OBSERVATION AND REAL-TIME ANALYSIS OF SPACE WEATHER EFFECTS ON GNSS THROUGH GNSS MEASUREMENTS

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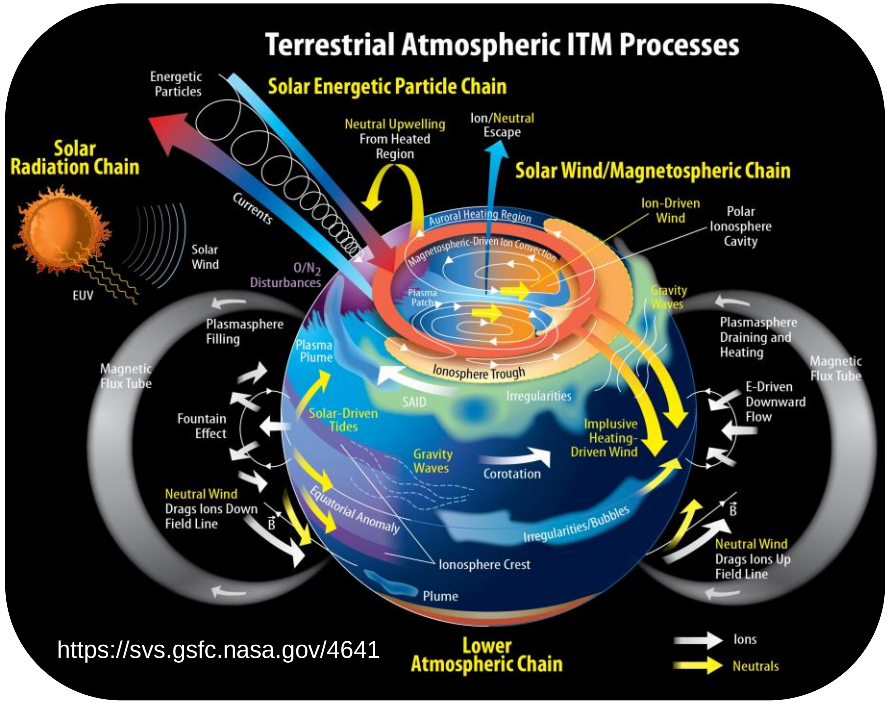
DLR

Space Weather is challenging for GNSS based navigation


https://spaceplace.nasa.gov/gallery-sun/en/



https://svs.gsfc.nasa.gov/4641


https://www.esa.int/ESA_Multimedia/Images/2018/01/Space_weather_effects

Climatological variations
- Radiation
- Solar Wind

Space Weather Events
- Solar Flares
- Radio Bursts
- CMEs
- SEPs

- Solar cycle, Solar rotation
- Day-Night
- Coupling Processes
- Seasons
- Region
- Forcing from below (Gravity Waves)

Ionospheric plasma causes
- Delay of the radio signals
- Signal strength fluctuations
- Defocussing of the signal

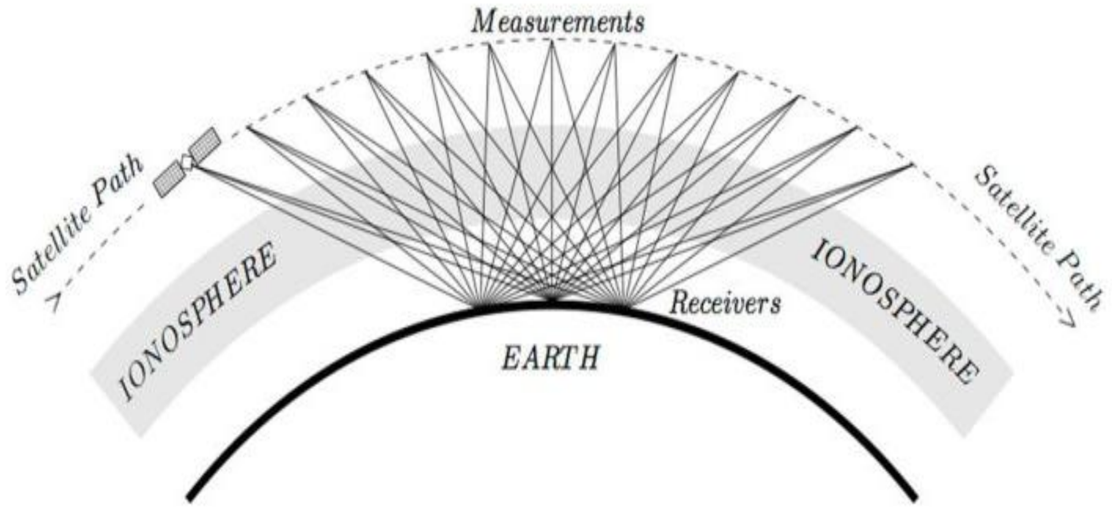
➔ ***Excess of Distance***
➔ ***Loss of signal***

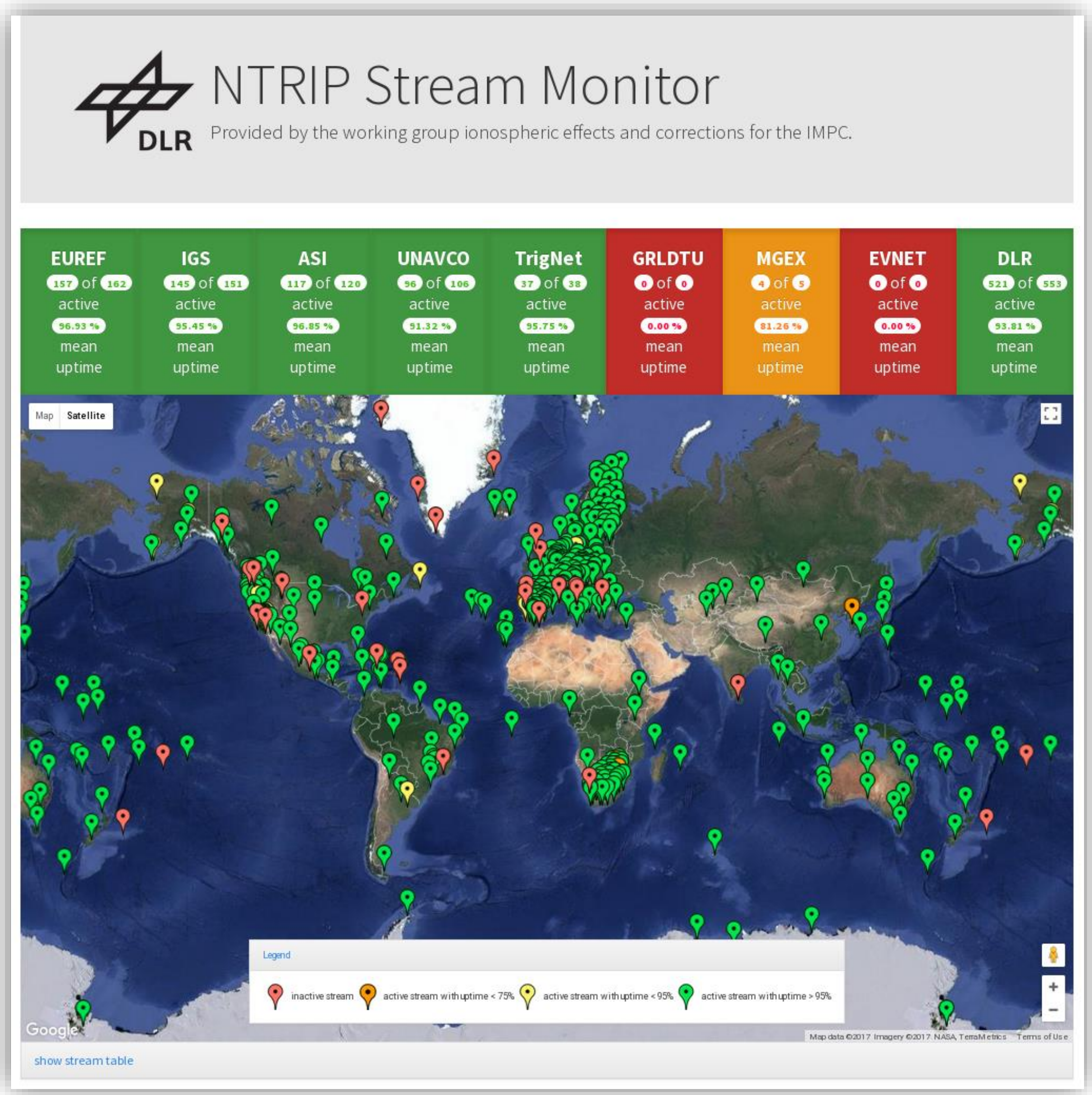
GNSS based Space Weather observation

Ground based GNSS observation providing TEC measurements are recently one of the most important data source for Space Weather research and services.

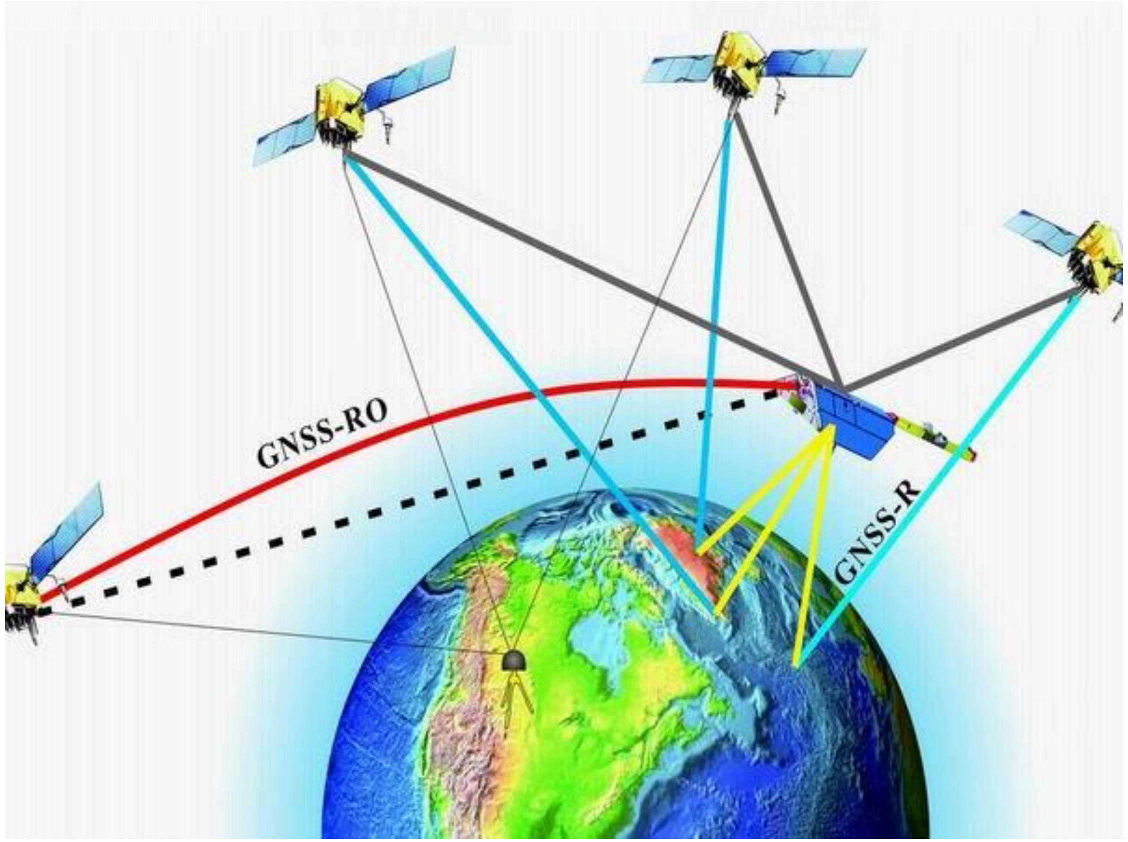
- Global coverage
- Multi-frequency, multi-GNSS
- Good horizontal resolution
- High temporal resolution
- (Near) Real time

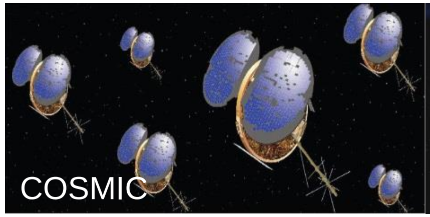
- Bad coverage over ocean and mountain regions
- No vertical resolution

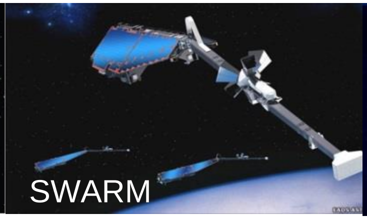




GNSS based Space Weather observation

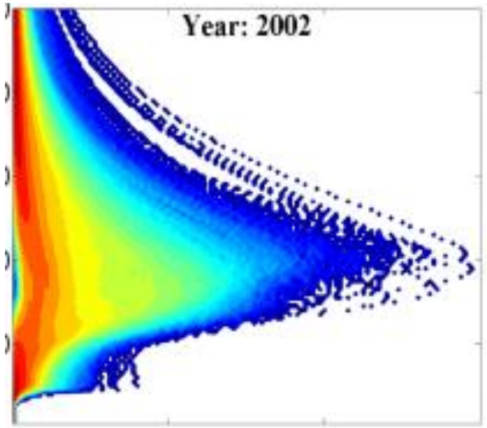




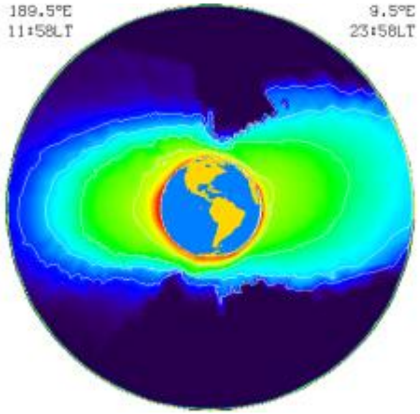


Space based GNSS measurements on board LEO Satellites play an increasing role in ionospheric monitoring

