Space weather services for civil aviation – PECASUS consortium

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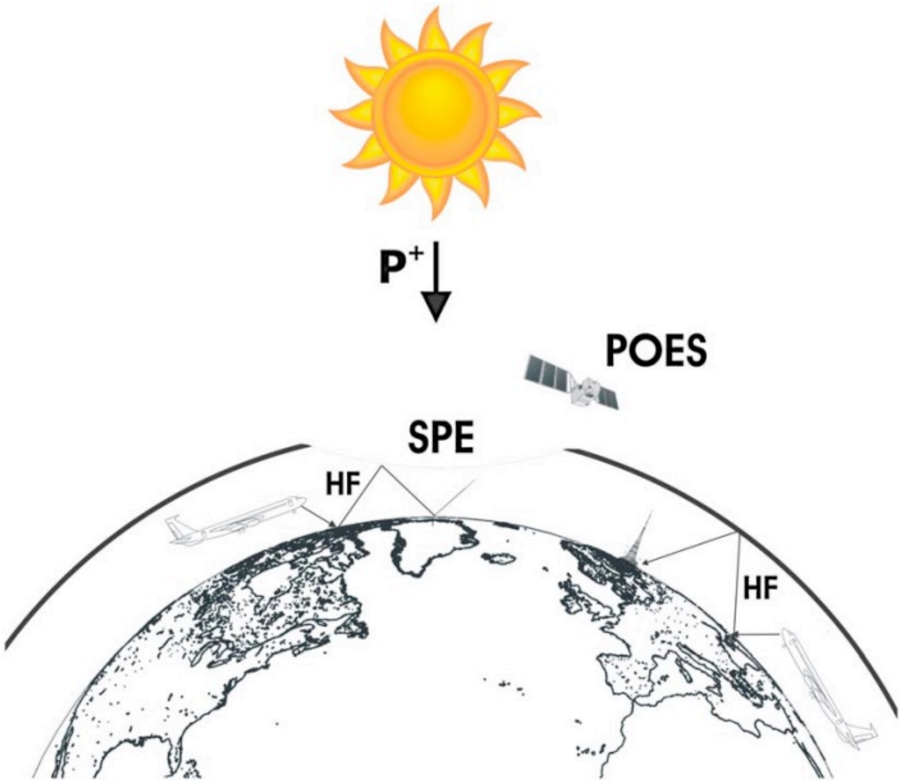
Contents

- Why space weather can be an issue in aviation?
- ICAO & its interests in space weather
- PECASUS partners and task division
- Lessons learnt

Aviation meets space weather – some events from history

January and March 2012 Solar Energetic Protons: HF Communication problems in polar flights

- Polar Air Traffic controllers:
  - *"limited reliable HF communications forced aircraft operators to use other communication methods,"*
  - *"at times, communications were impossible"*
- HF communication disruptions caused the air traffic control centers to increase the separation of the aircraft from 10 min to 15 min
- US Delta Air Lines: Routes from Hong Kong, Shanghai and Seoul took a more southerly route after the solar flare eruption



Reference: Neial et al., 2013

November 2015, solar radio burst: Problems in air traffic control radar

- Secondary Surveillance Radars (SSR) send coded queries to transponders aboard aircraft and get in return ancillary information on the plane:
  - identification,
  - barometric altitude of the aircraft
  - selected technical parameters.
- 1030 and 1090 MHz
- Ranges 370-460 km

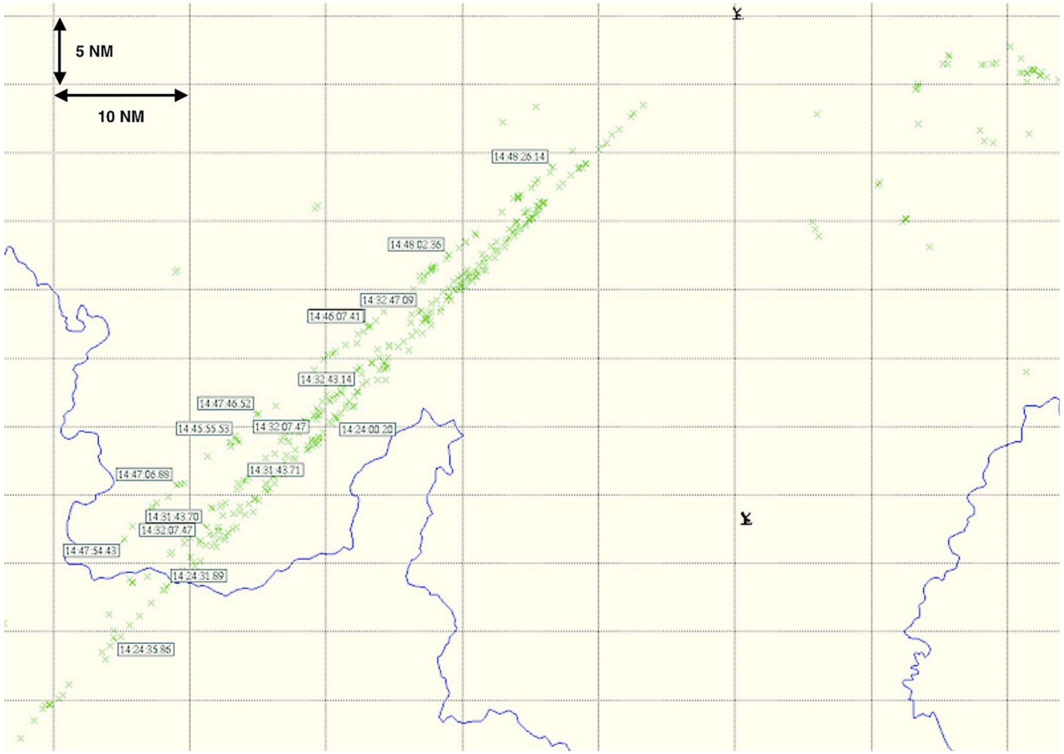


Figure: False echoes observed at the sun direction by a SSR at an Belgian airport due a strong solar radiowave burst at the radar Operation frequencies.

Reference: Marque et al, 2018
Photo: Mauro Sakamoto

September 2017, solar X-ray Flare: Limited availability GNSS augmenting systems

- European Geostationary Overlay Navigation System (EGNOS):
  - EGNOS is using GNSS measurements observed from precisely located reference stations within Europe and North Africa.
  - The measurements are processed by a central computing center, where differential corrections and integrity messages are calculated.
  - The calculation results are broadcasted for the covered area using geostationary satellites

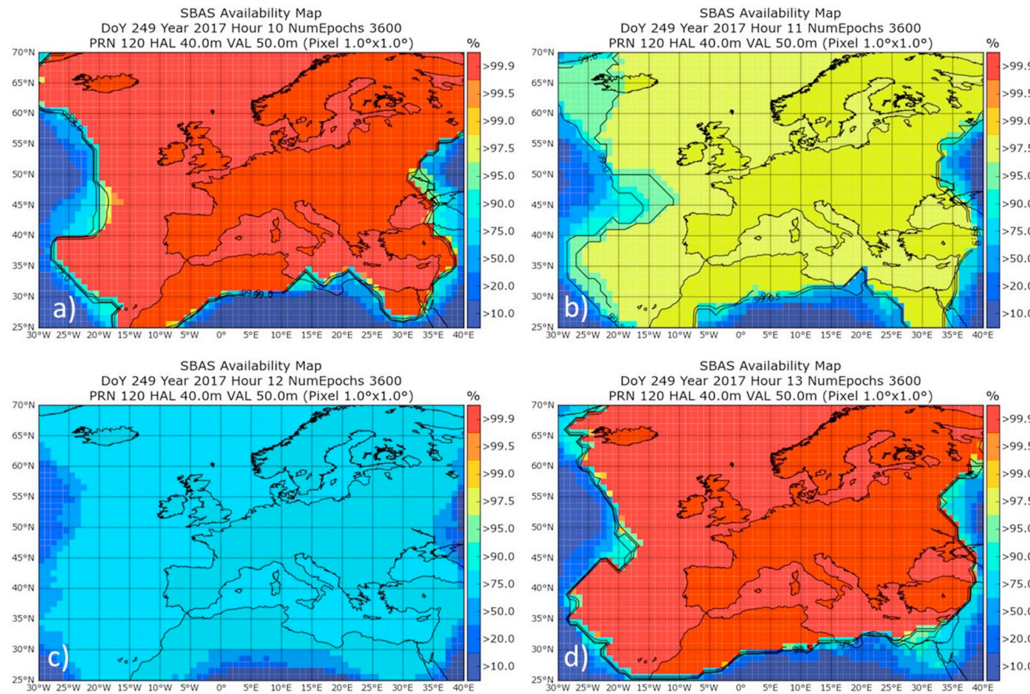
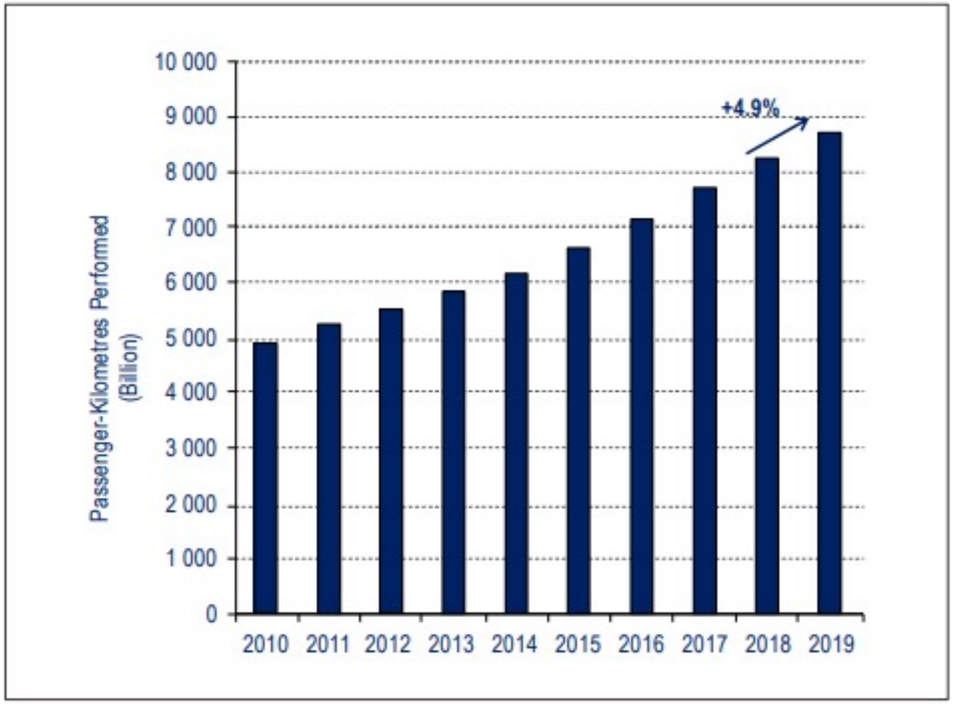


