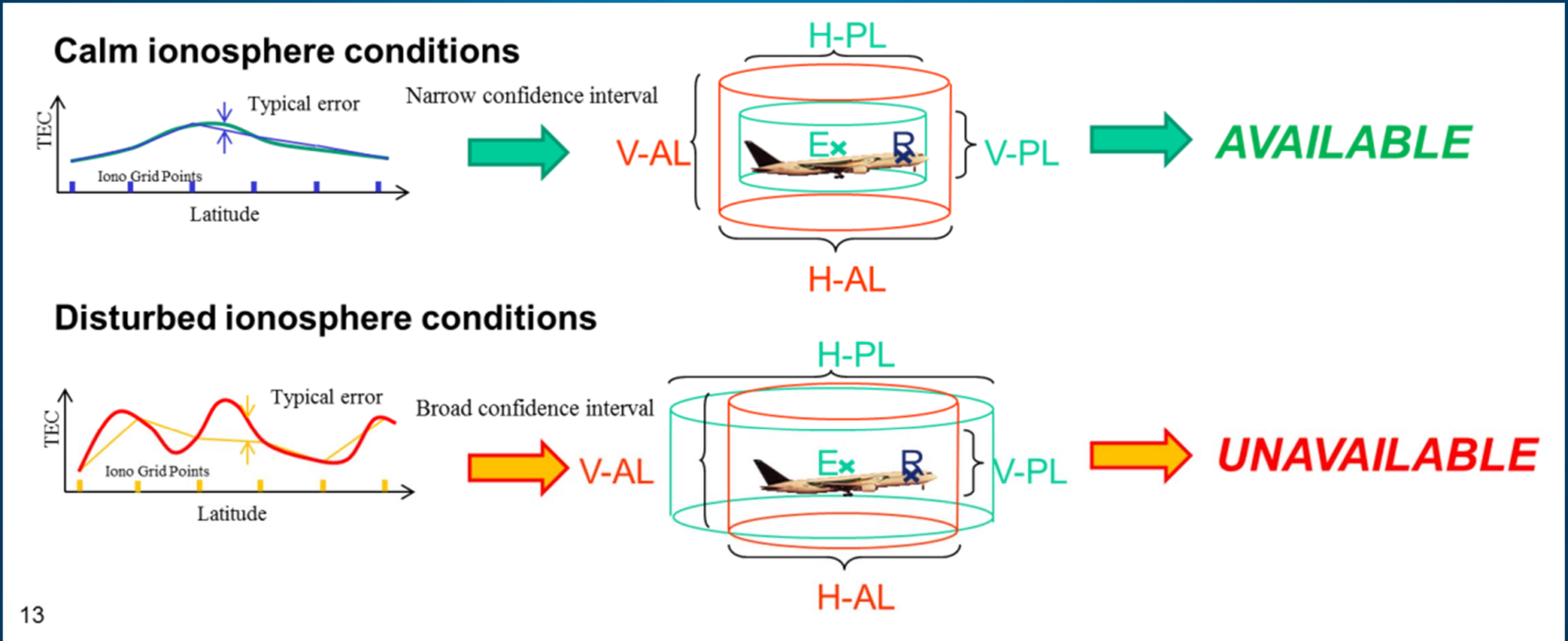


2011/07/01
quiet ionosphere Kp<4

2003/10/29
“Halloween” G5 geomagnetic storm Kp = 9

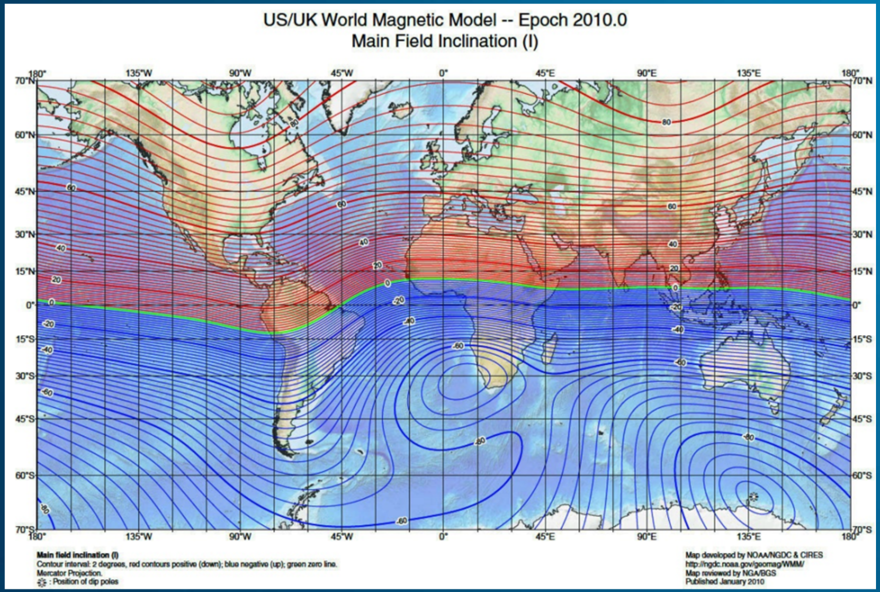
Impact of ionosphere on SBAS estimation

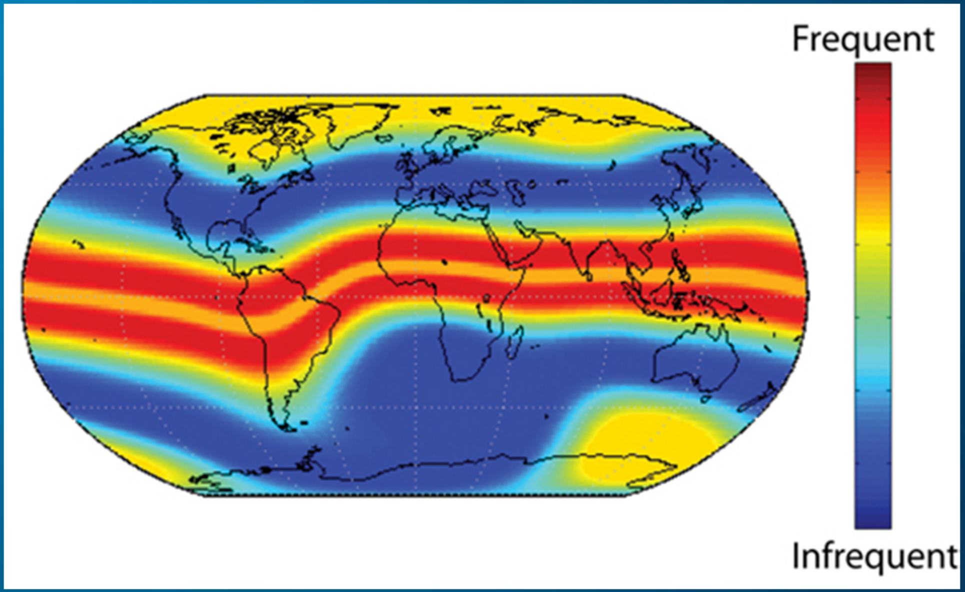
- SBAS correct the ionosphere delay by broadcasting maps with limited resolution. The high variability in space of the ionosphere may make the maps inaccurate and cause ionosphere delay interpolation errors.



Impact of ionosphere on GNSS measurements: scintillation

- Scintillation is the consequence of small-scale irregularities in the ionosphere that scatter radio waves and generate rapid fluctuations (scintillation) in the amplitude and phase of radio signals.
- The impact of scintillations on GNSS is to suppress some measurements of the Satellite-Receiver distance, reducing the availability of the positioning





Correlation between scintillation areas and Earth magnetic field

Part II

TAS-F R&D STUDIES OVER EQUATORIAL IONOSPHERE IN AFRICA

We are involved in several ionosphere study projects in equatorial regions

- TAS masters the modelling of mid-latitude. We decide to develop capability of the equatorial ionosphere by participating to 2 projects mainly focused on Africa and scintillation (equatorial and polar):

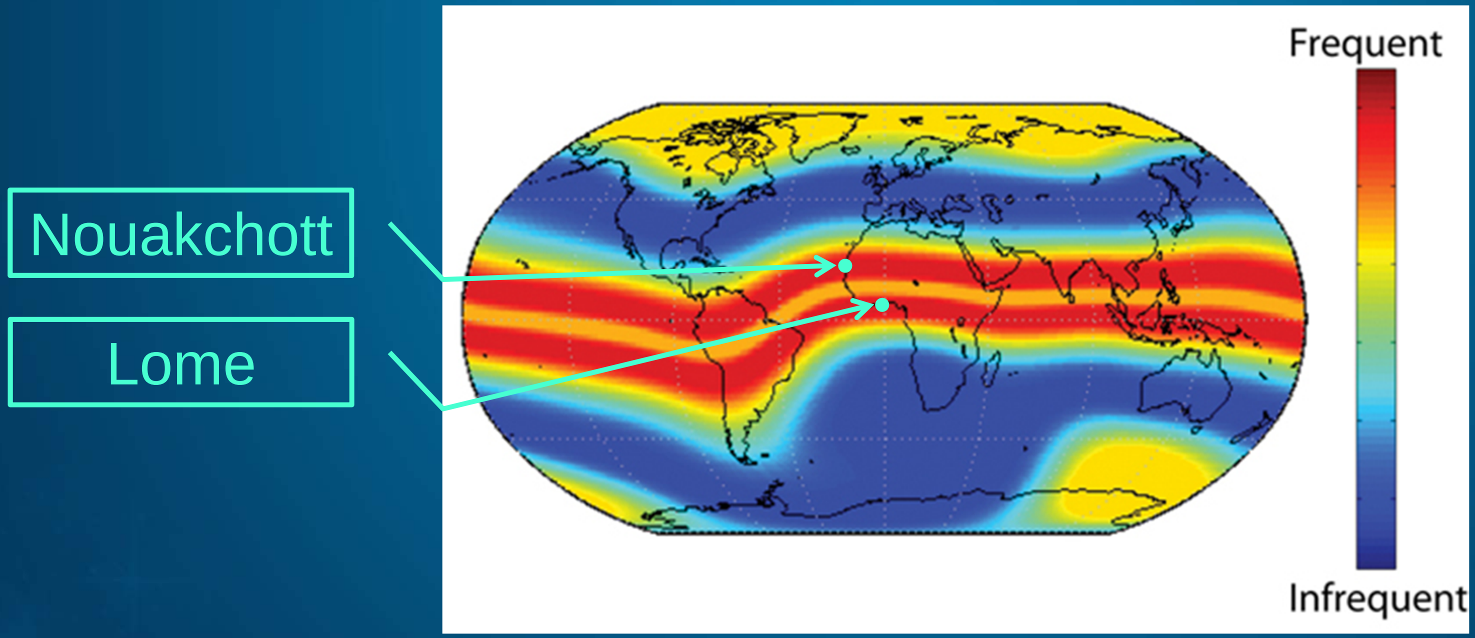
As the previous EGNOS algorithms were not designed to resist to equatorial ionosphere conditions, TAS decided to develop a new SBAS processing chain with:

- state of the art precise clock and orbit determination
- innovative ionosphere algorithms

based on its own R&D investments to prepare for Future and to demonstrate SBAS feasibility in equatorial regions