Radio Occultation



Topside

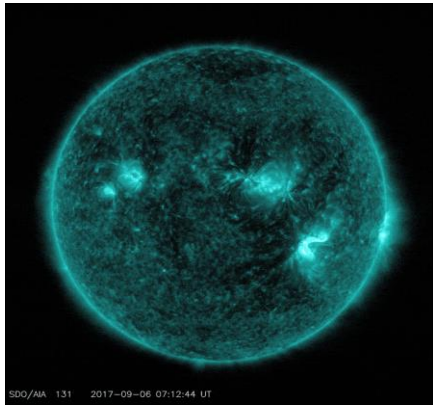


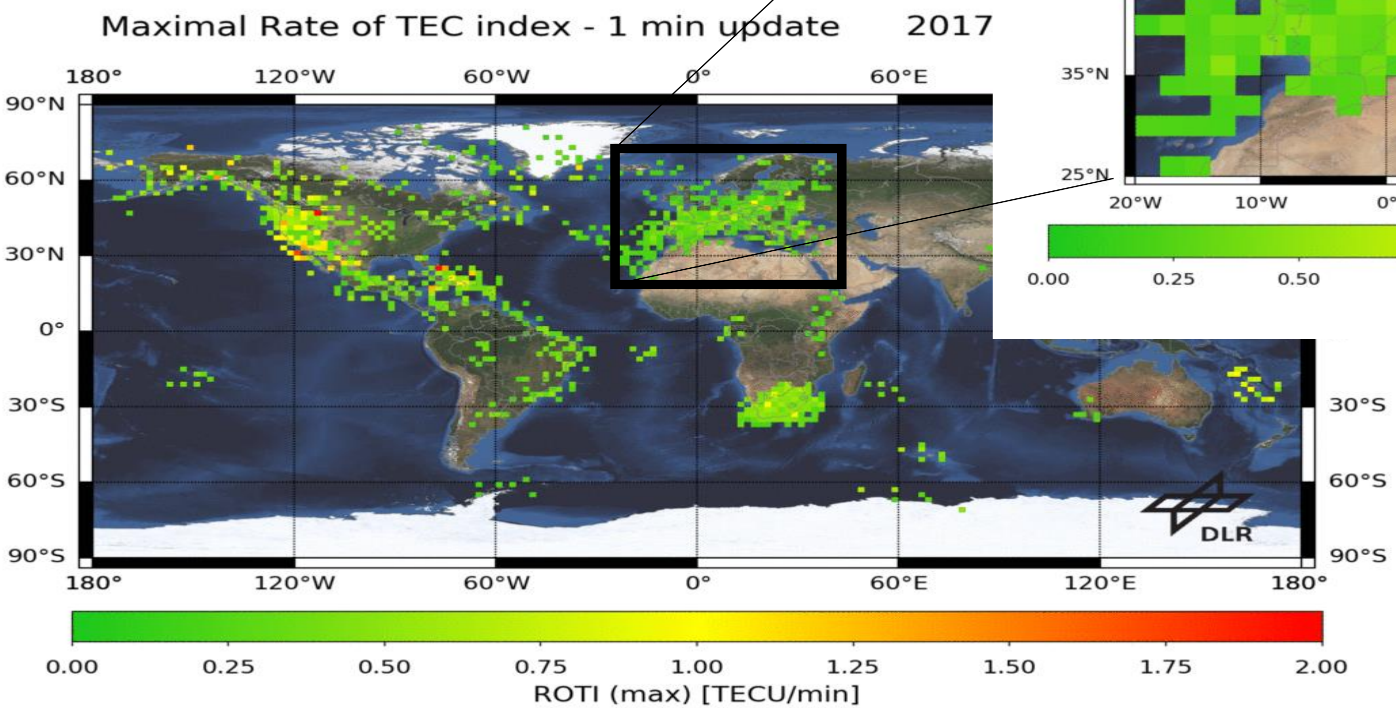
- Global coverage
- Good vertical resolution

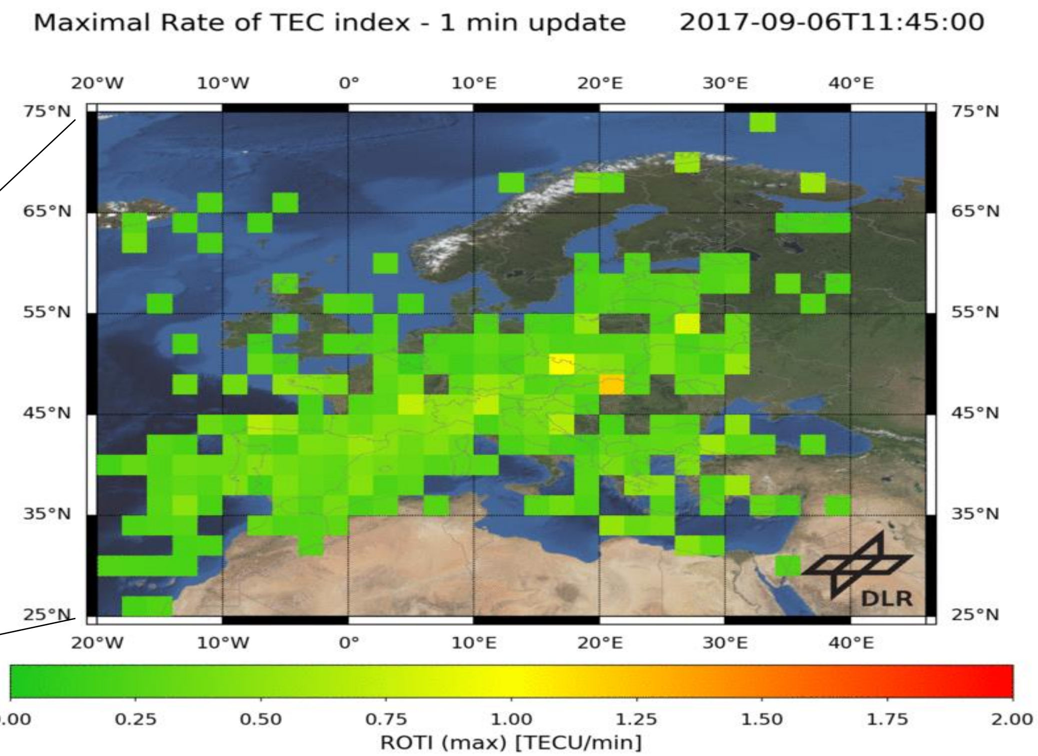
- Near real time capability depends on data download
- High spatial resolution depends on number of satellites

Space Weather Impact on GNSS – Solar Flare

Space Weather Event 06/09/2017 (Solar Flare X9.3, Ranking 14)



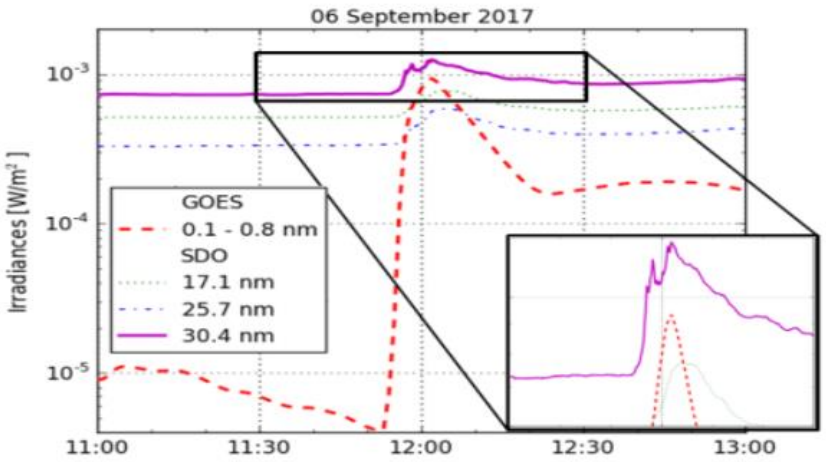




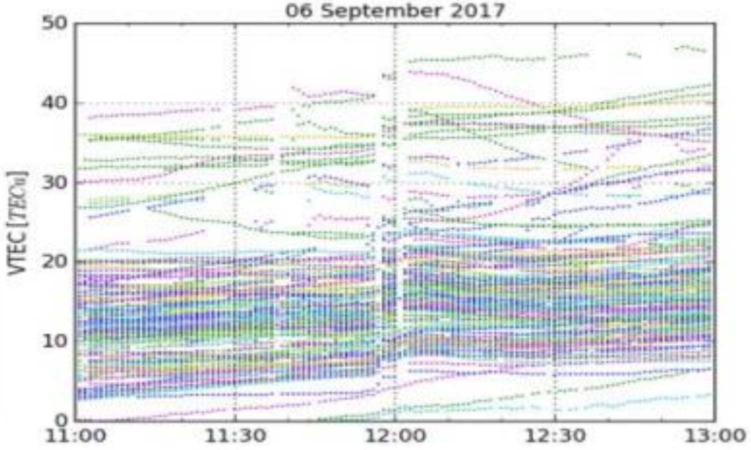
DLR Real Time ROTI in one minute Resolution at impc.dlr.de .

Space Weather Impact on GNSS – Solar Flare

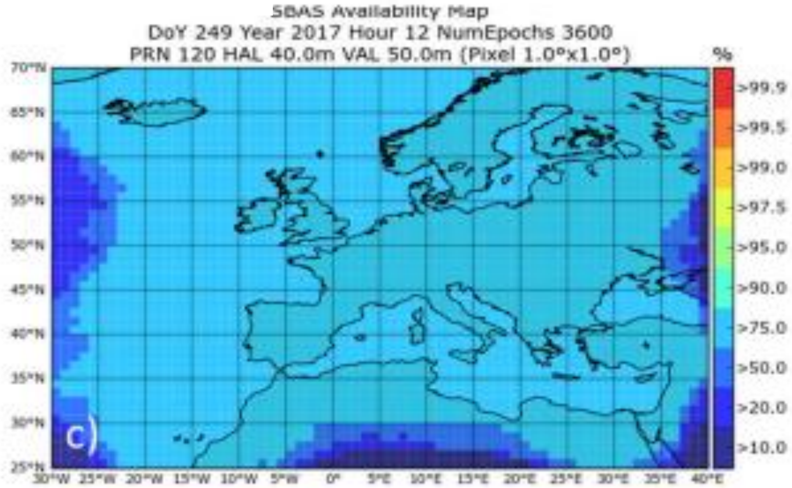
Source: X9.3 Solar Flare on 6th September 2017
Region: Earth Day Side
Duration: Minutes
Impact: Solar flares with a strong EUV component around 30 nm can seriousl affect GNSS positioning services used in e.g. aviation , maritime navigation. Al the GNSS satellite systems in view were affected in a similar way, including GPS, GLONASS and Galileo.



