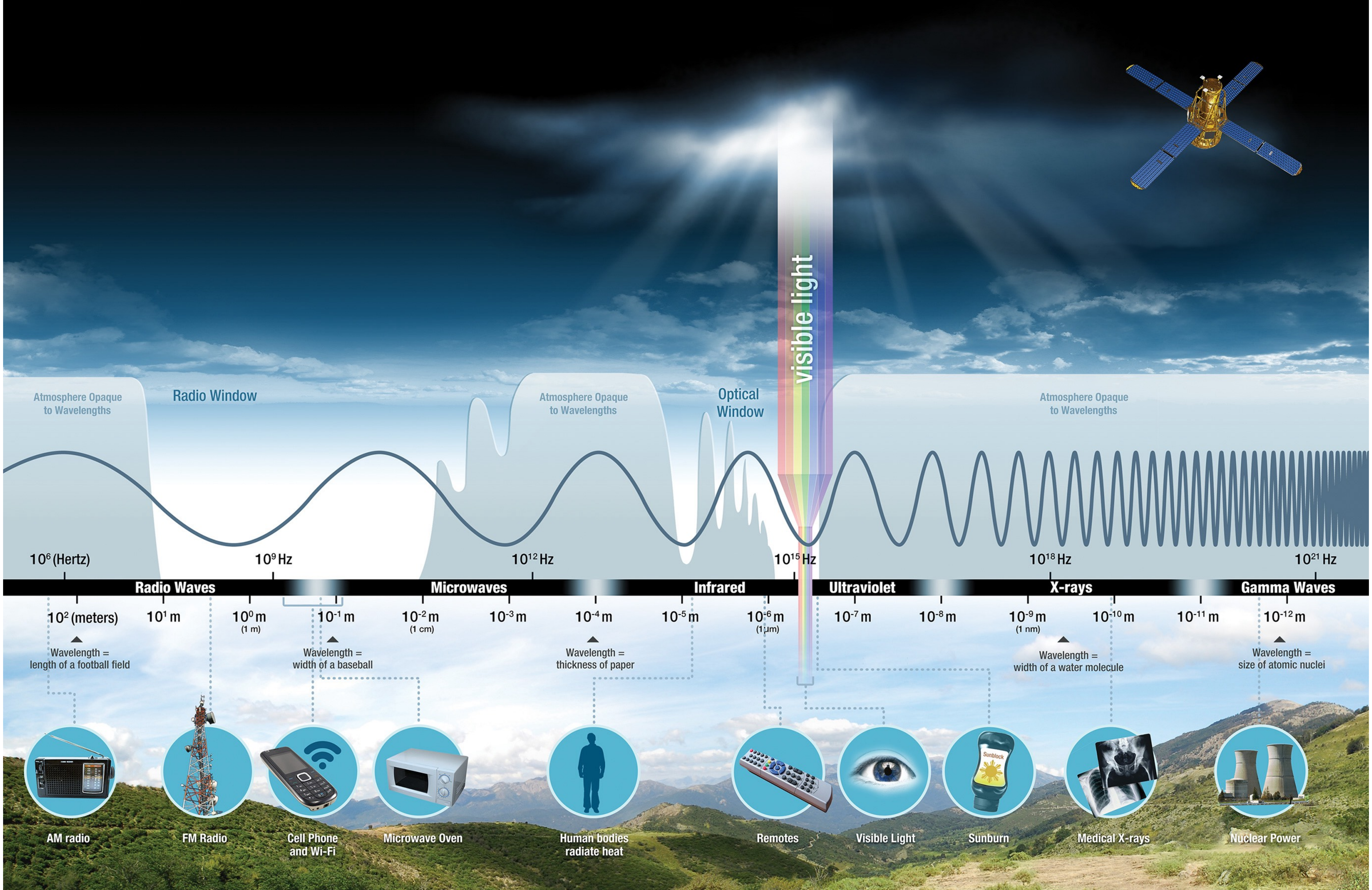
Solar radio bursts

Role of the ionosphere and space weather in military communications

Christophe Marqué - 29 January 2025


visible light
Atmosphere Opaque to Wavelengths
Radio Window
Atmosphere Opaque to Wavelengths
Optical Window
Atmosphere Opaque to Wavelengths
10^6 (Hertz)
10^9 Hz
10^{12} Hz
10^{15} Hz
10^{18} Hz
10^{21} Hz
Radio Waves
Microwaves
Infrared
Ultraviolet
X-rays
Gamma Waves
10^2 (meters)
10^1 m
10^0 m
(1 m)
10^{-1} m
10^{-2} m
(1 cm)
10^{-3} m
10^{-4} m
10^{-5} m
10^{-6} m
(1 µm)
10^{-7} m
10^{-8} m
10^{-9} m
(1 nm)
10^{-10} m
10^{-11} m
10^{-12} m
Wavelength = length of a football field
Wavelength = width of a baseball
Wavelength = thickness of paper
Wavelength = width of a water molecule
Wavelength = size of atomic nuclei
AM radio
FM Radio
Cell Phone and Wi-Fi
Microwave Oven
Human bodies radiate heat
Remotes
Visible Light
Sunburn
Medical X-rays
Nuclear Power
Sunblock

Defines noise

Noise in radio systems

"A time-varying electromagnetic phenomenon having components in the radio-frequency range, apparently not conveying information and which may be superimposed on, or combined with, a wanted signal."

ITU REC 573

Minimum noise level in systems

$$P_m = kT\Delta_\nu$$

$$P_m \approx -174\ dBm$$

$$T = 290\ K; \Delta_\nu = 1\ Hz; k = 1.38 \times 10^{-23} J\,.\,K^{-1}$$

Noise received by antenna

$$P_R = \frac{1}{2}\frac{G\lambda^2}{4\pi}F$$

Antenna, with gain G,
pointed at a source
with flux density F

Simple interference threshold

$$P_m = kT\Delta_\nu \equiv P_R = \frac{1}{2}\frac{G\lambda^2}{4\pi}F$$

Double the noise that enters the system

S/N decreases by 3 dB

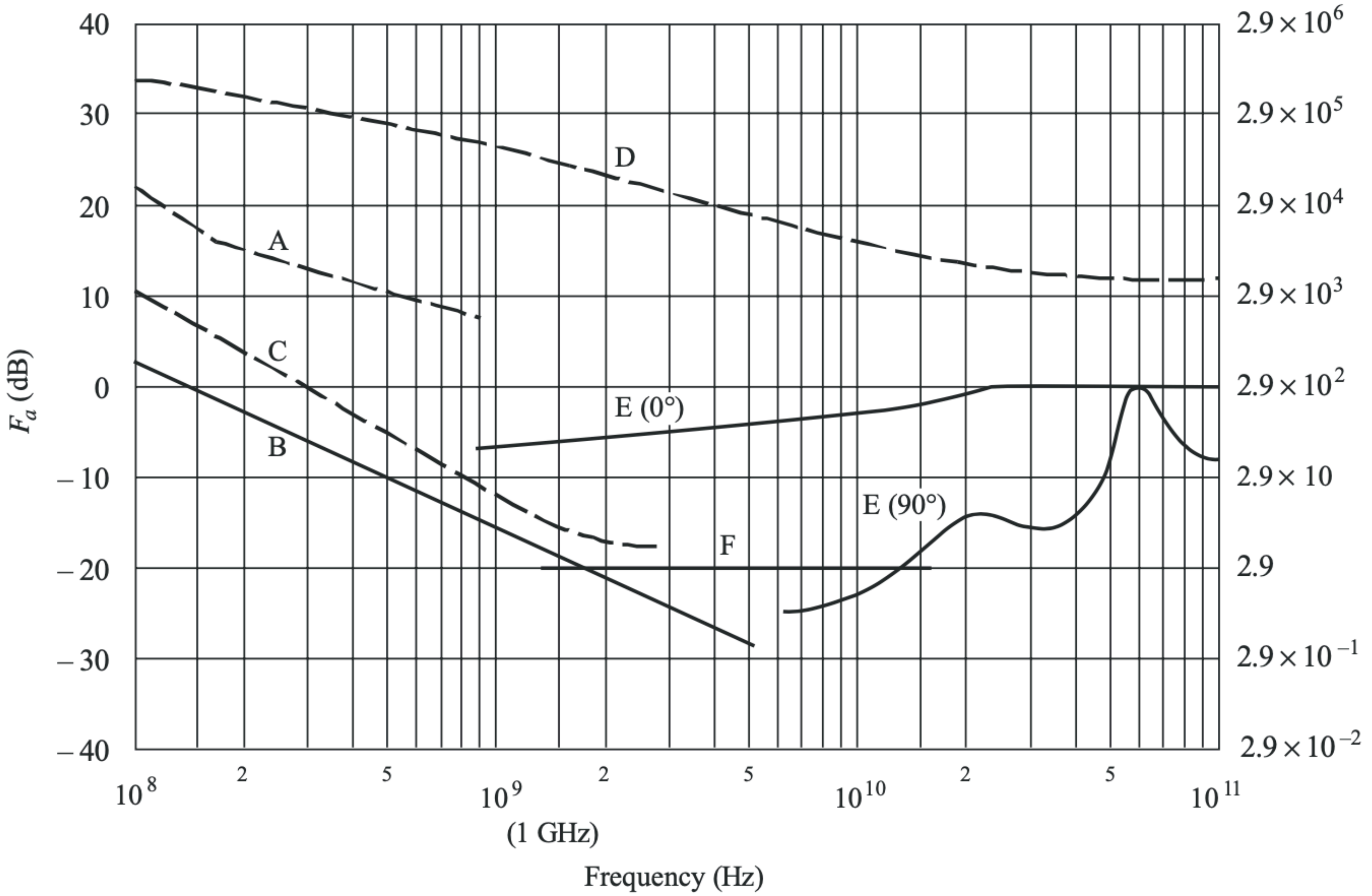
Quiet Sun impact

The radio Sun

The Sun is the strongest radio source in the sky

FIGURE 3

F_a versus frequency (10^8 to 10^{11} Hz)



A: estimated median city area man-made noise
B: galactic noise
C: galactic noise (toward galactic centre with infinitely narrow beamwidth)
D: quiet Sun (½° beamwidth directed at Sun)
E: sky noise due to oxygen and water vapour (very narrow beam antenna); upper curve, 0° elevation angle; lower curve, 90° elevation angle
F: black body (cosmic background), 2.7 K
—— minimum noise level expected

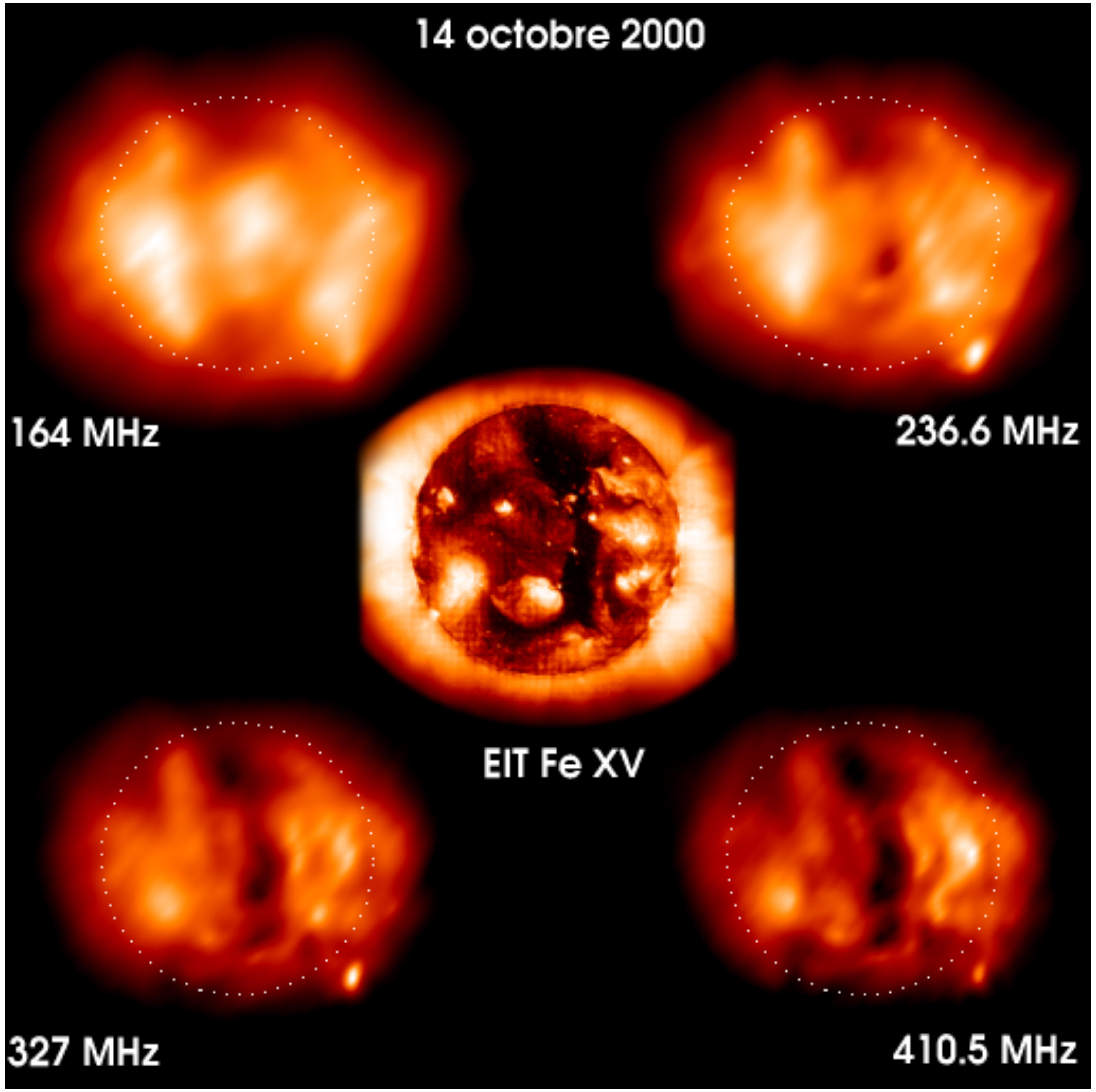
P.0372-03

ITU REC 372

Quiet Sun

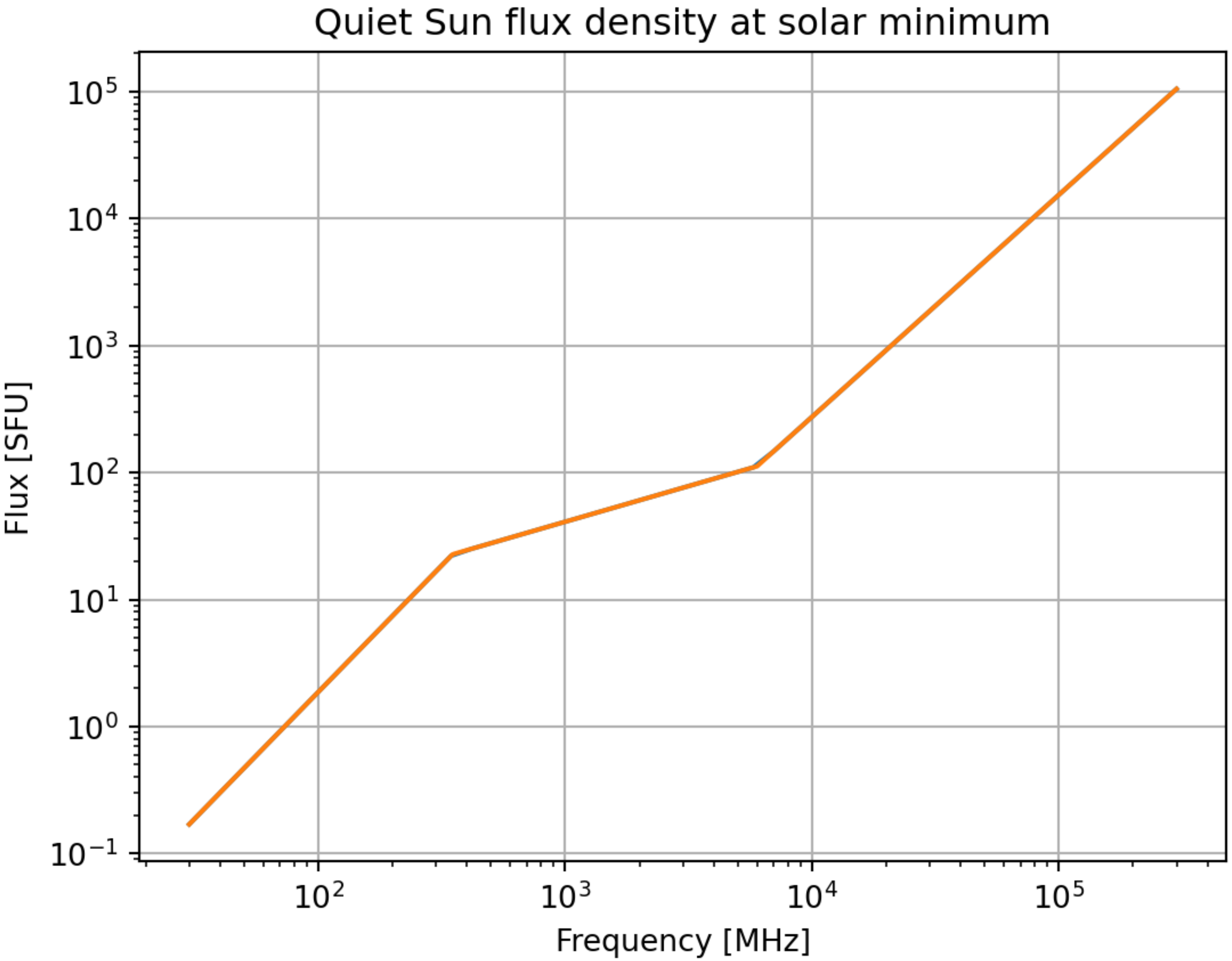
Thermal emission from hot corona

(free-free emission)



C. Marqué

Quiet Sun flux at solar cycle minimum



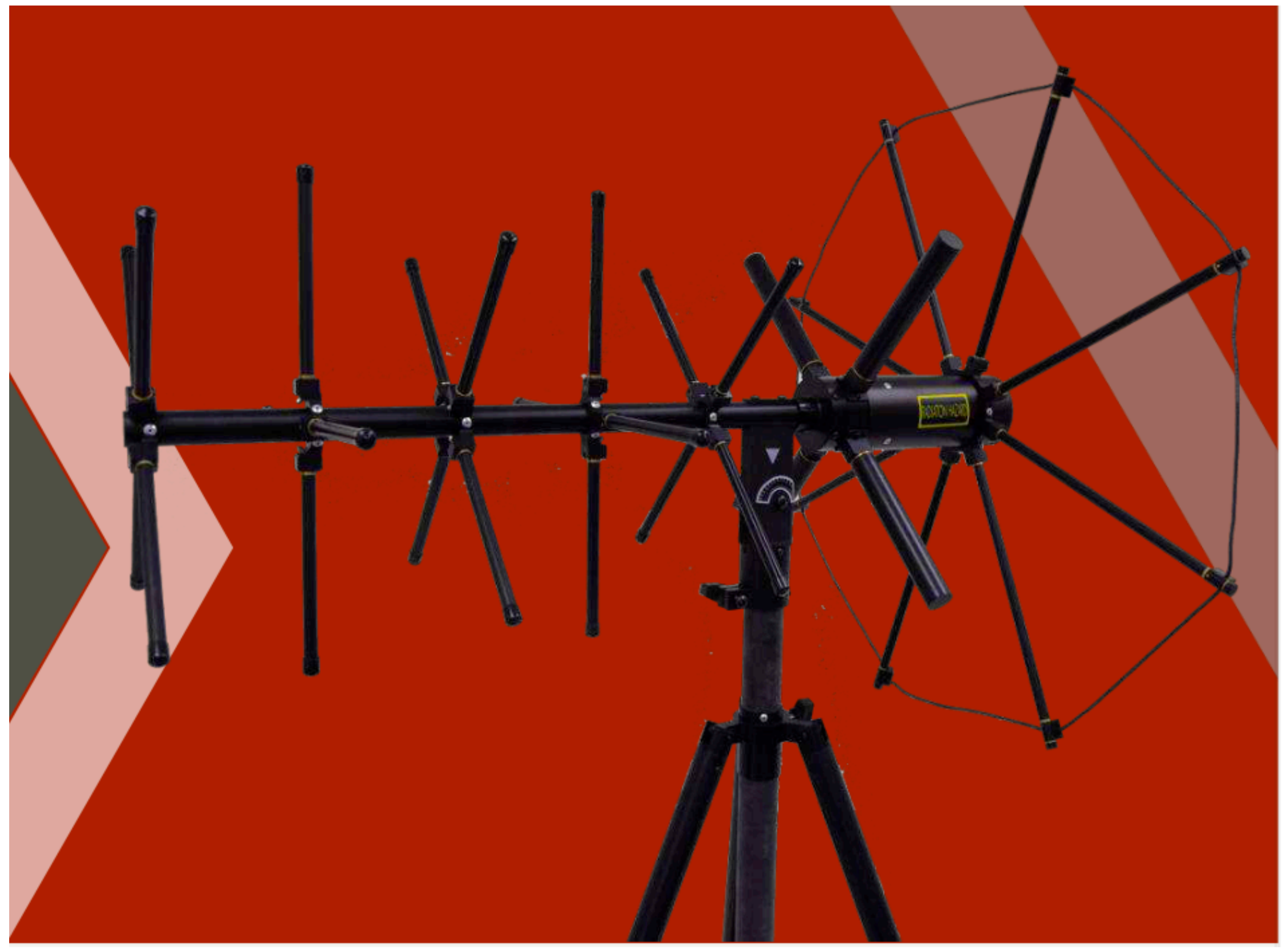
$F_{\odot} = 1.94 \cdot 10^{-4} f^{1.992}$ 30 - 350 MHz