Figure: Availablity of the Satellite Based Augmentation System for airliners (red= perfect availability; blue= compromised availability)
Reference: Berdemann et al, 2018

ICAO interests in space weather

The Stakeholder: ICAO

- International Civil Aviation Organization, founded in 1944
- Working under UN and in close collaboration with WMO
- Develops and maintains regulations and standards for enhanced safety in civil aviation
- Has added space weather to its guidance in November 2019. The new discipline is handled currently by the Meteorology Panel of ICAO.
- Cross polar flights: 7300 in 2007 → more than 10900 in 2011

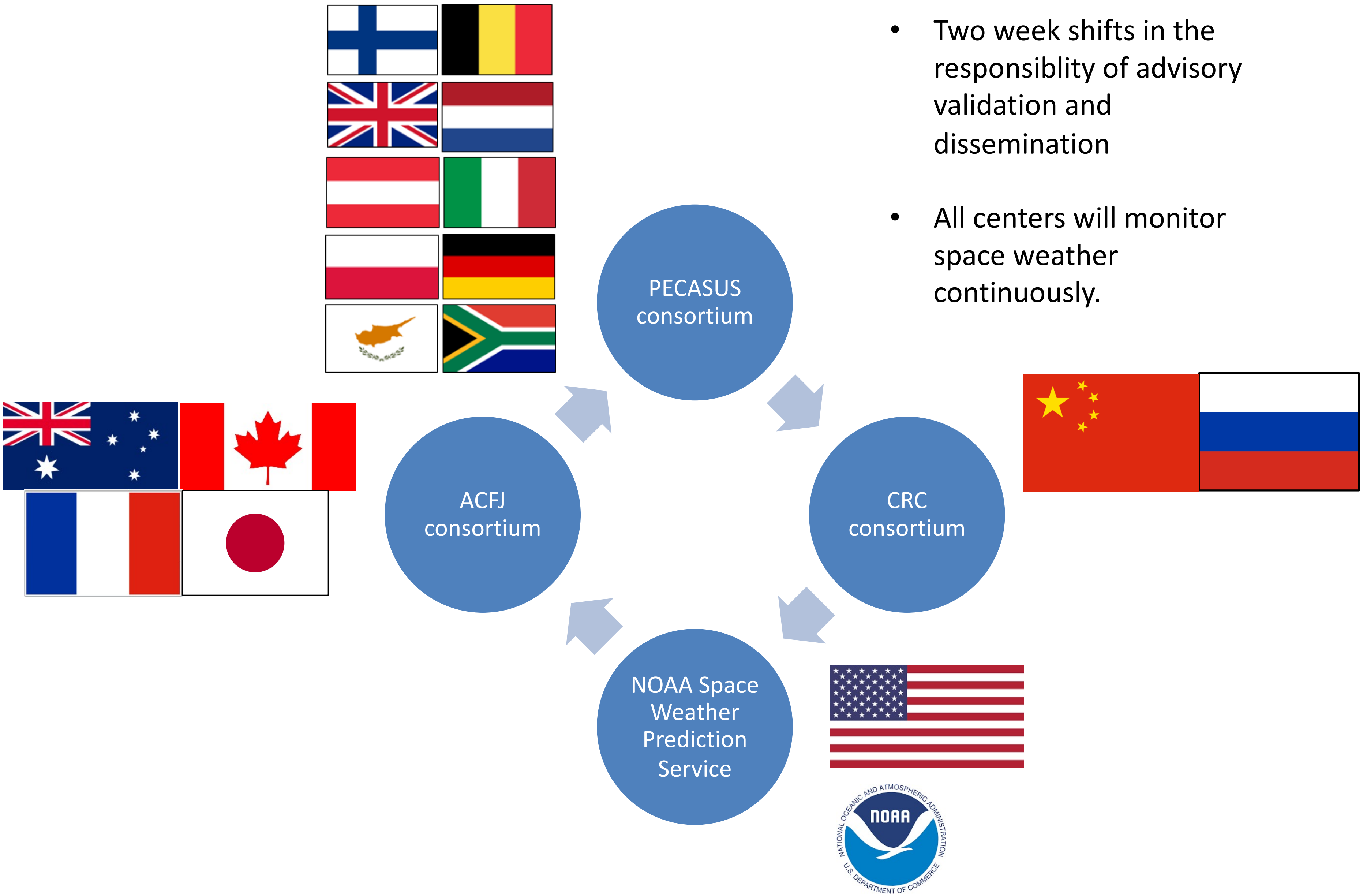


Statistics: ICAO

Figure 1. Passenger-Kilometres Performed
Total Scheduled Traffic, 2010-2019

Four global space weather centers

- Two week shifts in the responsiblity of advisory validation and dissemination
- All centers will monitor space weather continuously.



Impacts of ICAO interest & Thresholds

- Variations in Radiation at flight altitudes (RAD)
- Availability of GNSS based navigation (GNSS)
- Disturbances in HF communication (HF COM)
- To-be-added: Satellite communication (SATCOM)

Impact	Parameter	MOD	SEV
RAD	Effective dose	30 μSievert/h	80 μSievert/h
GNSS			
Ampl. Scint.	S_4	0.5	0.8
Phase Scint.	σ_ϕ	0.4 rad	0.7 rad
Total el. Cont.	TECU	125	175
HF COM			
Auroral Abs.	Kp	8	9
Pol. Cap. Abs.	Riometer abs.	2 dB	5 dB
Shortwave Fadeout	Solar X-rays	10^{-4}W/m^2 (X1)	10^{-3}W/m^2 (X10)
Post Storm Depr.	MUF	30%	50%