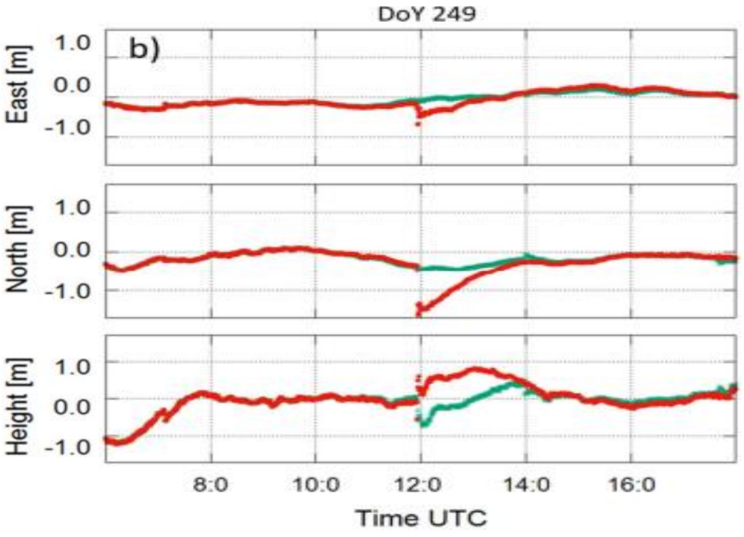
Loss of Lock



EGNOS



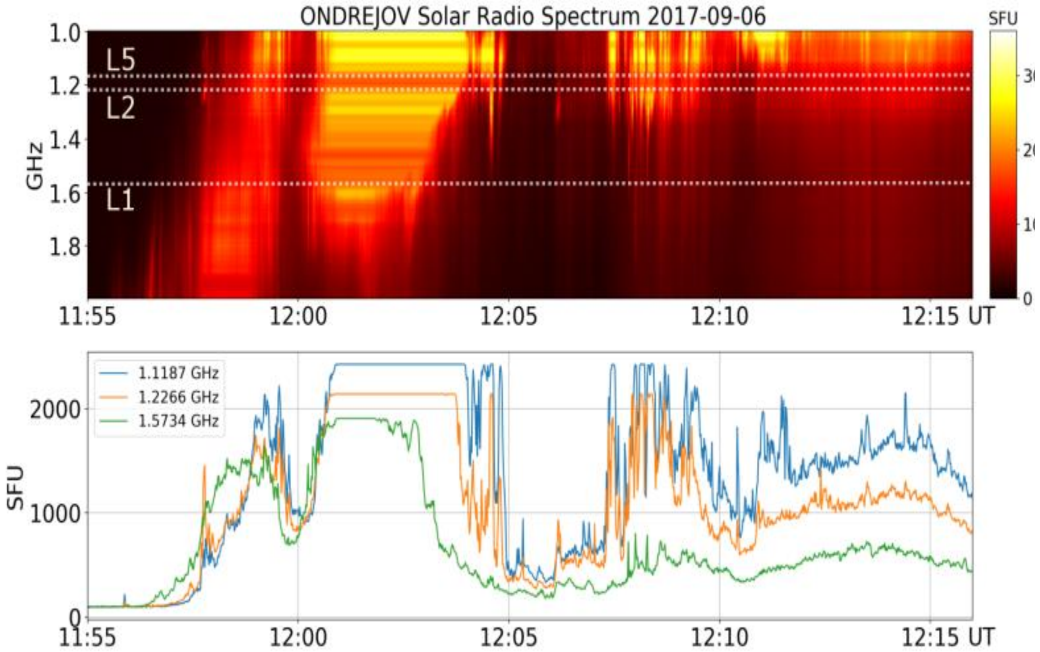
Precise Point Positioning



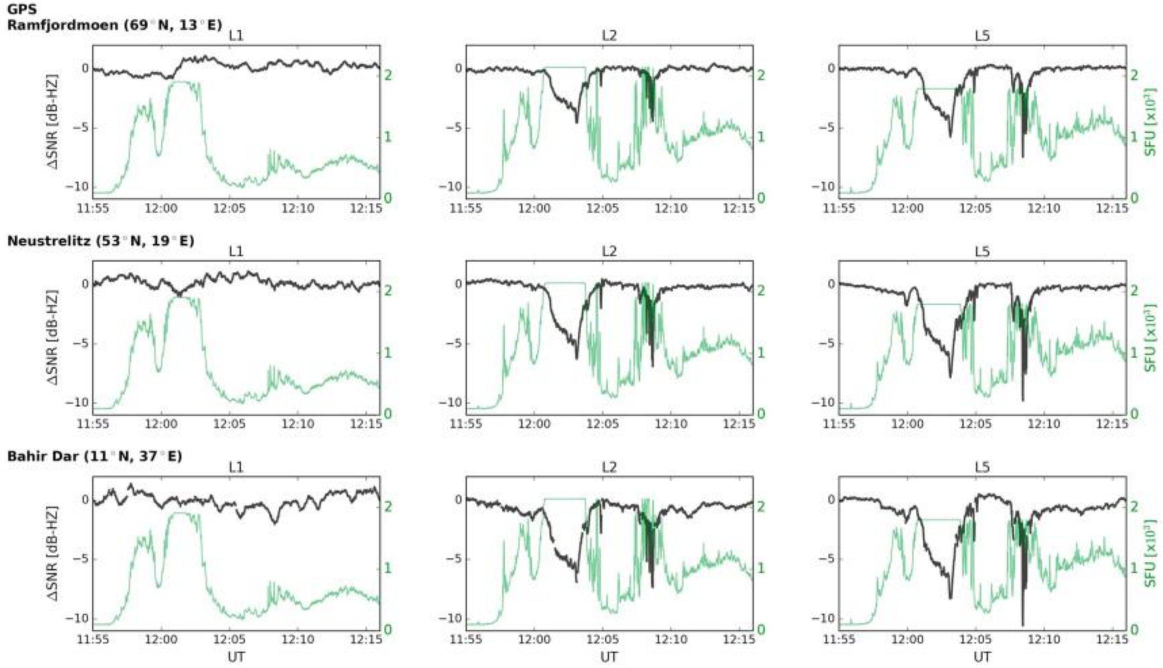
Berdermann, J., Kriegel, M., Banys, D., Heymann, F., Hoque, M. M., Wilken, V., et al. (2018). ***Ionospheric response to the X9.3 Flare on 6 September 2017 and its implication for navigation services over Europe****. Space Weather, 16. https://doi.org/10.1029/2018SW001933*

Space Weather Impact on GNSS – Radio Burst

Solar radio observation on the 6 September 2017



Ondrejov solar radio spectrum in the 1.0- to 2.0-GHz range (top) and flux intensity near the GPS frequencies (bottom).



Signal to noise ratio for different GPS frequencies at high, mid and low latitudes.

Source: Solar Radio Burst on 6th September 2017

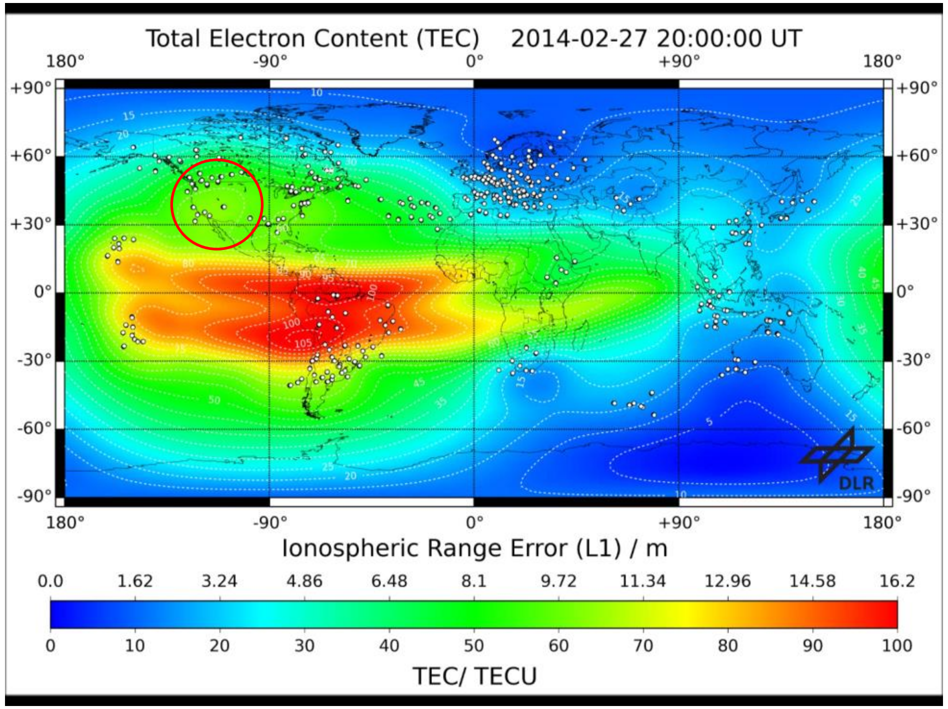
Region: Earth Day Side

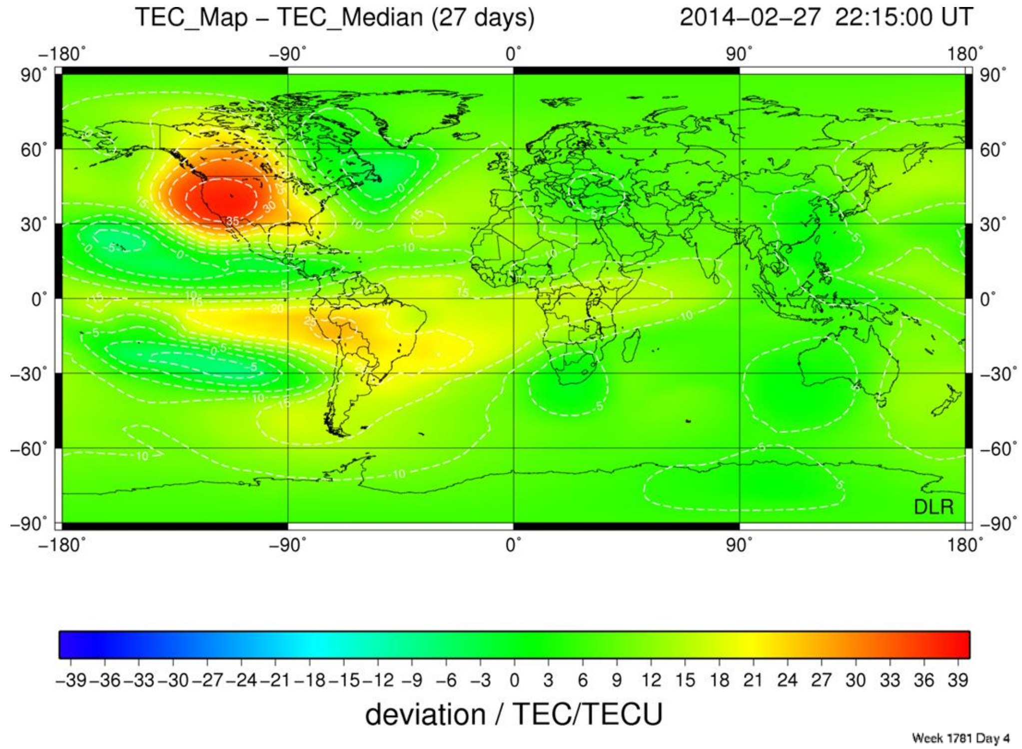
Duration: Minutes

Impact: The solar radio pulsation caused larger SNR reduction for GPS L2/L5 and GALILEO L5 frequencies. All the GNSS satellite systems in view were affected in a similar way, including GPS, GLONASS and Galileo.

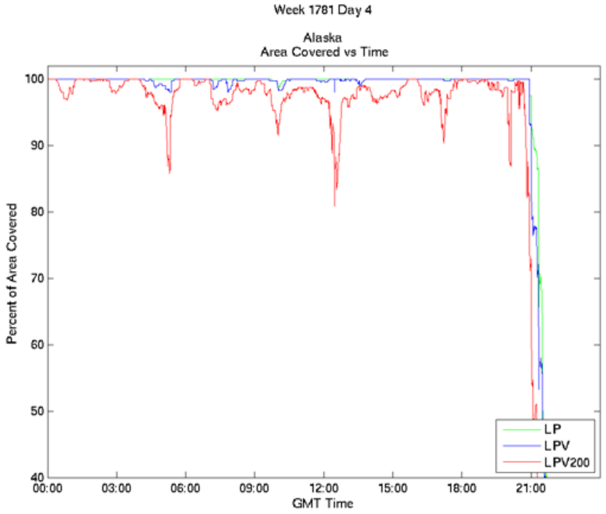
Sato, H. , Jakowski, N. , Berdermann , J. , Jiricka, K., Heßelbarth, A. , Banyś, D. , Wilken V. (2018), ***Solar Radio Burst Events on 6 September 2017 and Its Impact on GNSS Signal Frequencies****. Space Weather, 16. https://doi.org/10.1029/2018SW001933*

Space Weather Impact on GNSS – Ionospheric Storm



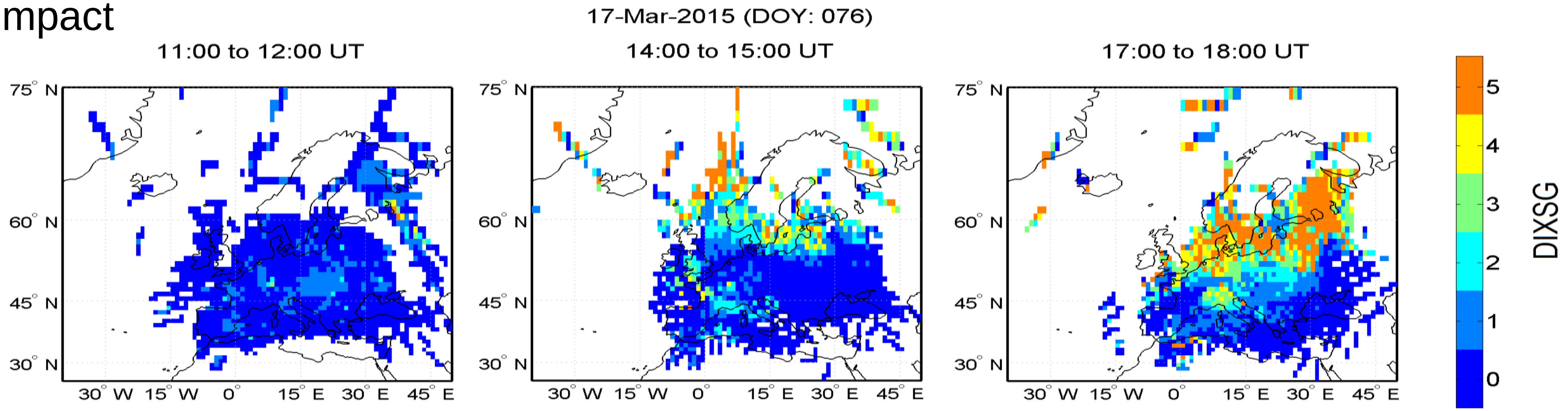


Source: Ionospheric storm on 27.02.2014
Region: North America
Duration: ca. 3h
Impact: Outages of SBAS due to storm induced Ionospheric Disturbances
No LPV availability of WAAS over Alaska on 27th February 2014.
(**L**ocalizer **P**erformance with **V**ertical Guidance)



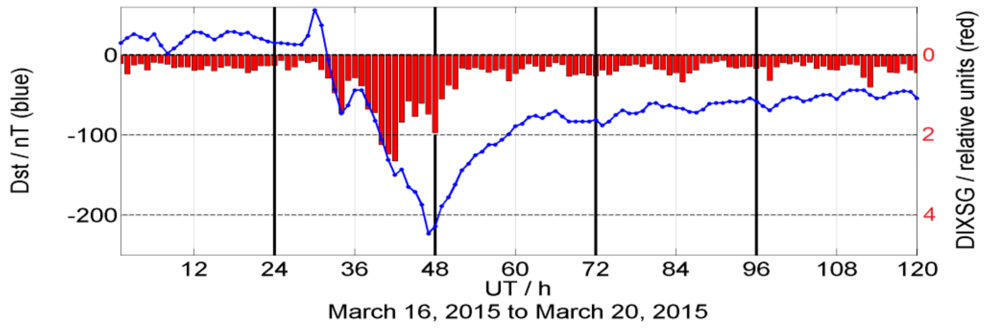
Characterization and Prediction of Ionospheric Disturbances

Disturbance Ionosphere Index Spatial Gradient (DIXSG) as a measure for ionospheric storm impact