$F_{\odot} = 8.45 \cdot 10^{-1} f^{0.5617}$ 350 - 6000 MHz

$F_{\odot} = 2.79 \cdot 10^{-5} f^{1.748}$ 6000 - 400000 MHz

$F_{\odot} [SFU = 10^{-22} W \cdot m^{-2} \cdot Hz^{-1}]$

Benz, 2009



SATCOM 300 MHz
Gain 9.7 dB

$$P_R = \frac{1}{2}\frac{G\lambda^2}{4\pi}F$$

SATCOM Ka band 20.7 GHz
Gain 52.1 dB

$$F_\odot \approx 17\ SFU$$

$$P_R = -182\ dBm$$

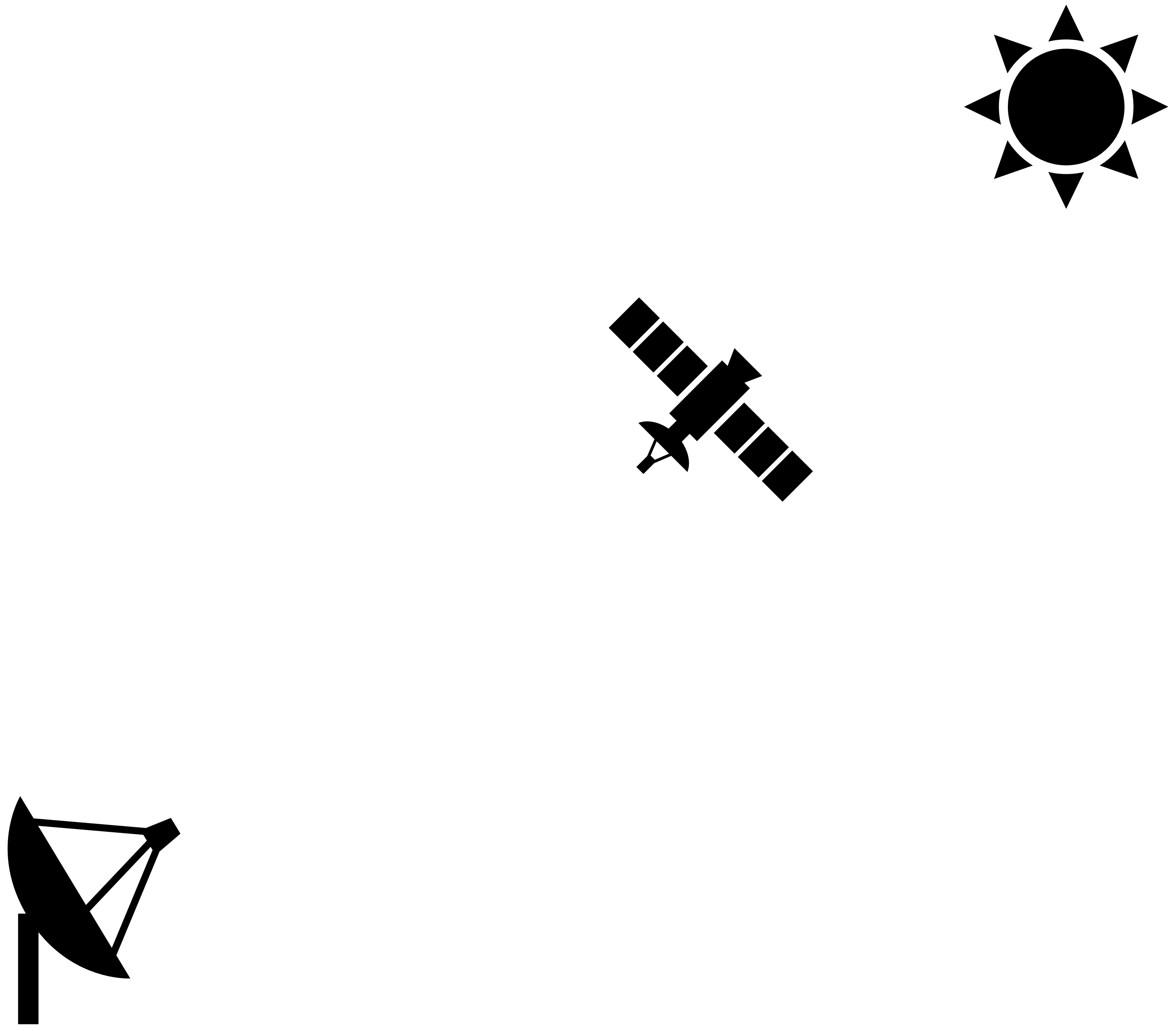
No issue with quiet sun

$$F_\odot \approx 977\ SFU$$

$$P_R = -159\ dBm$$

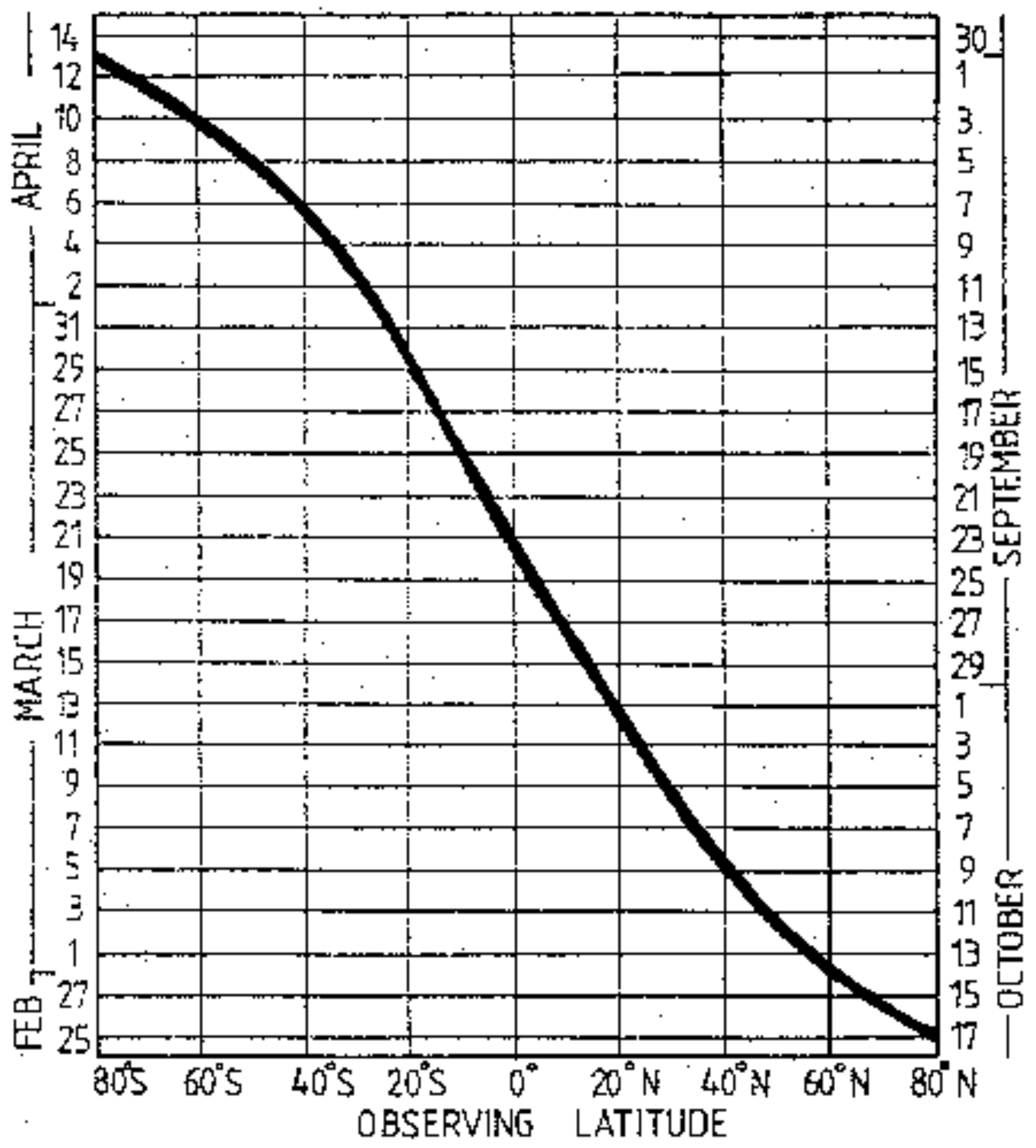
Potential problem with quiet sun

Solar outages at high frequency



Occur when the Sun is in the Field of View

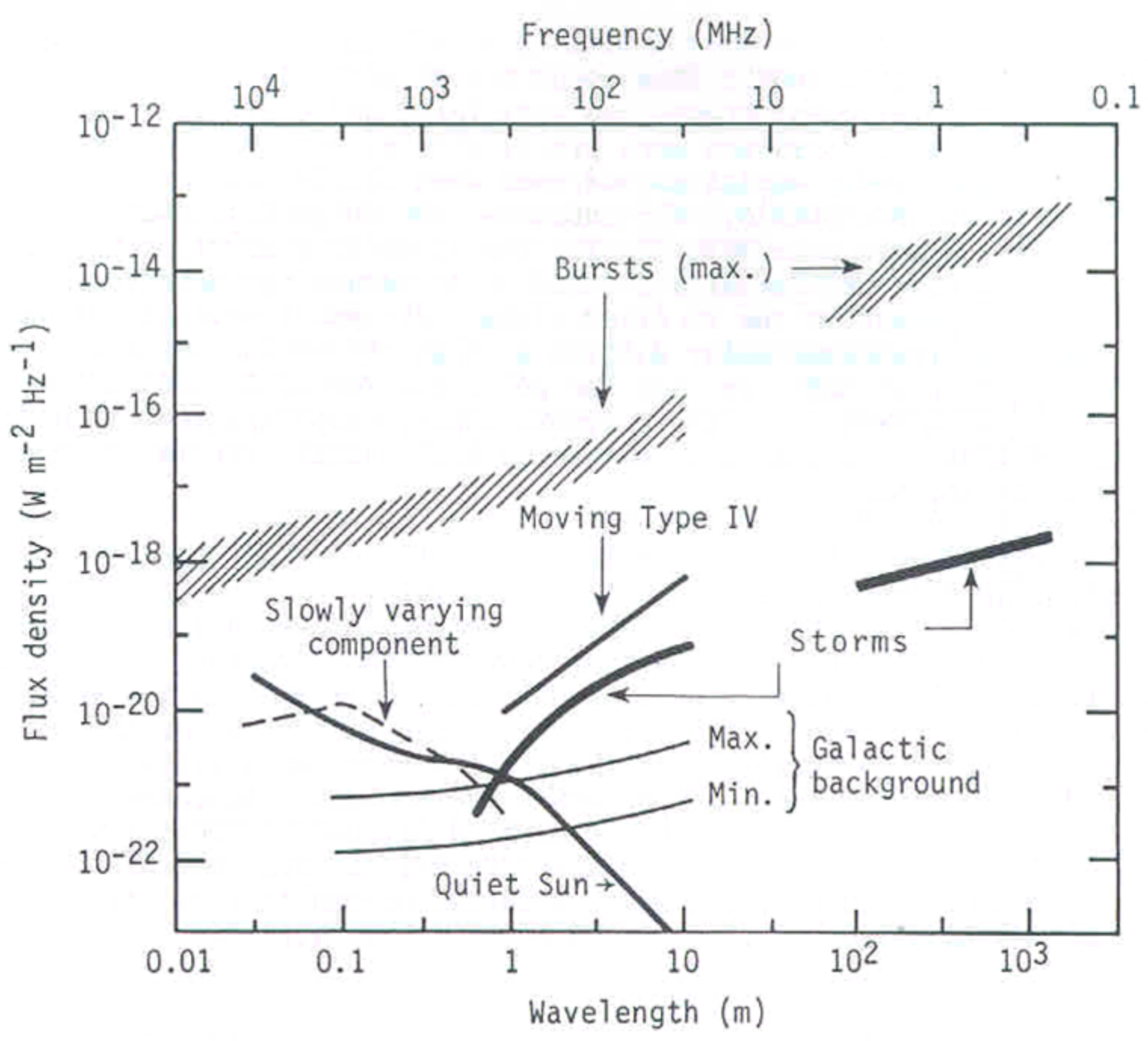
For geostationary satellites occur around equinoxes, for 10s of minutes/day for about 2 weeks



Kennewell & McDonald

Solar radio bursts

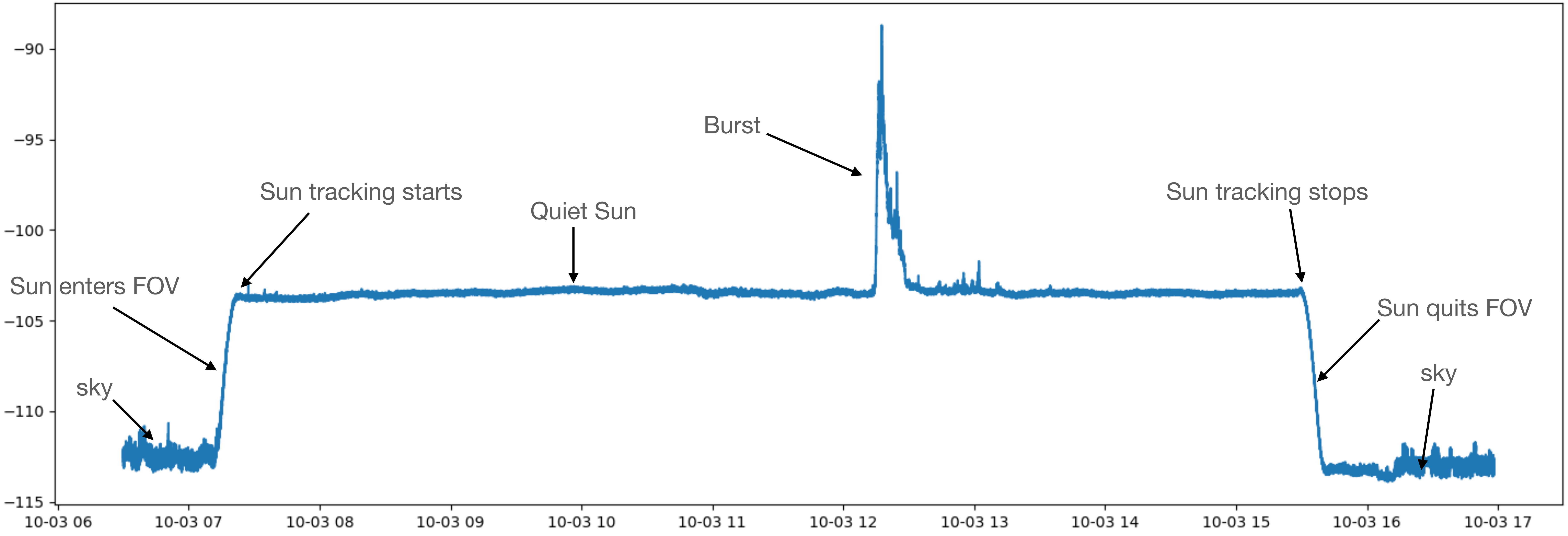
Solar radio bursts

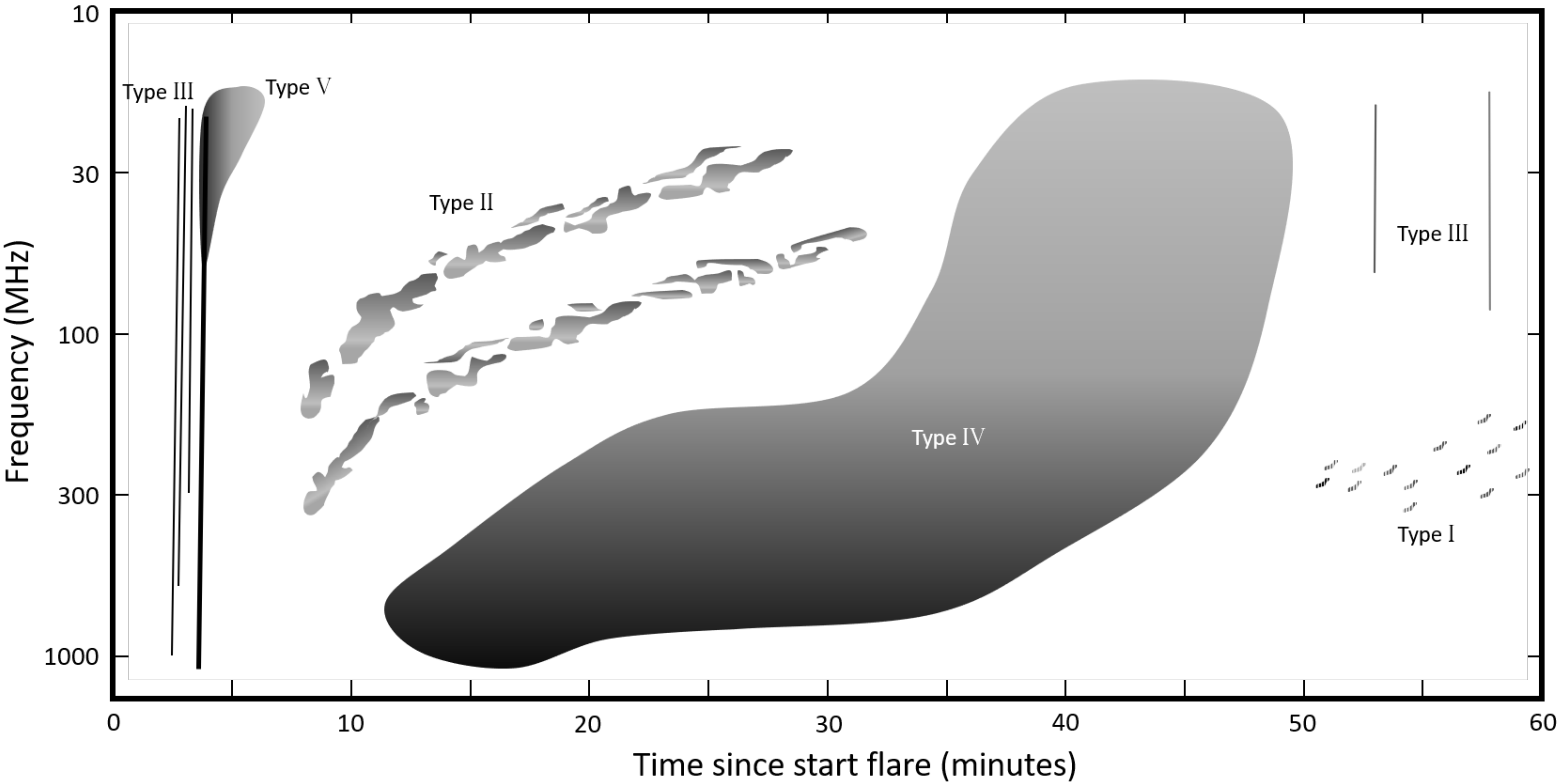


Bursts are mostly intense from HF to S bands

Example in L band

Solar observations from Belgium




10
30
100
300
1000
Frequency (MHz)
0
10
20
30
40
50
60
Time since start flare (minutes)
Type III
Type V
Type II
Type IV
Type III
Type I