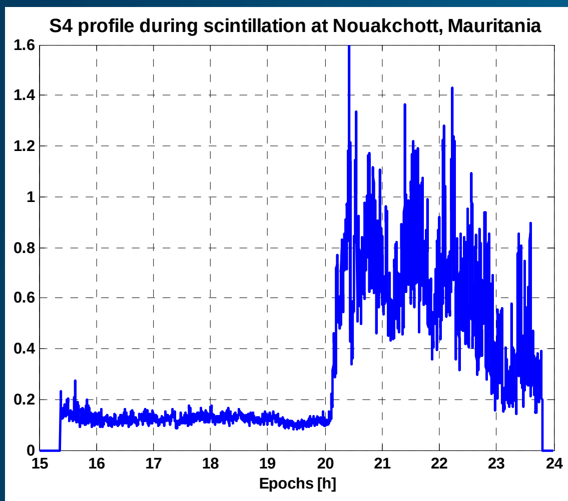
We studied algorithms for equatorial regions

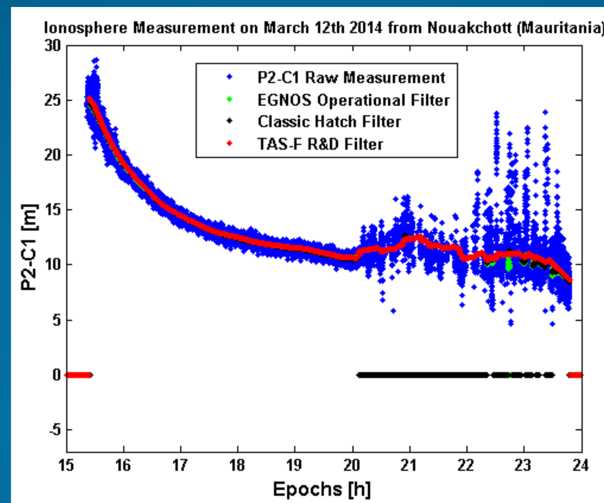
- Scintillation robustness
  - Advanced Ionosphere measurements smoothing filter able to perform under severe scintillation conditions
  - 2 example chosen:
    - Receiver located at Nouakchott (Mauritania) on March 12th 2014 (EGNOS Network)
    - Receiver located at Lome (Togo) on April 5th 2015 (SAGAIE Network)

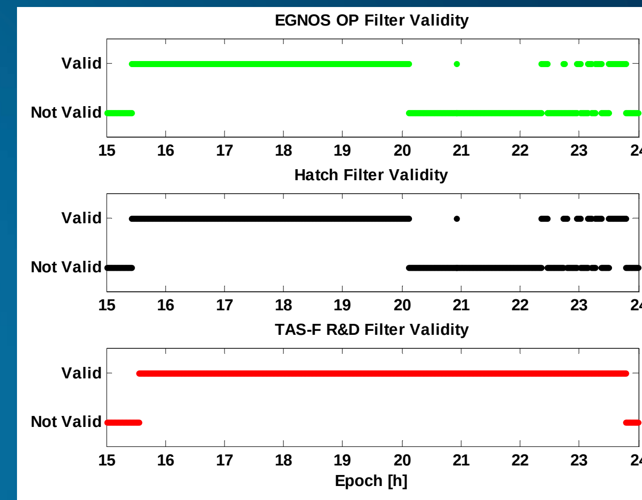


We studied algorithms for equatorial regions

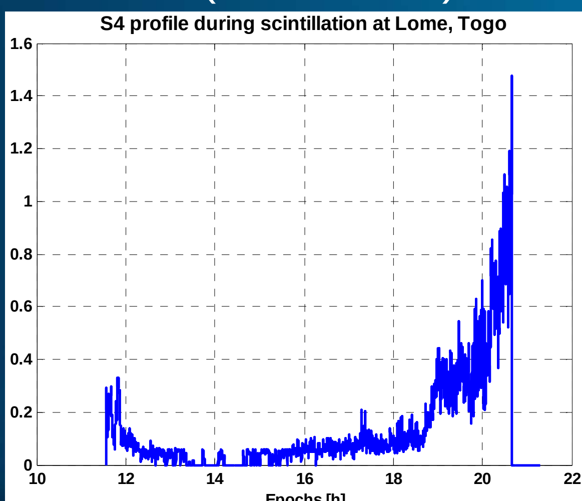
- Nouakchott (2014/03/12):

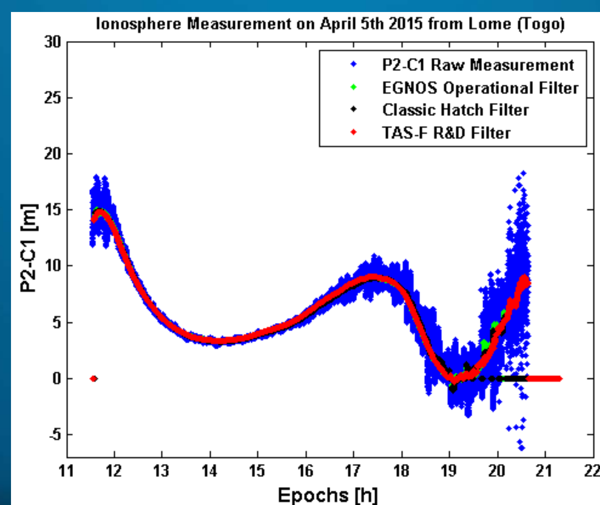


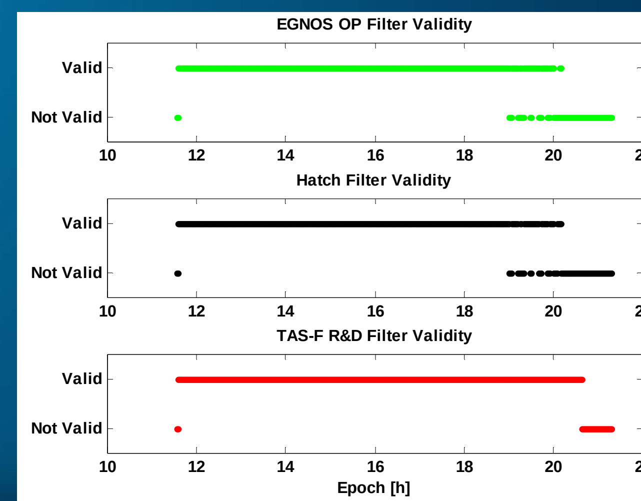




- Lome (2015/04/05):





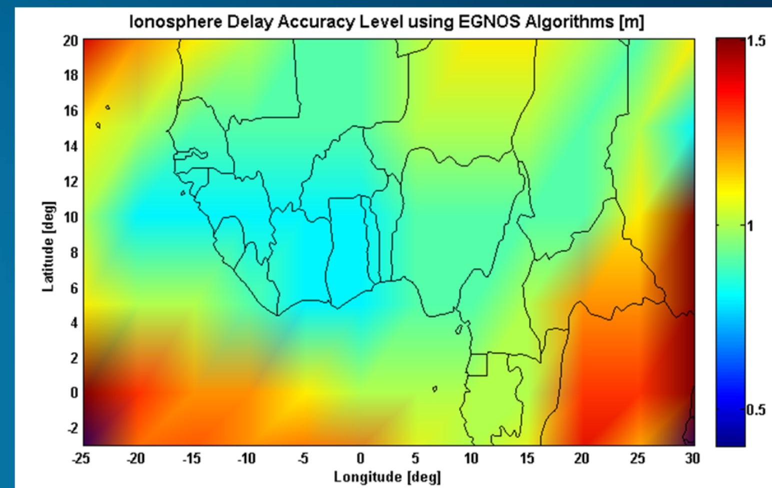


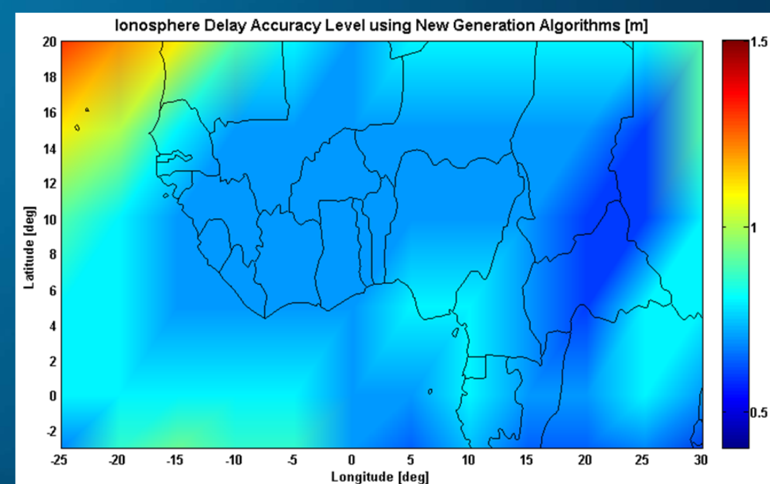
We studied algorithms for equatorial regions

- ❑ Ionosphere delay estimation evolutions
  - ❑ Mapping function, interpolation technique…

→ **Ionosphere delay accuracy improved by a factor of more than 30% in equatorial regions in comparison with Operational EGNOS**

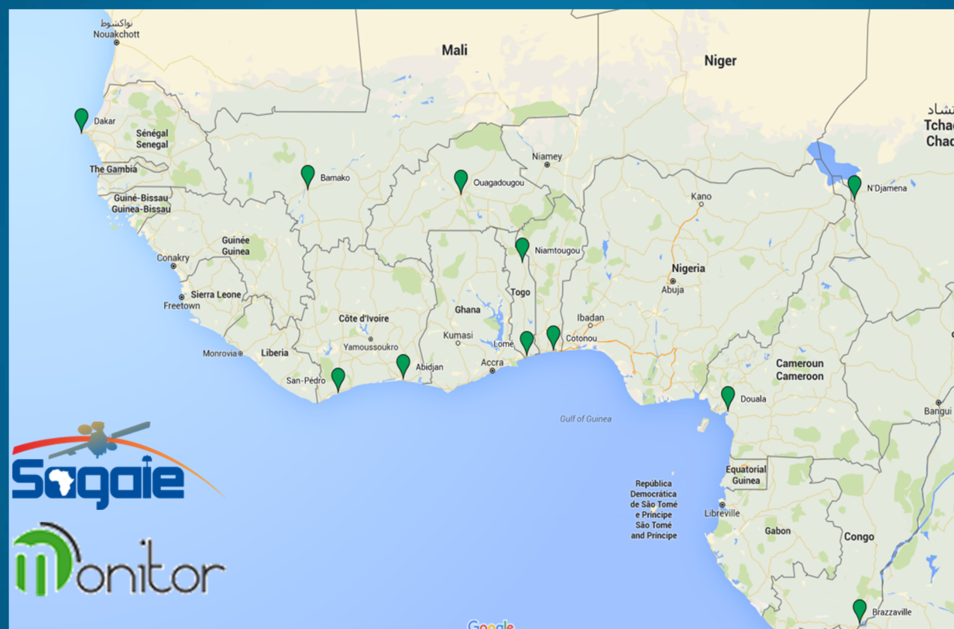
- ❑ Using these new algorithms chain, SBAS performance simulations have been performed fed by SAGAIE and MONITOR stations real data





Our Equatorial Algorithms Performances in Africa

- ❑ Using SAGAIE and MONITOR receivers, our processing chain has been run on the following network