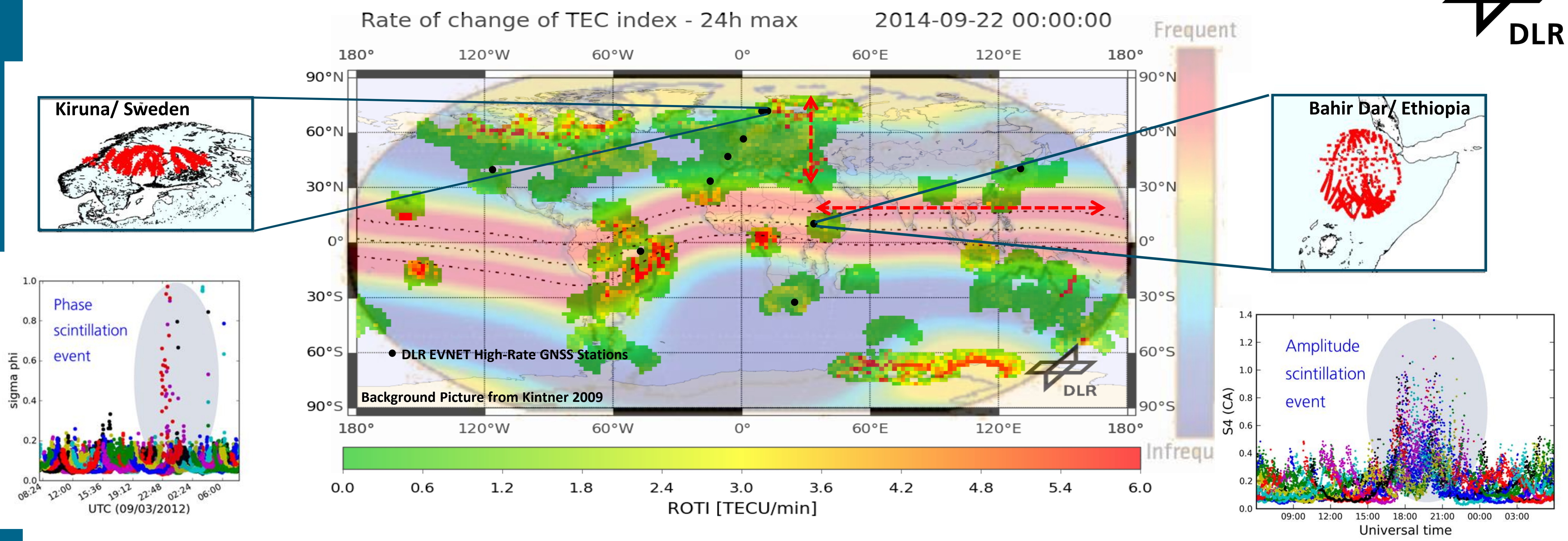
Ionospheric storm on the 17th March 2015 „St. Patrick Day Storm“

Important to develop methods and indices providing direct information on the performance of precise and safety-critical GNSS applications.



Wilken, V., Kriegel, M., Jakowski, N., Berdermann, J. , (2018), ***An ionospheric index suitable for estimating the degree of ionospheric perturbations,*** *Space Weather Space Clim. 8 A19 (2018) DOI: 10.1051/swsc/2018008*

Space Weather Impact on GNSS – Small scale irregularities

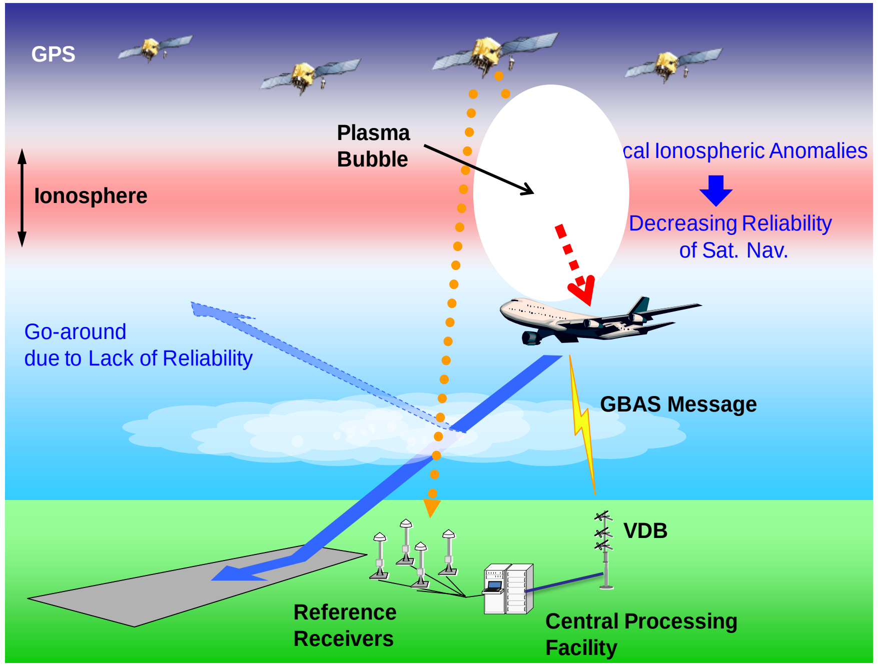


Polar Region:
Source: Geomagnetic Storms (Polar Region)
Impact: GNSS Signal is disturbed by gradients and may be lost in severe case.

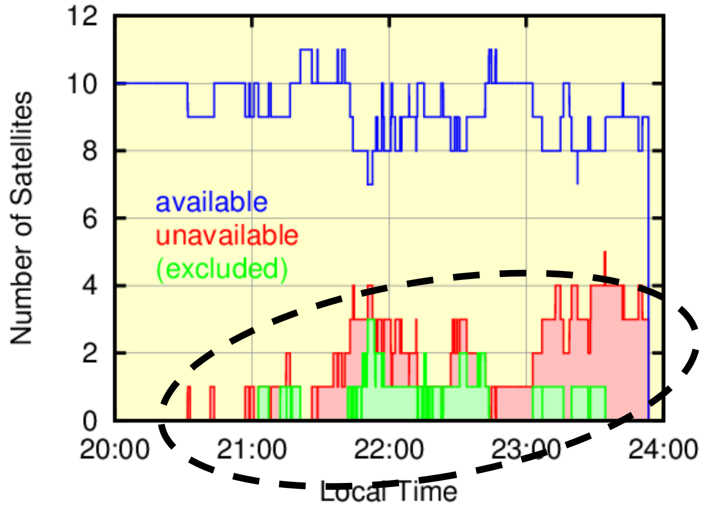
Equatorial Region:
Source: Flow inversion of the equatorial plasma during evening hours
Impact: GNSS Signal is disturbed by ionospheric irregularities (plasma bubble) and may be lost in severe case. Amplitude scintillation can cause stripes on L-band SAR images. Scintillation cause loss of spatial resolution.

Space Weather Impact on GNSS – Small scale irregularities

Plasma Bubble degrades availability of GNSS Precision Approach

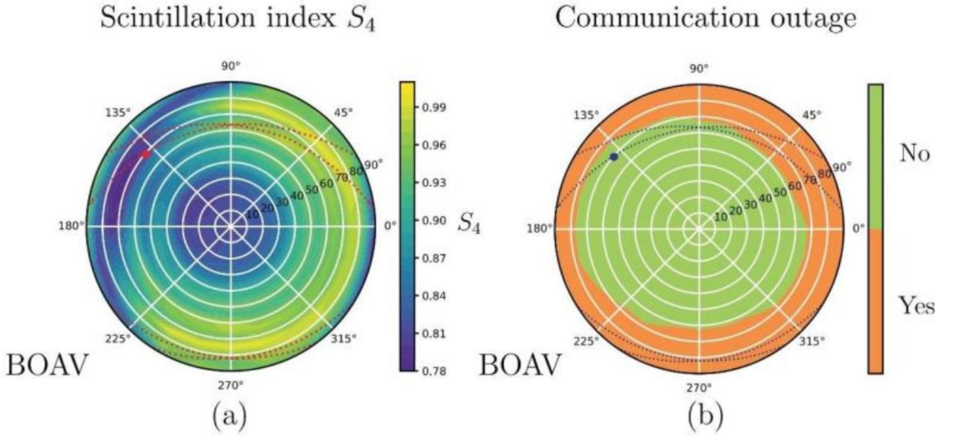


GNSS Signal is disturbed by ionospheric irregularities (plasma bubble) and may be lost in severe case.



Two divergent Information can cause hazardous misleading situations.

Scintillation effects on UHF satellite communication systems



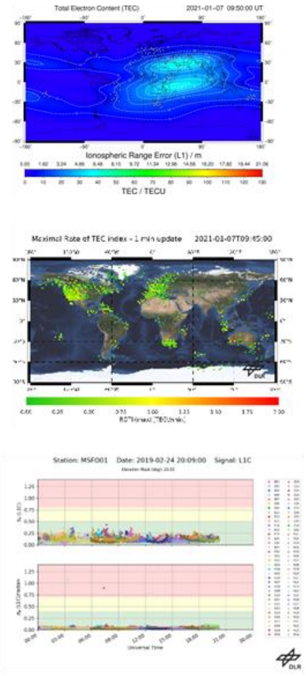
Risk of communication outage due to scintillation.

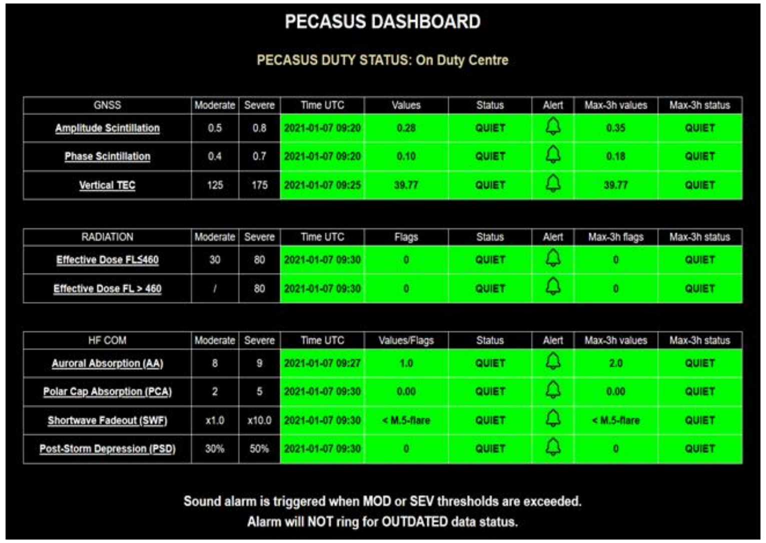
PECASUS for ICAO

The PECASUS consortium is one of the four global centers providing space weather advisories according to ICAO regulations.

SCAN ME

Continuous NRT delivery of GNSS related space weather data and scientific support in case of events





PECASUS DASHBOARD

PECASUS DUTY STATUS: On Duty Centre

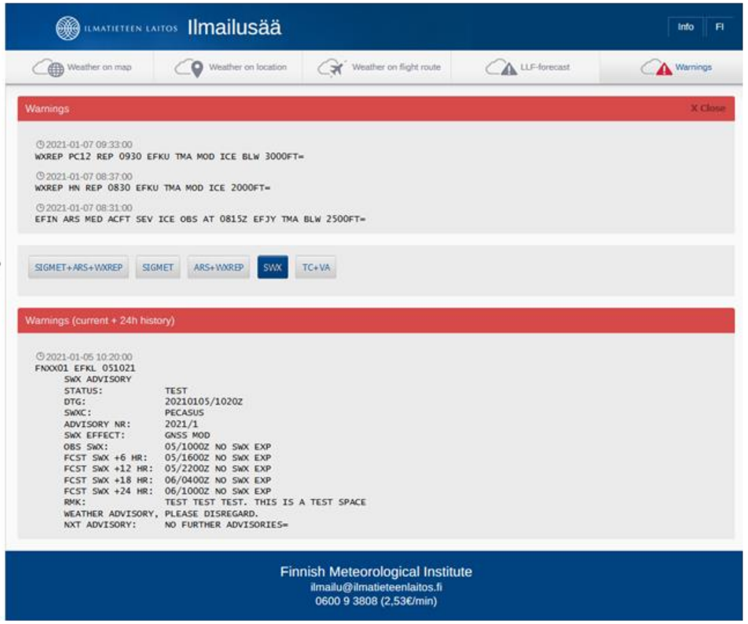
GNSS	Moderate	Severe	Time UTC	Values	Status	Alert	Max-3h values	Max-3h status
Amplitude Scintillation	0.5	0.8	2021-01-07 09:20	0.28	QUIET		0.35	QUIET
Phase Scintillation	0.4	0.7	2021-01-07 09:20	0.10	QUIET		0.18	QUIET
Vertical TEC	125	175	2021-01-07 09:25	39.77	QUIET		39.77	QUIET

RADIATION	Moderate	Severe	Time UTC	Flags	Status	Alert	Max-3h flags	Max-3h status
Effective Dose FL≤460	30	80	2021-01-07 09:30	0	QUIET		0	QUIET
Effective Dose FL > 460	/	80	2021-01-07 09:30	0	QUIET		0	QUIET

HF COM	Moderate	Severe	Time UTC	Values/Flags	Status	Alert	Max-3h values	Max-3h status
Auroral Absorption (AA)	8	9	2021-01-07 09:27	1.0	QUIET		2.0	QUIET
Polar Cap Absorption (PCA)	2	5	2021-01-07 09:30	0.00	QUIET		0.00	QUIET
Shortwave Fadeout (SWF)	x1.0	x10.0	2021-01-07 09:30	< M.5-flare	QUIET		< M.5-flare	QUIET
Post-Storm Depression (PSD)	30%	50%	2021-01-07 09:30	0	QUIET		0	QUIET

Sound alarm is triggered when MOD or SEV thresholds are exceeded.
Alarm will NOT ring for OUTDATED data status.