source: STCE

Radio bursts

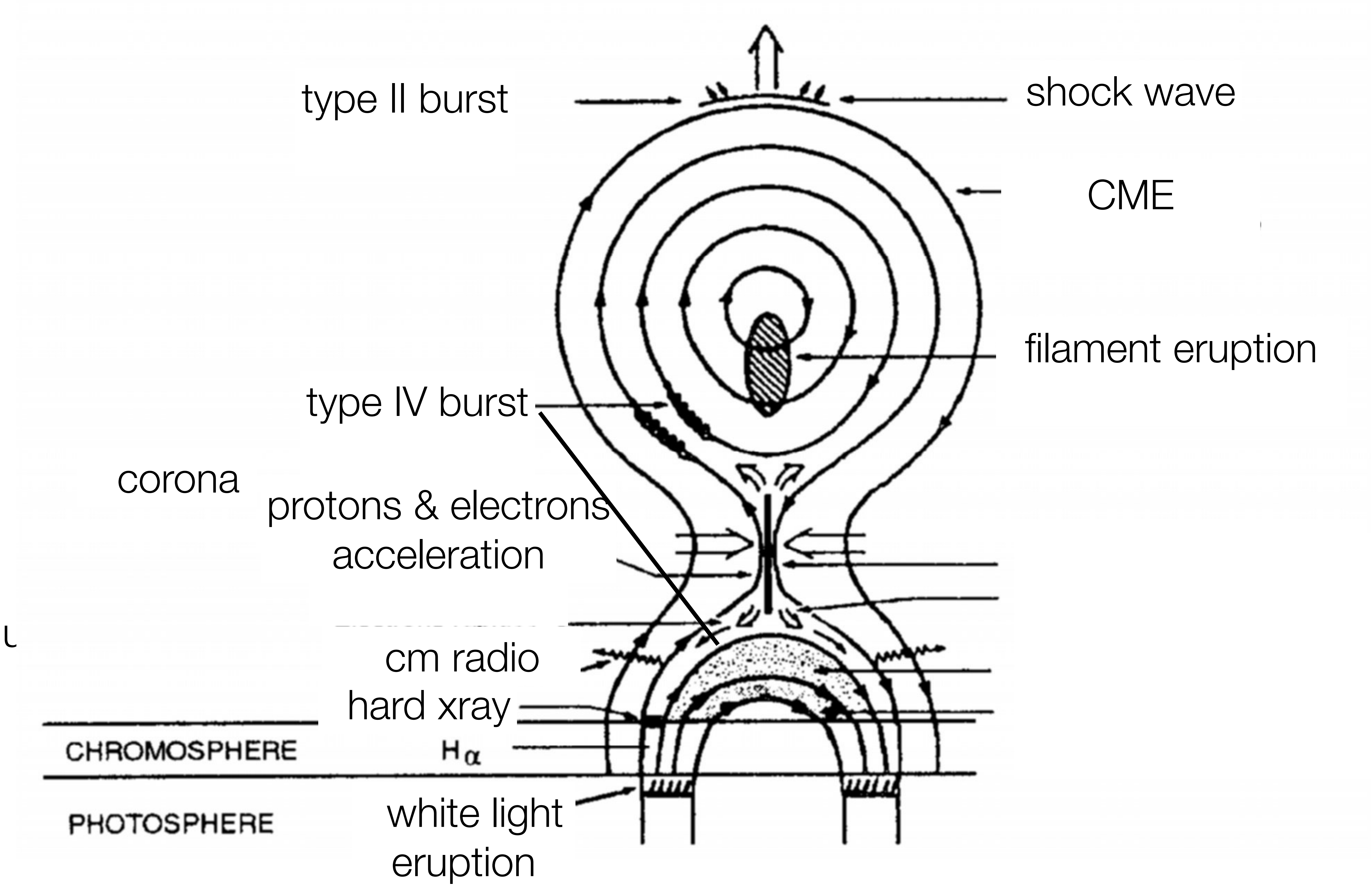
Solar radio bursts are produced by non thermal electrons accelerated during eruptive events of all magnitudes

For frequencies (f) below ~ 1 GHz, the dominant emission is called plasma emission, where energetic electrons trigger local plasma oscillations which are then converted into E. M. radiations

$$f \propto \sqrt{n_e}$$

Spectral signatures (type I, type II, type III ...)

Above, ECM, gyroemissions, gyrosynchrotrons or bremstrahlu emissions dominate



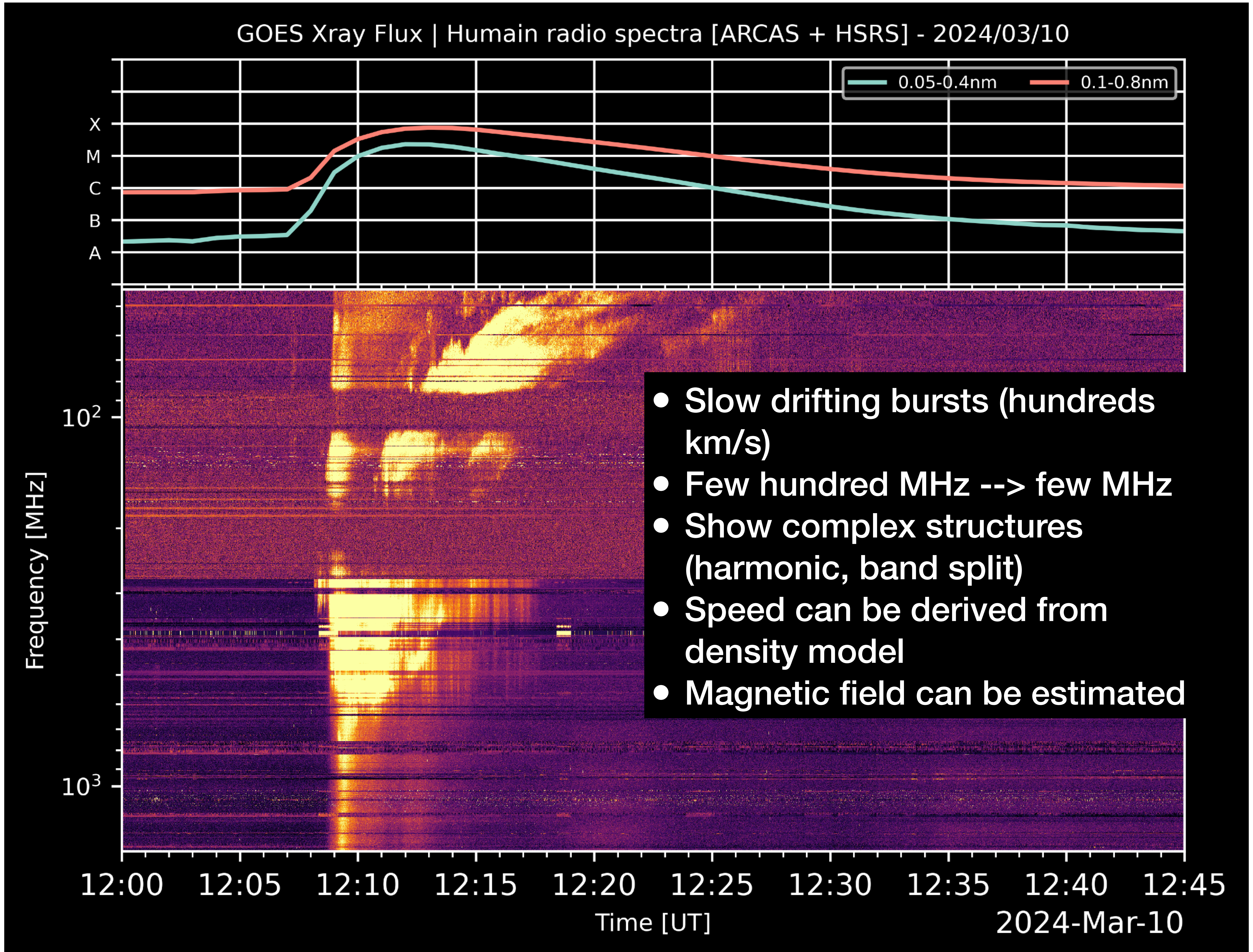
Type I & noise storms

Non flaring radio bursts linked to sunspots

- Energised electrons in loops
- Observed from 200-300 MHz down to 20-30 MHz
- Type I are the individual bursts, storm is the ensemble
- Can occur with groups and storms of type III bursts

Type II bursts

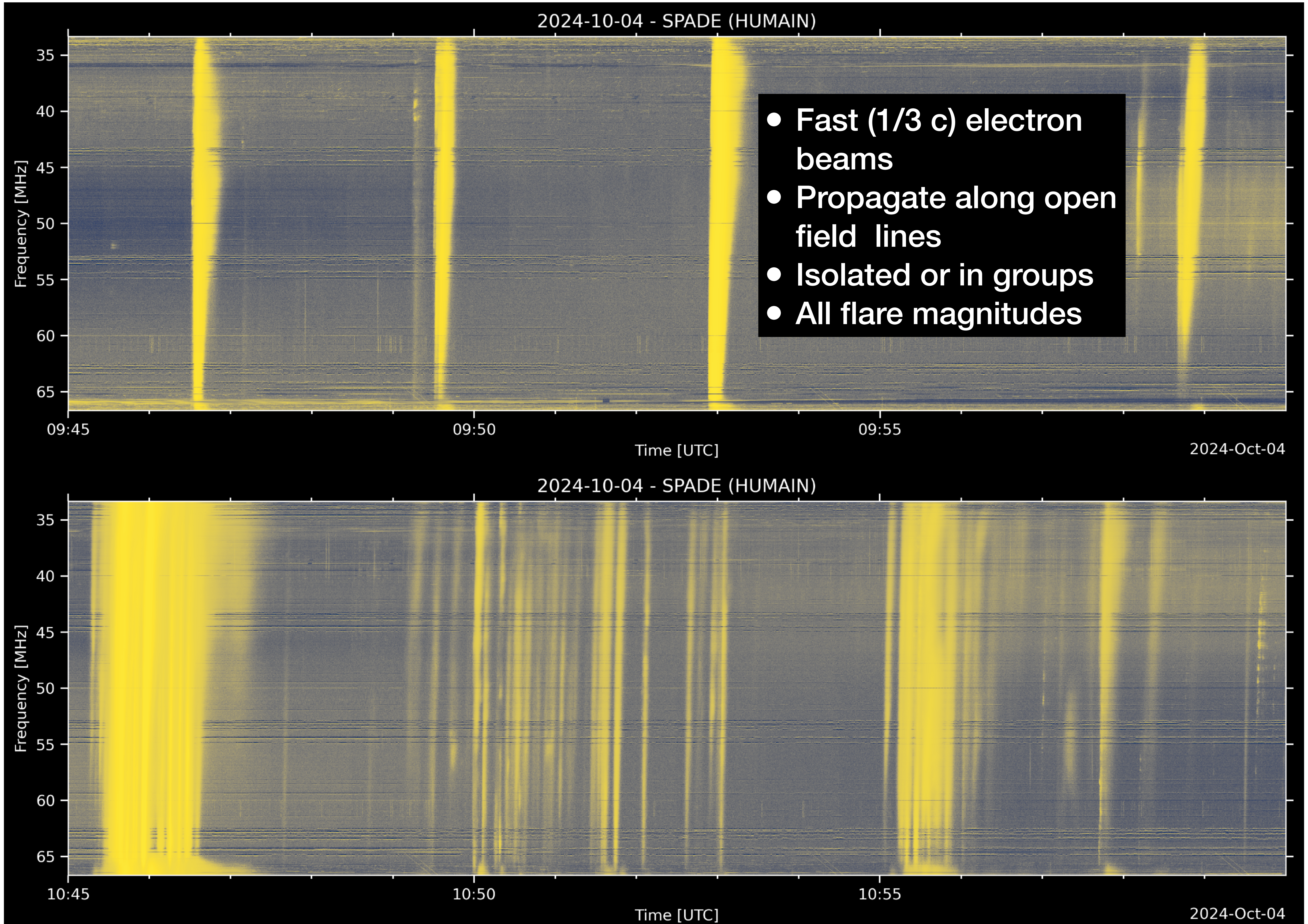
linked to shock waves propagating out in the corona



- Slow drifting bursts (hundreds km/s)
- Few hundred MHz --> few MHz
- Show complex structures (harmonic, band split)
- Speed can be derived from density model
- Magnetic field can be estimated

Type III bursts

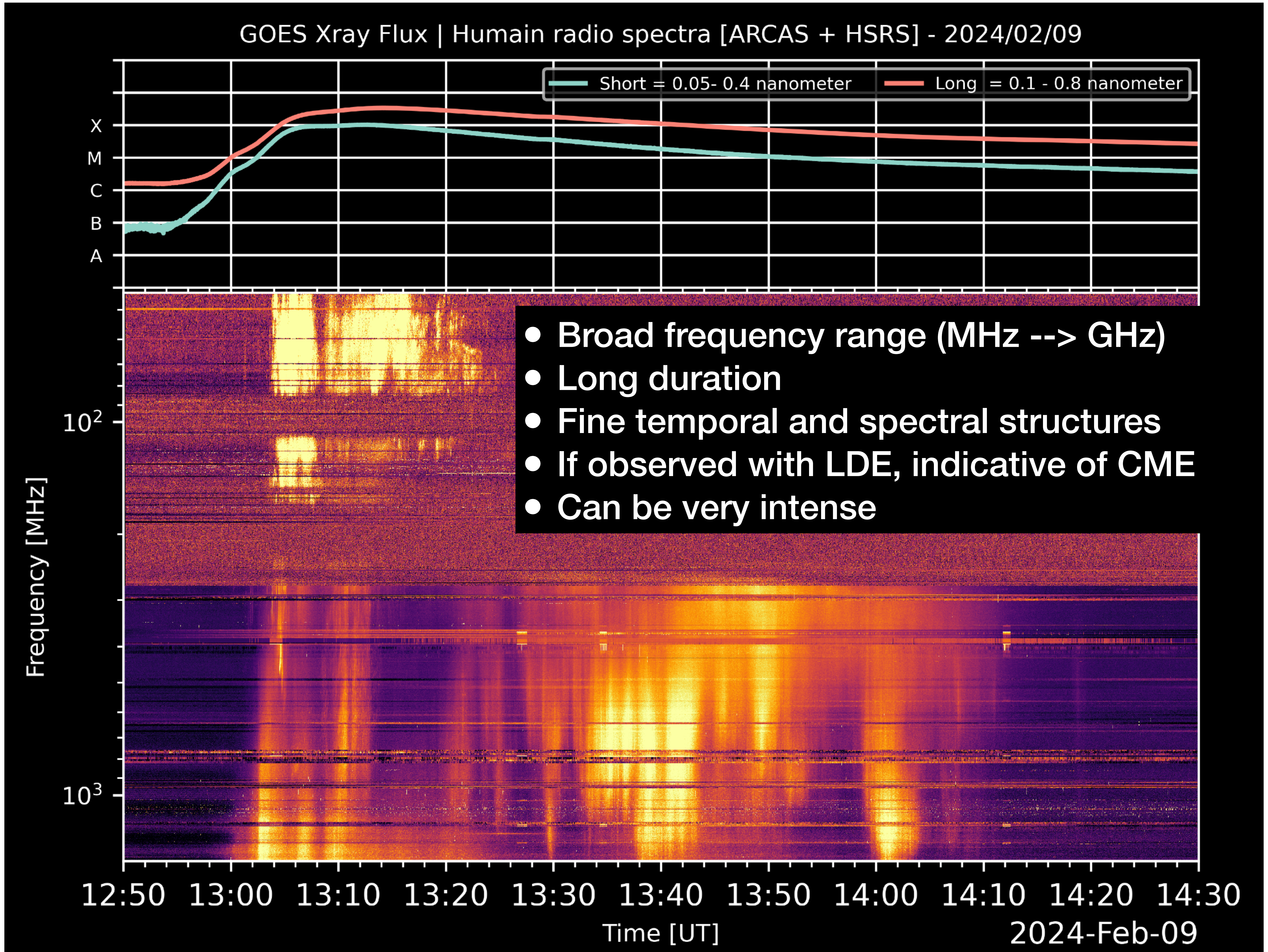
Most frequent type of bursts



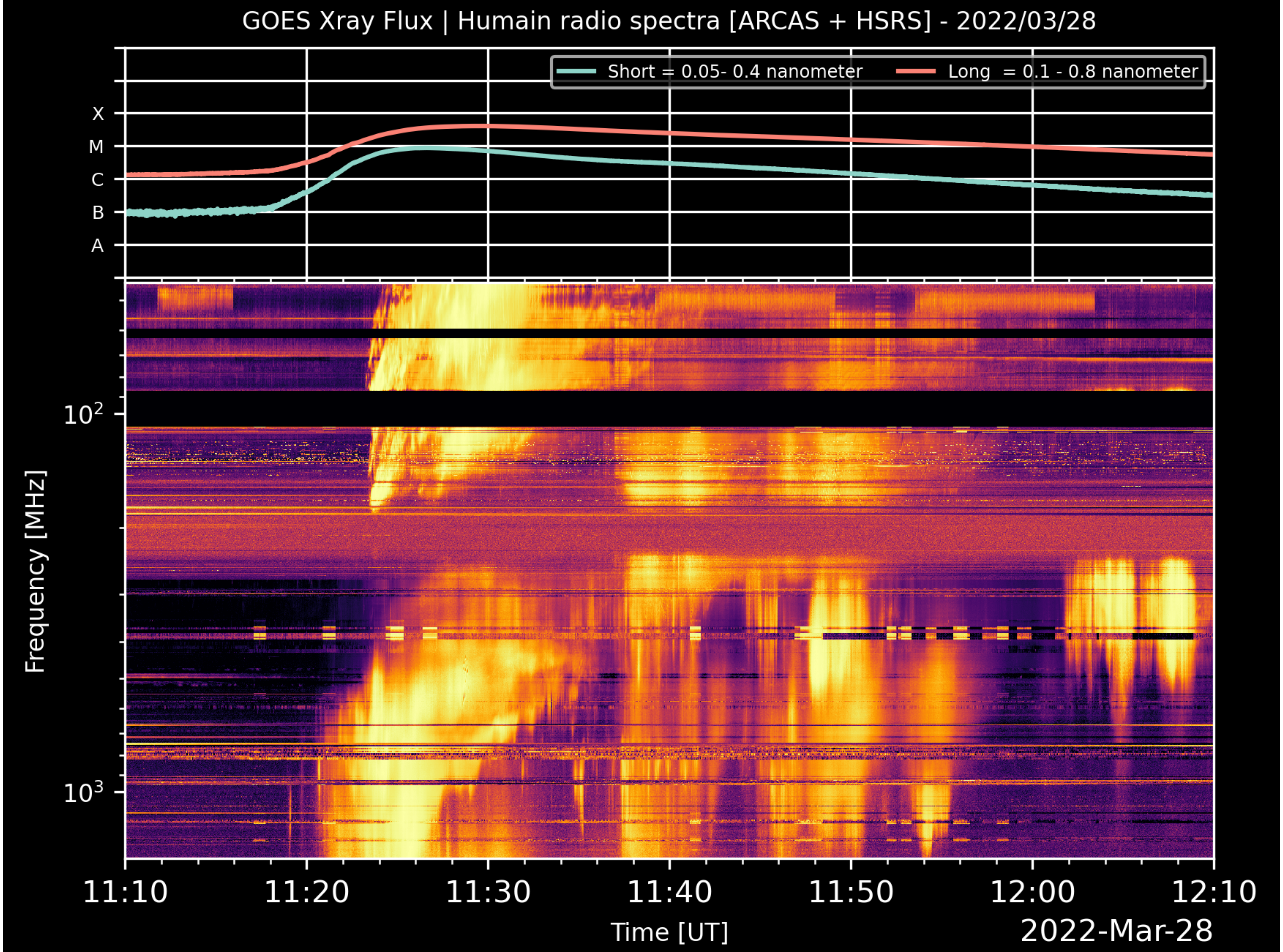
- Fast (1/3 c) electron beams
- Propagate along open field lines
- Isolated or in groups
- All flare magnitudes