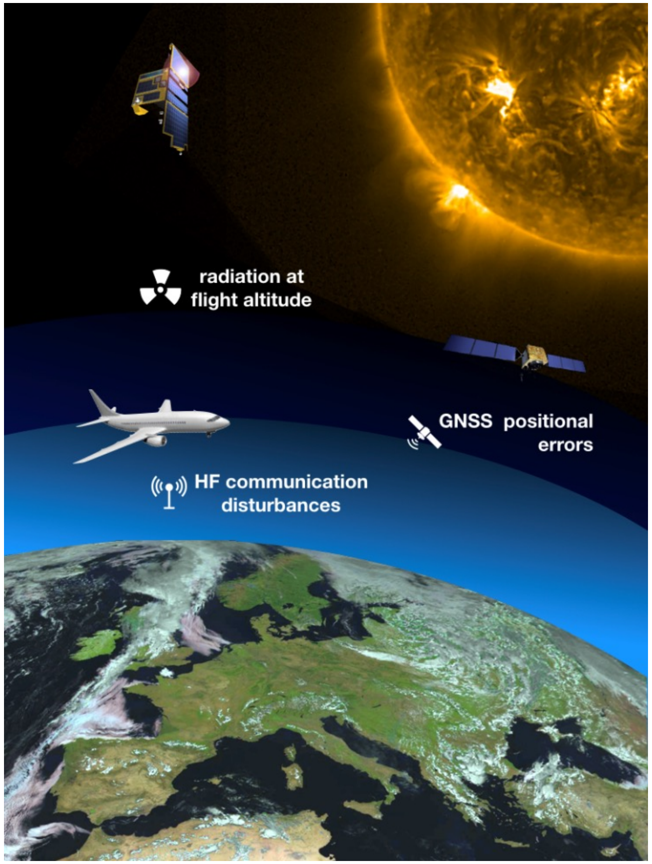
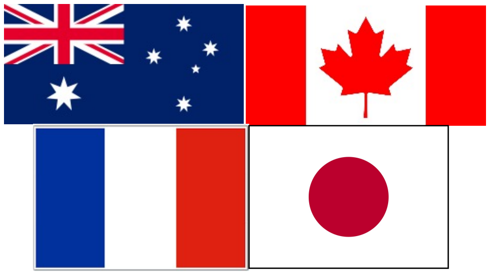


Figure: ESA/Proba-2 & EUMETSAT

First real advisories

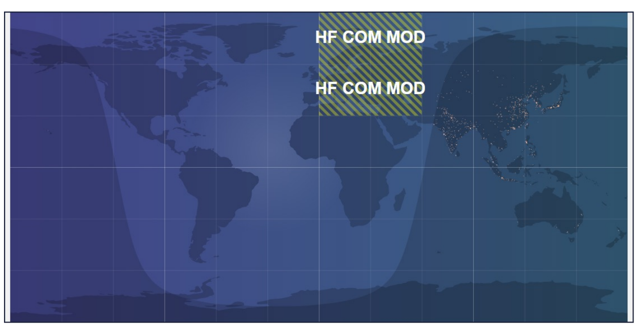
On duty center: ACFJ



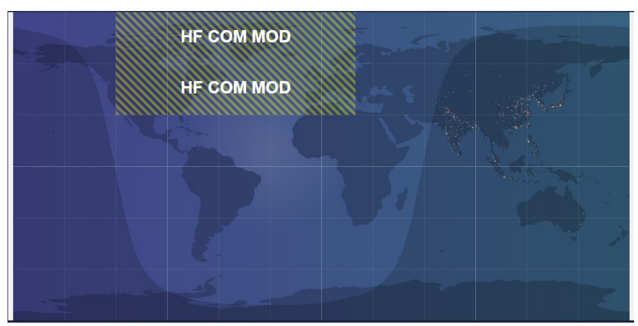
Kp=6 Sep 27 21-24 UTC
First advisory: Sep 28 0555
Last advisory: Oct 01 2213
All together 13 advisories in ~3,5 days

```
SWX ADVISORY
DTG:                20200928/0555Z
SWXC:               ACFJ
ADVISORY NR:        2020/26
SWX EFFECT:         HF COM MOD
OBS SWX:            28/0532Z HNH MNH E000 - E060
FCST SWX +6 HR:     28/1200Z NO SWX EXP
FCST SWX +12 HR:    28/1800Z NO SWX EXP
FCST SWX +18 HR:    29/0000Z NO SWX EXP
FCST SWX +24 HR:    29/0600Z NO SWX EXP
RMK:                SPACE WEATHER EVENT (MAXIMUM USABLE FREQUENCY
DEPRESSION) IN PROGRESS IMPACTING HIGHER HF COM
FREQUENCY BAND. LOWER FREQUENCIES MAY BE LESS
IMPACTED. ISOLATED AREAS OF SEV HF COM DEGRADATION
POSSIBLE.
NXT ADVISORY:       WILL BE ISSUED BY 20200928/1140Z=
```

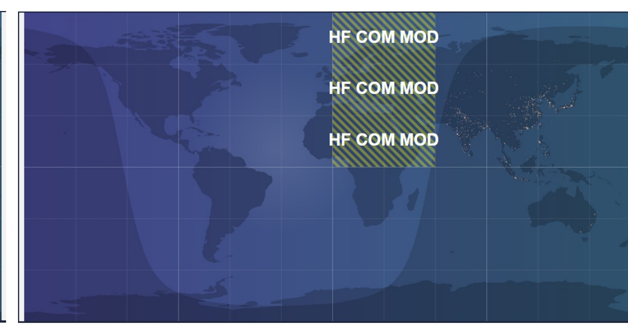
```
SWX ADVISORY
DTG:                20201001/2213Z
SWXC:               ACFJ
ADVISORY NR:        2020/38
NR RPLC:            2020/37
SWX EFFECT:         HF COM MOD
OBS SWX:            01/2202Z NO SWX EXP
FCST SWX +6 HR:     02/0500Z NO SWX EXP
FCST SWX +12 HR:    02/1100Z NO SWX EXP
FCST SWX +18 HR:    02/1700Z NO SWX EXP
FCST SWX +24 HR:    02/2300Z NO SWX EXP
RMK:                EVENT UPDATE. END OF HF COM (MAXIMUM USABLE
FREQUENCY DEPRESSION) EVENT
NXT ADVISORY:       NO FURTHER ADVISORIES =
```



HF COM 2020/26



HF COM 2020/29



HF COM 2020/37

Note: Day-night terminator for 14 UTC in all plots

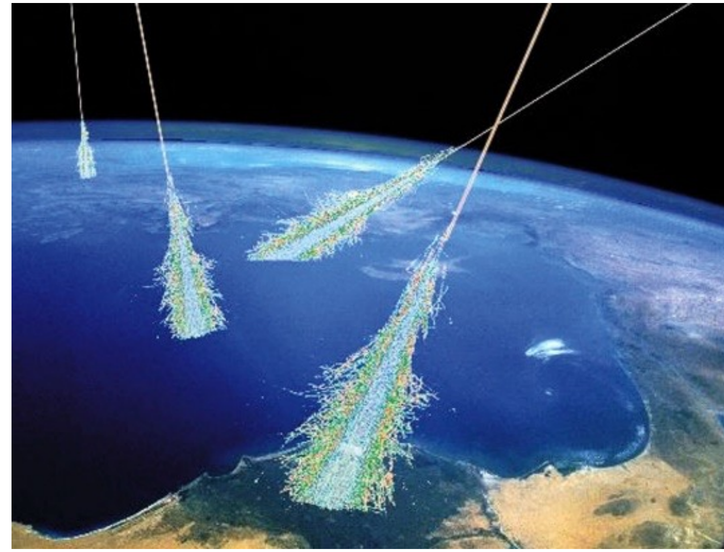
The PECASUS concept

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

"Collaboration based on a history of strong partnerships"

Radiation at flight altitudes

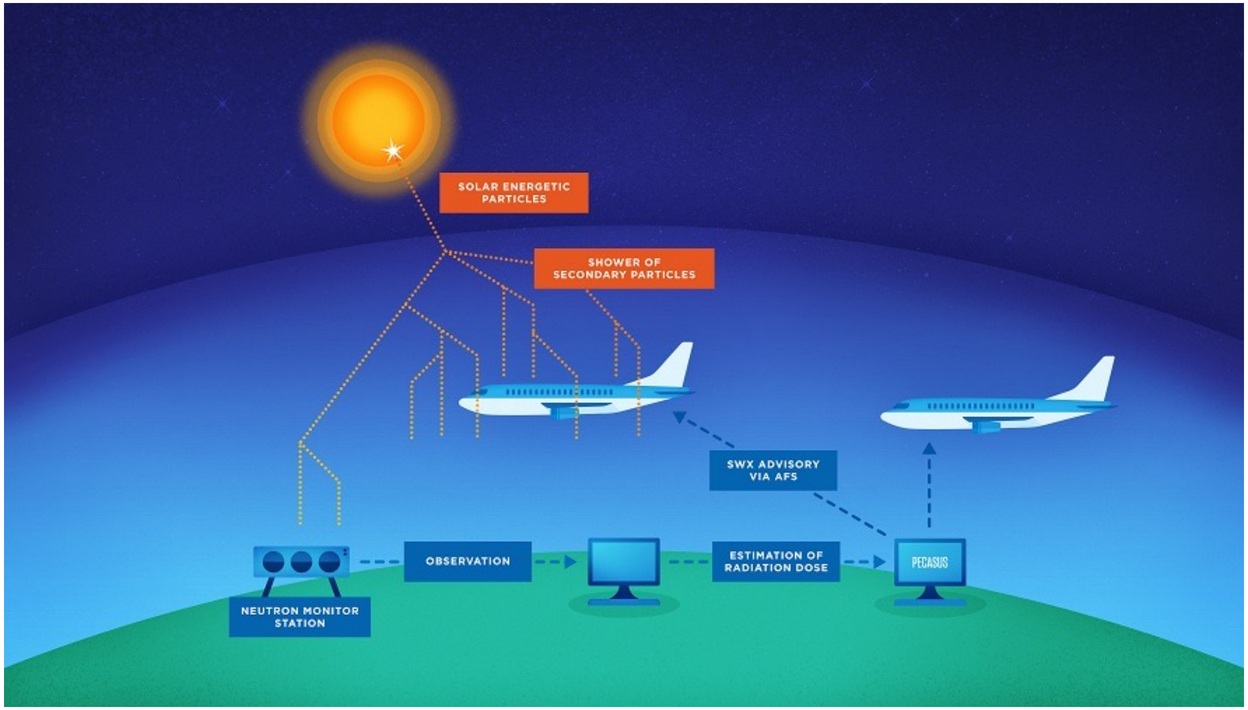
- **Two factors modulating radiation at flight altitudes**
  - Cosmic background radiation
  - Solar Proton Events
- **We have two shields against radiation**
  - Earth's magnetic field
  - Earth's atmosphere
- **Largest events are seen as Ground Level Enhancements (GLE) observed by ground based neutron detectors**
- **Oulu database:**
  - 68 GLEs since 1966
  - Strongest on Jan 20 2005
  - Latest on Sep 10 2017
- **Cross continent flights in nominal conditions:** 50µSv
- **Model estimates for strong Solar Proton Events:** 570-870µSv
- **Annual dose in Finland due to natural background:** 3200µSv
- **If the annual dose for air crew is estimated to exceed** 1000µSv **the flight company shall establish monitoring routines**