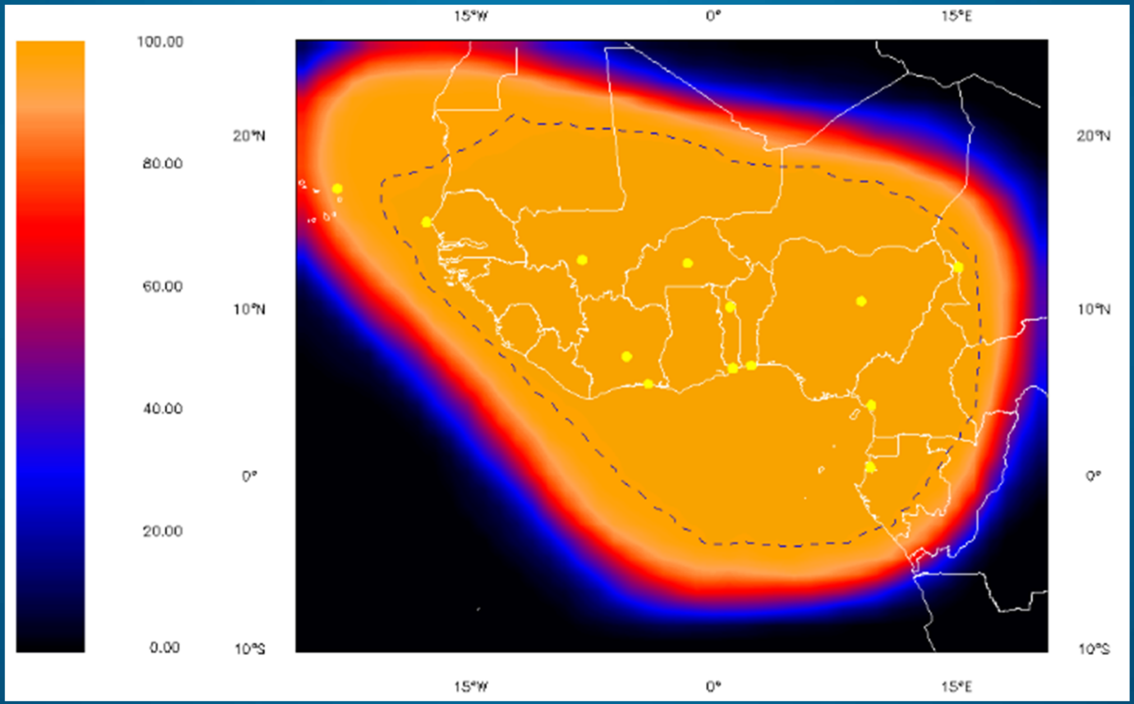
→ The following results are the Precise Approach APV-I service availability computed over 24h (including scintillation periods) without GEO ranging

Our Equatorial Algorithms Performances in Africa

- For a **G1 storm** day (2015/07/23) but with a B3 maximum solar flare level (low):

Precise Approach APV-I Availability

Blue dotted line = 99% availability contour



Iono integrity margin > 47%

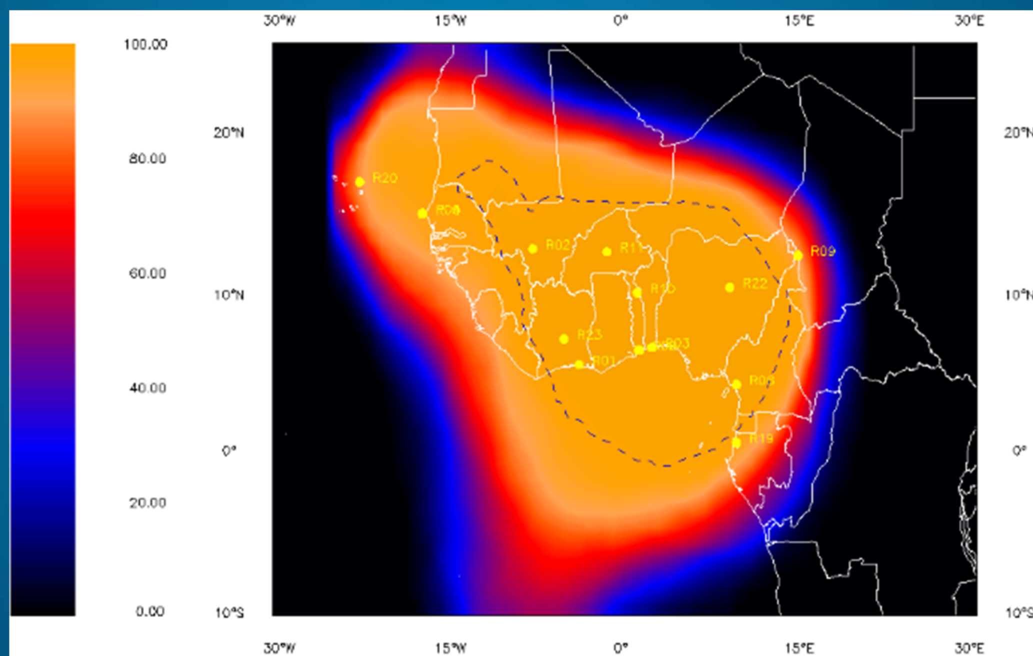
→ **MINIMUM ICAO REQUIRED APV-I AVAILABILITY LEVEL REACHED !**

Our Equatorial Algorithms Performances in Africa

- For a **G2 storm** day (2016/04/07) but with a C2 maximum solar flare level (medium):

Precise Approach APV-I Availability

Blue dotted line = 99% availability contour



Iono integrity margin > 32%

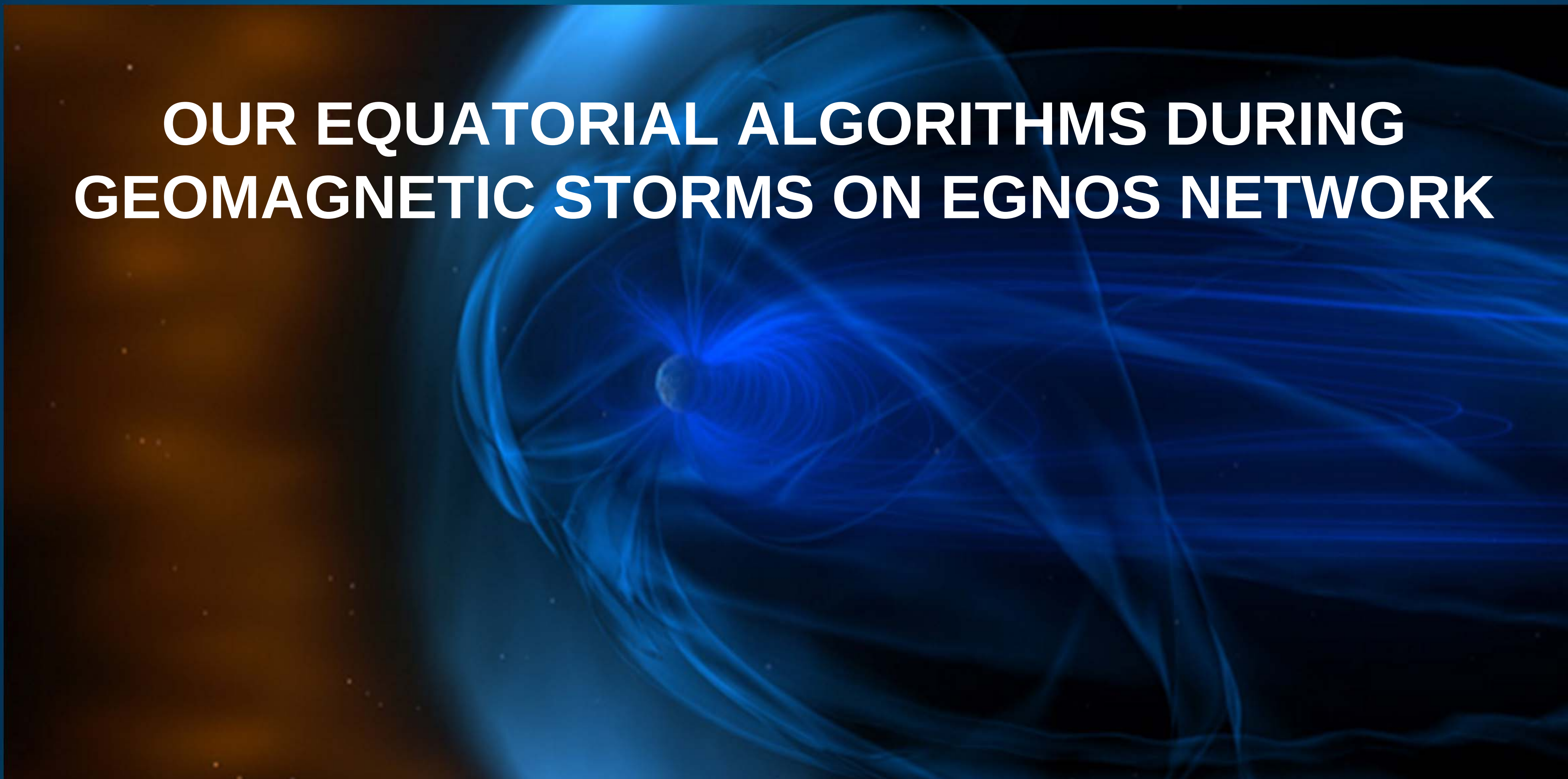
→ MINIMUM ICAO REQUIRED APV-I AVAILABILITY LEVEL REACHED ON AREAS CONTAINING THE CORRECT STATIONS DENSITY !

Feedback from Africa

Additional analyses have been performed over 2 months data (February and March 2016) using SAGAIE/Monitor network and demonstrated that **APV-I 99% availability was always met** at least above areas containing the correct stations density (compatible with SBAS need to monitor the ionosphere) like in the previous slide.

→ this experimentation clearly demonstrated the feasibility of at least APV-I precise approach service with SBAS under equatorial conditions.