Type IV bursts

Energetic electrons trapped in post-flare loops



- Broad frequency range (MHz --> GHz)
- Long duration
- Fine temporal and spectral structures
- If observed with LDE, indicative of CME
- Can be very intense

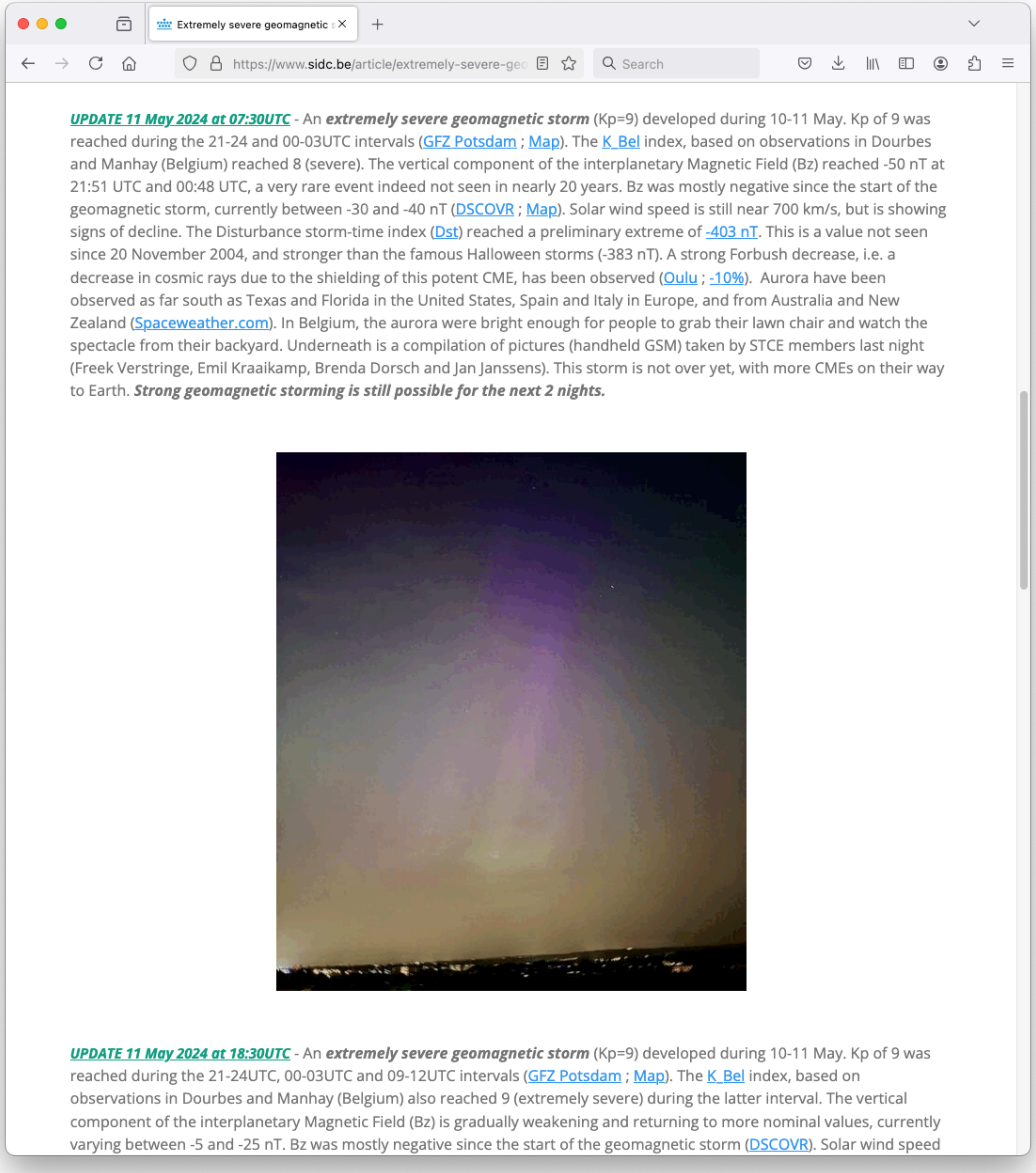

GOES Xray Flux | Humain radio spectra [ARCAS + HSRS] - 2022/03/28
Short = 0.05- 0.4 nanometer
Long = 0.1 - 0.8 nanometer
X
M
C
B
A
10^2
10^3
Frequency [MHz]
11:10
11:20
11:30
11:40
11:50
12:00
12:10
Time [UT]
2022-Mar-28

	Frequency range	**Properties**	**Impact**
Noise storms / Type I	HF, VHF	can be intense, long duration (days), frequent	**Possible**
Type II	HF, VHF	last few minutes, rare	**No**
Type III	HF, VHF	Intense, short duration, very frequent	**No**
Type IV	HF, VHF, UHF	Intense, long duration, broadband	**Yes**

Impact of SRBs

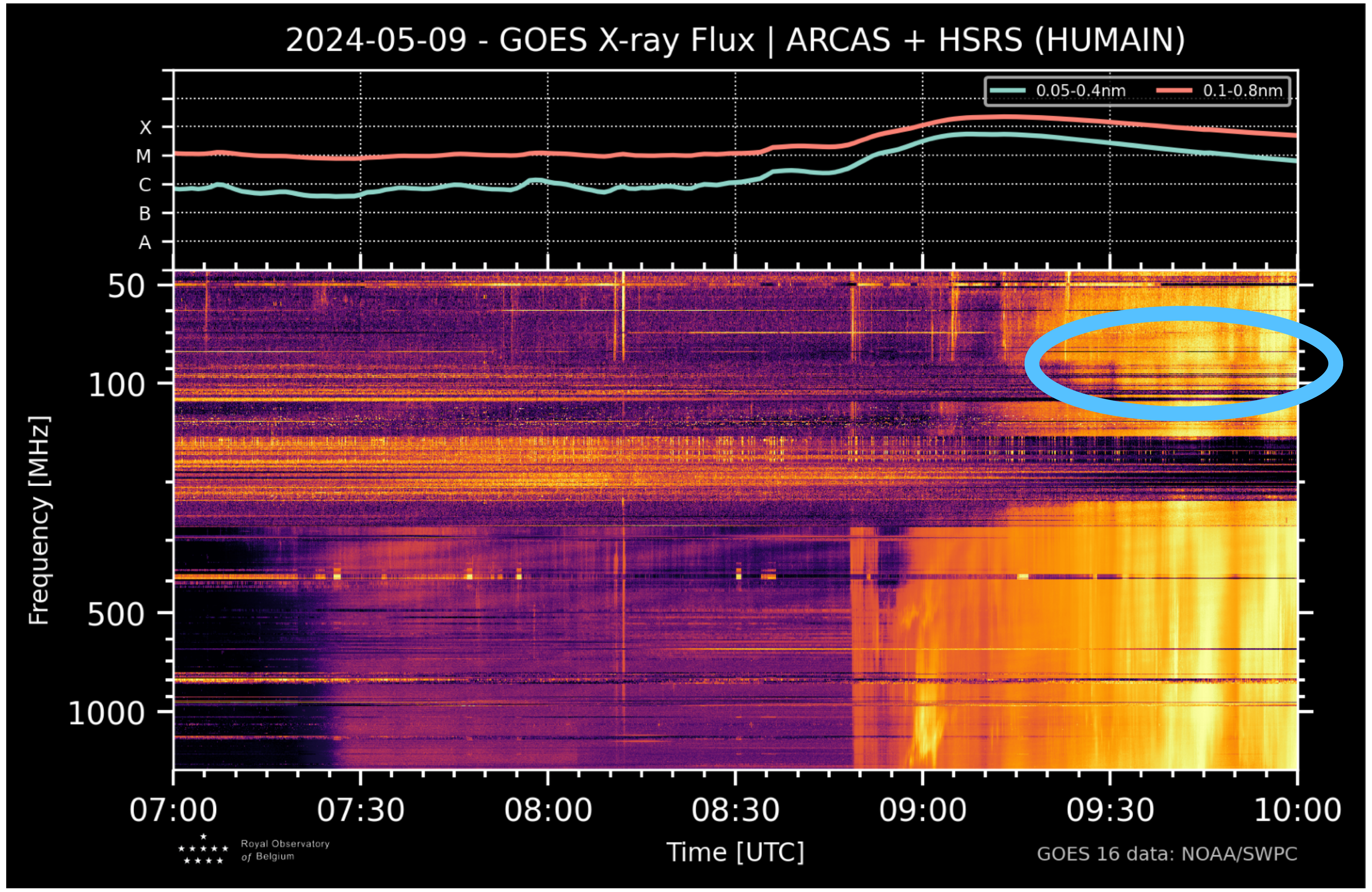
May 2024 events

- **Series of radio bursts observed from May 4 till May 14**
- **Mostly decimetric type IV bursts (energetic electrons trapped in post flare loops)**
- **2 Major events on May 8 and May 9**

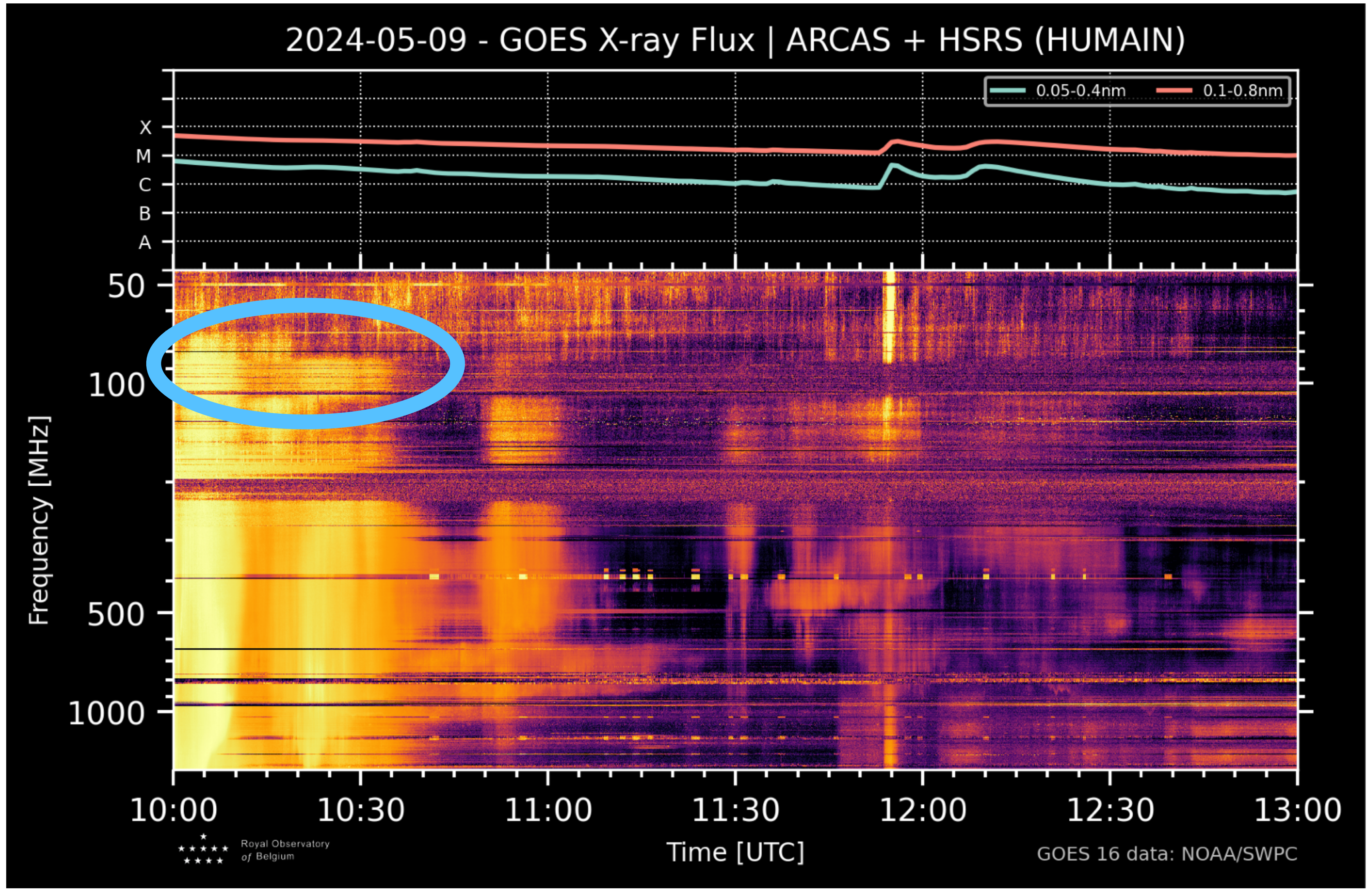


UPDATE 11 May 2024 at 07:30UTC - An ***extremely severe geomagnetic storm*** (Kp=9) developed during 10-11 May. Kp of 9 was reached during the 21-24 and 00-03UTC intervals (GFZ Potsdam ; Map). The K_Bel index, based on observations in Dourbes and Manhay (Belgium) reached 8 (severe). The vertical component of the interplanetary Magnetic Field (Bz) reached -50 nT at 21:51 UTC and 00:48 UTC, a very rare event indeed not seen in nearly 20 years. Bz was mostly negative since the start of the geomagnetic storm, currently between -30 and -40 nT (DSCOVR ; Map). Solar wind speed is still near 700 km/s, but is showing signs of decline. The Disturbance storm-time index (Dst) reached a preliminary extreme of -403 nT. This is a value not seen since 20 November 2004, and stronger than the famous Halloween storms (-383 nT). A strong Forbush decrease, i.e. a decrease in cosmic rays due to the shielding of this potent CME, has been observed (Oulu ; -10%). Aurora have been observed as far south as Texas and Florida in the United States, Spain and Italy in Europe, and from Australia and New Zealand (Spaceweather.com). In Belgium, the aurora were bright enough for people to grab their lawn chair and watch the spectacle from their backyard. Underneath is a compilation of pictures (handheld GSM) taken by STCE members last night (Freek Verstringe, Emil Kraaikamp, Brenda Dorsch and Jan Janssens). This storm is not over yet, with more CMEs on their way to Earth. ***Strong geomagnetic storming is still possible for the next 2 nights.***

UPDATE 11 May 2024 at 18:30UTC - An ***extremely severe geomagnetic storm*** (Kp=9) developed during 10-11 May. Kp of 9 was reached during the 21-24UTC, 00-03UTC and 09-12UTC intervals (GFZ Potsdam ; Map). The K_Bel index, based on observations in Dourbes and Manhay (Belgium) also reached 9 (extremely severe) during the latter interval. The vertical component of the interplanetary Magnetic Field (Bz) is gradually weakening and returning to more nominal values, currently varying between -5 and -25 nT. Bz was mostly negative since the start of the geomagnetic storm (DSCOVR). Solar wind speed


2024-05-09 - GOES X-ray Flux | ARCAS + HSRS (HUMAIN)

GOES 16 data: NOAA/SWPC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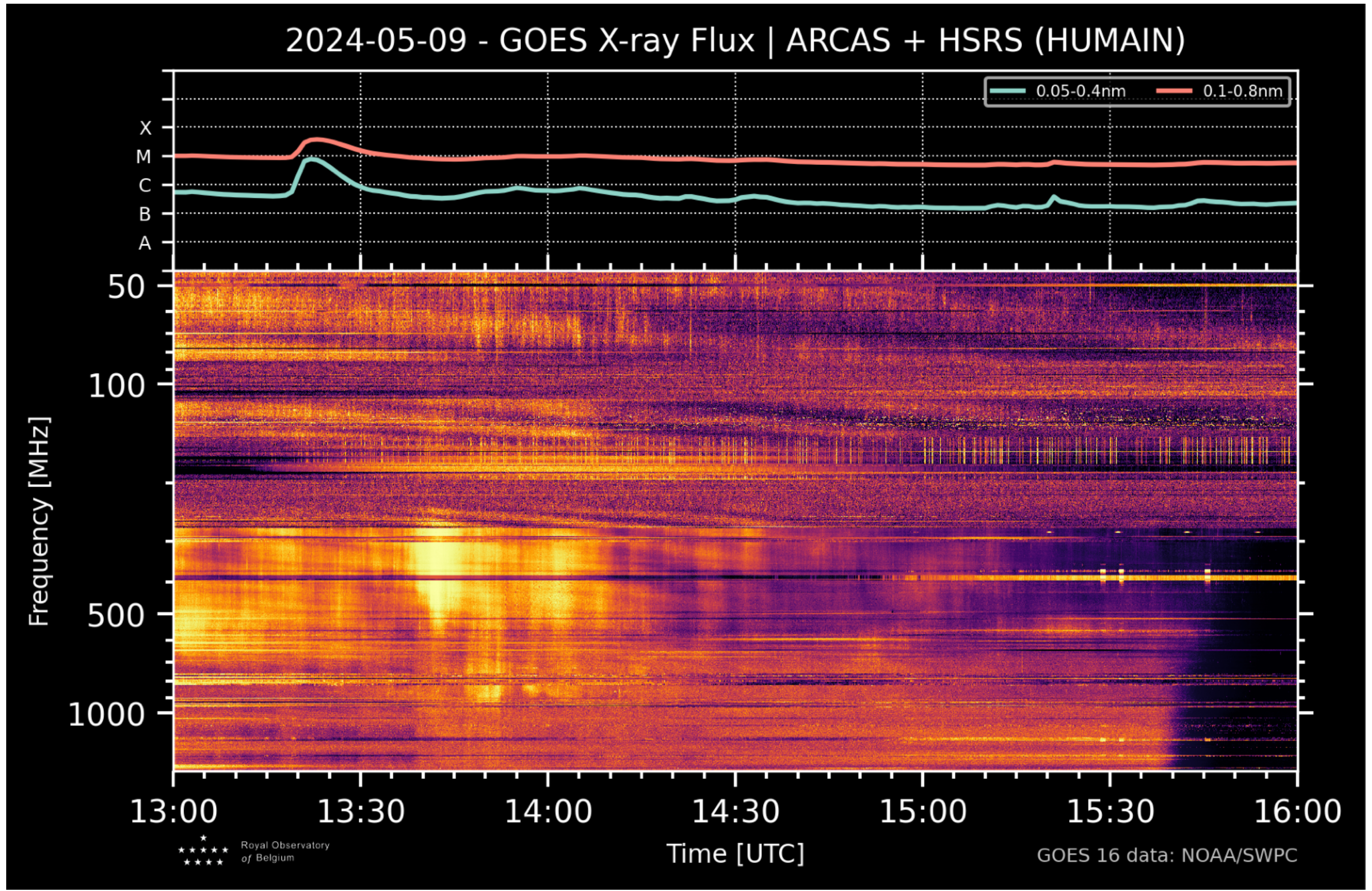
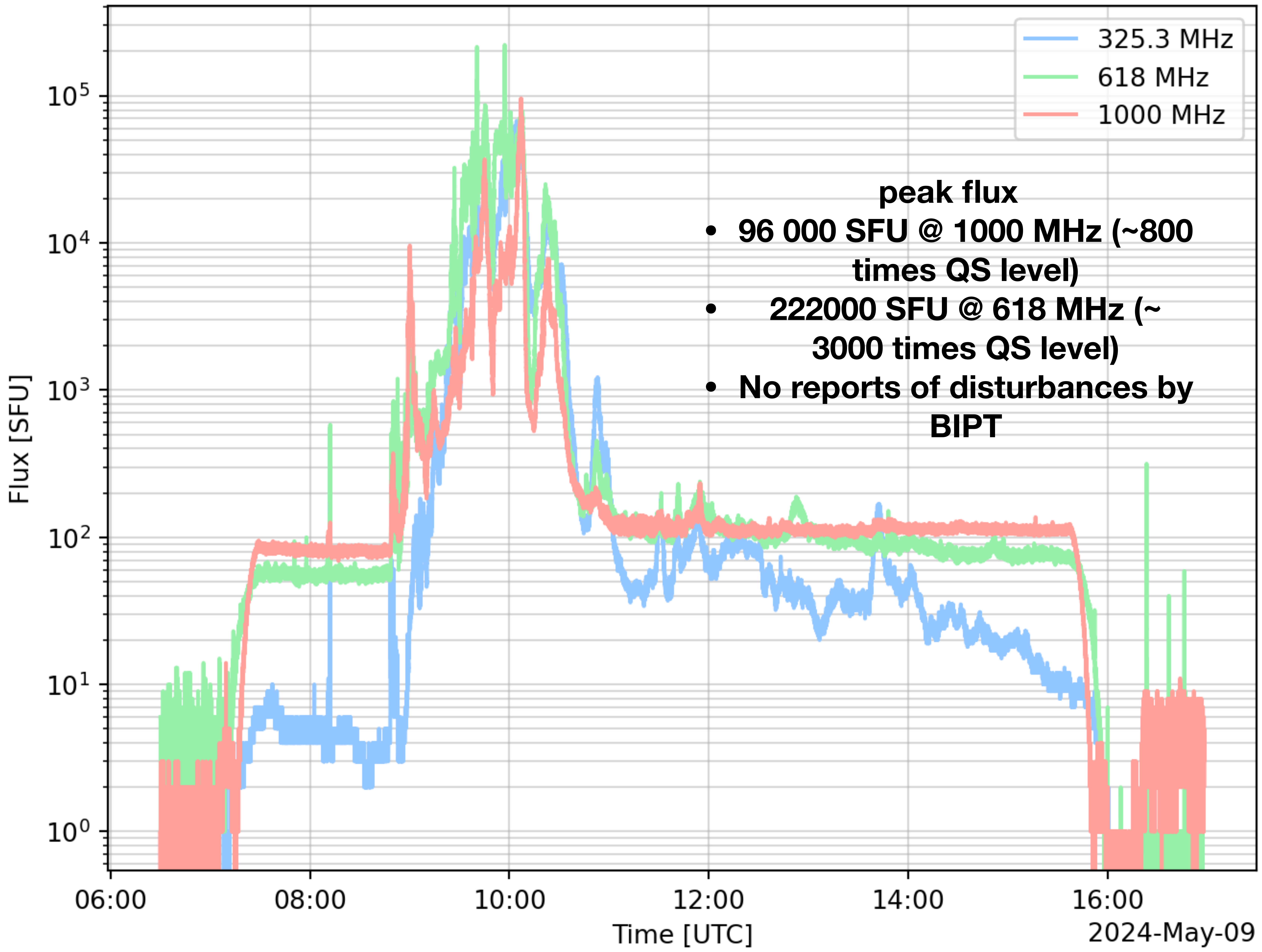
GOES 16 data: NOAA/SWPC