Neutron Monitor Data Base stations

Critical input for RAD Advisories

- **Ground based Neutron Monitor data**:
  - Particularly high latitude stations
  - Ground Level Enhancements
- **GOES geostationary satellite >100 MeV proton fluxes**
- **AVIDOS tool: Estimates of effective doses at flight altitudes**



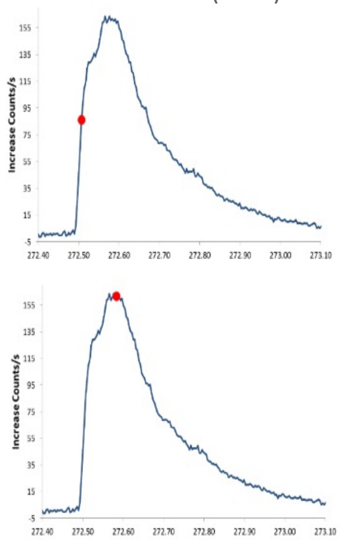
Drawing: STCE & FMI

Radiation environment

Minute INPUT-Data

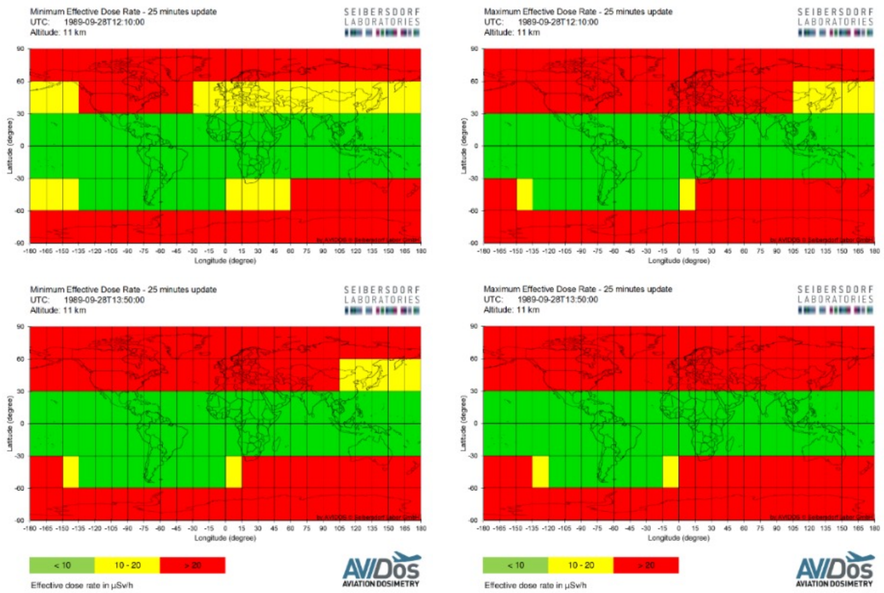
Global OUTPUT-Data - every 5 minutes

Neutron Monitor (Oulu)



Minimum expected dose rate

Maximum expected dose rate



- Radiation environment at aviation altitudes is controlled by galactic cosmic radiation and solar eruptions.
- Radiation conditions are characterized with
  - the AVIDOS tool (Seibersdorf Laboratories)
  - Solar Energetic Particles (SEP) alerts are generated with a set of forecast tools (COMESEP, HESPERIA, and UMASEP-500) to increase alertness of the duty officers.

Figures: Seibersdorf Laboratories

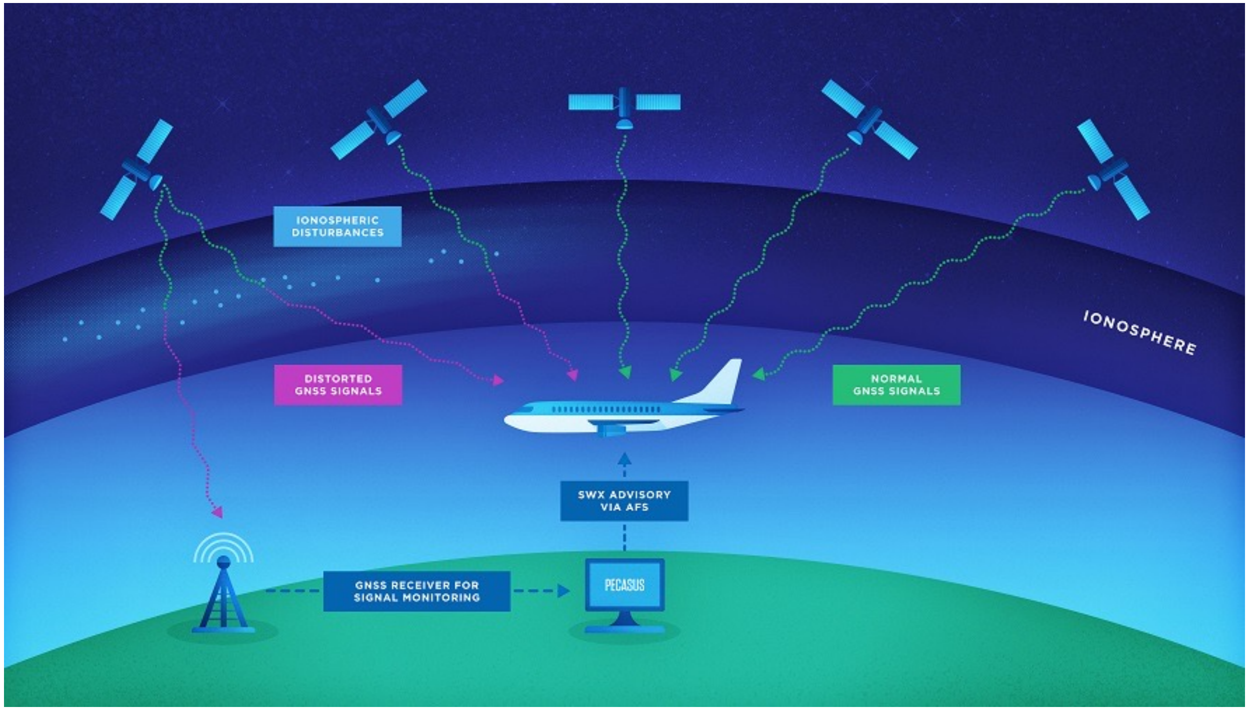
Critical input for GNSS advisories

TEC:

- GNSS receiver data from networks like IGS, EUREF,
- **Models** like IRI, NeQuick, NTCM.