ICAO Space Weather Advisories



ILMATIETEEN LAITOS Ilmailusää

Info | FI

Weather on map | Weather on location | Weather on flight route | LLF-forecast | Warnings

Warnings — X Close

2021-01-07 09:33:00
WXREP PC12 REP 0930 EFKU TMA MOD ICE BLW 3000FT=

2021-01-07 08:37:00
WXREP HN REP 0830 EFKU TMA MOD ICE 2000FT=

2021-01-07 08:31:00
EFIN ARS MED ACFT SEV ICE OBS AT 0815Z EFJY TMA BLW 2500FT=

SIGMET+ARS+WXREP | SIGMET | ARS+WXREP | SWX | TC+VA

Warnings (current + 24h history)

2021-01-05 10:20:00

```
FNXX01 EFKL 051021
     SWX ADVISORY
     STATUS:           TEST
     DTG:              20210105/1020Z
     SWXC:             PECASUS
     ADVISORY NR:      2021/1
     SWX EFFECT:       GNSS MOD
     OBS SWX:          05/1000Z NO SWX EXP
     FCST SWX +6 HR:   05/1600Z NO SWX EXP
     FCST SWX +12 HR:  05/2200Z NO SWX EXP
     FCST SWX +18 HR:  06/0400Z NO SWX EXP
     FCST SWX +24 HR:  06/1000Z NO SWX EXP
     RMK:              TEST TEST TEST. THIS IS A TEST SPACE
     WEATHER ADVISORY, PLEASE DISREGARD.
     NXT ADVISORY:     NO FURTHER ADVISORIES=
```

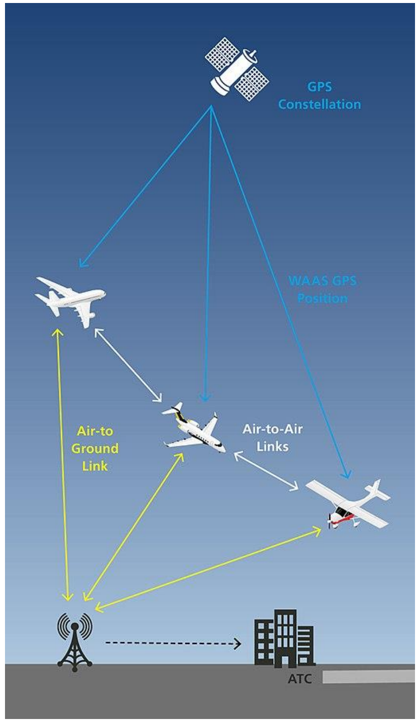
Finnish Meteorological Institute
ilmailu@ilmatieteenlaitos.fi
0600 9 3808 (2,53€/min)

Data Analysis, Event detection, Decision Making, Alerting

FMI — Finnish Meteorological Institute
Met Office — Met Office UK
DLR — The German Aerospace Center
KNMI — Royal Netherlands Meteorological Institute
STCE — The Solar-Terrestrial Centre of Excellence in Belgium
FU — Frederick University (Cyprus)
SRC — Space Research Center of the Polish Academy of Sciences
SL — The Seibersdorf Laboratories in Austria
INGV — Istituto Nazionale di Geofisica e Vulcanologia (Italy)
SANSA — South African National Space Agency

ADS-Messages

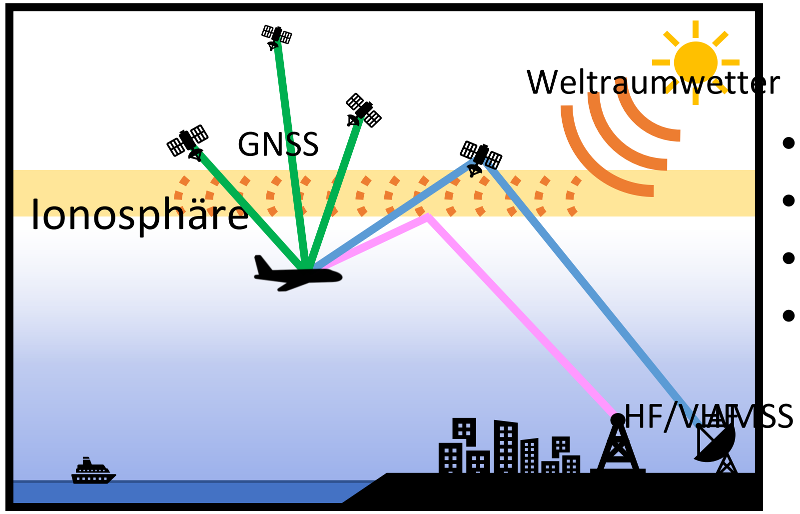
- **A**utomated **D**ependent **S**urveillance is a system to monitor and control flight routes
  - **A**ddressed (sent on request)
  - **B**roadcast (sent continuously)
  - **C**ontract (transmitted as part of a data link)
- Possible space weather impacts:
  - Data gaps due to signal loss (UHF, SATCOM)
  - Position errors (GNSS)



ADS-B

- Aircraft information
- Position information
- Speed information

Research perspective: High-rate and -resolution, global data set

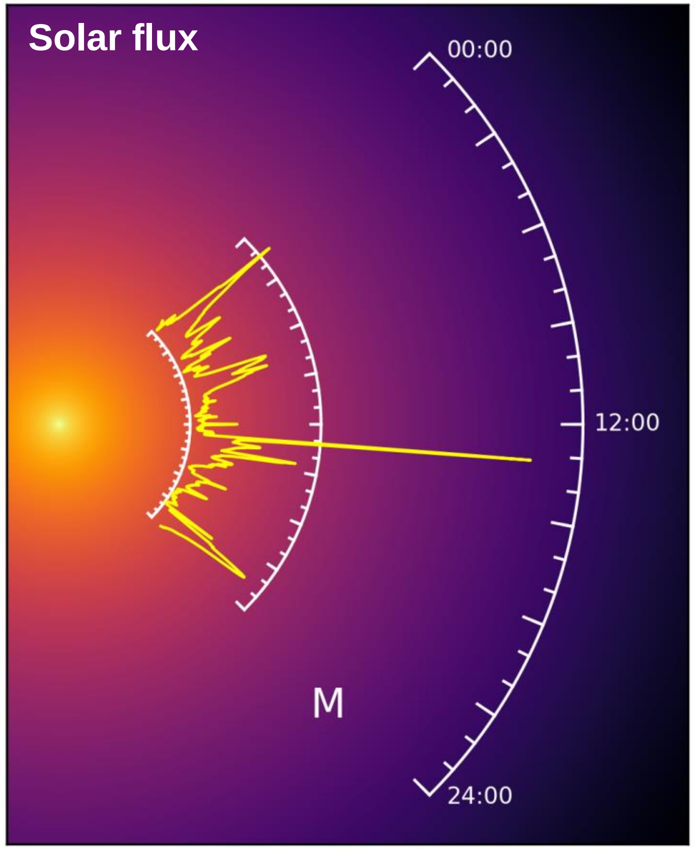


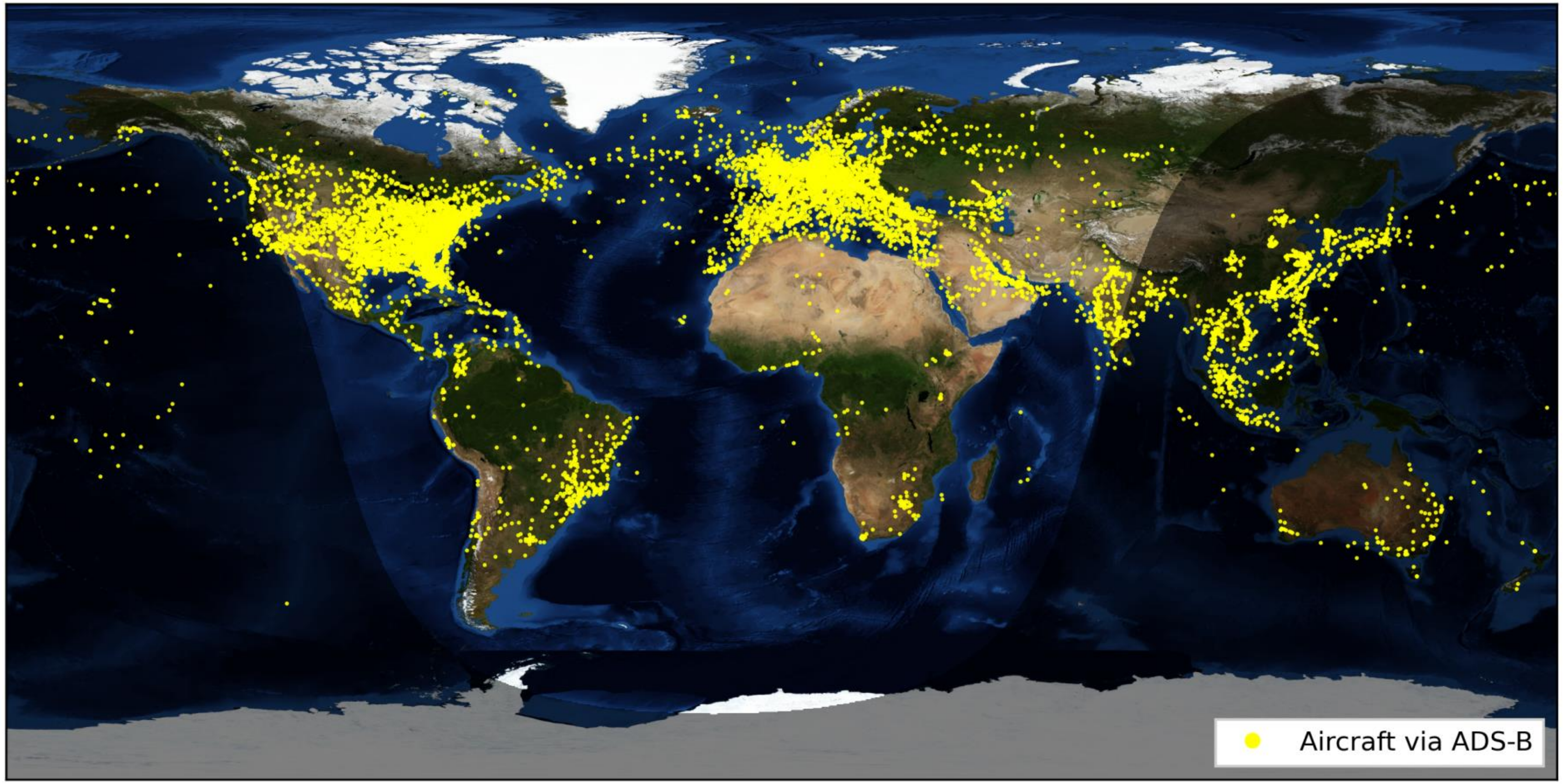
ADS-C

- Continuous data link
- Aircraft information
- Position information
- Navigation information

Space weather effects on ADS-B: Flare 1st May 2023

(Automatic Dependent Surveillance – Broadcast)

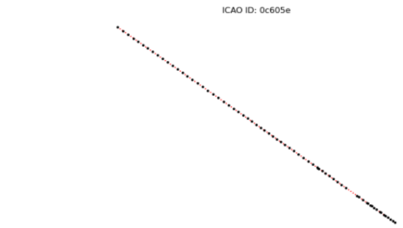




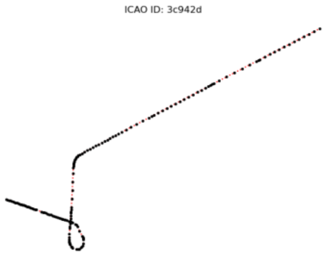
- Approx. 14000 aircraft recorded during M-class flare 1st May 2023 (13:02-13:09)
- Expected impacts: data gaps, position errors

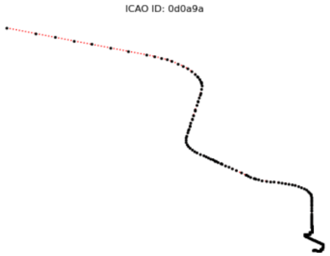
Examples – data appropriate for analysis?