2024-05-09 - GOES X-ray Flux | ARCAS + HSRS (HUMAIN)

GOES 16 data: NOAA/SWPC

May 9

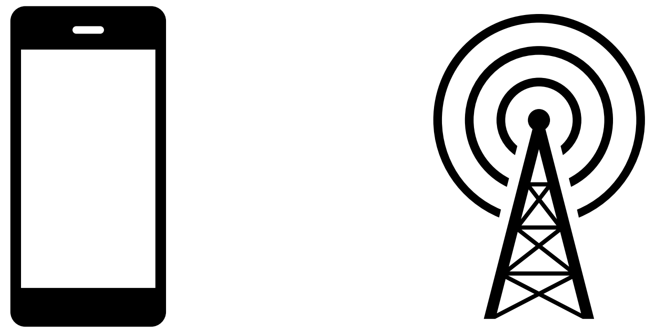
- **Very intense type IV burst linked to X class flare**
- **Solar flux observed even within the FM band rejection filter ! (blue)**

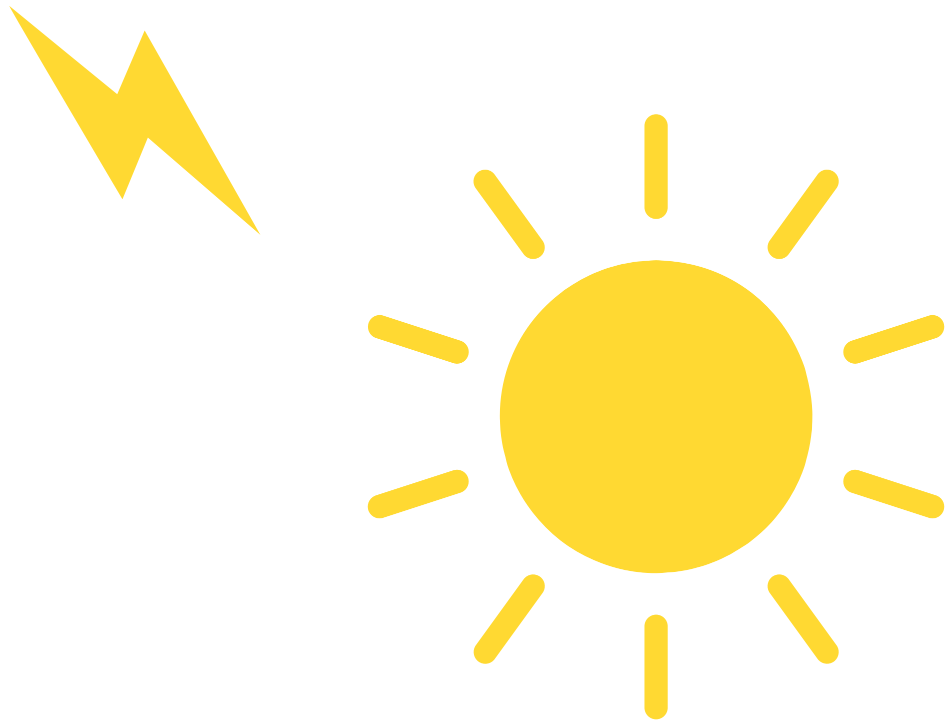


peak flux

- **96 000 SFU @ 1000 MHz (~800 times QS level)**
- **222000 SFU @ 618 MHz (~ 3000 times QS level)**
- **No reports of disturbances by BIPT**

Cell phones





Interference of cell phone towers

Only published report on proven effects of SRBs on cell phones

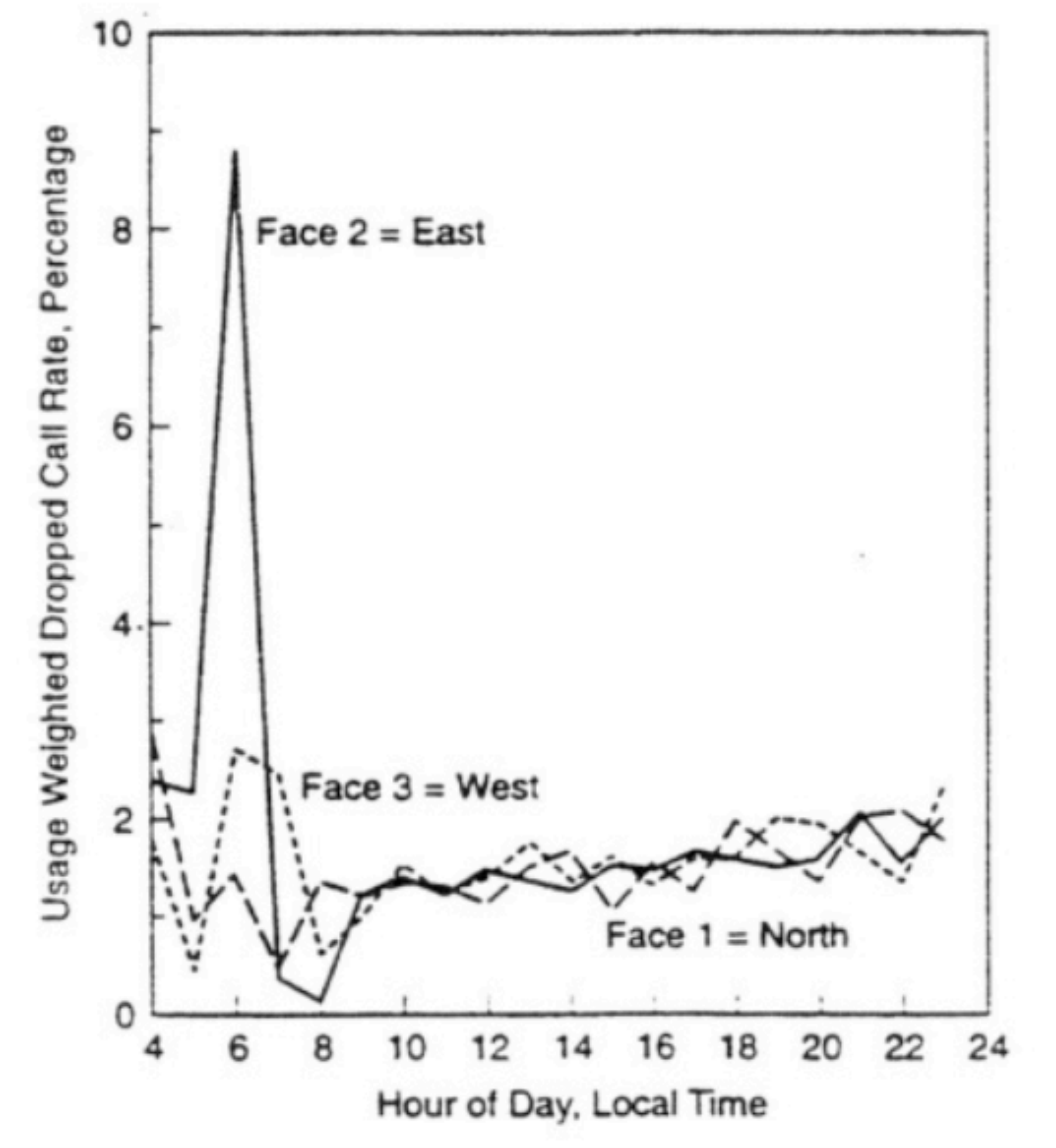


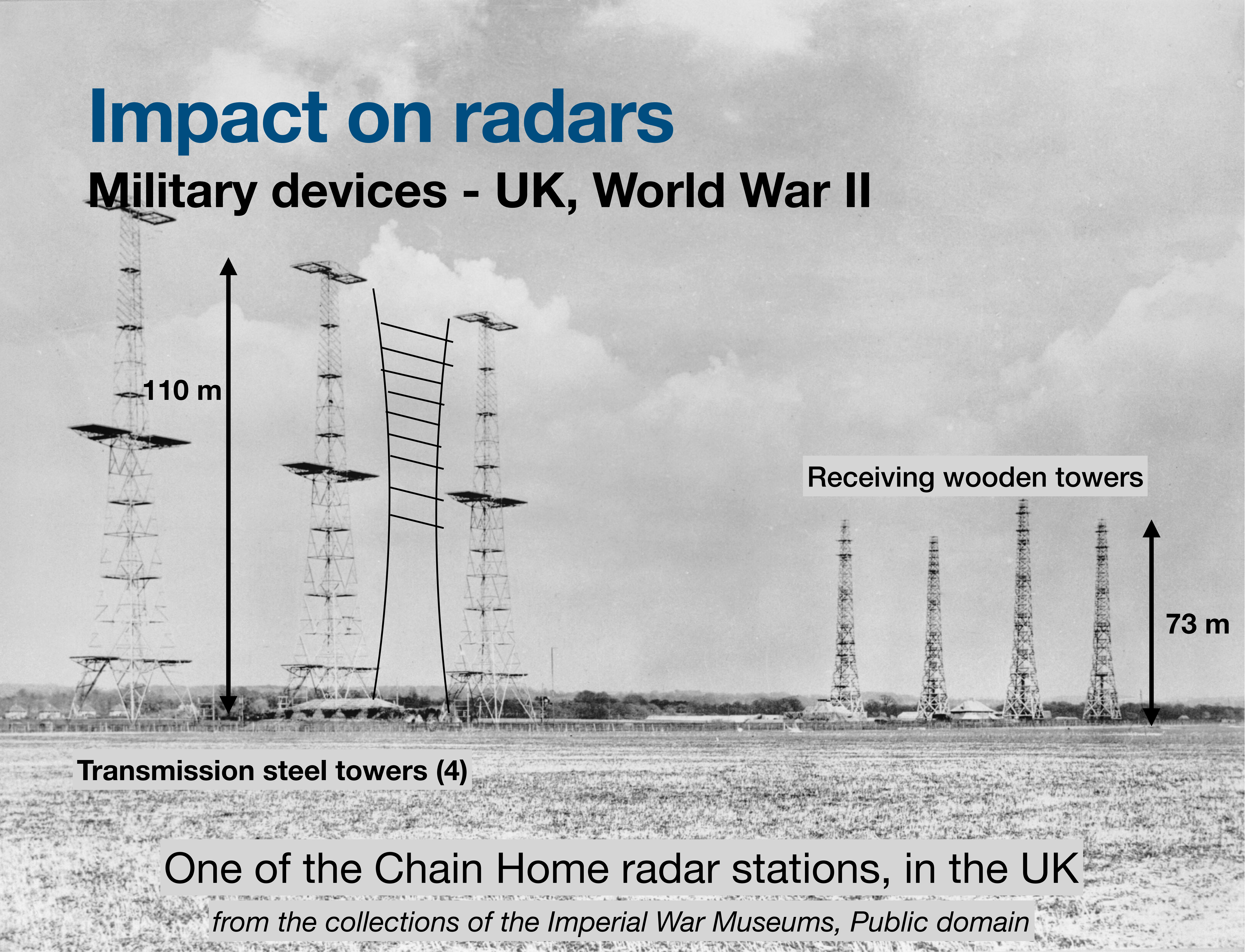
Figure 1. Usage-weighted dropped call rate for a wireless system base station, showing an enhanced level of dropped calls on the east-facing receivers near local sunrise. From Lanzerotti et al. (1999).

Gary et al. 2001

Surveillance radars

Impact on radars

Military devices - UK, World War II



110 m

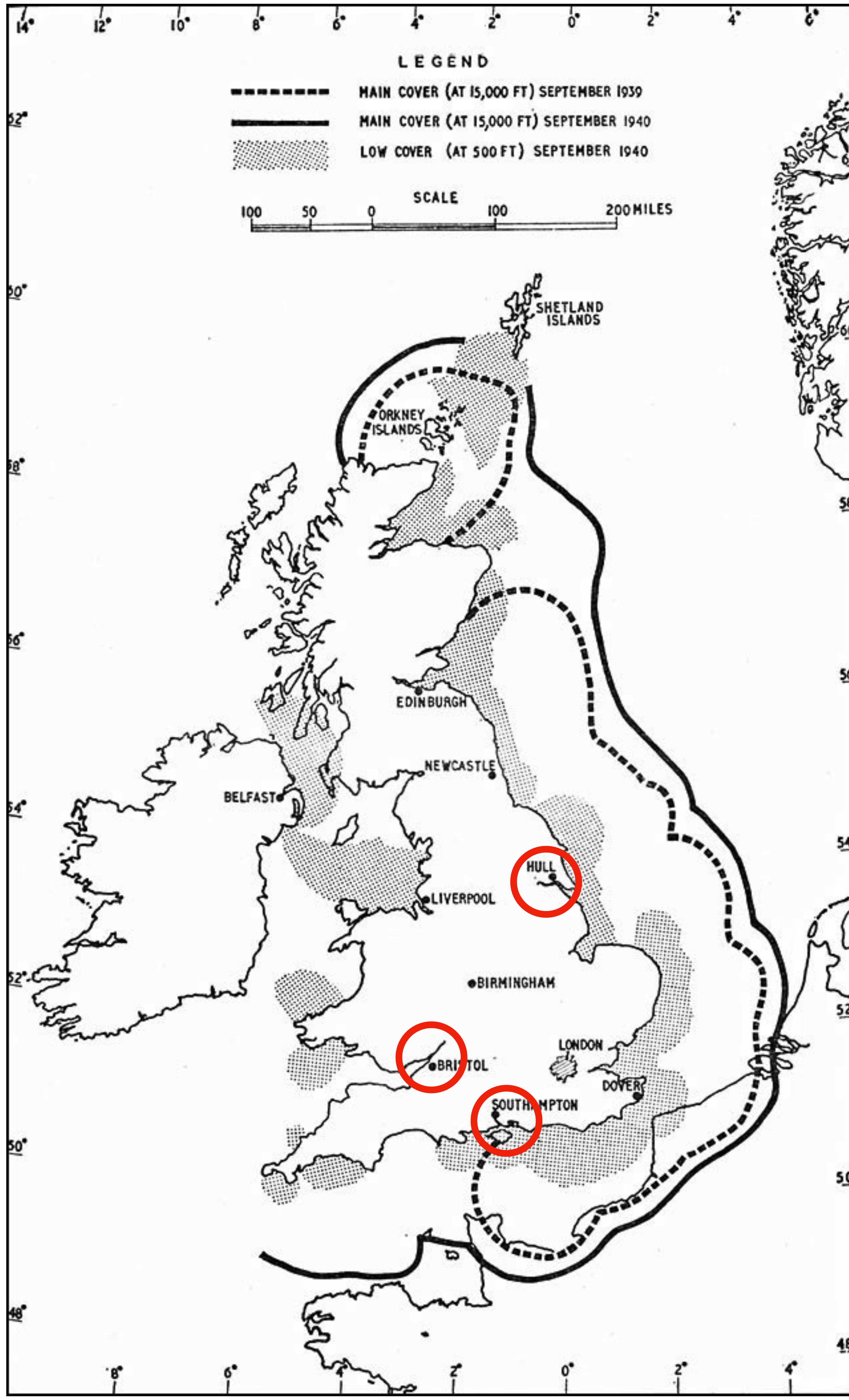
Receiving wooden towers

73 m

Transmission steel towers (4)