Scintillation:

- Dedicated scintillation receiver network
- 50 Hz sampling rates
- S4: STD in one minute window, normalized with amplitude.
- σ_ϕ: STD de-trended phase signal , in rad



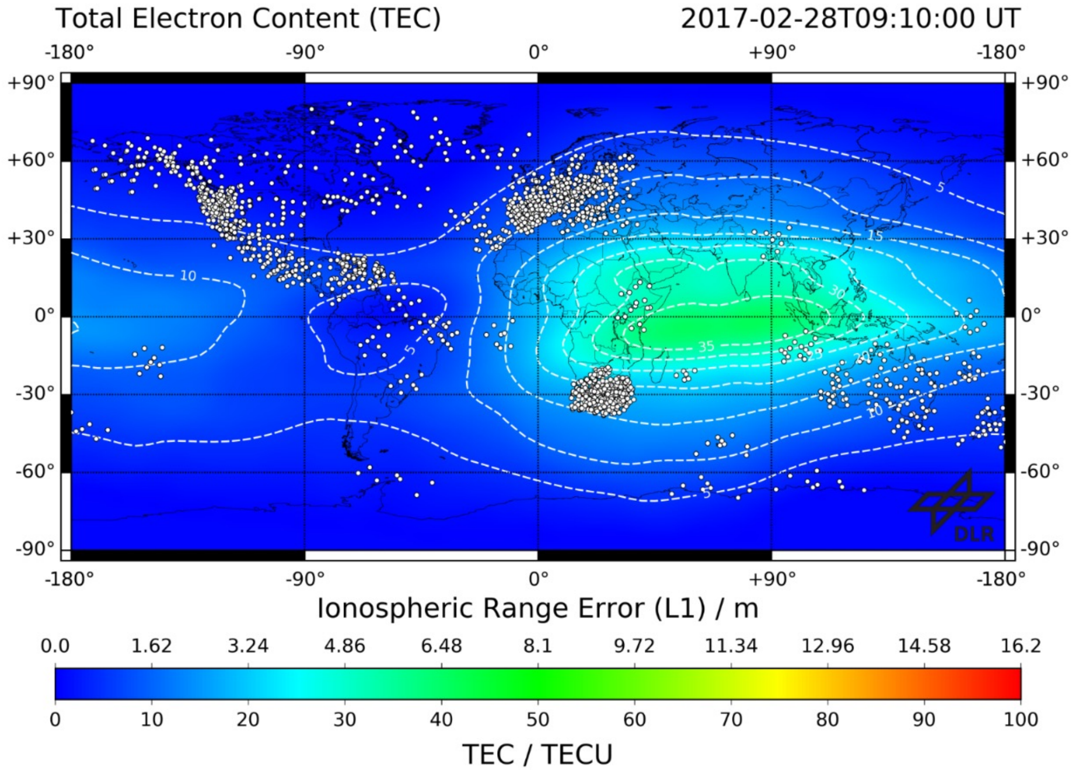
Drawing: STCE & FMI

$$TEC^{slnt,carr} = \frac{f_1^2 \cdot f_2^2}{K(f_1^2 - f_2^2)} \cdot (L_1 - L_2)$$

$$TEC^{slnt,code} = \frac{f_1^2 \cdot f_2^2}{K(f_1^2 - f_2^2)} \cdot (P_2 - P_1)$$

$$VTEC = STEC(1 - (\frac{R_e \cos\epsilon}{R_e + h_{sp}})^2)^{1/2},$$

GNSS Navigation



Figures: DLR, INGV

$$d_I \approx \frac{K}{f^2}\int n_e ds = \frac{K}{f^2} TEC^{slnt}$$

- TEC and Scintillation nowcasts and forecasts are provided by joint efforts of DLR and INGV
- GNSS input data are acquired and processed in real time from several global and regional GNSS receiver networks.
- Scintillation data are collected by DLR, INGV and their collaborators

Critical inputs for HF COM advisories

Short wave fade out:

- GOES X-ray flux
- **Model:** D-RAP

Polar Cap Absorption:

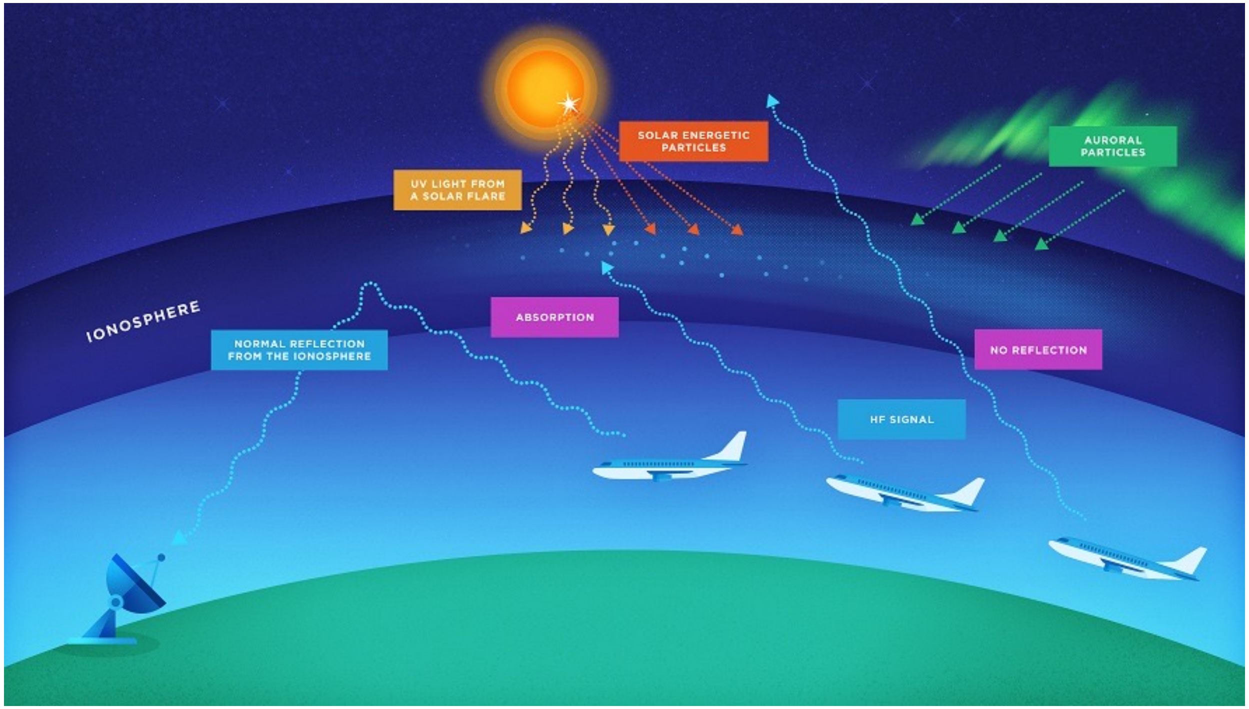
- GOES proton fluxes
- **Model:** D-RAP

Auroral Absorption:

- Kp index (3h & high-res)

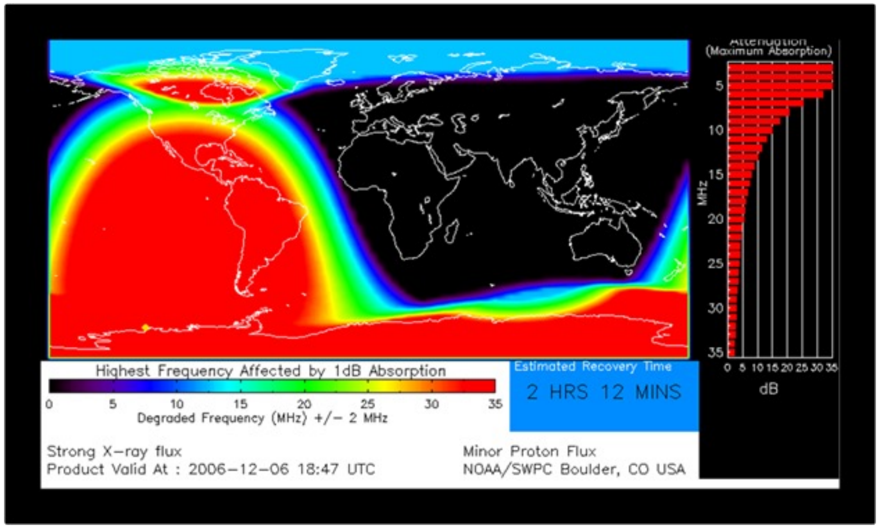
Post-storm depression:

- Ionosonde networks
- Kp index (3h & high-res)
- **Models** like NeQuick, EUROMAP, IRTAM



Drawing: STCE & FMI

Radio signal absorption in the ionosphere (1/2)