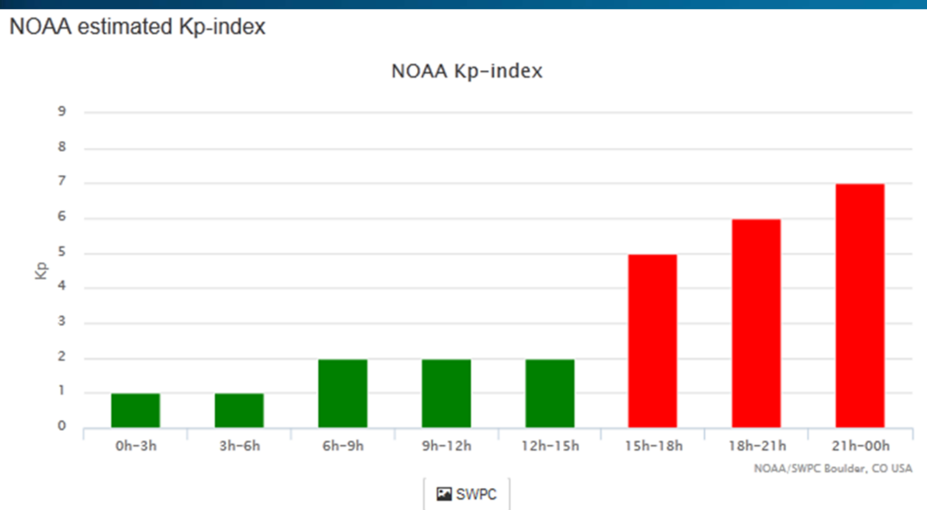
Part III



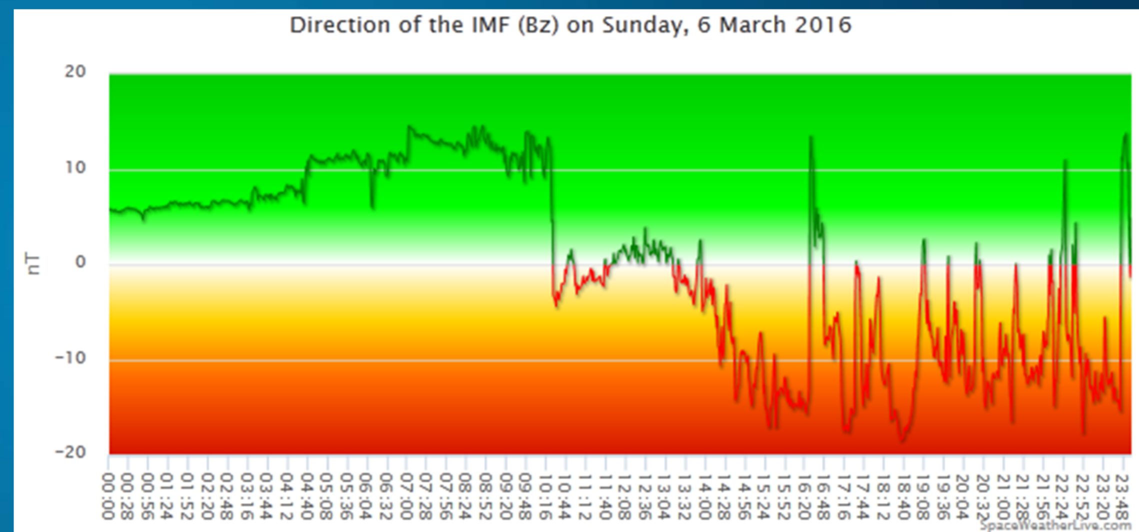
OUR EQUATORIAL ALGORITHMS DURING GEOMAGNETIC STORMS ON EGNOS NETWORK

G2/G3 Class Storm on March 06th 2016

- On March 6th 2016, a G2+ class storm appeared. This storm is detailed below:



00-03h	03-06h	06-09h	09-12h	12-15h	15-18h	18-21h	21-00h
1	1	2	2	2	5	6	7

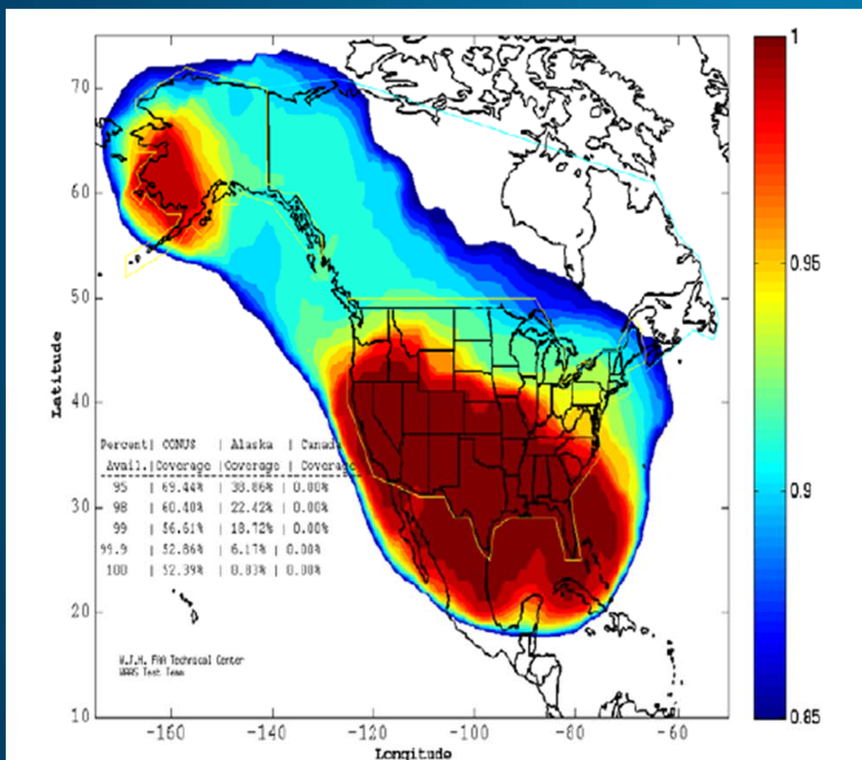


According to experts analyses, it seems that a small coronal mass ejection (not detected by instruments) occurred this day causing IMF direction rapid fluctuations

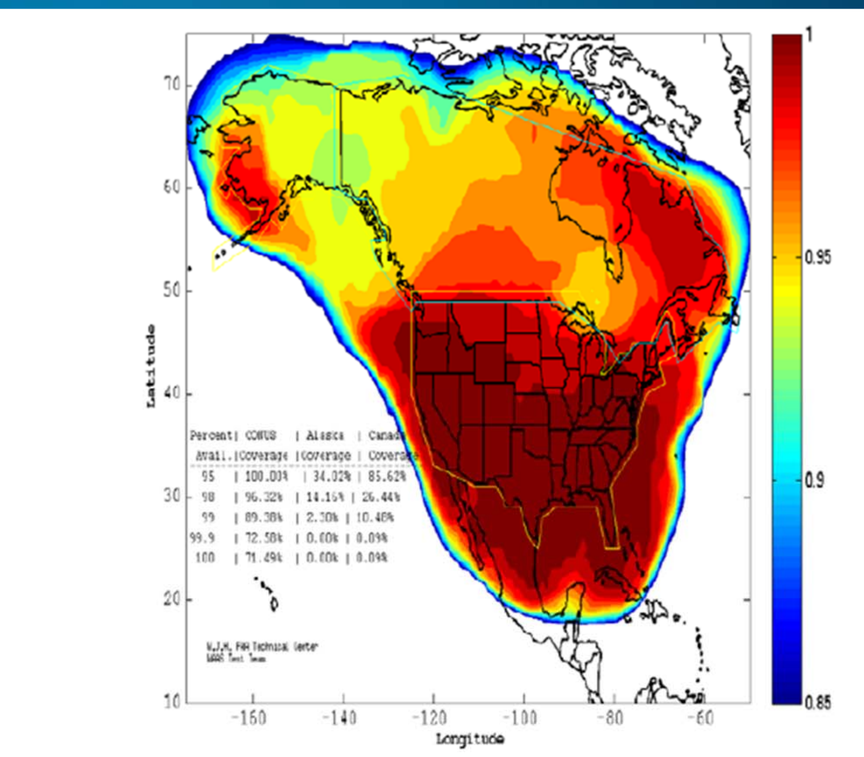
ThalesAlenia Space

March 06th 2016 : Impact on SBAS

- During this day, SBAS performances degradations have been observed on both WAAS and EGNOS systems
- WAAS : DR 130, LPV200 Availability degradation on March 6th and 7th



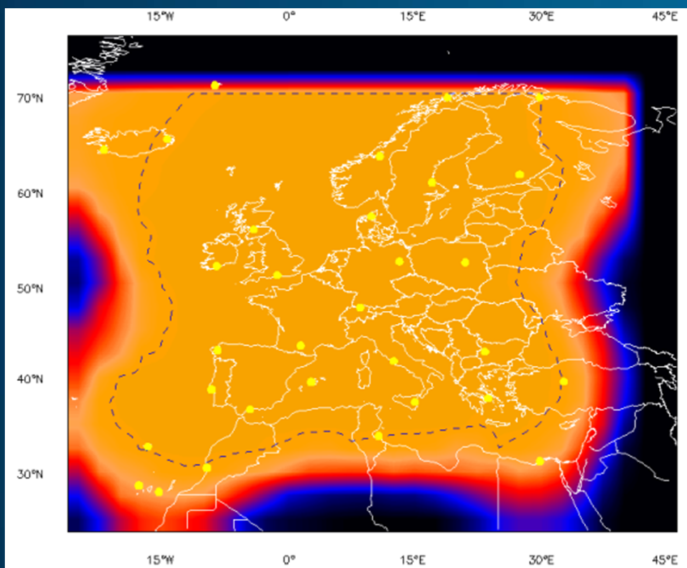
2016/03/06



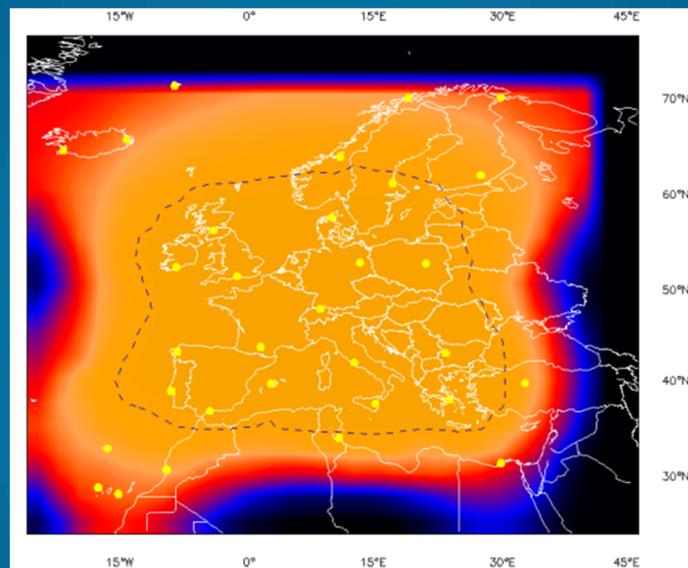
2016/03/07

March 06th 2016 : Impact on SBAS

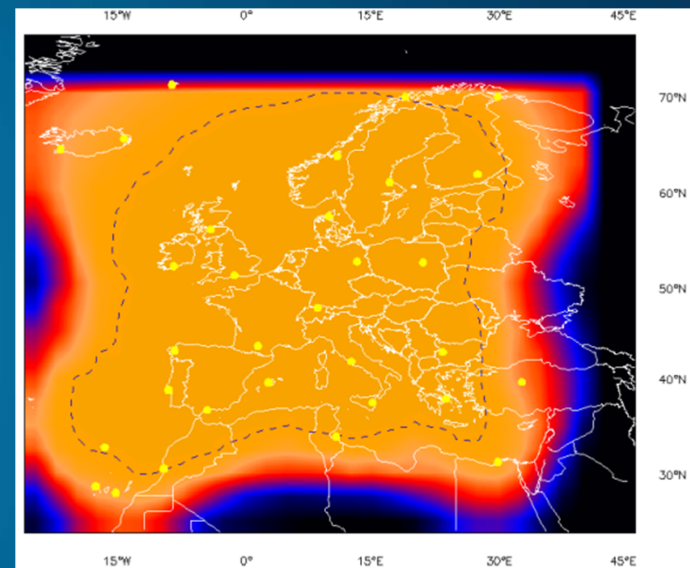
- EGNOS : LPV200 Availability degradation