One of the Chain Home radar stations, in the UK

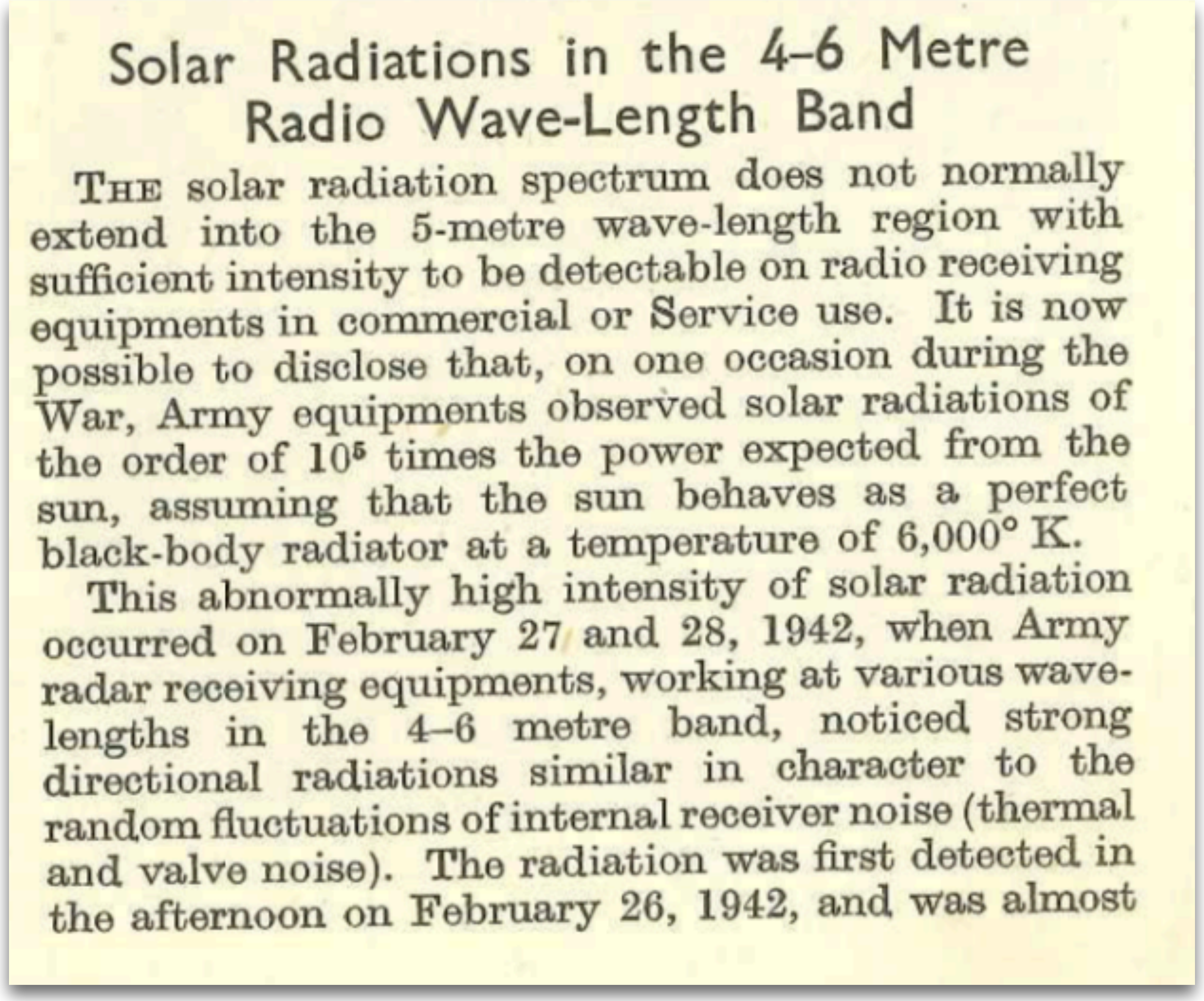
from the collections of the Imperial War Museums, Public domain



WIKIPEDIA

Impact on radars

Military devices - UK, World War II

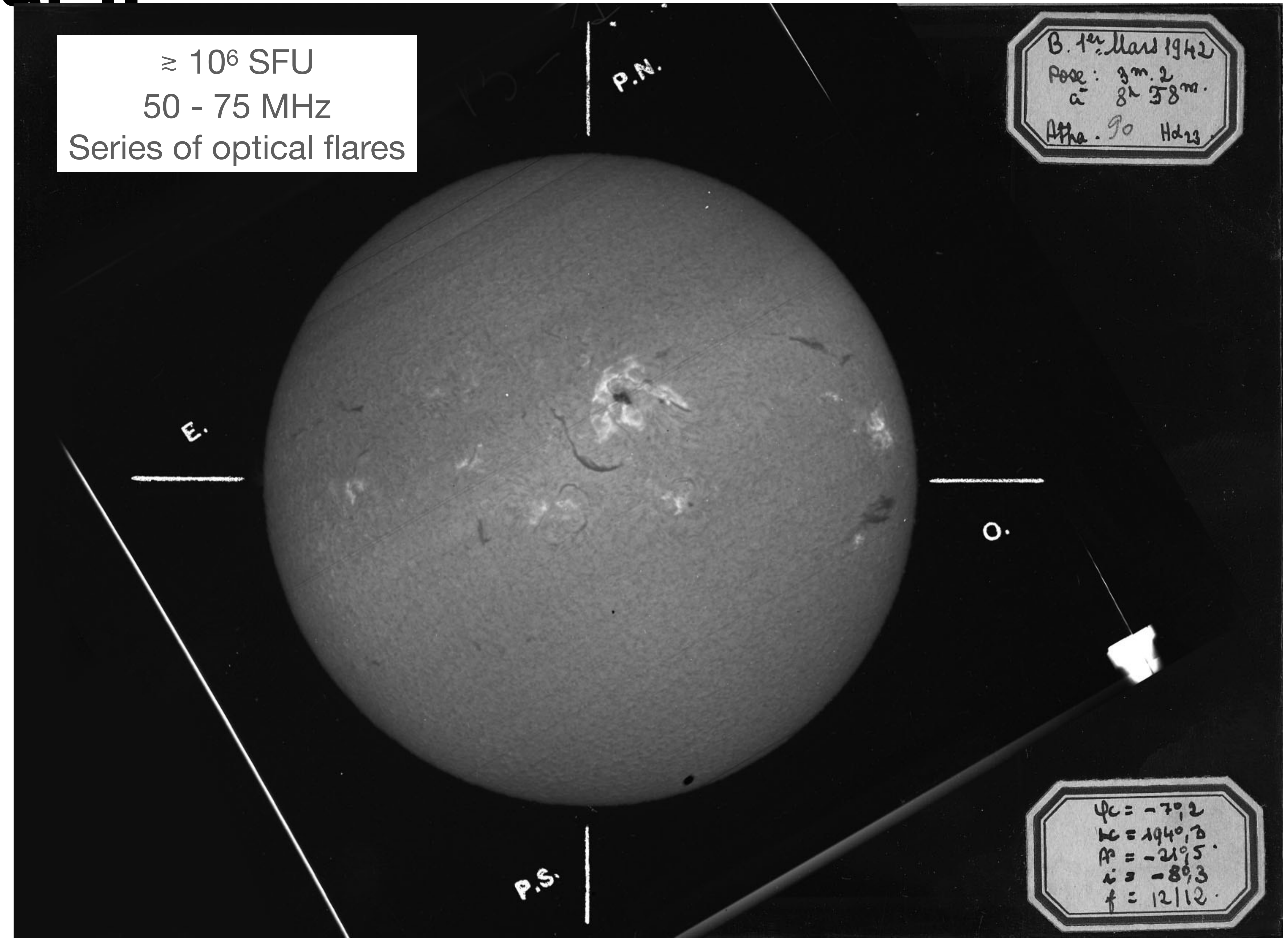


Solar Radiations in the 4–6 Metre Radio Wave-Length Band

THE solar radiation spectrum does not normally extend into the 5-metre wave-length region with sufficient intensity to be detectable on radio receiving equipments in commercial or Service use. It is now possible to disclose that, on one occasion during the War, Army equipments observed solar radiations of the order of 10^5 times the power expected from the sun, assuming that the sun behaves as a perfect black-body radiator at a temperature of 6,000° K.

This abnormally high intensity of solar radiation occurred on February 27 and 28, 1942, when Army radar receiving equipments, working at various wave-lengths in the 4–6 metre band, noticed strong directional radiations similar in character to the random fluctuations of internal receiver noise (thermal and valve noise). The radiation was first detected in the afternoon on February 26, 1942, and was almost

Hey, 1946



$\gtrsim 10^6$ SFU

50 - 75 MHz

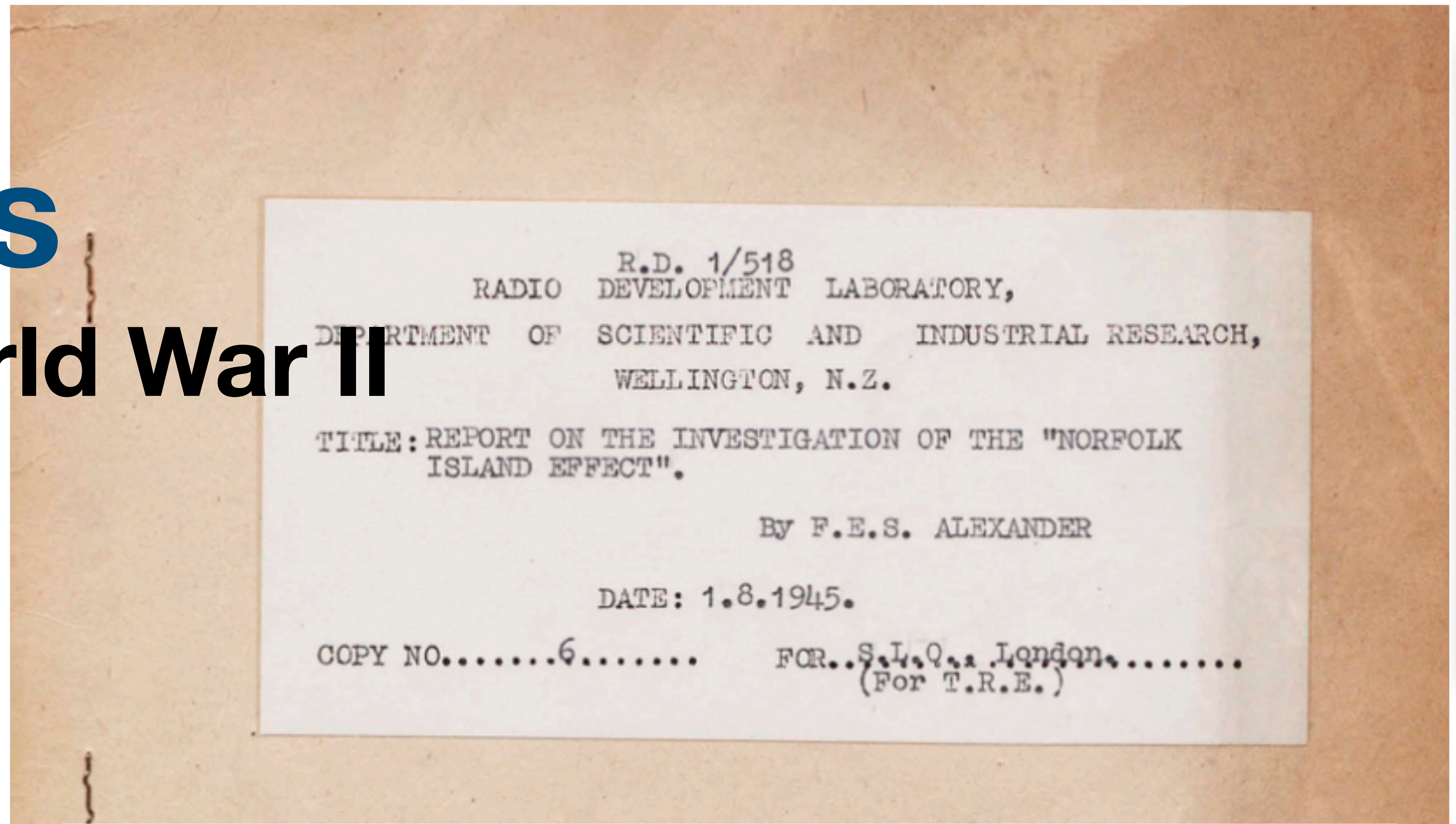
Series of optical flares

source: https://observations-solaires.obspm.fr/

Impact on radars

Military radars - NZ, World War II

- In March - April1945, Royal New Zealand Air Force radar station on the Norfolk Island picked up increase level of noise at Sun rise and Sun set at 200 MHz
- The head of the ORS of Radio Development Lab., Elisabeth Alexander investigated it, with new measurements and linked it to the Sun itself



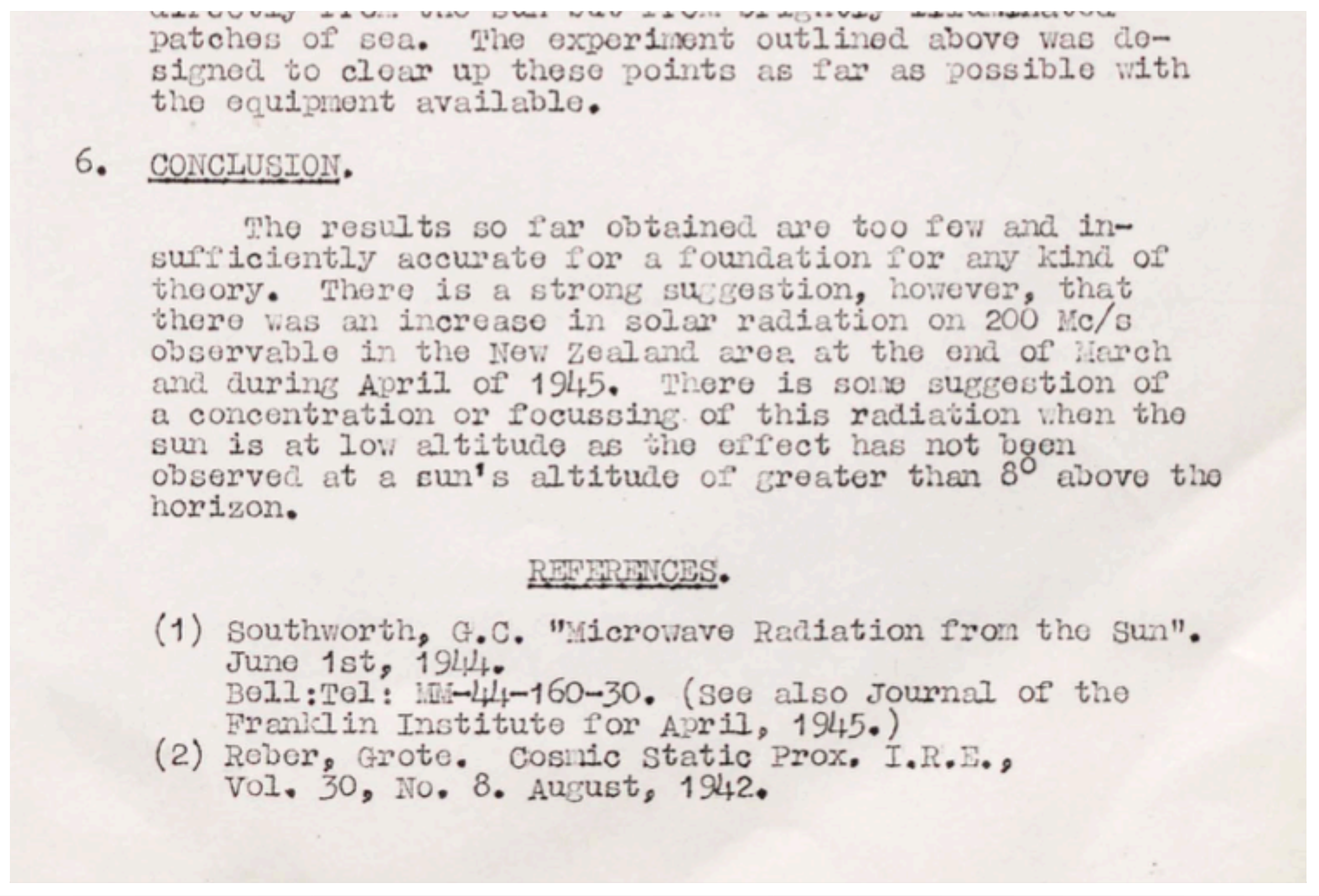
R.D. 1/518
RADIO DEVELOPMENT LABORATORY,
DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH,
WELLINGTON, N.Z.

TITLE: REPORT ON THE INVESTIGATION OF THE "NORFOLK ISLAND EFFECT".

By F.E.S. ALEXANDER

DATE: 1.8.1945.

COPY NO.......6.......   FOR..S.L.O.. London........
(For T.R.E.)



patches of sea. The experiment outlined above was designed to clear up these points as far as possible with the equipment available.

6\. CONCLUSION.

The results so far obtained are too few and insufficiently accurate for a foundation for any kind of theory. There is a strong suggestion, however, that there was an increase in solar radiation on 200 Mc/s observable in the New Zealand area at the end of March and during April of 1945. There is some suggestion of a concentration or focussing of this radiation when the sun is at low altitude as the effect has not been observed at a sun's altitude of greater than 8° above the horizon.

REFERENCES.

(1) Southworth, G.C. "Microwave Radiation from the Sun". June 1st, 1944.
Bell:Tel: MM-44-160-30. (See also Journal of the Franklin Institute for April, 1945.)
(2) Reber, Grote. Cosmic Static Prox. I.R.E., Vol. 30, No. 8. August, 1942.

Elizabeth Alexander

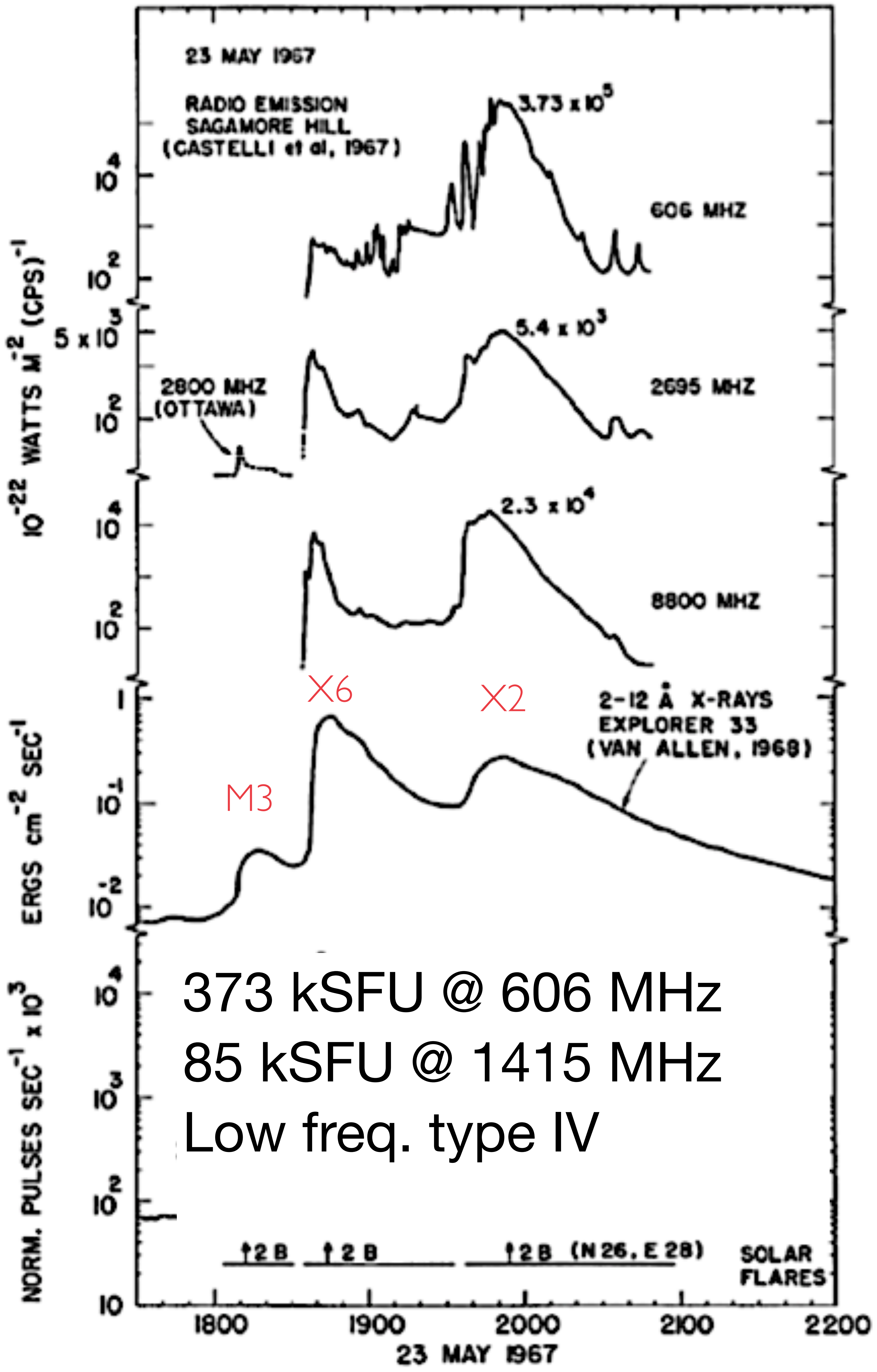
Likely the radar picked up intense noise storm emission from sunspot groups

Impact on radars

Military devices - Cold war

Jamming of Ballistic Missile Early Warning System (BMEWS) radars at 440 MHz

"Cold War military commanders viewed full scale jamming of surveillance sensors as a potential act of war. (...) the online memorial tributes to Col C. K. Anderson, (...) clearly credit him and his NORAD solar forecasting staff (...) with providing the information that eventually calmed nerves and allowed aircraft engines to cool as they returned to normal alert stance."