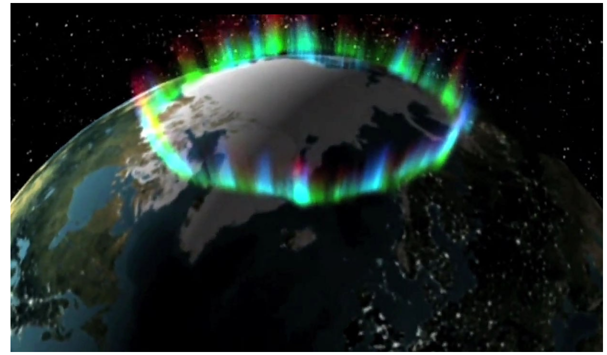


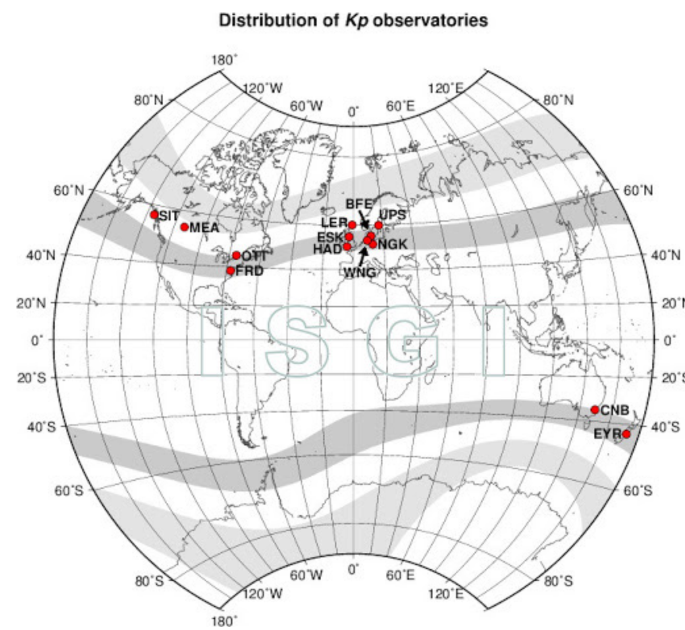
Figures: NOAA/UKMO

- Ionospheric D-layer (60-90 km):
  - Region where electron density can enhance due to solar energetic particles and X-ray burst and the electrons collide often with neutral atmosphere
  - → radiowaves get absorbed and not reflected.
- D-RAP tool:
  - Inputs geostationary observations of
    - solar X-rays
    - fluxes energetic protons (> 1 MeV)
  - Output:
    - Dayside D-layer absorption, ”Short wave fadeout” (duration of some hours)
    - Polar Cap absorption (duration of days)

Radio signal absorption in the ionosphere (2/2)

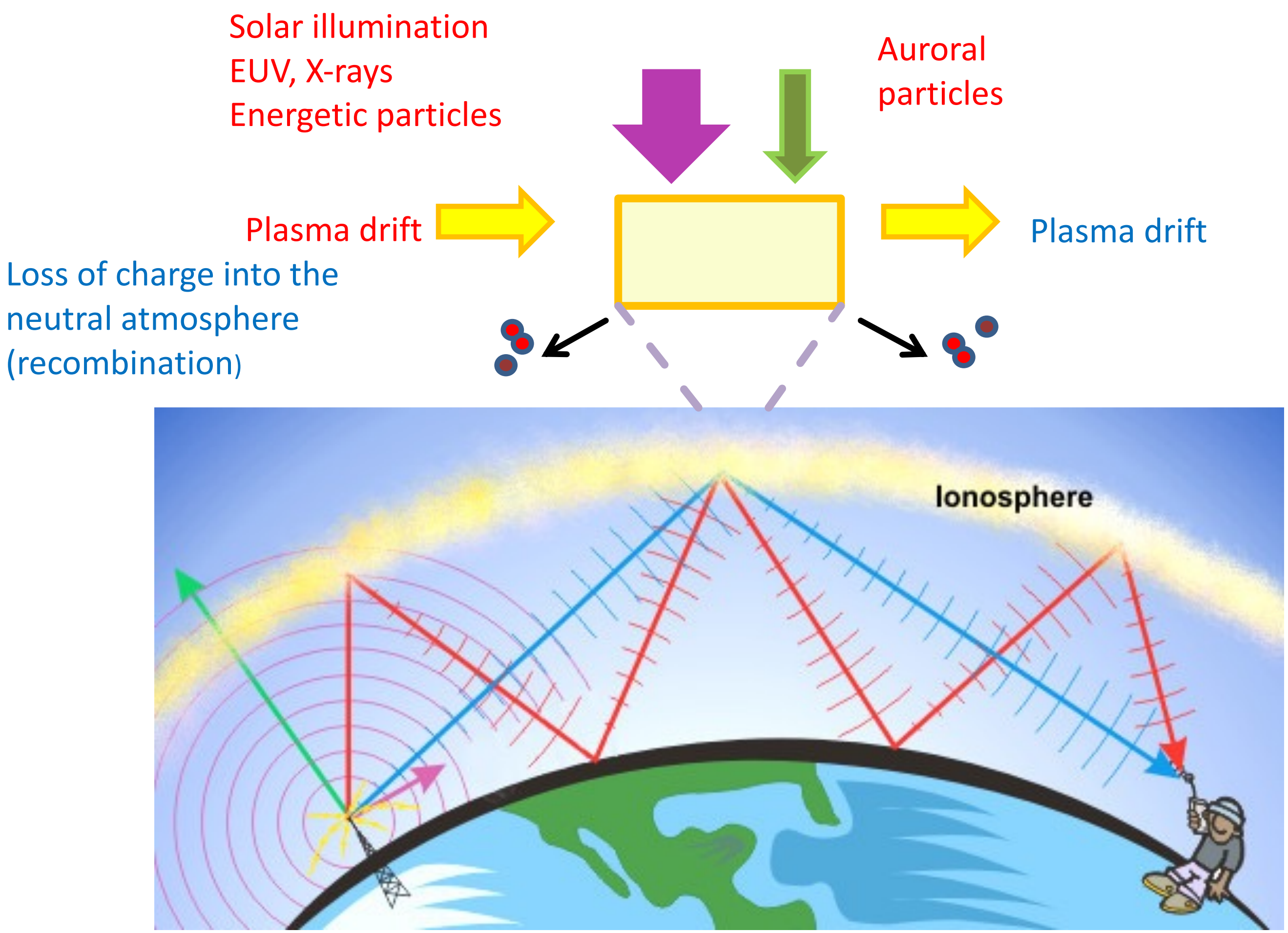
- Energetic electron precipitation can cause also D-layer absorption at high latitudes
- The energy spectra and spatio-temporal variations of electrons cannot be estimated with geostationary satellite measurements
- Electron precipitation is strong particularly during geomagnetic storms → Occurrence of auroral absorption is estimated with the Kp index
- Kp index
  - 3-hour time resolution
  - Deviation from regular daily variations
  - Scale 0…9
  - Kp>8 1-7 times per year.





Figures: *International Service of Geomagnetic Indices and Wikiversity*

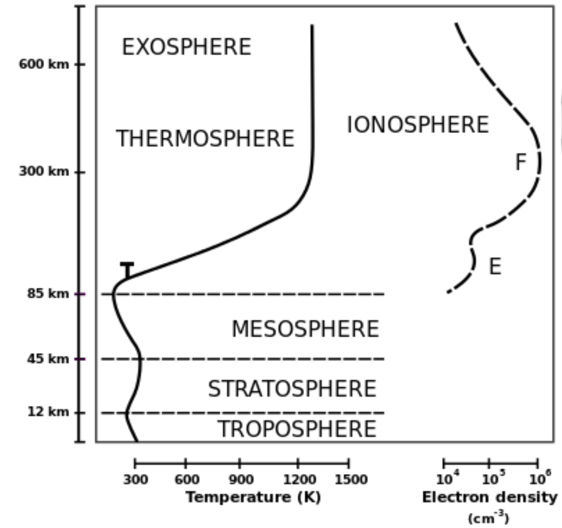
Electron density ionospheric F-layer



Radiowave reflection in F-layer

- HF radio waves reflect from the ionosphere
- Ionospheric refractive index:
- $n^2 = 1 - \left(\frac{2\pi f_p}{2\pi f}\right)^2$
- $N_e = 10^{10} - 10^{12}\ m^{-3} \rightarrow$ 1-8 MHz
- Ionosonde provides altitude profile of eletron density up to the F-layer maximum.

$$f_p = \frac{1}{2\pi}\left(\frac{e^2 n_e}{\epsilon_0 m_e}\right)^{1/2} = \left(80\frac{n_e}{\mathrm{m}^{-3}}\right)^{1/2}\mathrm{Hz}$$