2016/03/05



2016/03/06

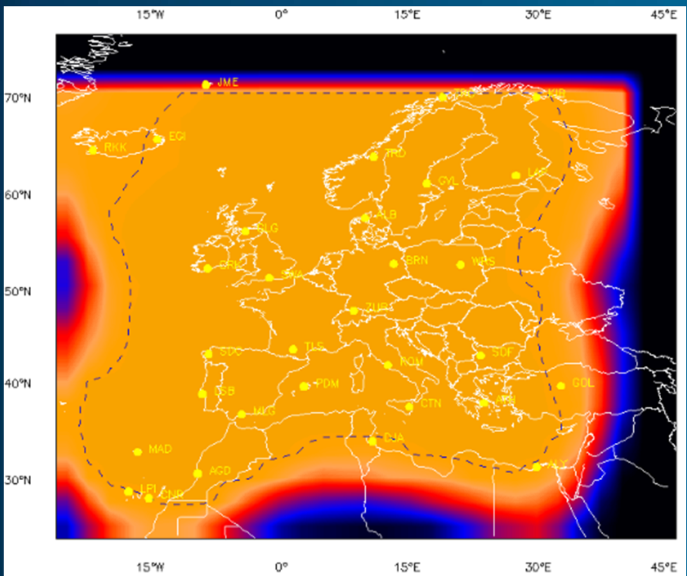


2016/03/07

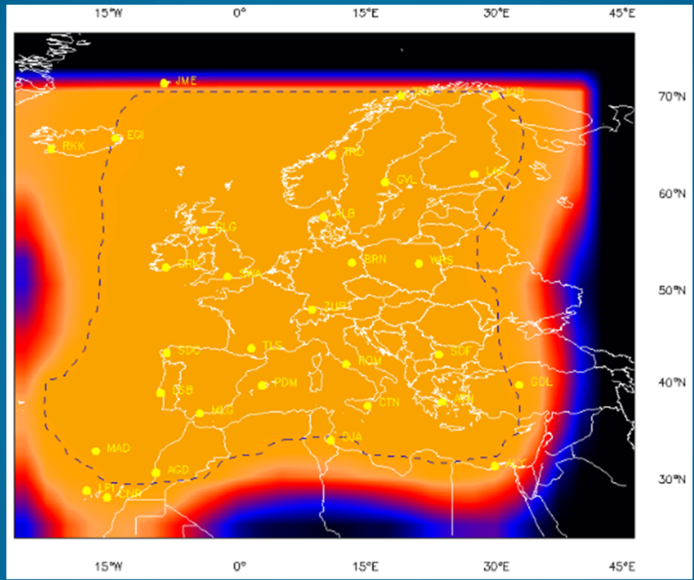
Blue dotted line = 99% availability contour

March 06th 2016 : Impact on SBAS

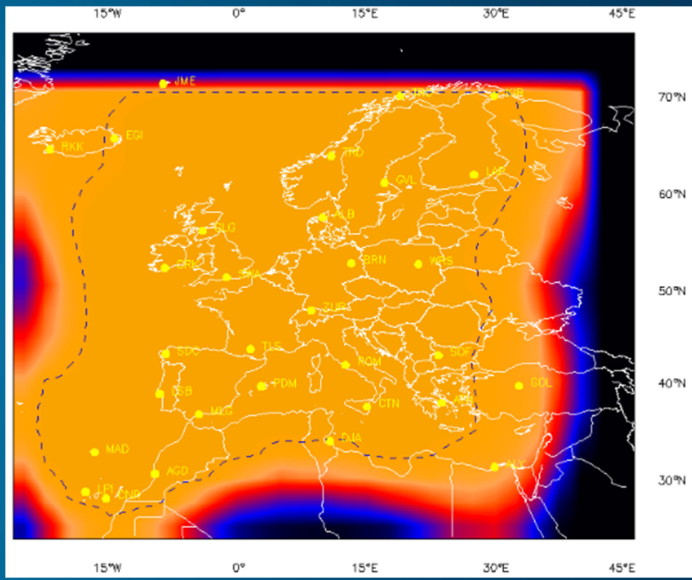
❑ OUR EQUATORIAL ALGORITHMS : LPV200 availability



2016/03/05
Iono integrity
margin > 49%



2016/03/06
Iono integrity
margin > 52%

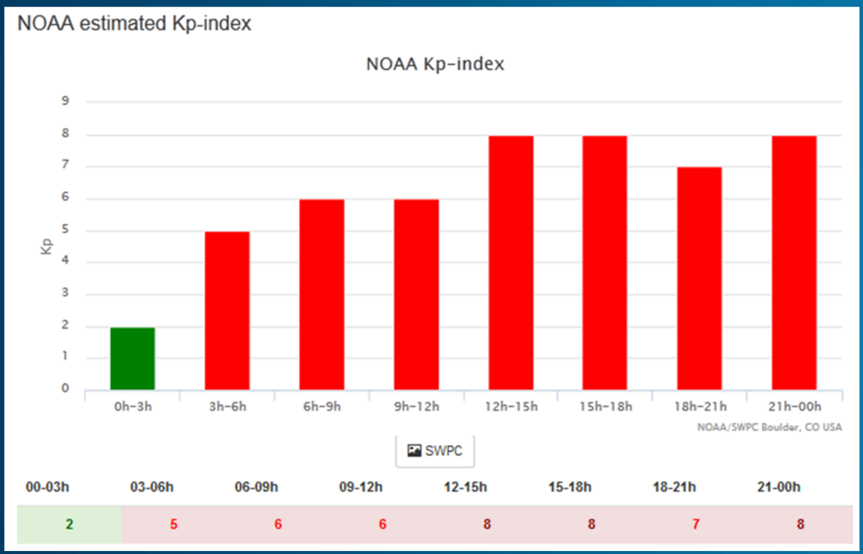


2016/03/07
Iono integrity
margin > 47%

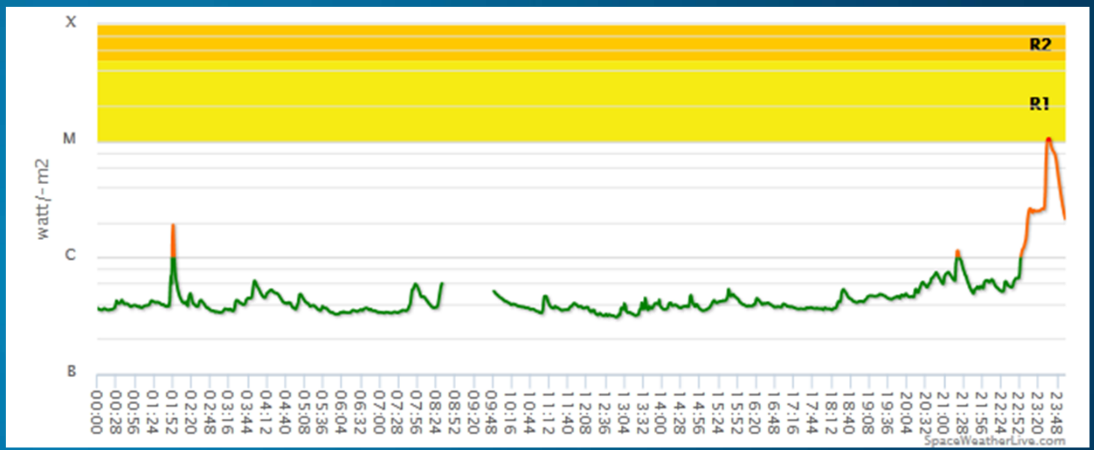
→ OUR EQUATORIAL ALGORITHMS NOT IMPACTED BY THIS G2 CLASS STORM

St Patrick 2015 Severe G4 Storm

- On March 17th 2015, a severe G4 class storm appeared. This storm is detailed below:



Kp indices



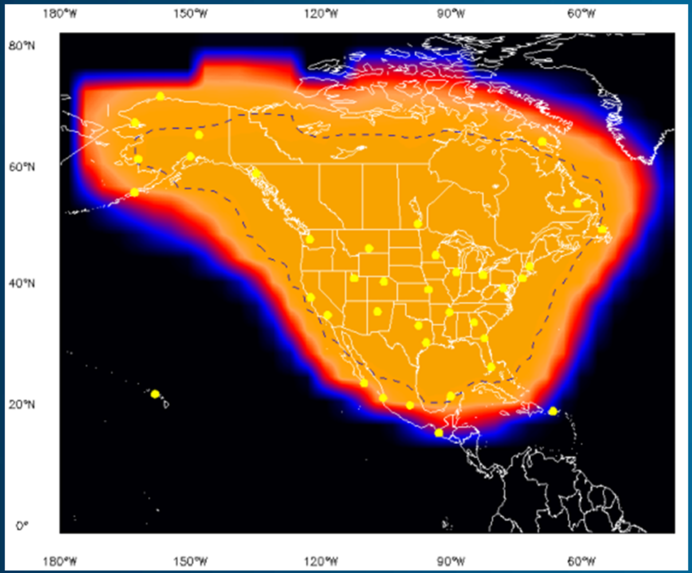
Solar Flare level

Severe **G4 class storm** following coronal mass ejection associated with a C9-M1 solar flare. (For recall G5 is the maximum class)

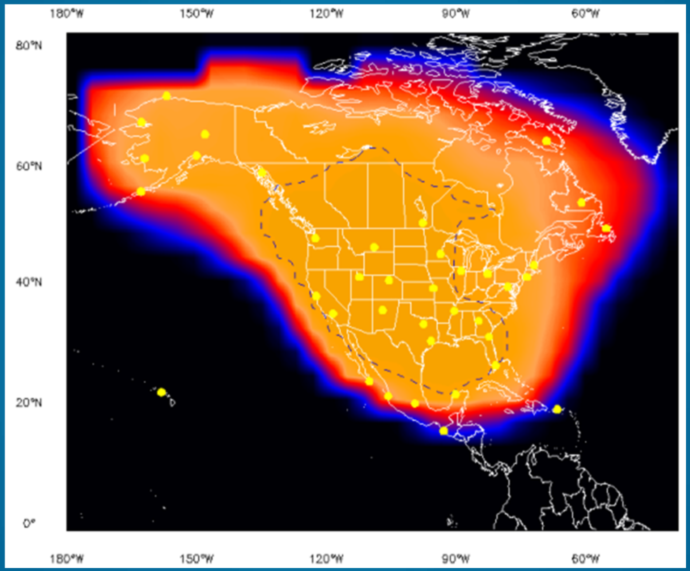
→ The strongest geomagnetic storm of the current solar cycle

St Patrick 2015 Storm: Impact on SBAS

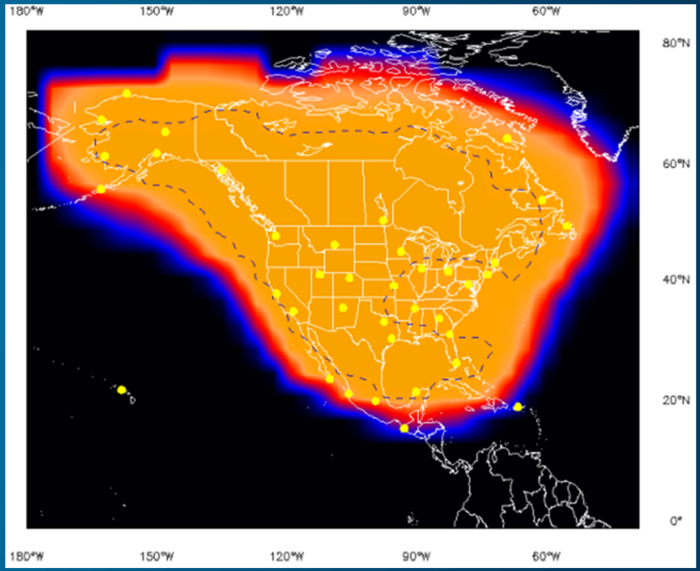
- WAAS : DR 127, LPV200 Availability degradation on March 17th 2015 (using ESVS tool for availability maps plots)