373 kSFU @ 606 MHz
85 kSFU @ 1415 MHz
Low freq. type IV

Knipp et al. 2016

MT. WILSON

MAGNETOGRAM
Solid
Dotte

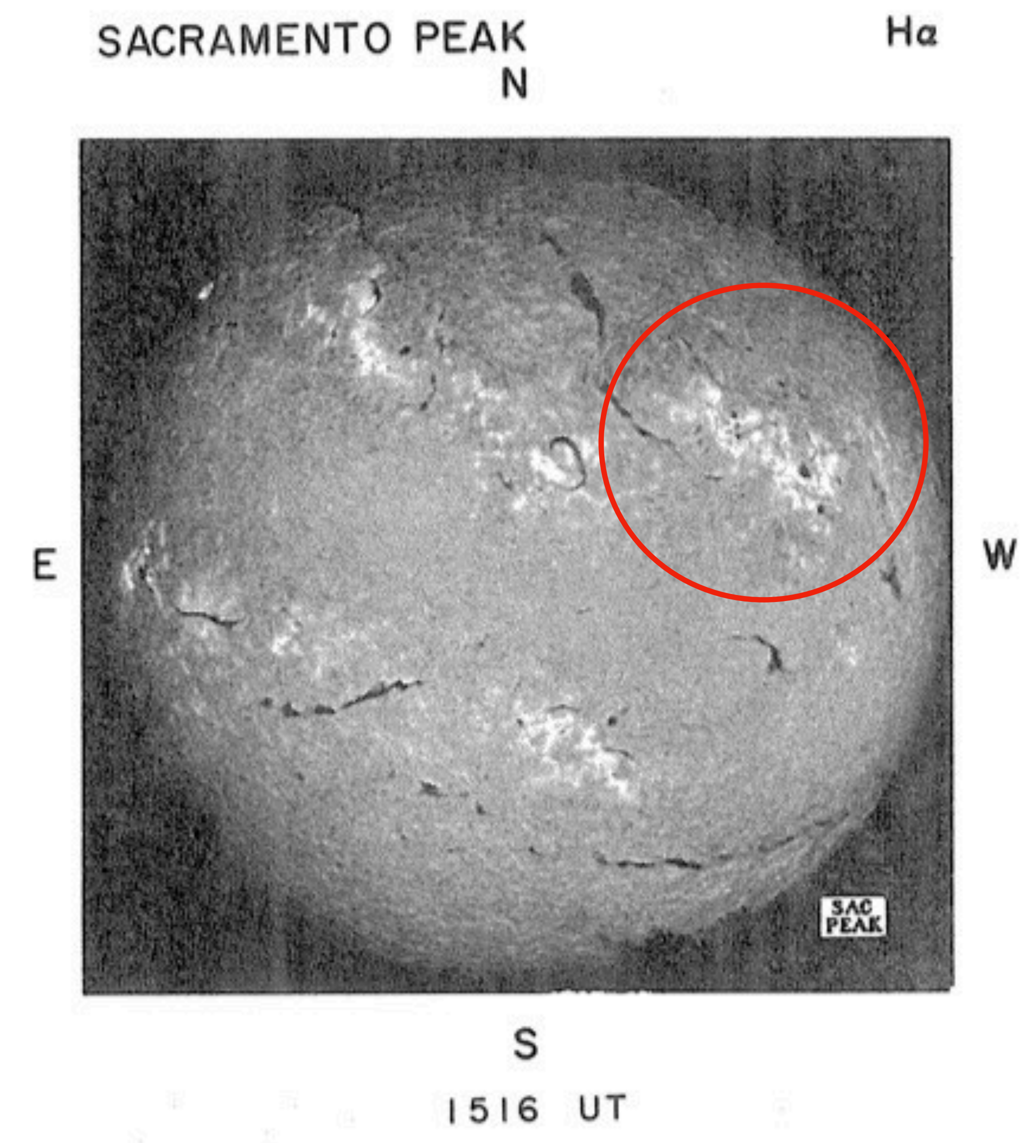
Np

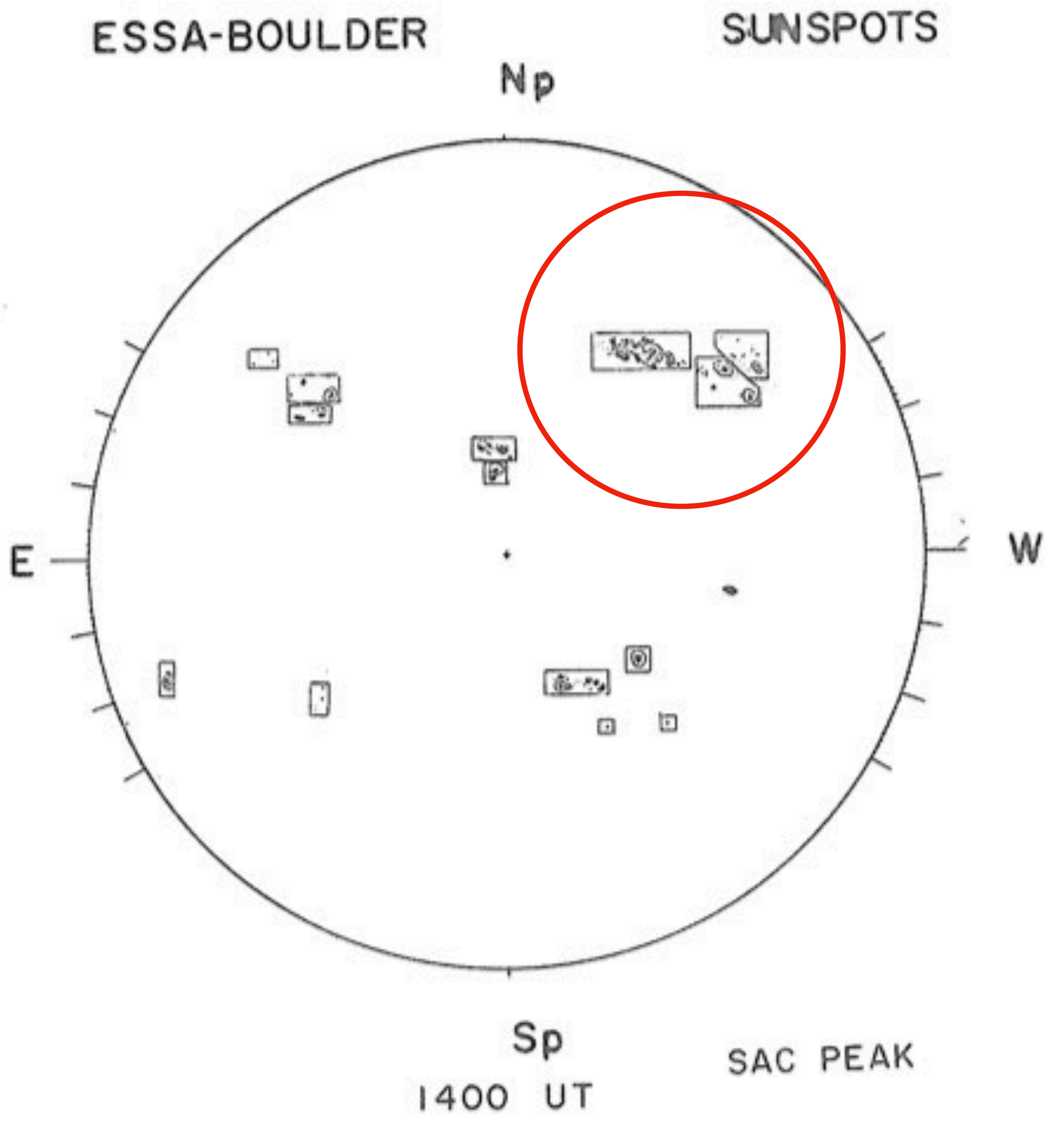
E

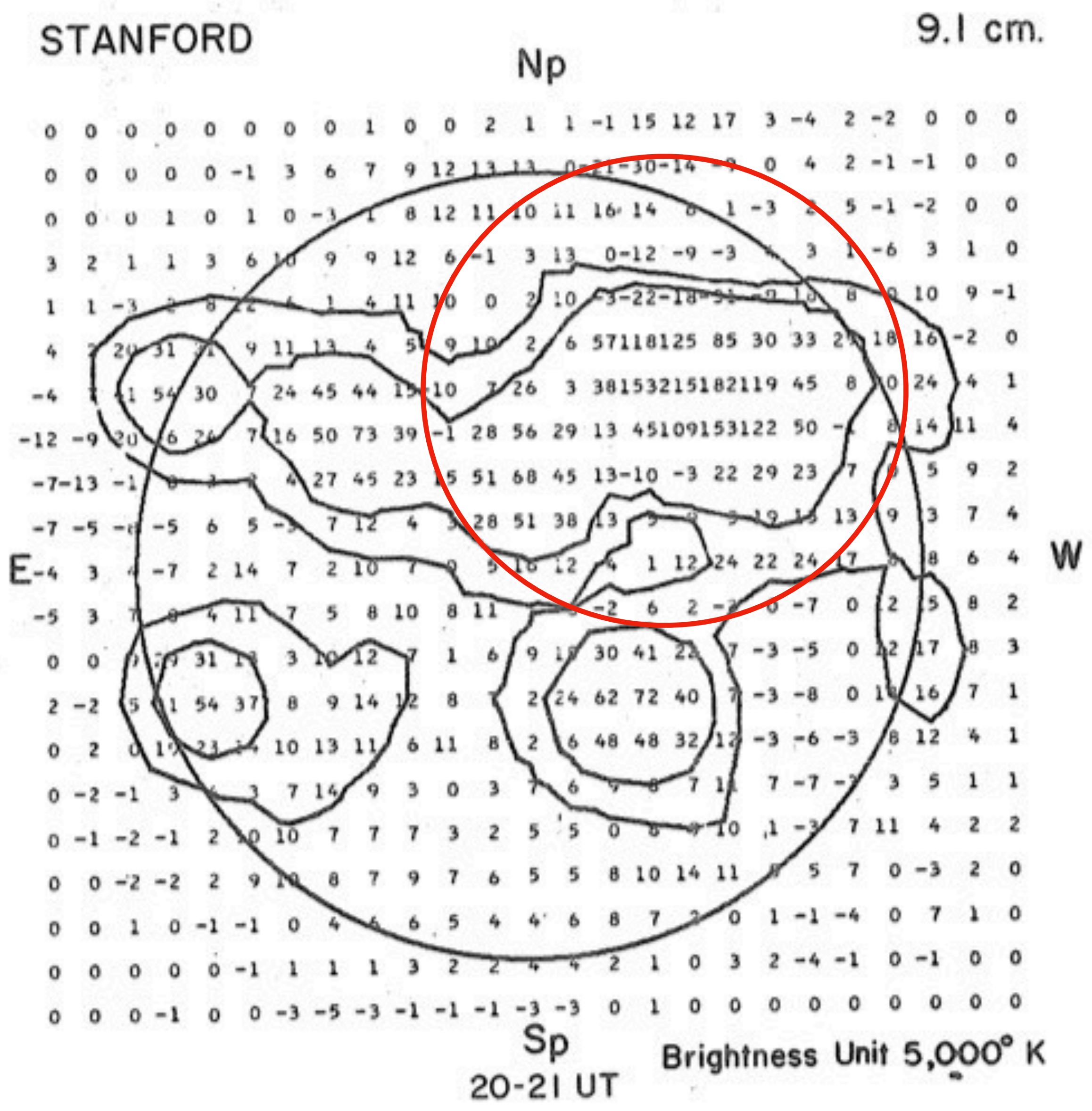
NO DATA

Sp

MAY 27, 1967 (P=-17.51, B_0=-1.29, L_0=207.53)







FLEURS, AUSTRALIA

21 cm.

N

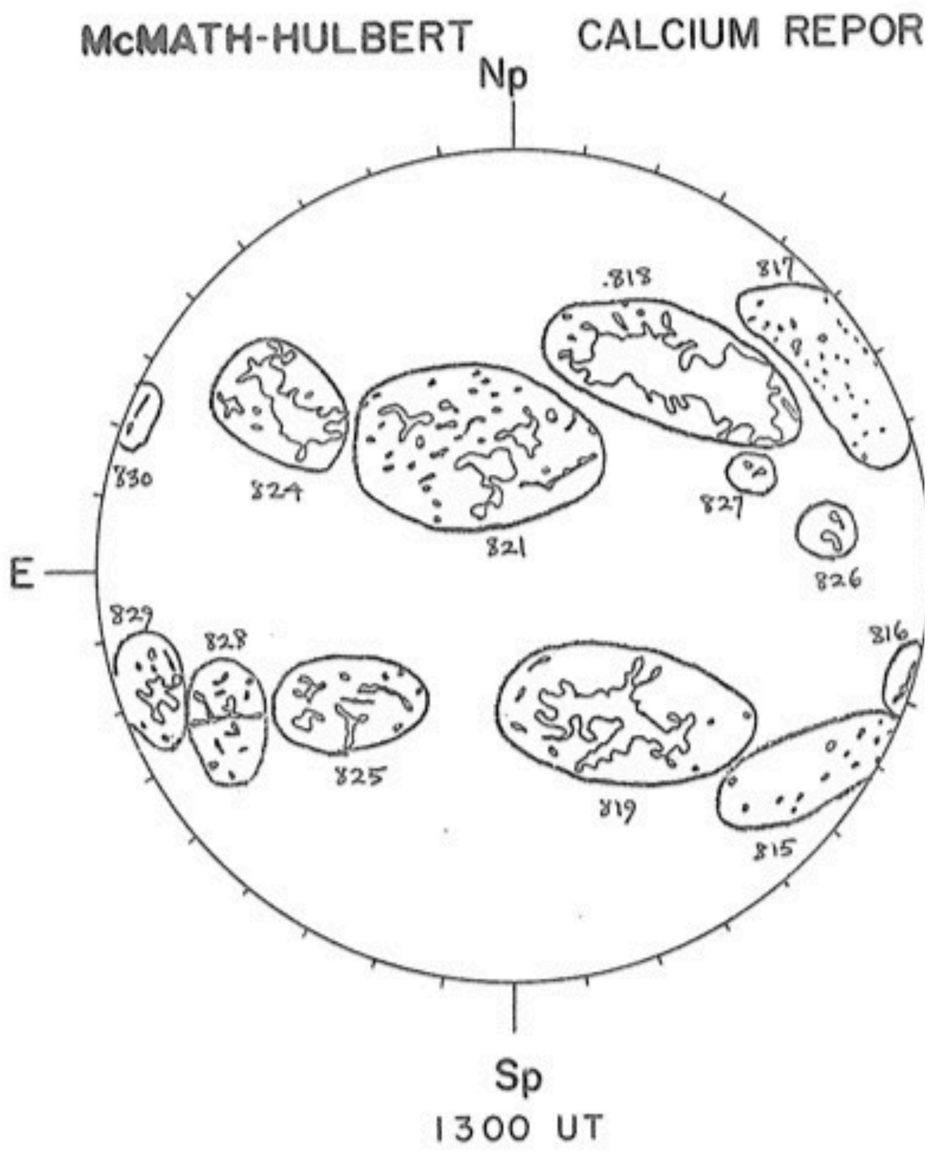
W E

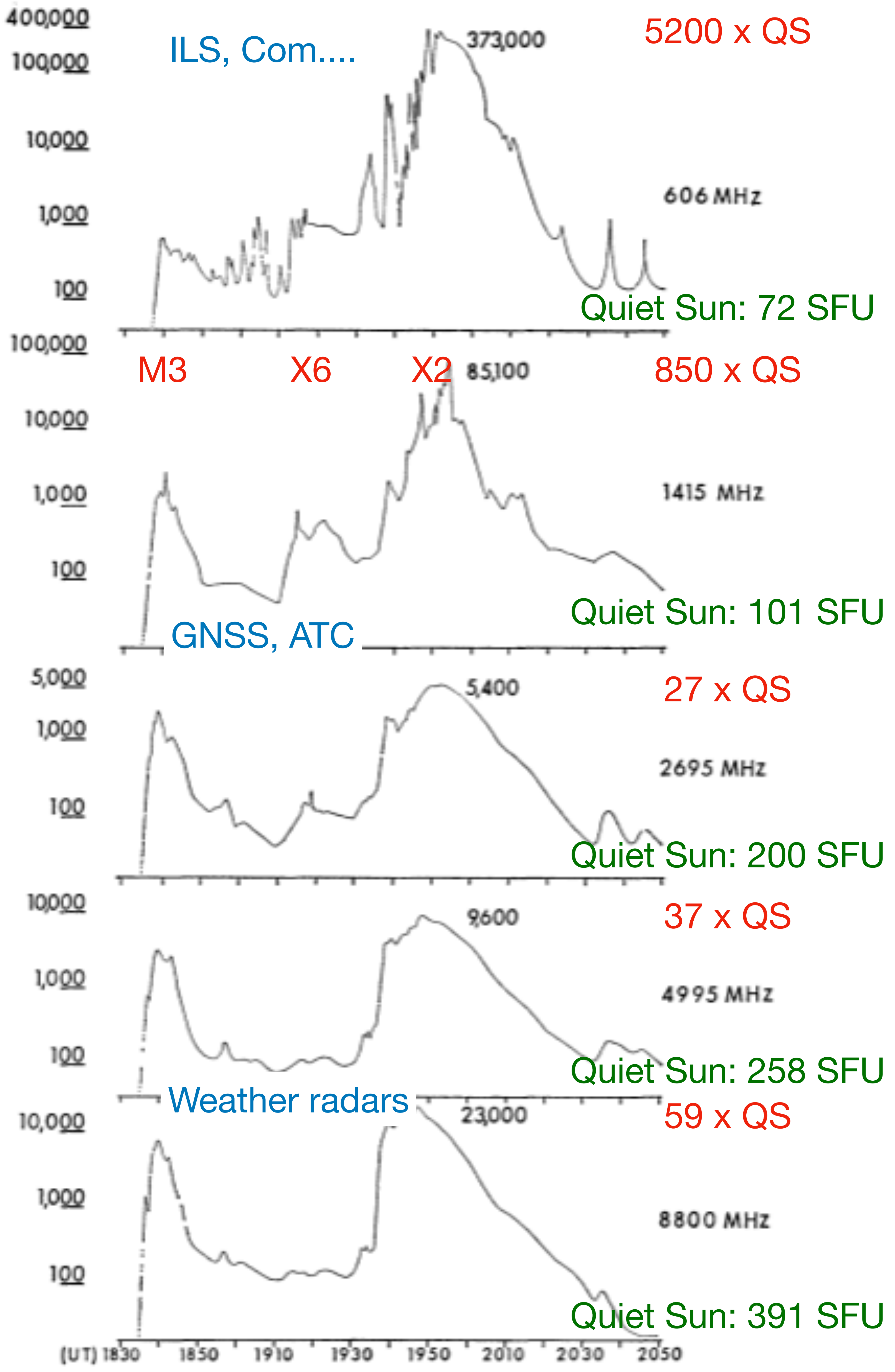
NO DATA

S

Resolution 3 Minutes of Arc

02-03 UT Brightness Unit 1,700° K





ILS, Com....