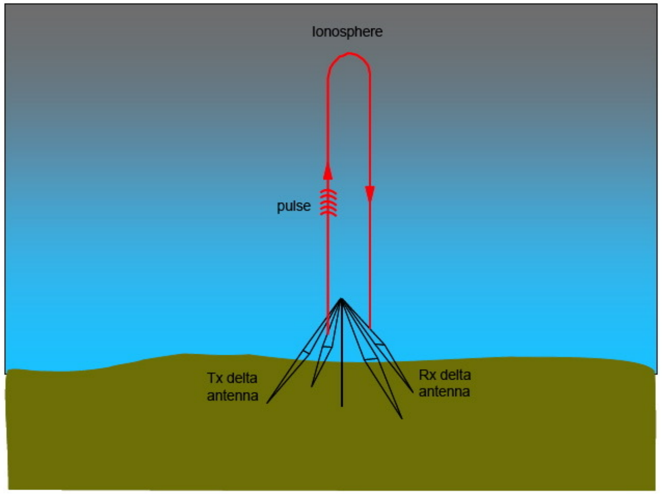
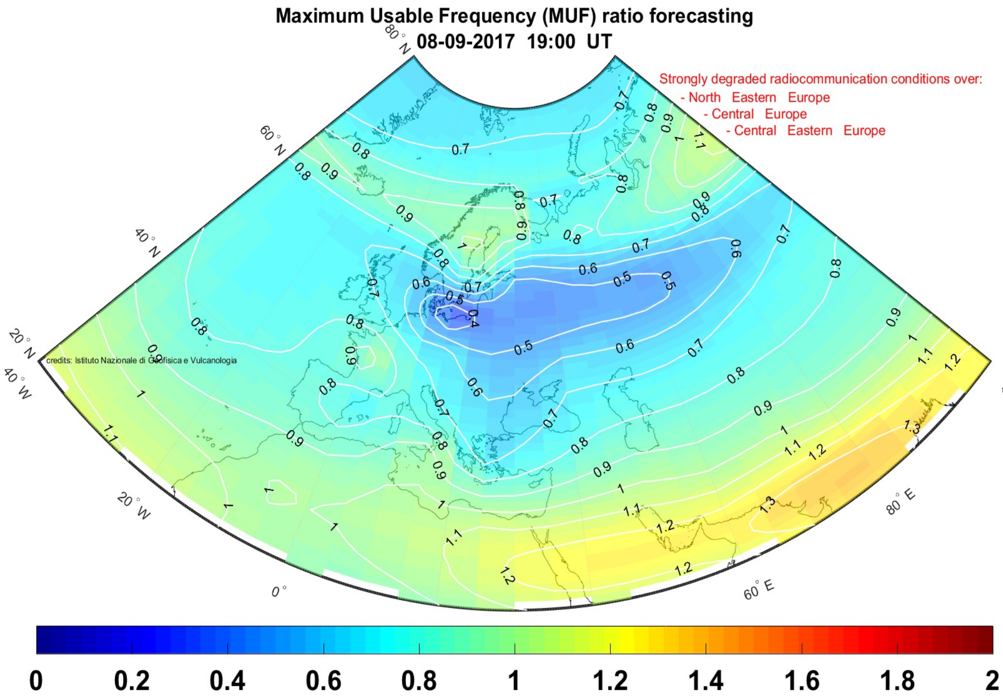
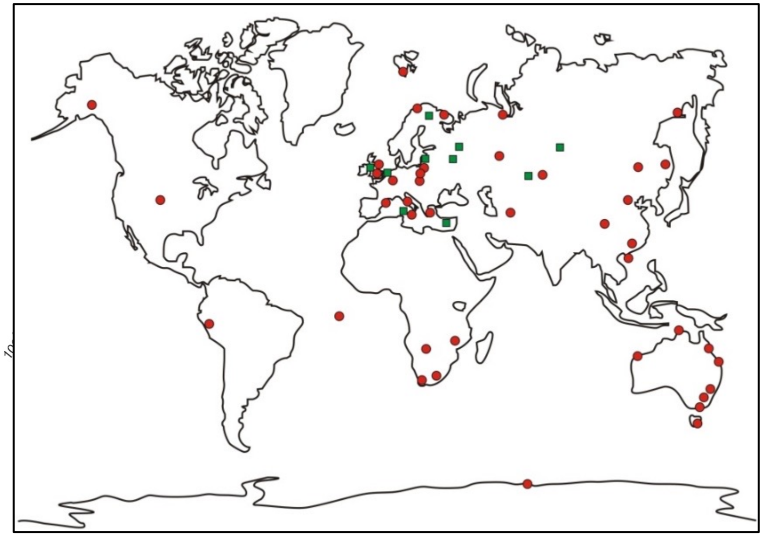