2015/03/16



2015/03/17

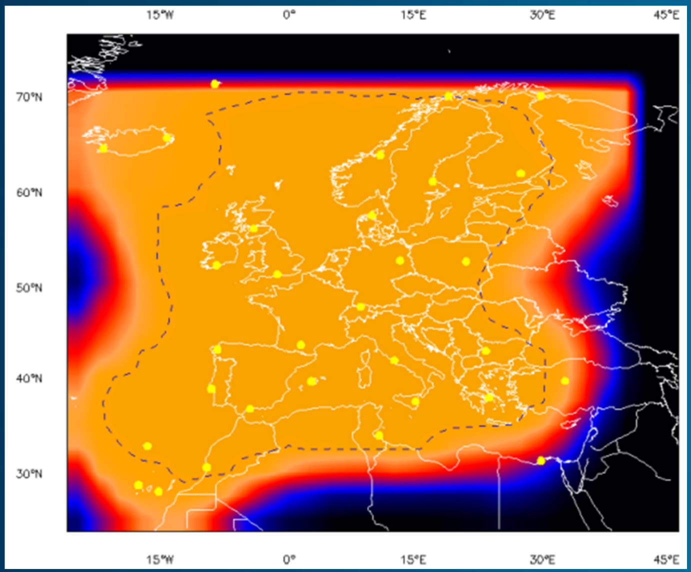


2015/03/18

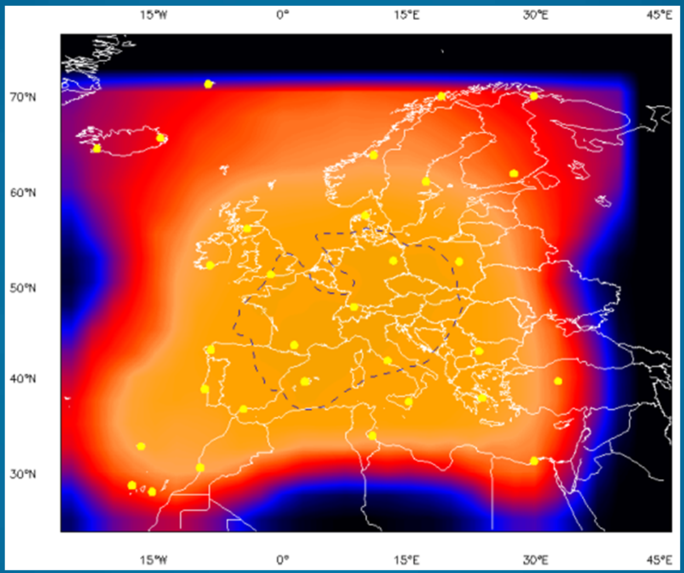
Blue dotted line = 99% availability contour

St Patrick 2015 Storm: Impact on SBAS

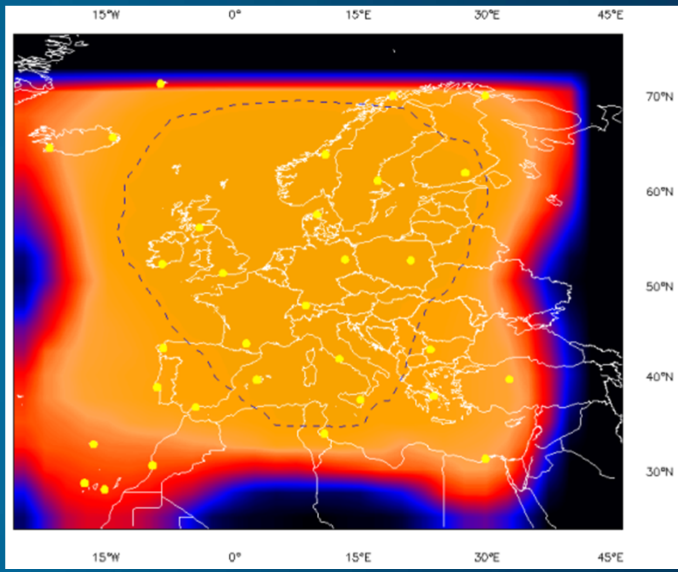
- ❑ EGNOS: LPV200 Availability degradation



2015/03/16



2015/03/17

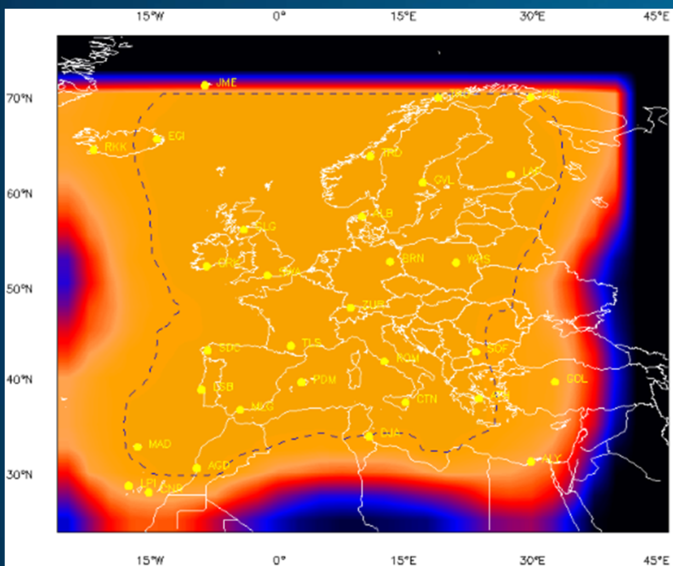


2015/03/18

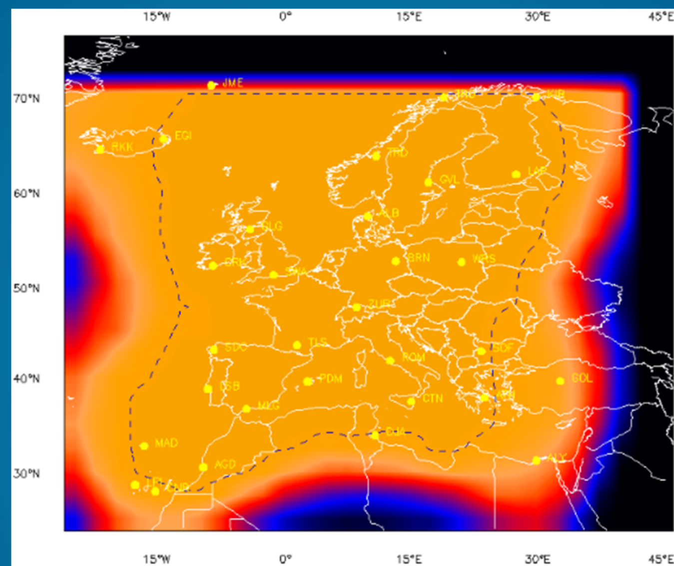
Blue dotted line = 99% availability contour

St Patrick 2015 Storm: Impact on SBAS

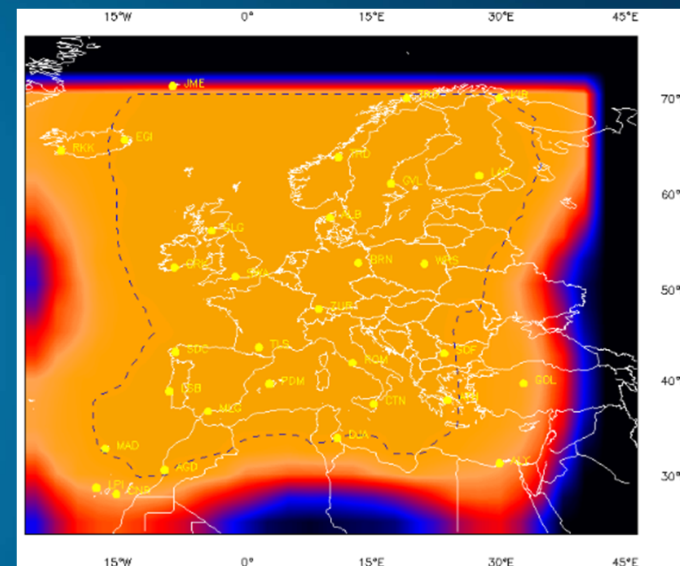
- TAS-F EQUATORIAL ALGORITHMS : LPV200 availability



2015/03/16
Iono integrity
margin > 31%



2015/03/17
Iono integrity
margin > 33%



2015/03/18
Iono integrity
margin > 45%

→ OUR EQUATORIAL ALGORITHMS NOT IMPACTED BY THIS G4 CLASS STORM

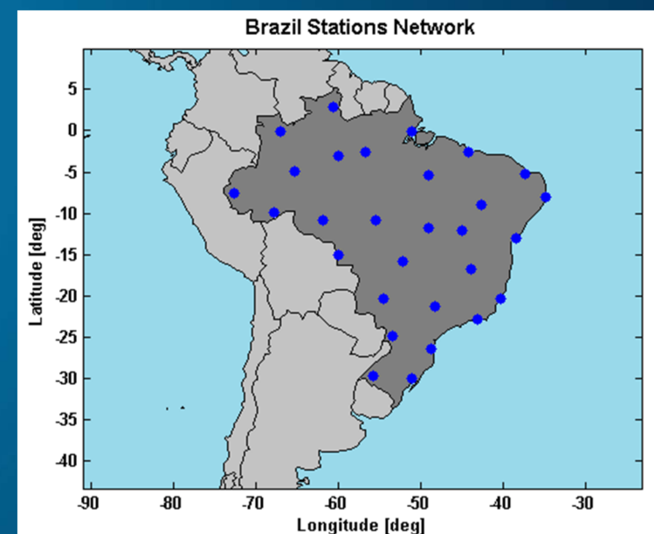
Part V

EQUATORIAL ALGORITHMS IN BRAZIL

Equatorial Algorithms testing in Brazil

- In the frame of a study with Brazilian INPE in contact with the DECEA/ICEA, we performed preliminary studies using 30 stations of the IBGE.

→ only 1/15 Hz rate available measurements which required adaptation of our processing.