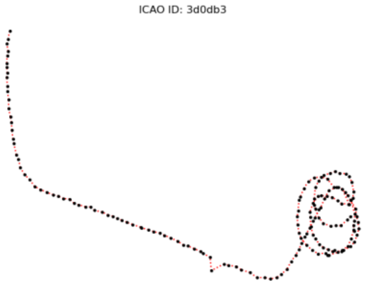
On route



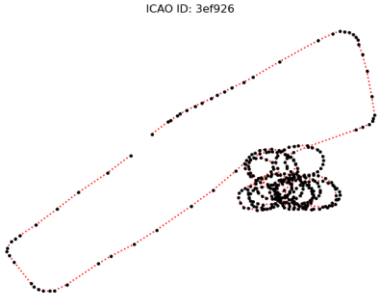
Takeoff and landing



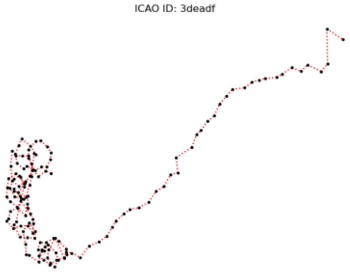




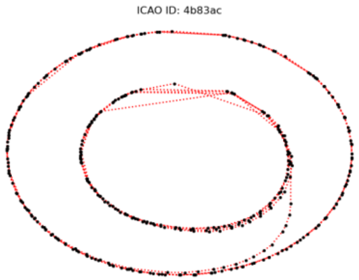
Type




Glider



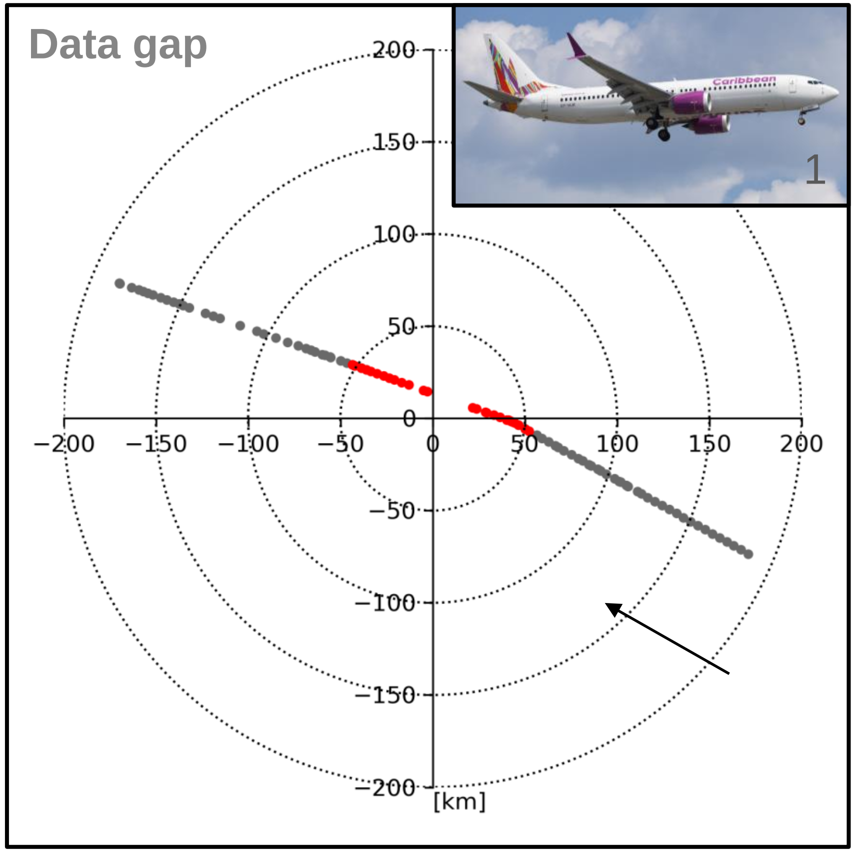

Helicopter

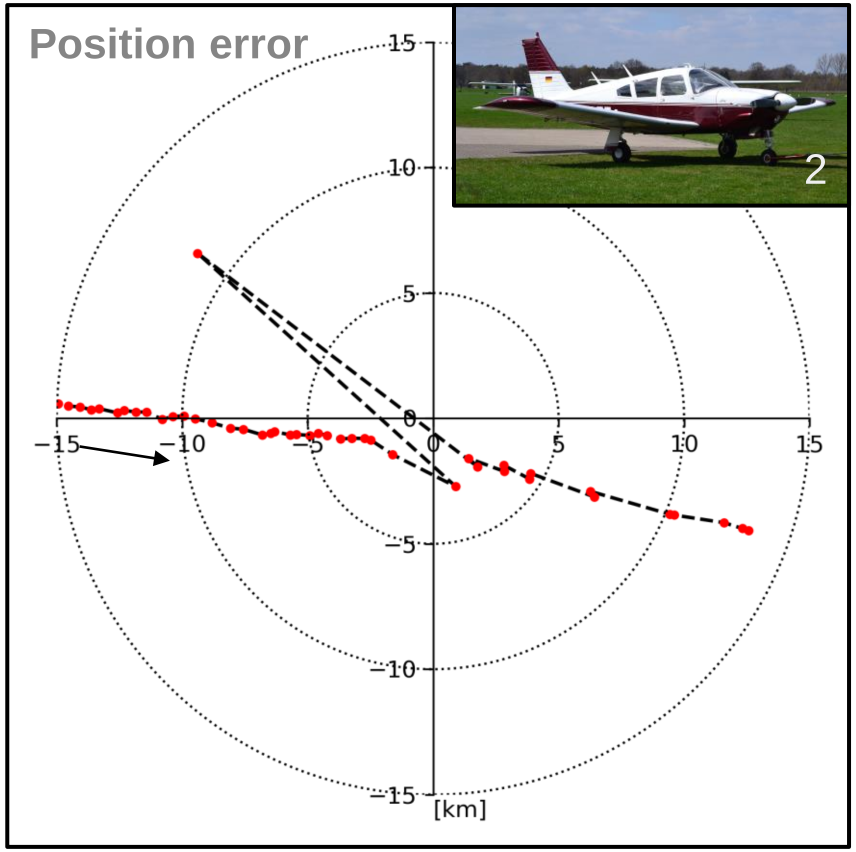



Drone

Space weather effects on ADS-B: Flare 1st May 2023

(Automatic Dependent Surveillance – Broadcast)

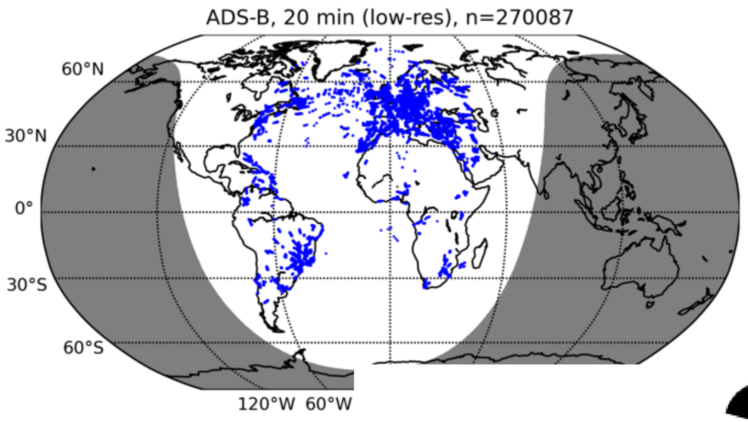




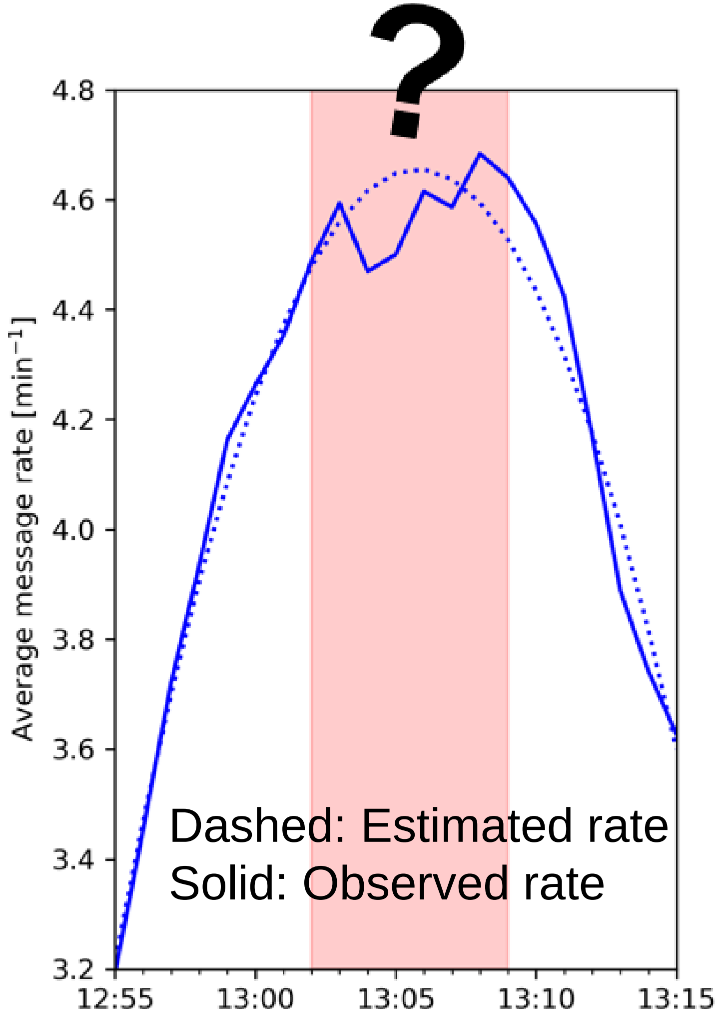
Red dots: ADS-B messages during flare (13:02-13:09)
Arrow: Flight direction

1 source: https://www.jetphotos.com/photo/11081148
2 source: https://commons.wikimedia.org/wiki/File:Piper_PA-28R-200_Cherokee_Arrow_%28D-EATT%29_02.jpg

Discussion ADS-B



- Position errors:
  - How to differentiate from other impacts?
  - How to detect smaller position errors successful during flares?
- Other Problems:
  - No messages over certain countries/regions
  - Different rates depending on type/source
- Open challenges:
  - Definition of position error
  - Definition of data gaps
  - Selection of impacted aircraft



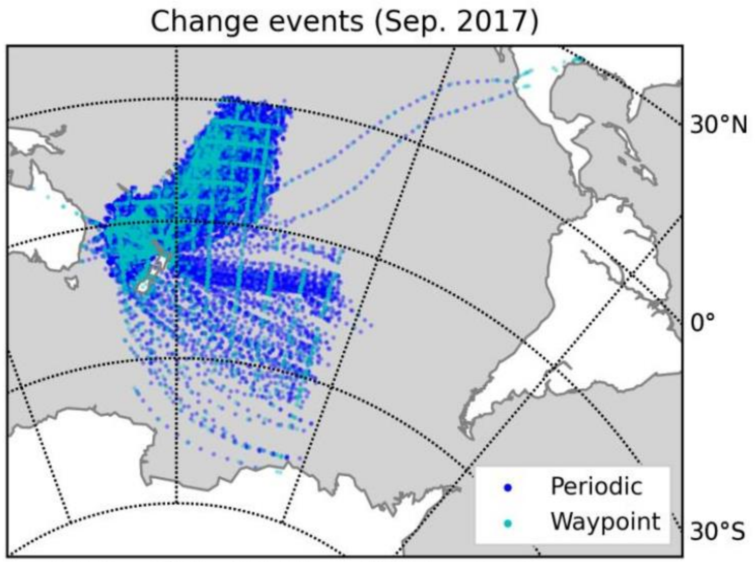
ADS-C messages: Events

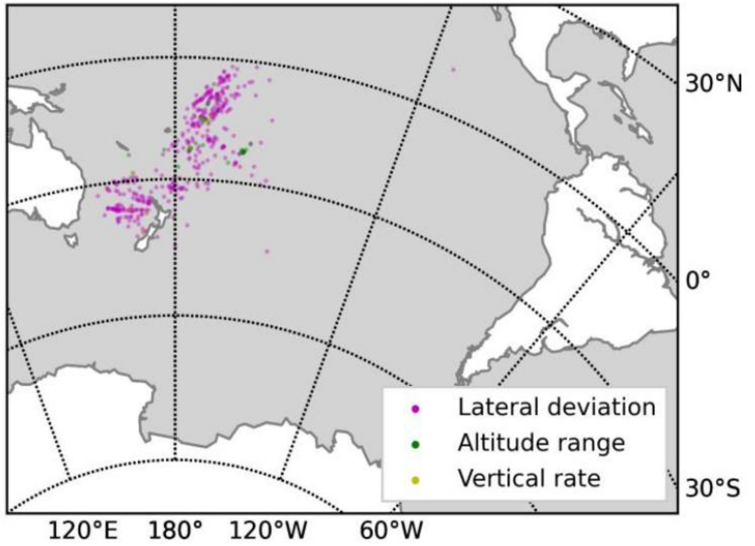
ADS-C data link is established between an air traffic service (ATS) unit and an aircraft in order to exchange standard information as well as contract-specific information.

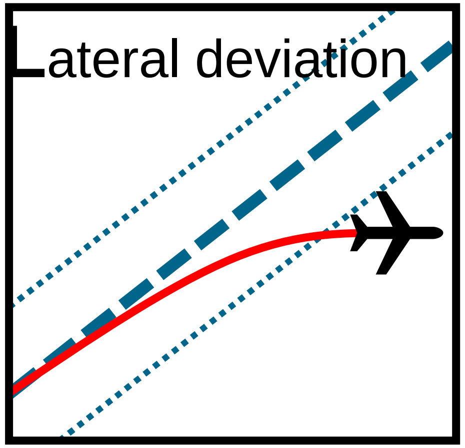
Analysis of ADS-C downlink reports for September 2017
(approx. 54000 messages)

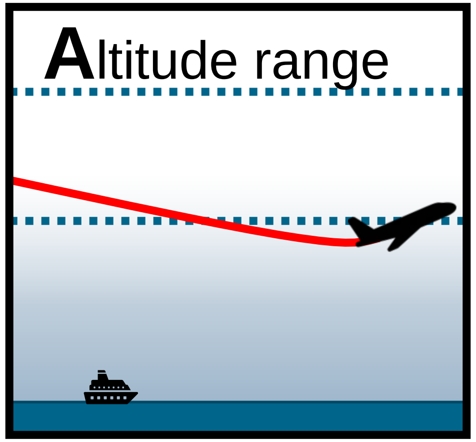
Regularly established contracts: Periodic
Waypoint

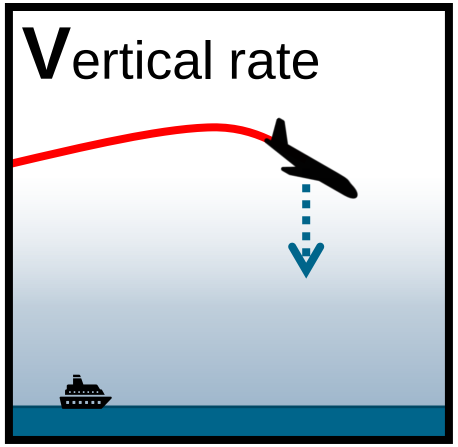
Irregularly established contracts: Lateral deviation event
Altitude range change event
Vertical rate change event