Figure: www-amateur-radio-wiki.net

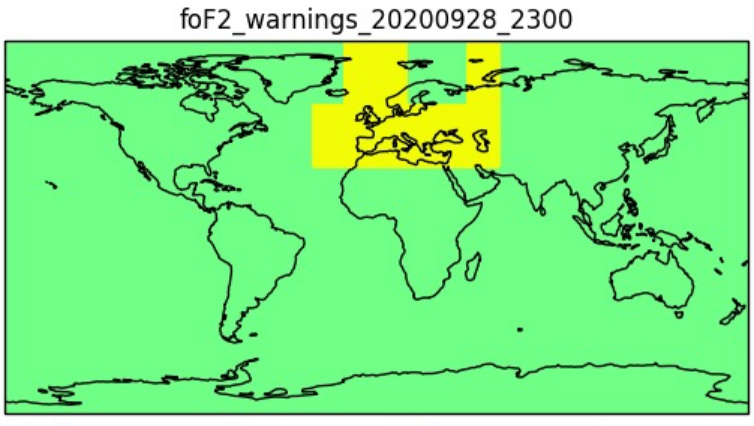
HF communication/MUF





Figures: INGV and CBK/SRC

- Time and space variations of **Maximum Usable Frequency** are monitored with methodologies developed in SRC and INGV.
- The nowcasts use advanced kriging techniques and are based on both NRT ionospheric observations and monthly median conditions by empirical ionospheric models.
- FU and SANSA contribute to the service with their ionosonde data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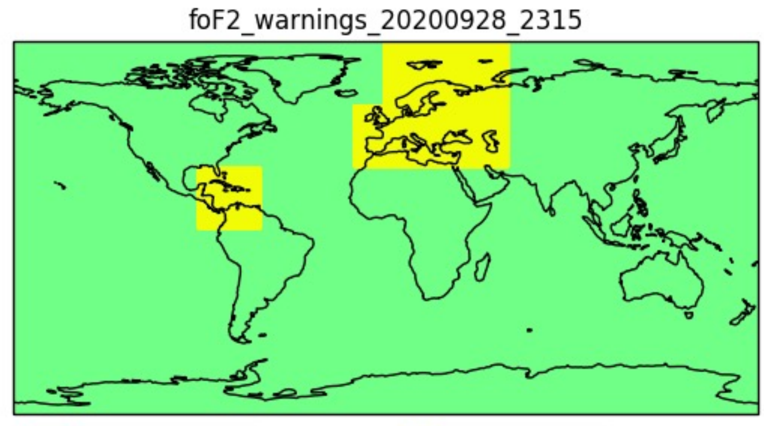
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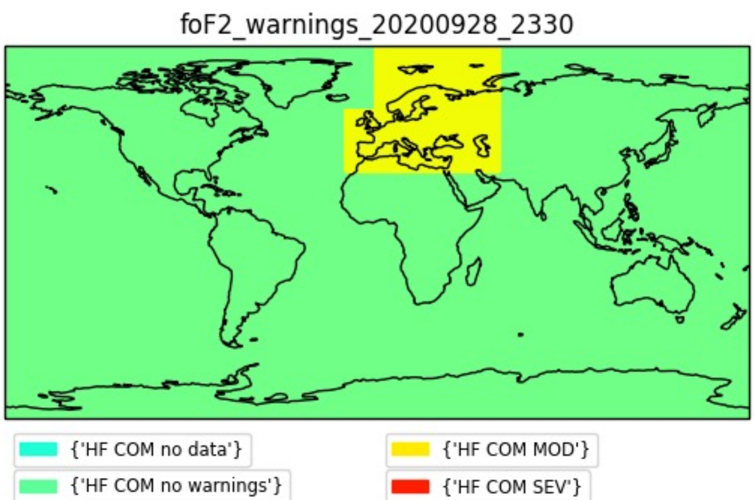
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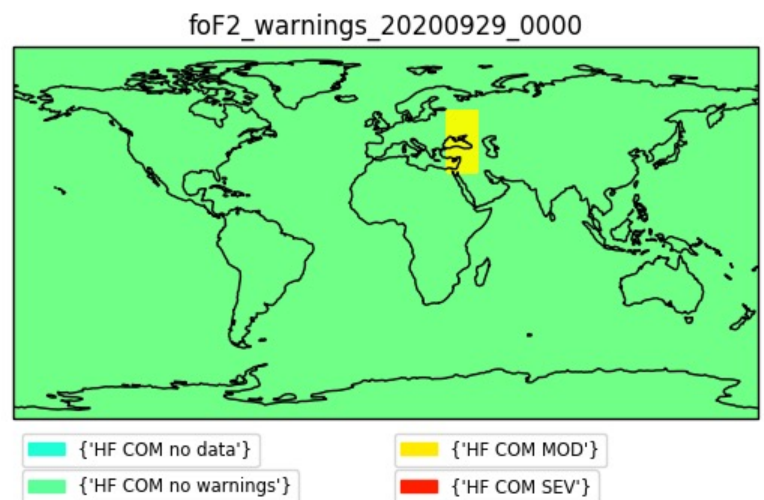
{'HF COM MOD'}
{'HF COM SEV'}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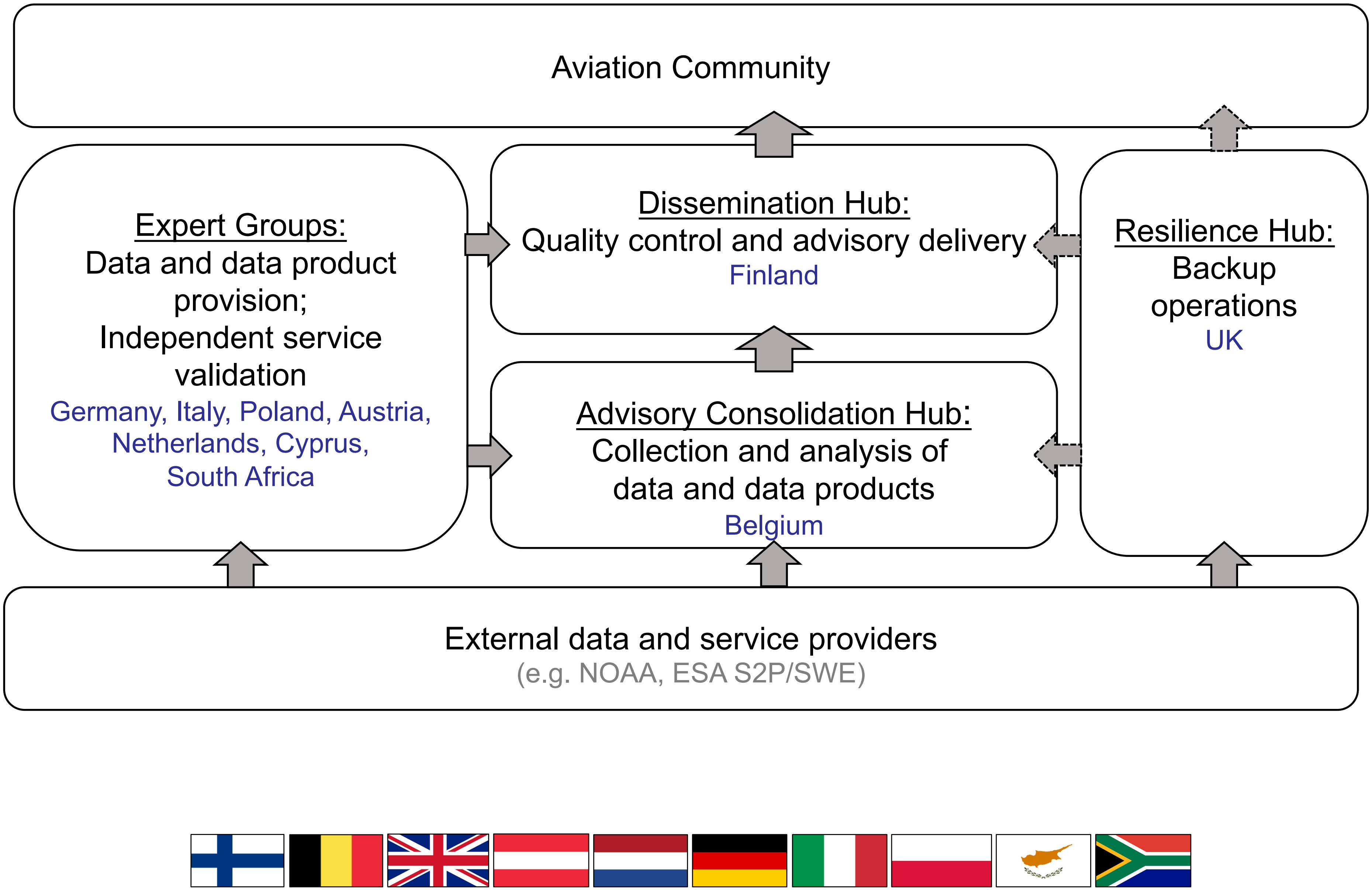
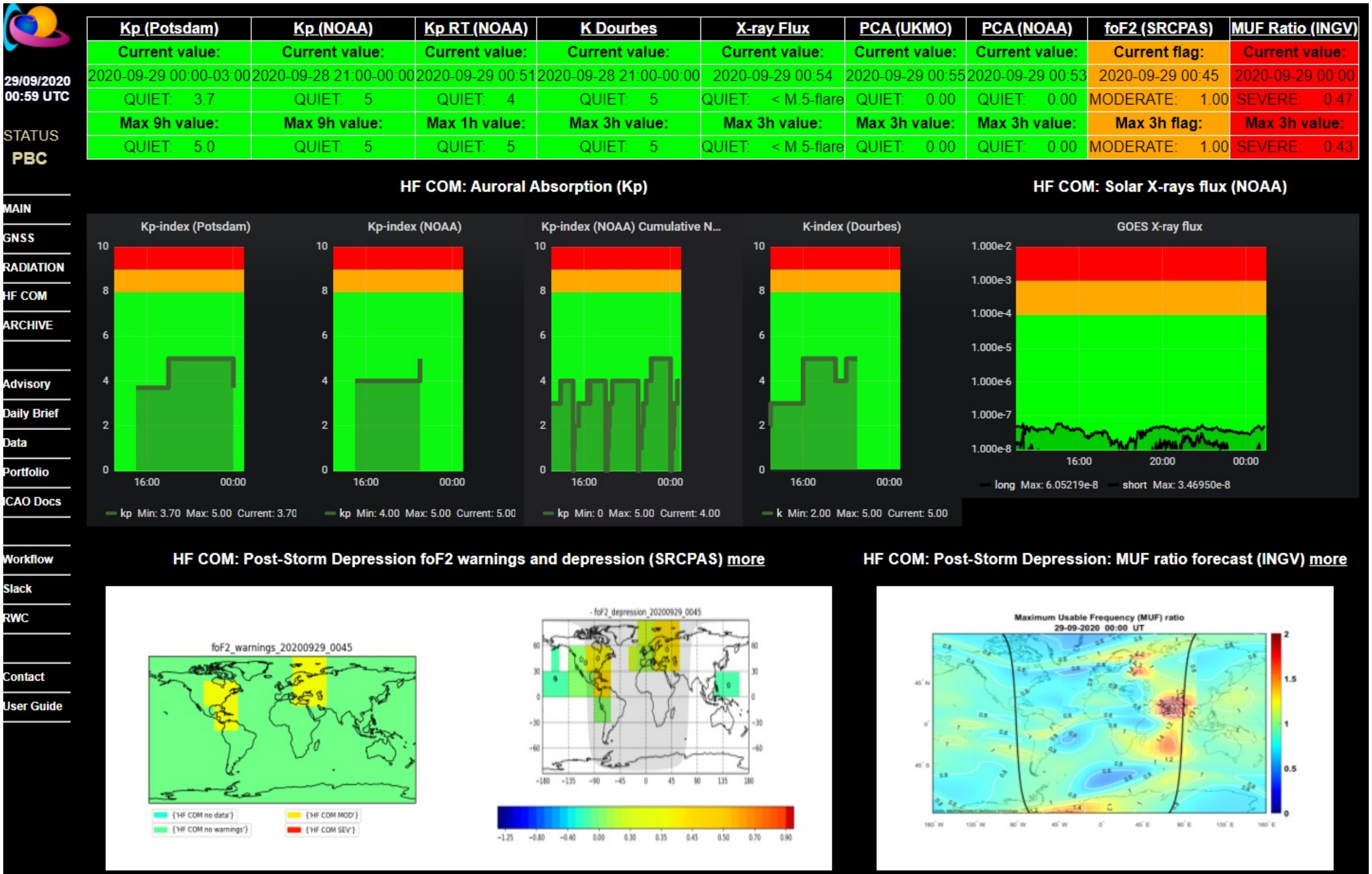
Space weather monitoring


Aviation Community
Expert Groups:
Data and data product provision;
Independent service validation
Germany, Italy, Poland, Austria, Netherlands, Cyprus, South Africa
Dissemination Hub:
Quality control and advisory delivery
Finland
Advisory Consolidation Hub:
Collection and analysis of data and data products
Belgium
Resilience Hub:
Backup operations
UK
External data and service providers
(e.g. NOAA, ESA S2P/SWE)

PECASUS Dashboard developed in Consolidation Hub (STCE)



Lessons learnt

- Luckily we started during quiet solar activity → Time for testing the dissemination channels & sending procedures

- Frequent and Challenging cases: Post storm depression and Scintillation
  - Monitoring capabilities depend on ionosonde/receiver networks available
  - Sporadic appearance both in time and space

- Rare and Challenging cases: Radiation alerts
  - Need for prompt reactions
  - >35 flight levels to handle

- Discussions among the Centers will still continue for consolidated approaches to fulfill the ICAO requirements:
  - Guidance for Issuance of Space Weather advisories & Handover Manual with recurrent and controlled updates
  - Homogenizing of products (HF/Post-storm depression)

Thanks for your attention!
Questions?