- Several days have been tested with equatorial algorithms:
  - April 20th and 21st 2015 with G1 storm on 21st (with 30 stations)

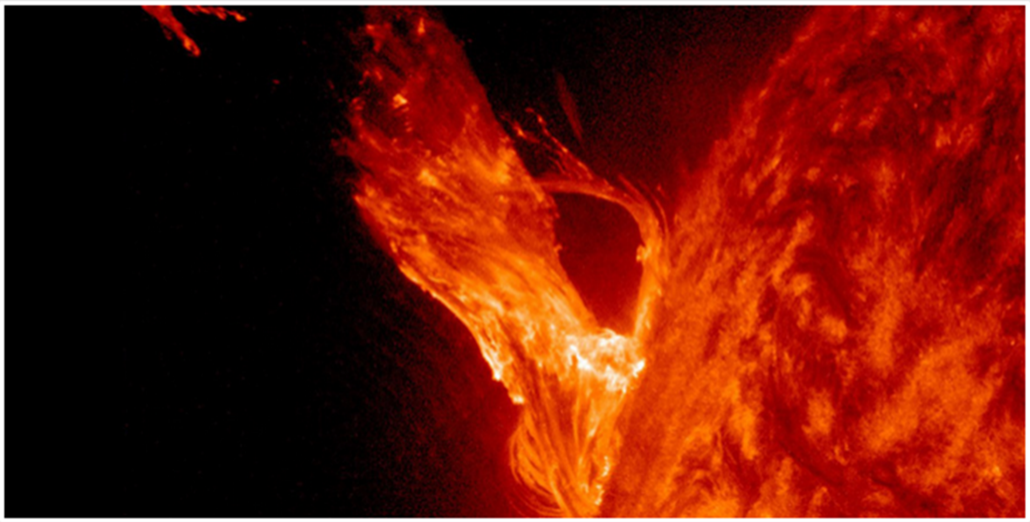
- Availability computed with GPS only without GEO ranging, over 24h period (without interruption)

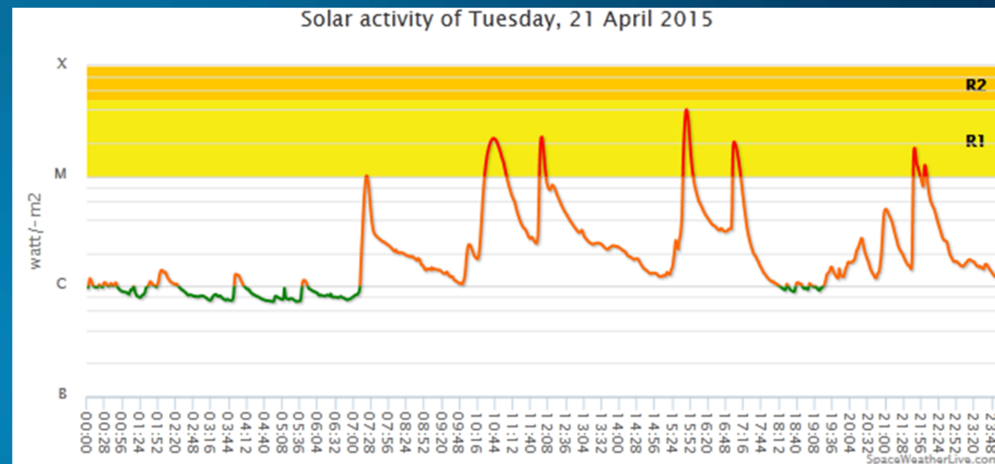
G1 Class Storm on April 21st 2015

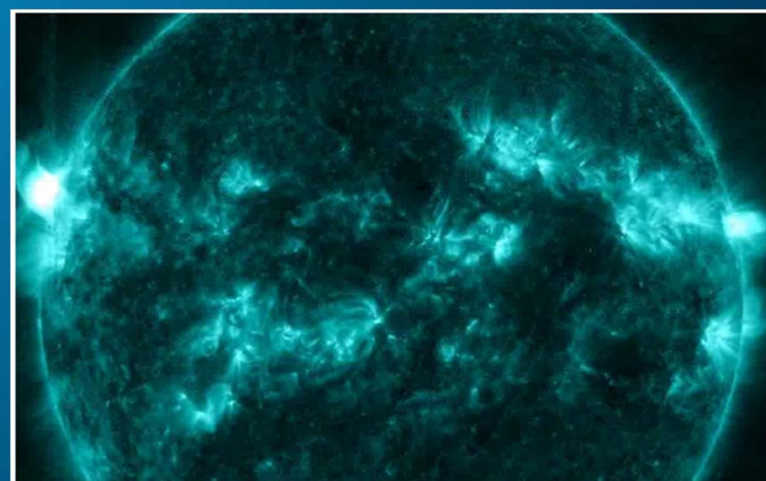
- On April 21st 2015 → **G1 storm class with <u>strong solar flares</u> level**

Three M-class solar flares, CH effects, CME watch

Tuesday, 21 April 2015 - 14:11 UTC



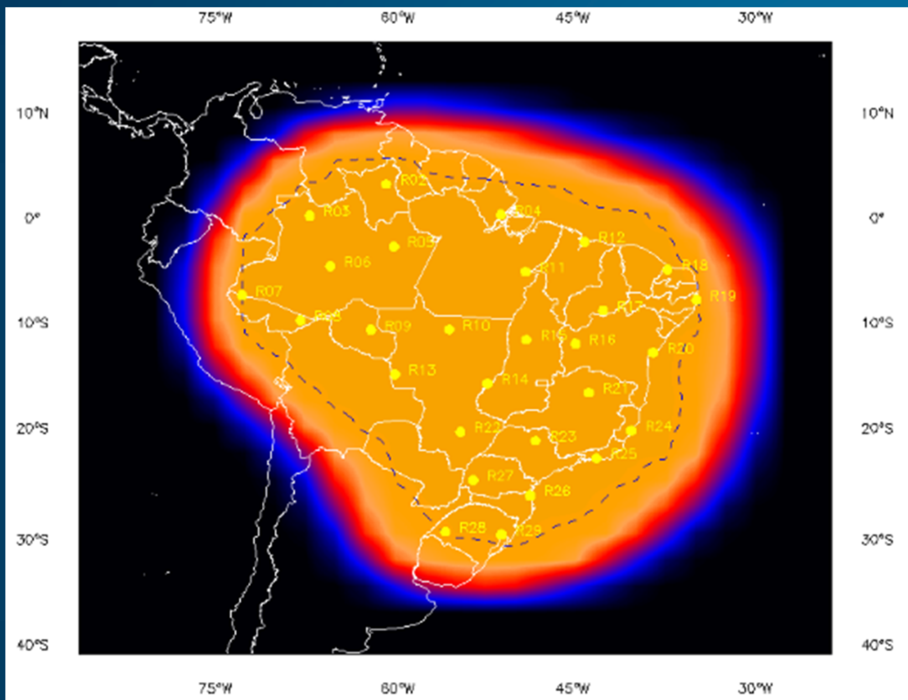




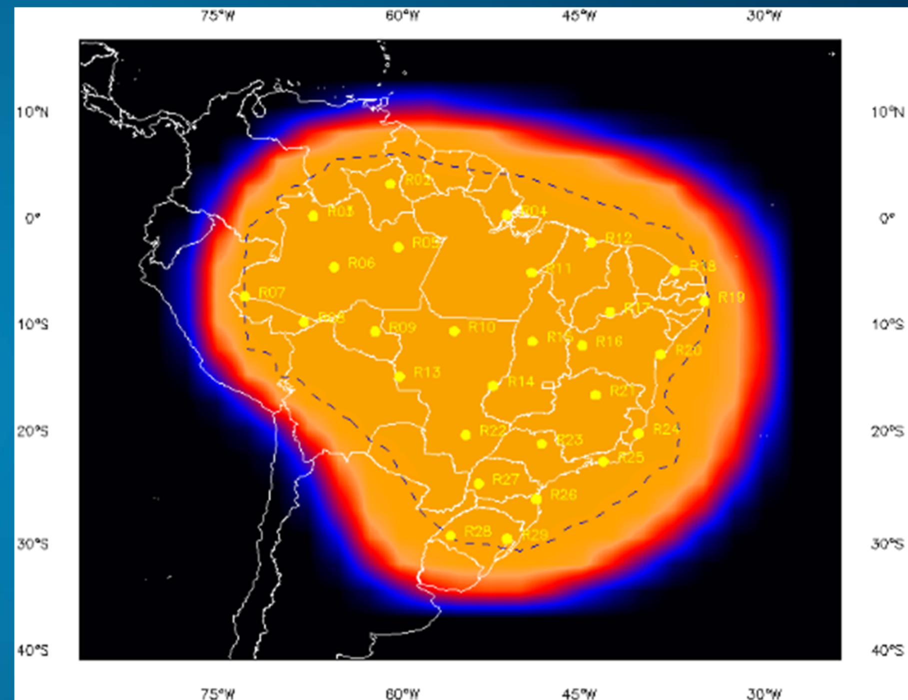
Coronal hole effects and CME watch

G1 Class Storm on April 21st 2015

❑ OUR EQUATORIAL ALGORITHMS : APV-I availability



2015/04/20
Iono integrity margin > 15%



2015/04/21
Iono integrity margin > 26%

→ APV-I 99% availability reached in Brazil. This G1 storm has no impact on APV-I availability performances.

Part V

CONCLUSIONS

Conclusion

- The ionosphere is the main concern of satellite navigation operating system in equatorial regions which undergo severe electronic density fluctuations (TEC gradients) but also phenomena like scintillation caused by the irregularities observed in these locations.
- Studies performed in Africa allowed to design a new generation of algorithms able to provide huge improvements concerning ionosphere modelling in equatorial regions.
- These new generation algorithms demonstrated their robustness against worst geomagnetic storms of the current solar cycle that affected both WAAS and EGNOS.
- Concerning the South American region, the feasibility studies performed in Brazil allow to confirm results obtained in Africa.

→ **Using these new algorithms a specific SBAS test bed should now be deployed to confirm the precise approach APV-I service capabilities over a long duration period in South America.**

→ **Thales Alenia Space is willing to do this in co-development with South American entities.**

Thank you
for your attention

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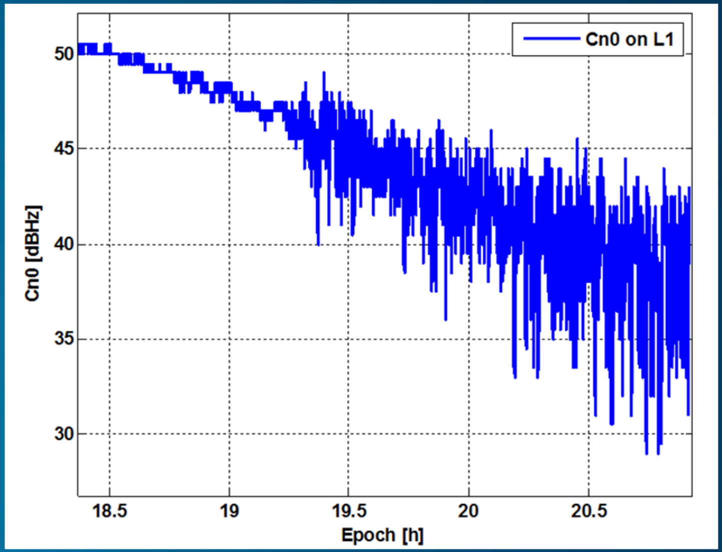
Part VI

APPENDIX

Impact of ionosphere on GNSS measurements: scintillation

- ❑ 2 kind of scintillation:
  - ❑ Amplitude scintillation → Equatorial regions
  - ❑ Phase scintillation → High latitudes
- ❑ Amplitude scintillation:
  - ❑ Short term fading on signal that can get below GPS receiver lock threshold → Loss of Locks
- ❑ Phase scintillation:
  - ❑ Rapid carrier phase changes obtained from receiver lock loop → Cycle slips and sometimes loss of lock

- ❑ Scintillation = one of the most significant threats for GNSS operating near equatorial or polar latitudes



GPS receiver signal strength fading caused by scintillation in Africa


Aurora Borealis

SBAS versus GBAS trade-off in equatorial regions

A GBAS is local : 1 airport

- A single L_1/L_2 station with redundant receivers is deployed and geo-referenced
- The difference in pseudo-range between measurement and theory is broadcast as a single correction for each satellite
- Each correction comes with a confidence interval

⇒ Does not separate ionosphere delay from satellite error
⇒ Potentially very accurate in calm ionosphere
⇒ Undergoes the ionosphere disturbance without observing its level
⇒ High margins => Low service level

An SBAS covers a continent

Many geo-referenced L_1/L_2 stations:

- observe the satellites and the ionosphere
- separate the contributors with sophisticated algorithms.
- Satellite and ionosphere corrections are broadcast separately to cover any user situation
- Each correction comes with a confidence interval
- Ionosphere alerts if disturbed ionosphere

⇒ Less margin (able to stop if problem)
⇒ Higher service levels.