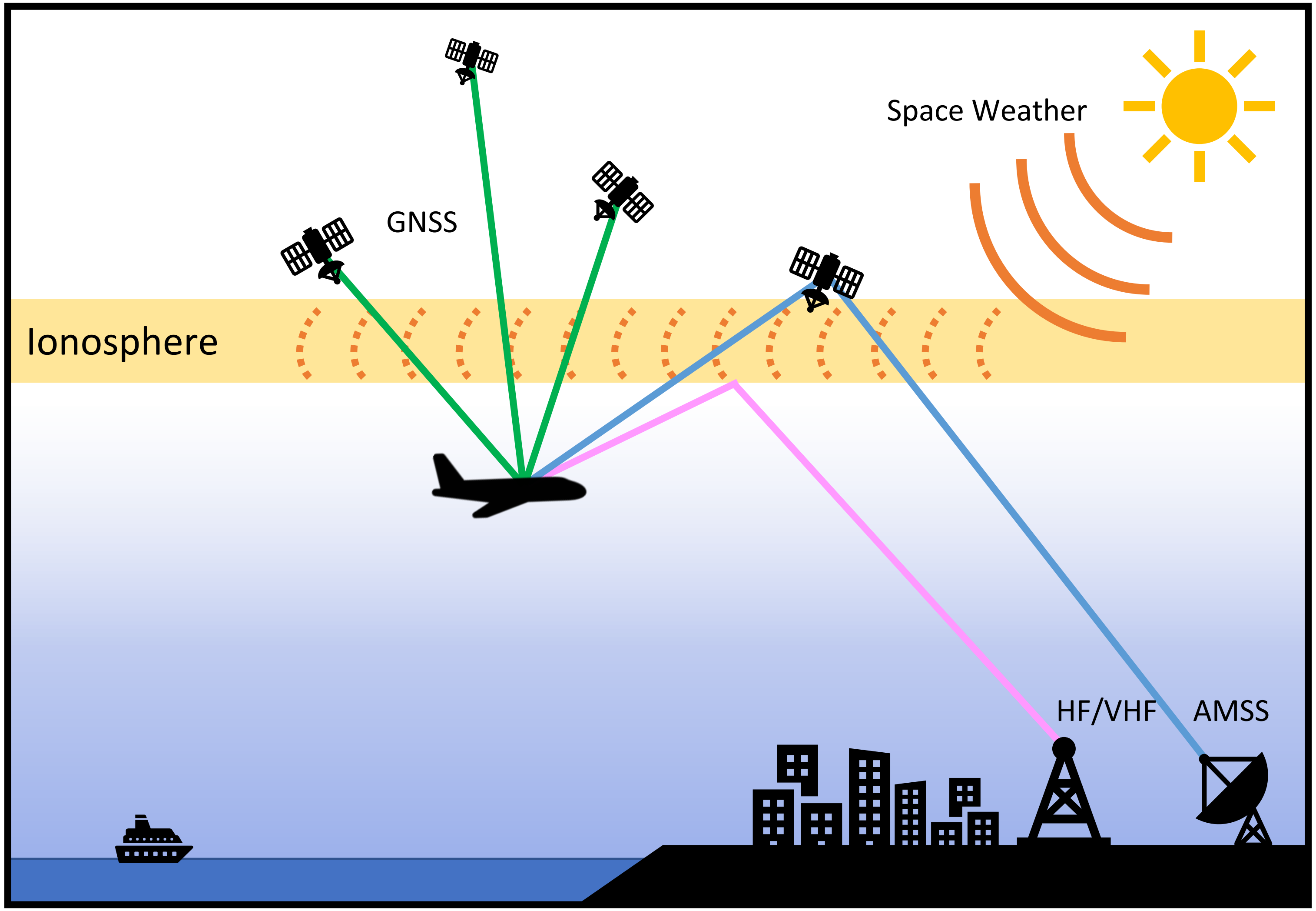








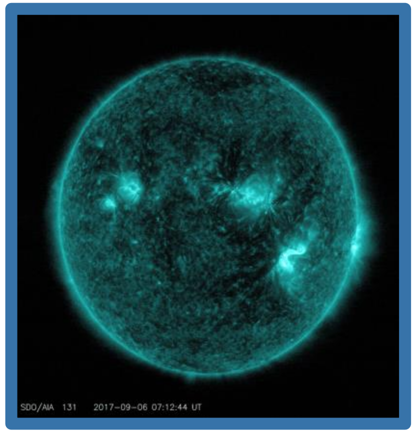
ADS-C-Messages: Context space weather?

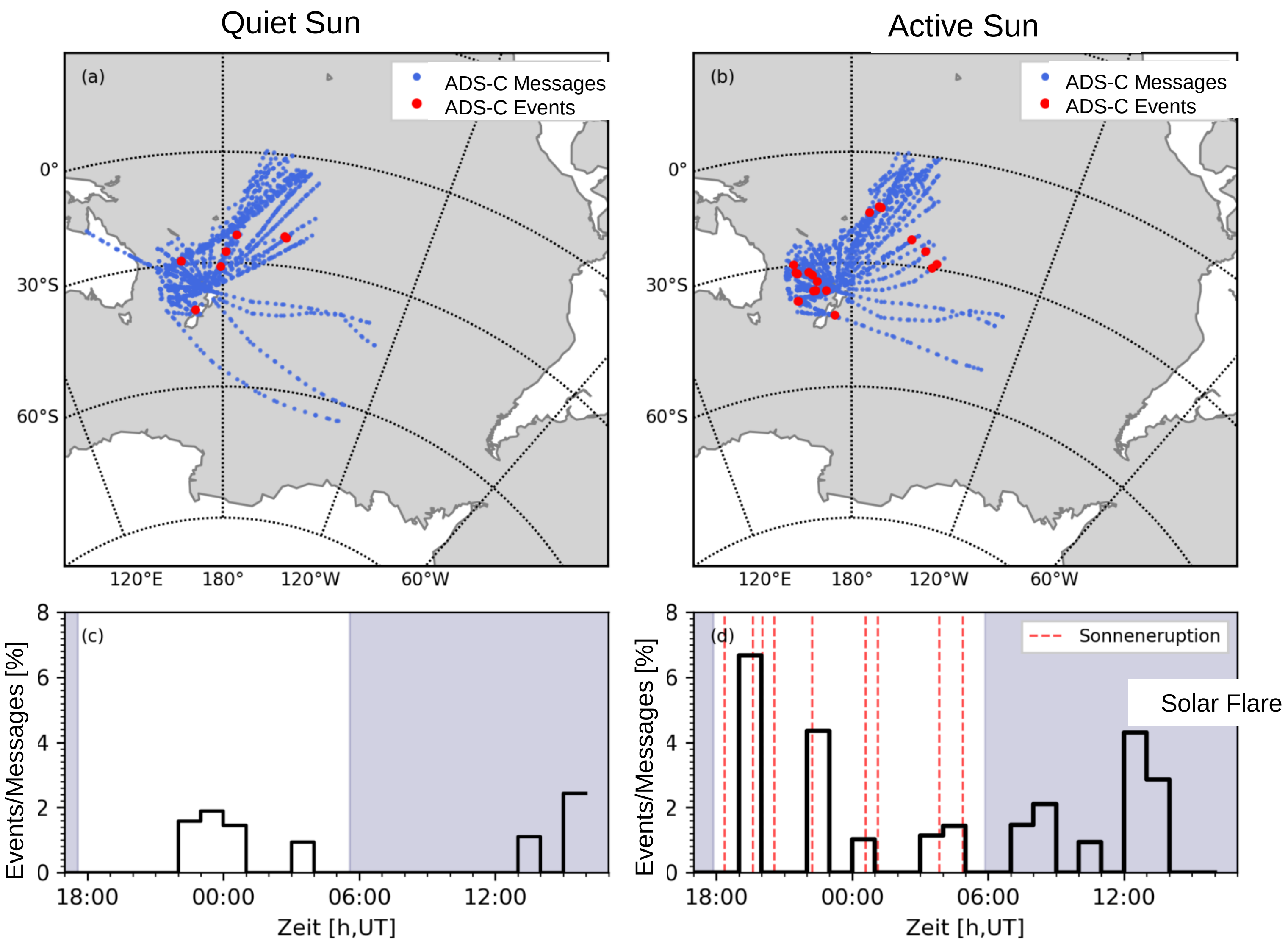


Space weather → Ionospheric storm → Navigation impairment → "Faulty" ADS-C events

Global **N**avigation **S**atellite **S**ystem
Aeronautical **M**obile-**S**atellite **S**ervice

ADS-C messages on different solar activity.

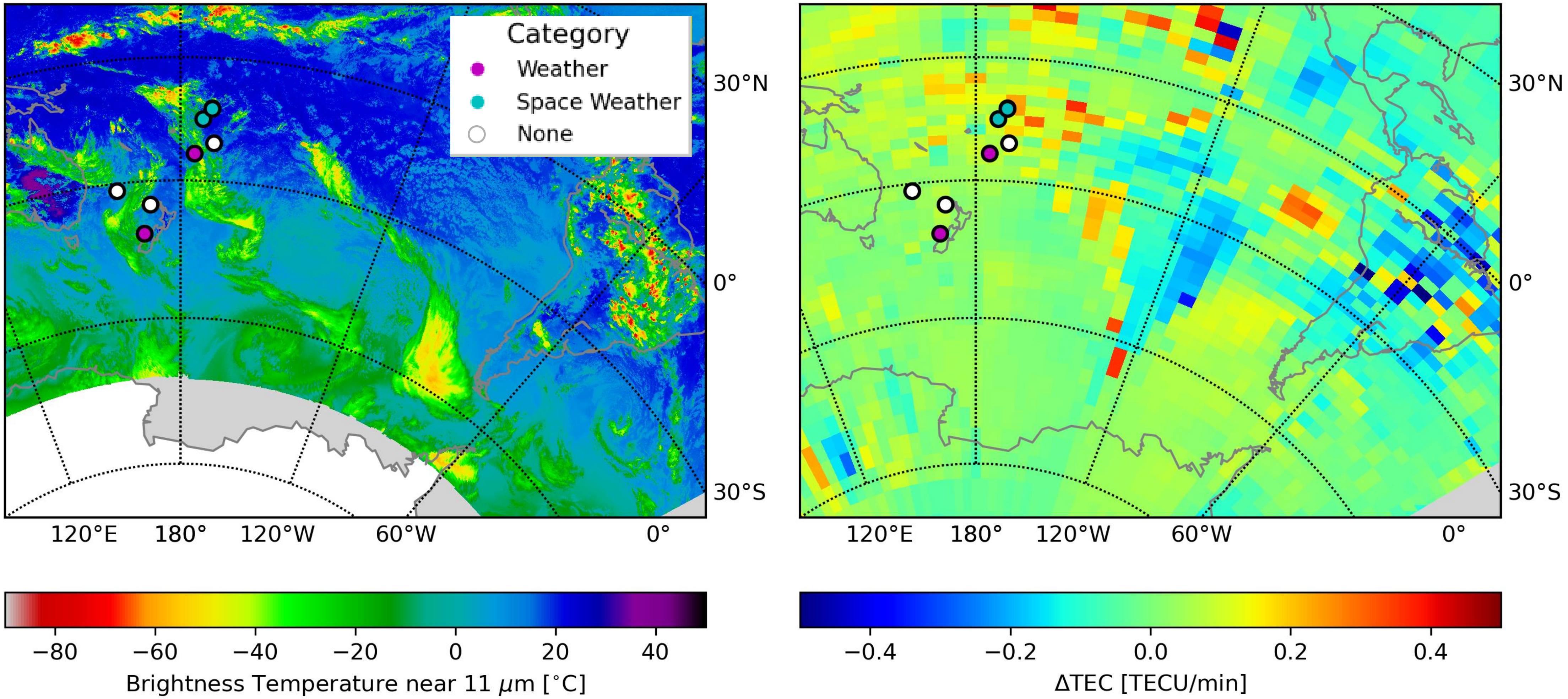




We thank the Airways Corporation of New Zealand and the FAA William J. Hughes Technical Center for making the ADS-C records available. We thank Klaus Sievers (Vereinigung Cockpit) for forwarding the datasets and providing feedback.

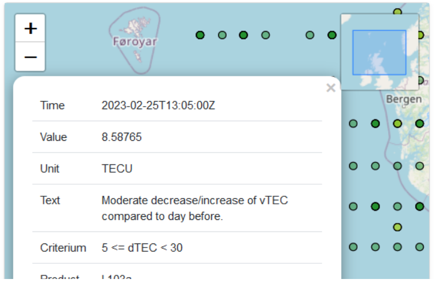
Recent Steps:

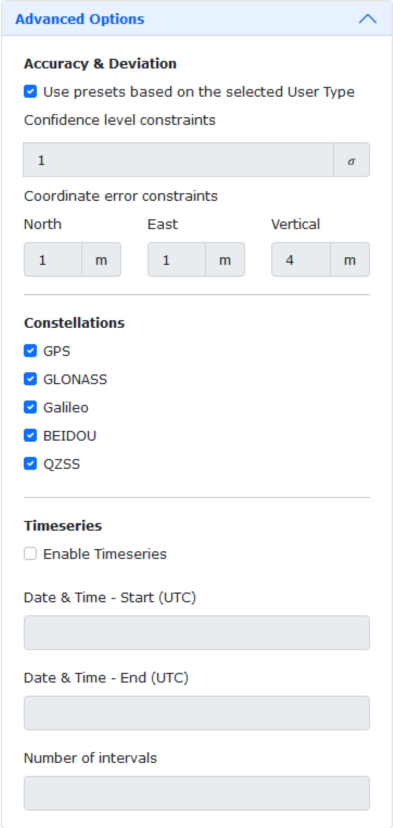
- To analyze the impact of weather and space weather
- Analyze more data sets if available

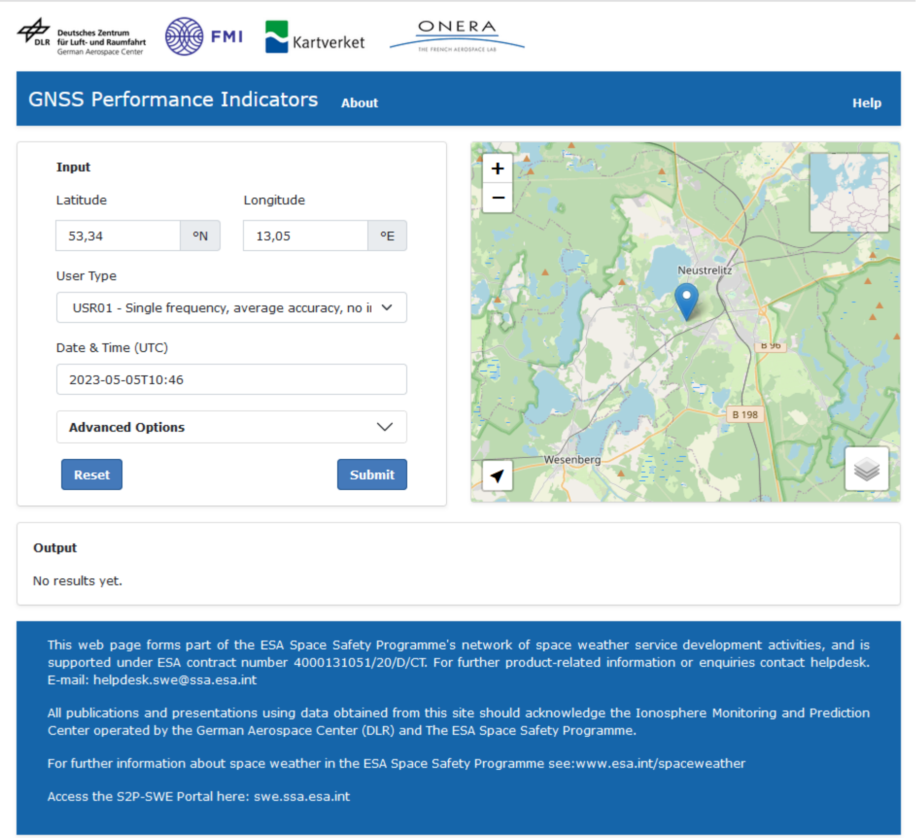


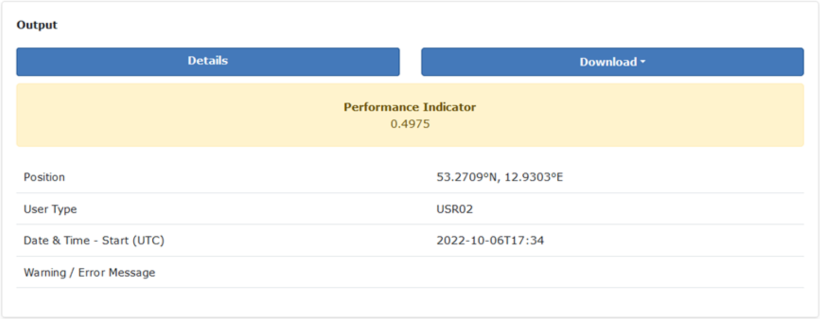
SWIGPAD (Space Weather Impact on GNSS Performance Application Development)

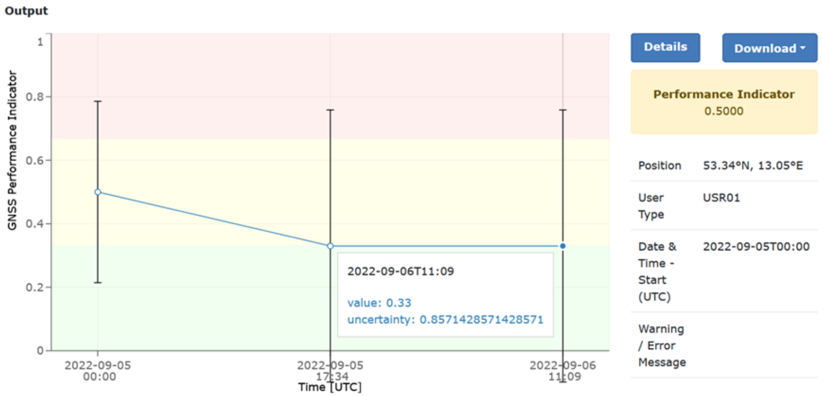
- A software application for evaluating the effects of space weather on GNSS positioning addressing 6 different user groups
- Based on data products of the ESA Ionospheric Weather Expert Center (ESA SW Portal)







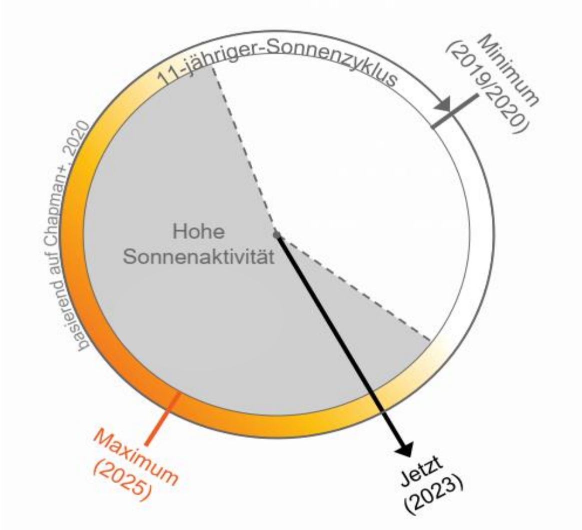


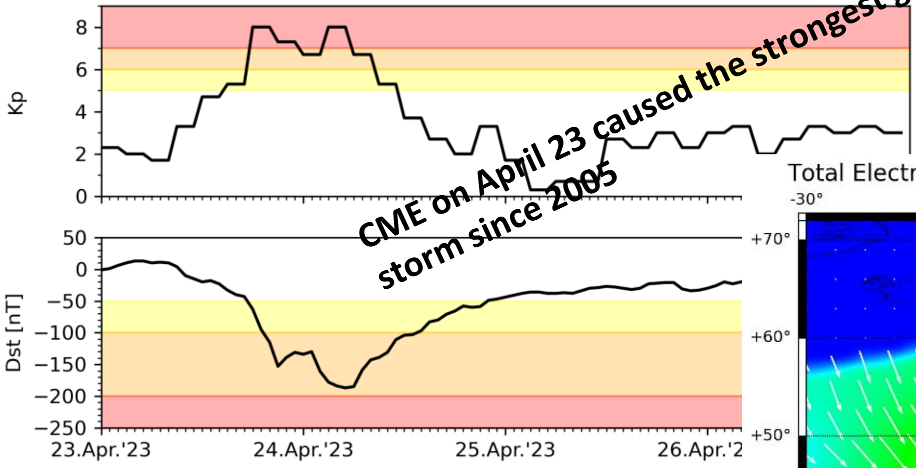


Work has been performed in the frame of ESA Space Safety Programme's network of Space Weather Service development and pre-operational activities, supported under ESA Contract 4000131051/20/D/CT.

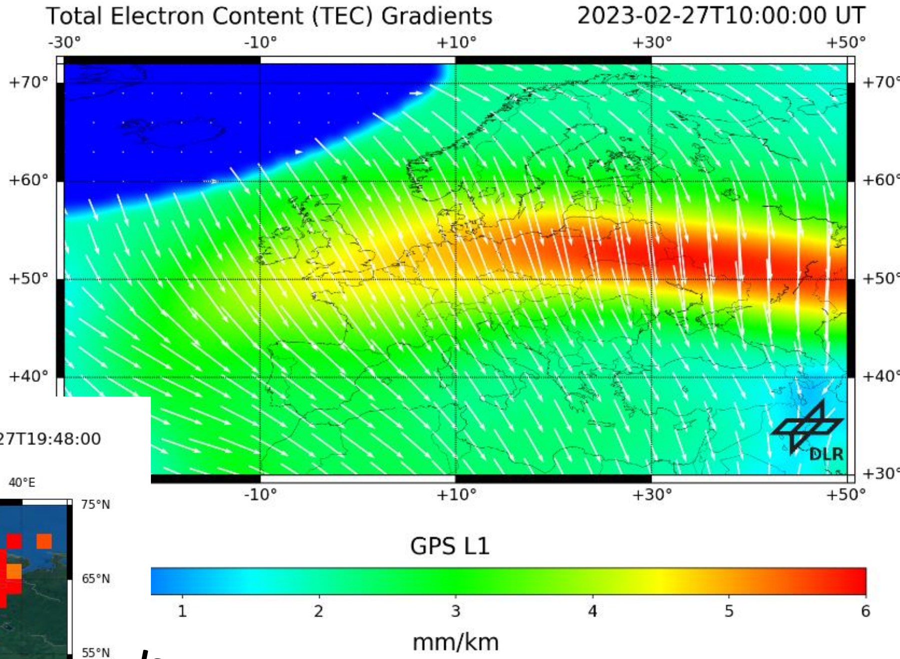
Current Space Weather situation is optimal for impact studies!

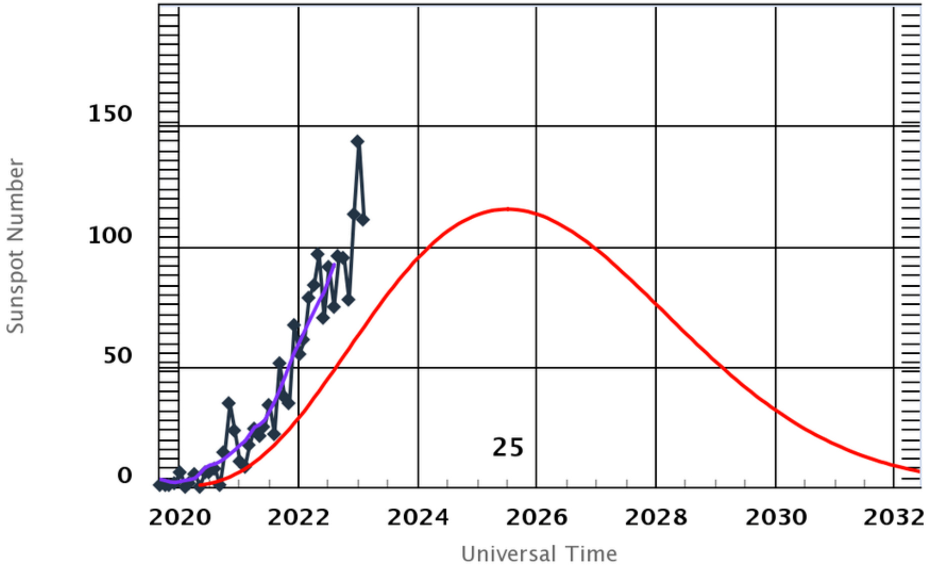
Multiple space weather events with moderate and severe geomagnetic storms impacting satellite navigation are expected on the upcoming path to solar maximum



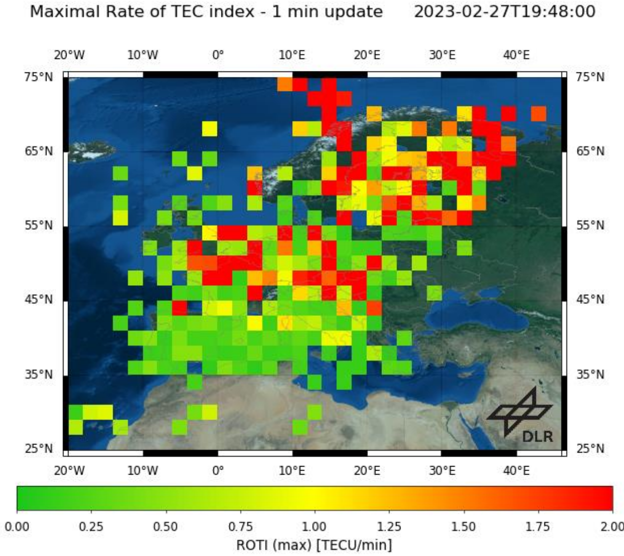


CME on April 23 caused the strongest geomagnetic storm since 2005



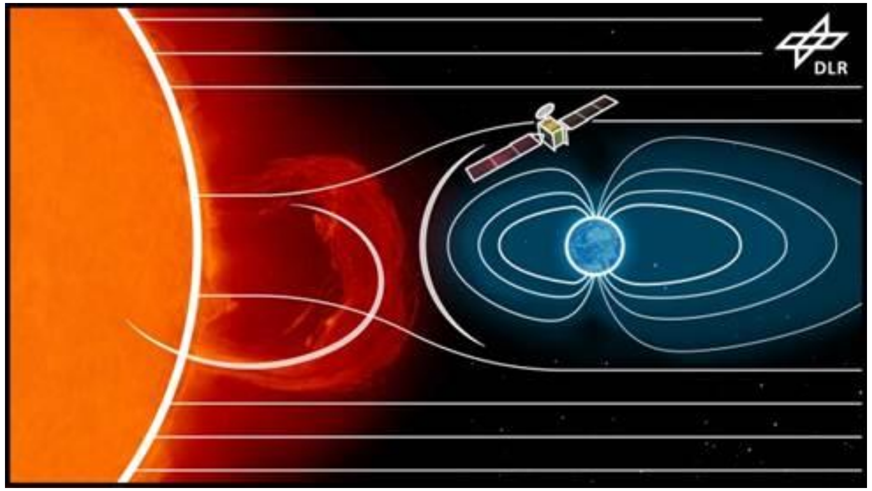


https://www.swpc.noaa.gov/products/solar-cycle-progression



Ionospheric storm based gradients and scintillation occurrence on February 27th.

Thank you!



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