+ Serves hundreds of airports/airfields

SBAS is the best system to ensure ionosphere monitoring integrity in equatorial regions. GBAS can be used to complement SBAS to improve aircrafts accuracy close to airports. However, Precise Approach APV-I can be reached using SBAS only over equatorial regions with “state of the art” algorithms.

TAS involved in several ionosphere study projects in equatorial regions

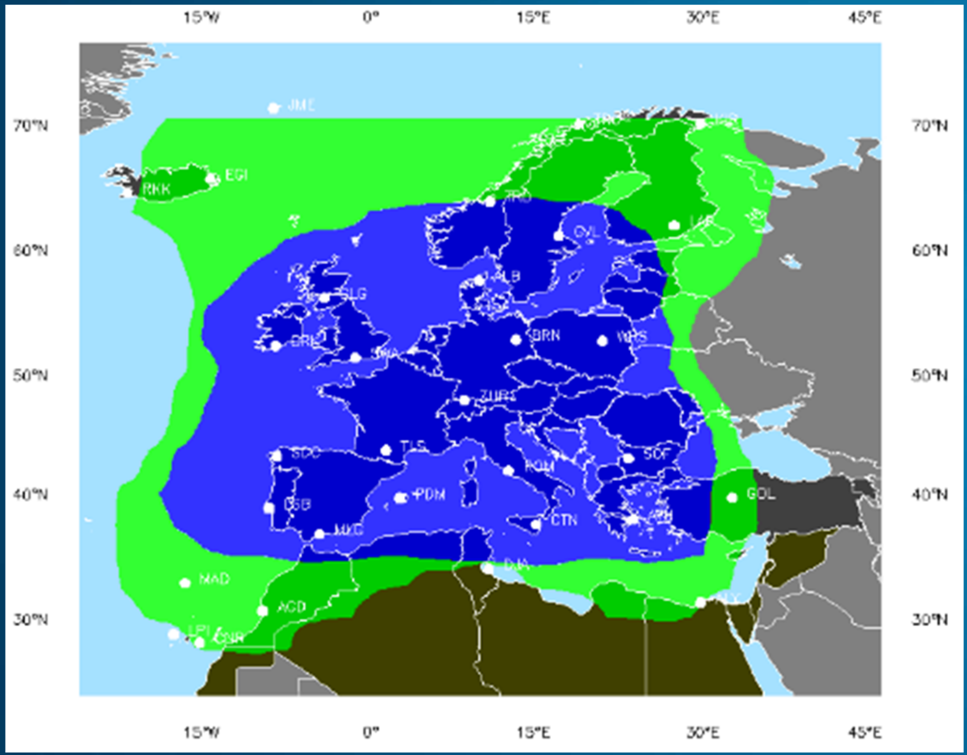
- SAGAIE ("Station ASECNA GNSS pour l'Analyse de la Ionosphère Equatoriale"):
  - SAGAIE is a project lead by CNES (French Spatial Agency) in collaboration with ASECNA (Civil Aviation Navigation Security Agency for Africa and Madagascar)
  - SAGAIE is focused on equatorial ionosphere studies (gradients, TEC values, scintillation analyses) for a better observation and understanding of different ionosphere phenomenon occurring in such areas
- MONITOR:
  - Monitor is an ESA (European Space Agency) project focused on ionosphere monitoring in the frame of EGEP (European GNSS Evolution Programme) gathering several European industries and agencies (as IEEA, CLS, CNES, DLR, EUROCONTROL….)
  - The aim is to observe both high latitude and equatorial ionosphere with a dedicated study of scintillation effects on GNSS receivers

As current EGNOS algorithms are not designed to resist to equatorial ionosphere conditions, TAS decided to develop a new SBAS processing chain with:
- state of the art precise clock and orbit determination
- innovating ionosphere algorithms

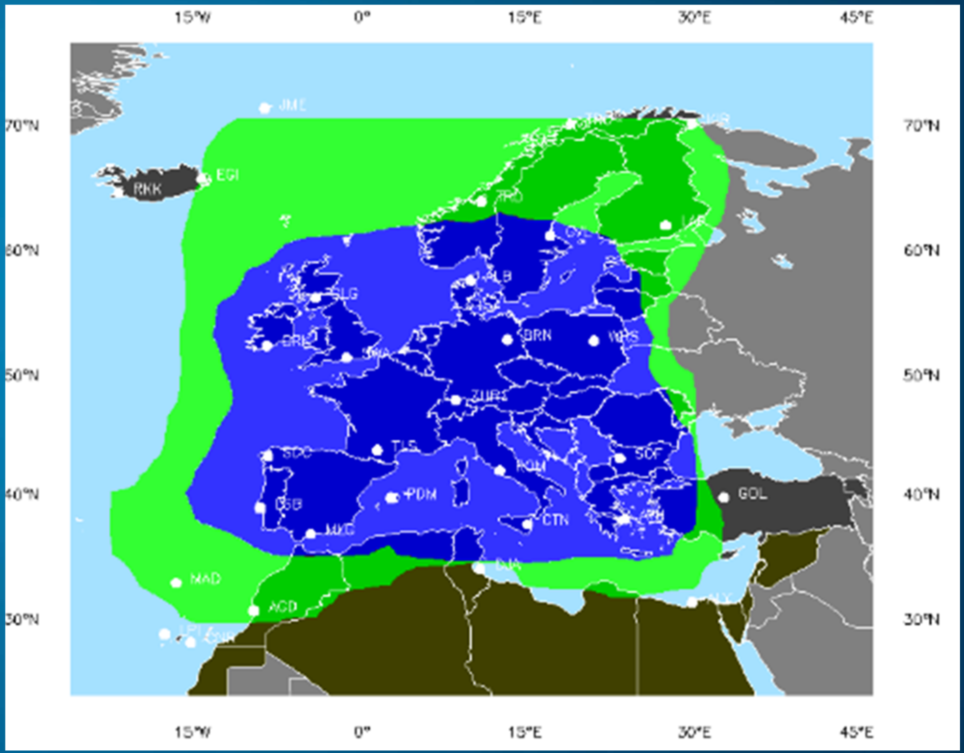
based on its own R&D investments to prepare for Future and to demonstrate SBAS feasibility in equatorial regions

March 06th 2016 : Impact on SBAS

- ICAO SARPs minimum required availability comparison EGNOS versus TAS-F Equatorial Algorithms on March 6th 2016



APV-I
99% availability

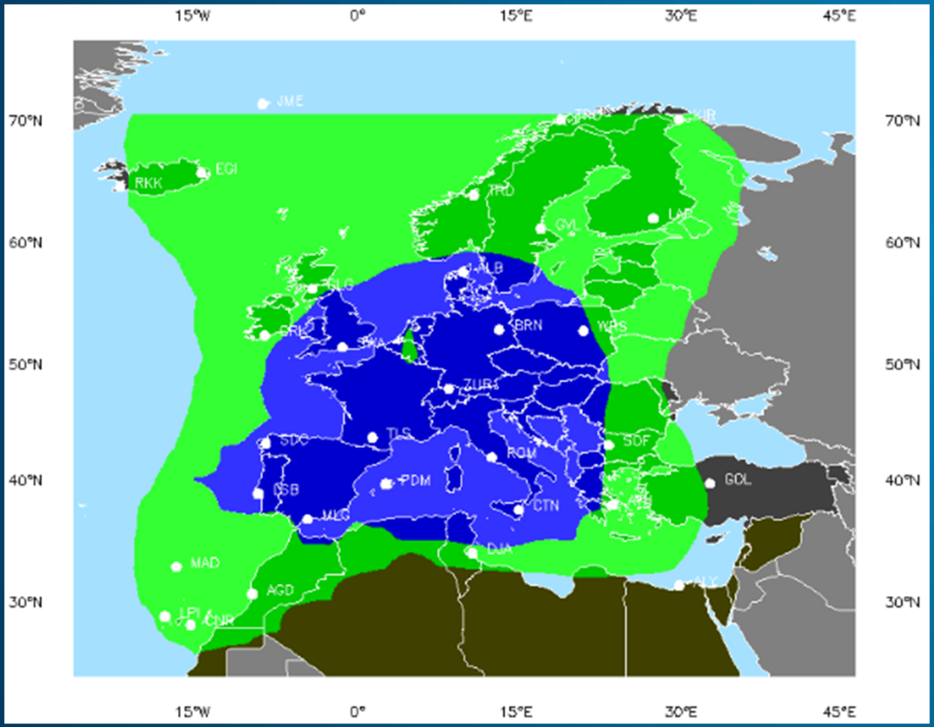


LPV200
99% availability

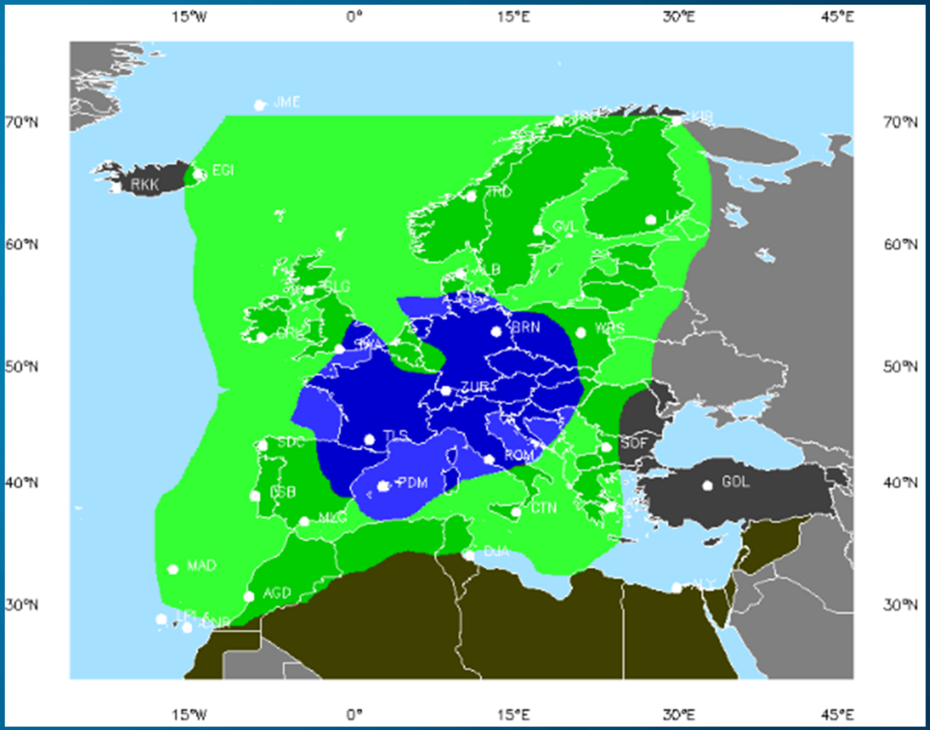
Degraded Performance
Equivalent Performance
Improved Performance

St Patrick 2015 Storm: Impact on SBAS

- ICAO SARPs minimum required availability comparison EGNOS versus TAS-F Equatorial Algorithms on St Patrick Storm (March 17th 2015)



APV-I
99% availability



LPV200
99% availability

Degraded Performance
Equivalent Performance
Improved Performance