5200 x QS

Quiet Sun: 72 SFU

M3

X6

X2

850 x QS

Quiet Sun: 101 SFU

GNSS, ATC

27 x QS

Quiet Sun: 200 SFU

37 x QS

Quiet Sun: 258 SFU

Weather radars

59 x QS

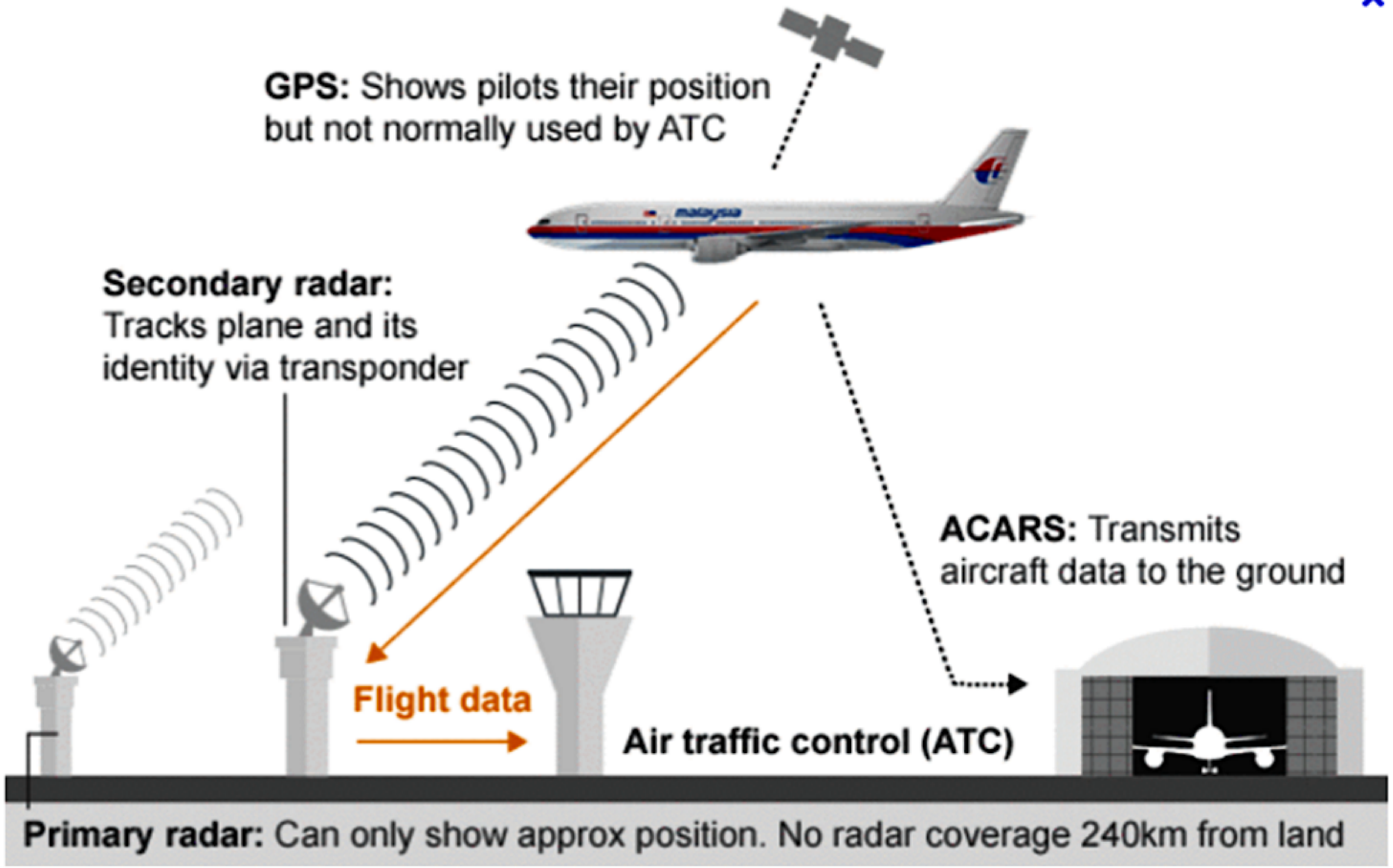
Quiet Sun: 391 SFU

Air traffic radars

Civil aviation

Primary radars : 2800 MHz

Secondary radars: 1030 & 1090 MHz



GPS: Shows pilots their position but not normally used by ATC

Secondary radar: Tracks plane and its identity via transponder

ACARS: Transmits aircraft data to the ground

Primary radar: Can only show approx position. No radar coverage 240km from land

Source: BBC

November 4 2015

A media storm

- ATC radars in Sweden suffered severe disturbances between 14:20 UT and 16:00 UT
- Incoming flights were deviated, no departures allowed
- Geomagnetic storm was initially considered as the source of disturbances (media)

thewatchers.adorraeli.com/2015/11/05/the-sweden-case-aircrafts-disappear-from-radars-due-to-solar-storm/

The Sweden Case: Airplanes disappear from radars due to "solar storm"

Posted by Adonai on November 05, 2015 in categories Featured articles, Geomagnetic storms, Solar activity

www.usatoday.com/story/travel/roadwarriorvoices/2015/11/07/solar-storm-made-every-plane-in-sweden-disappear-from-the-countrys-radar-screens/83312456/

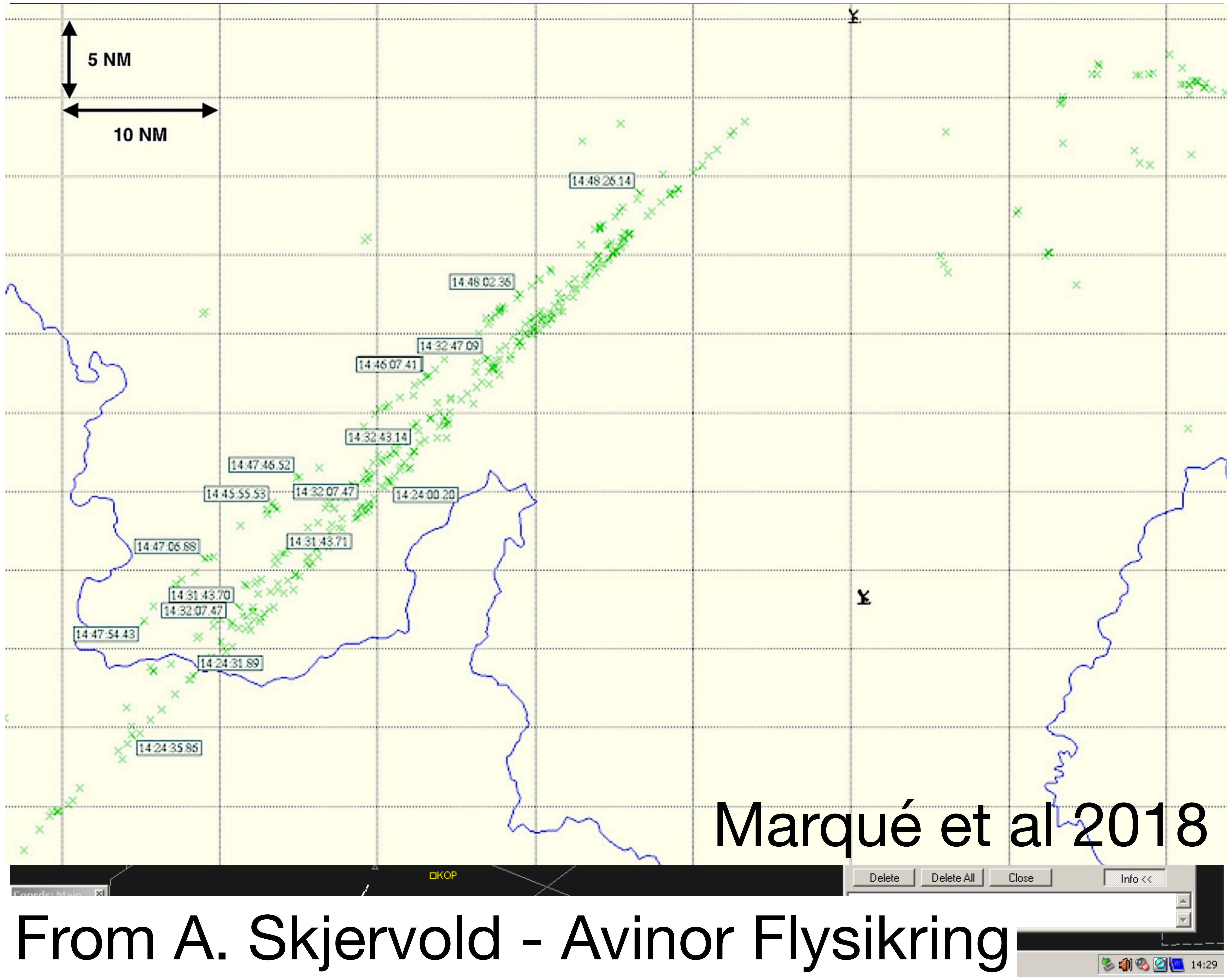
Solar storm made every plane in Sweden disappear from the country's radar screens

Jelisa Castrodale, USA TODAY 9 a.m. EST November 7, 2015

Photo: NASA Goddard Space Flight Center/Flickr

A European wide disruption

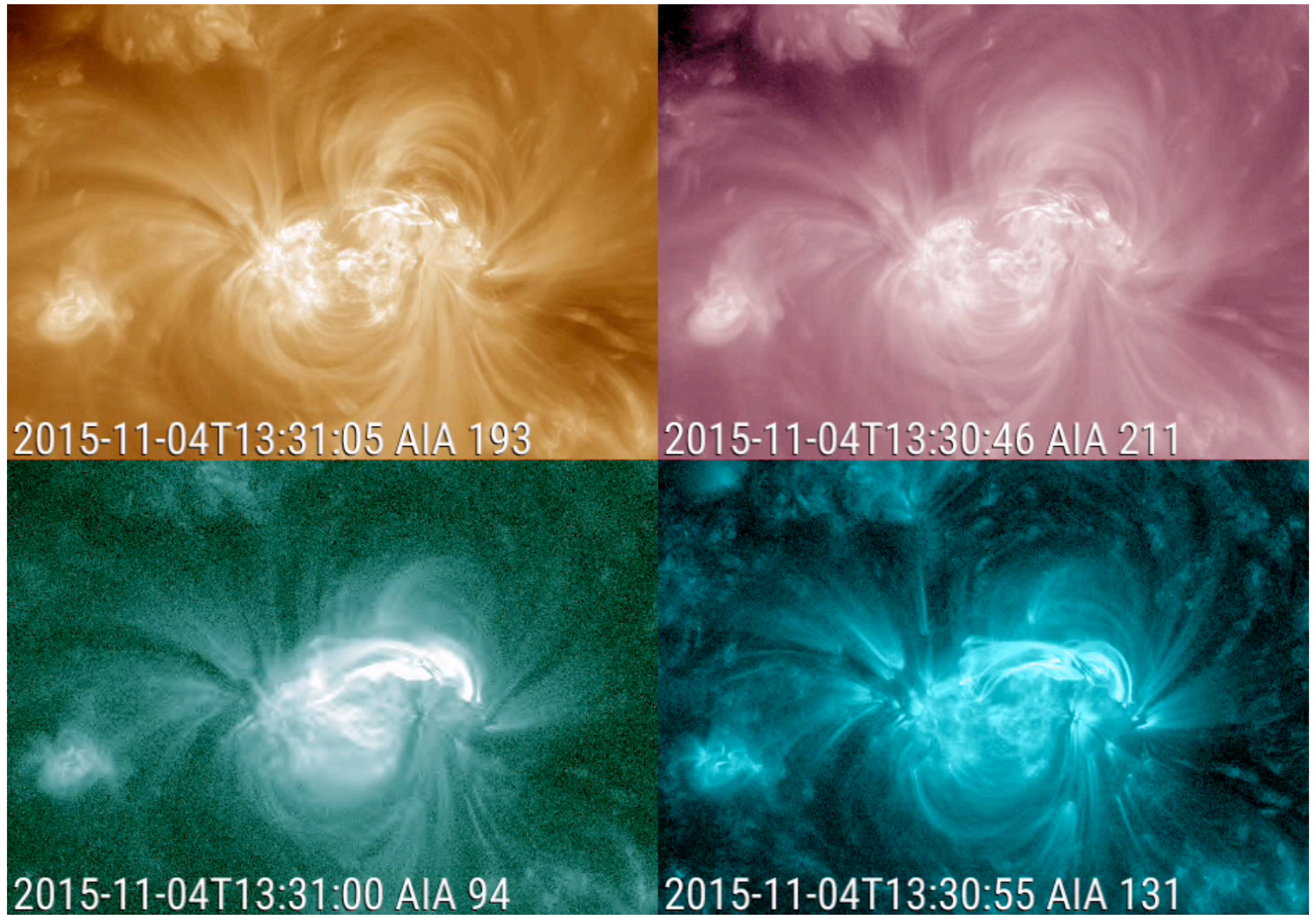
- Sweden: ATC radars suffered severe disturbances 14:20 UT - 16:00 UT
- Sweden: Partial closure of air space for an hour
- Minor disturbances in Norway, Belgium



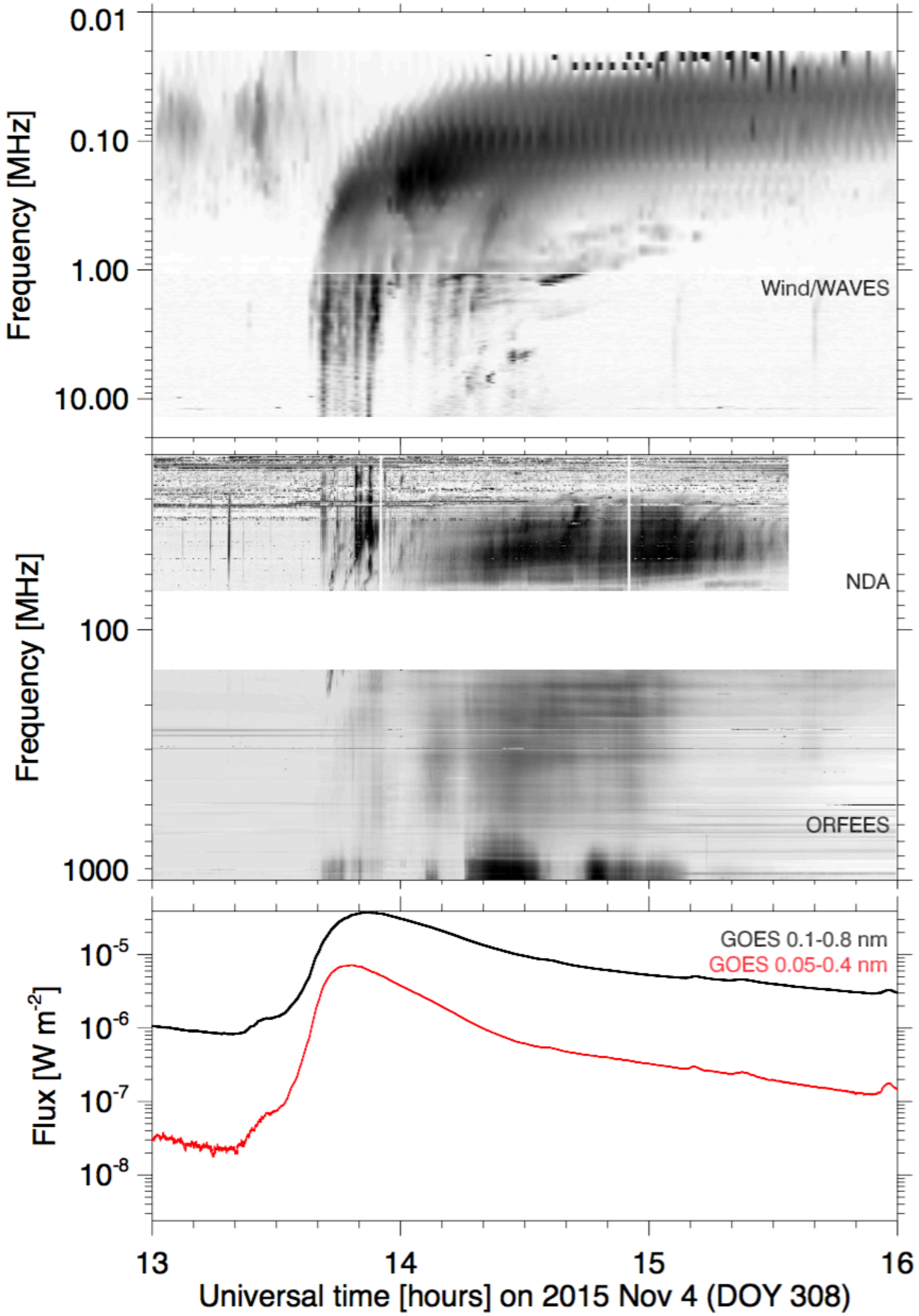
Marqué et al 2018

From A. Skjervold - Avinor Flysikring

Solar event

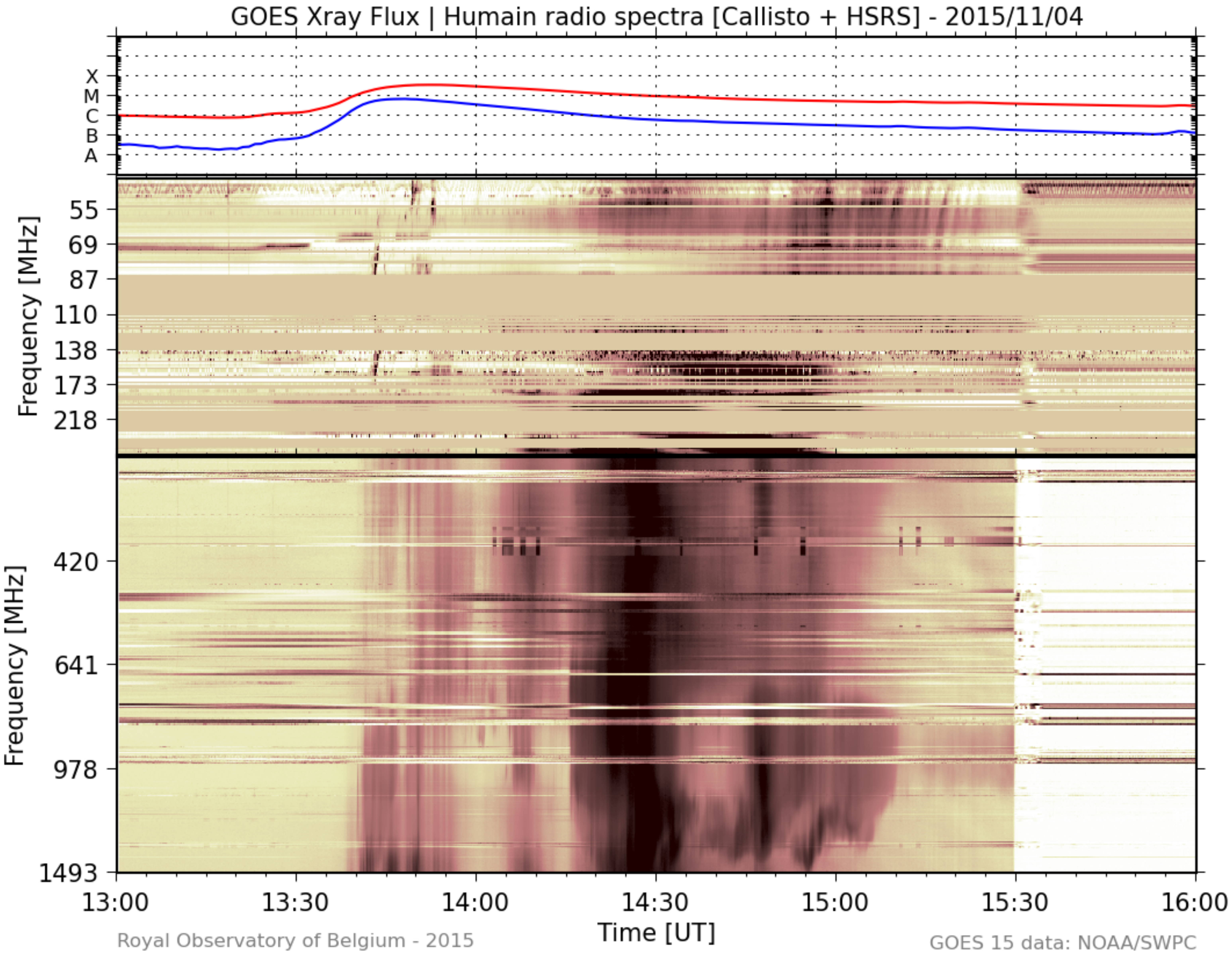


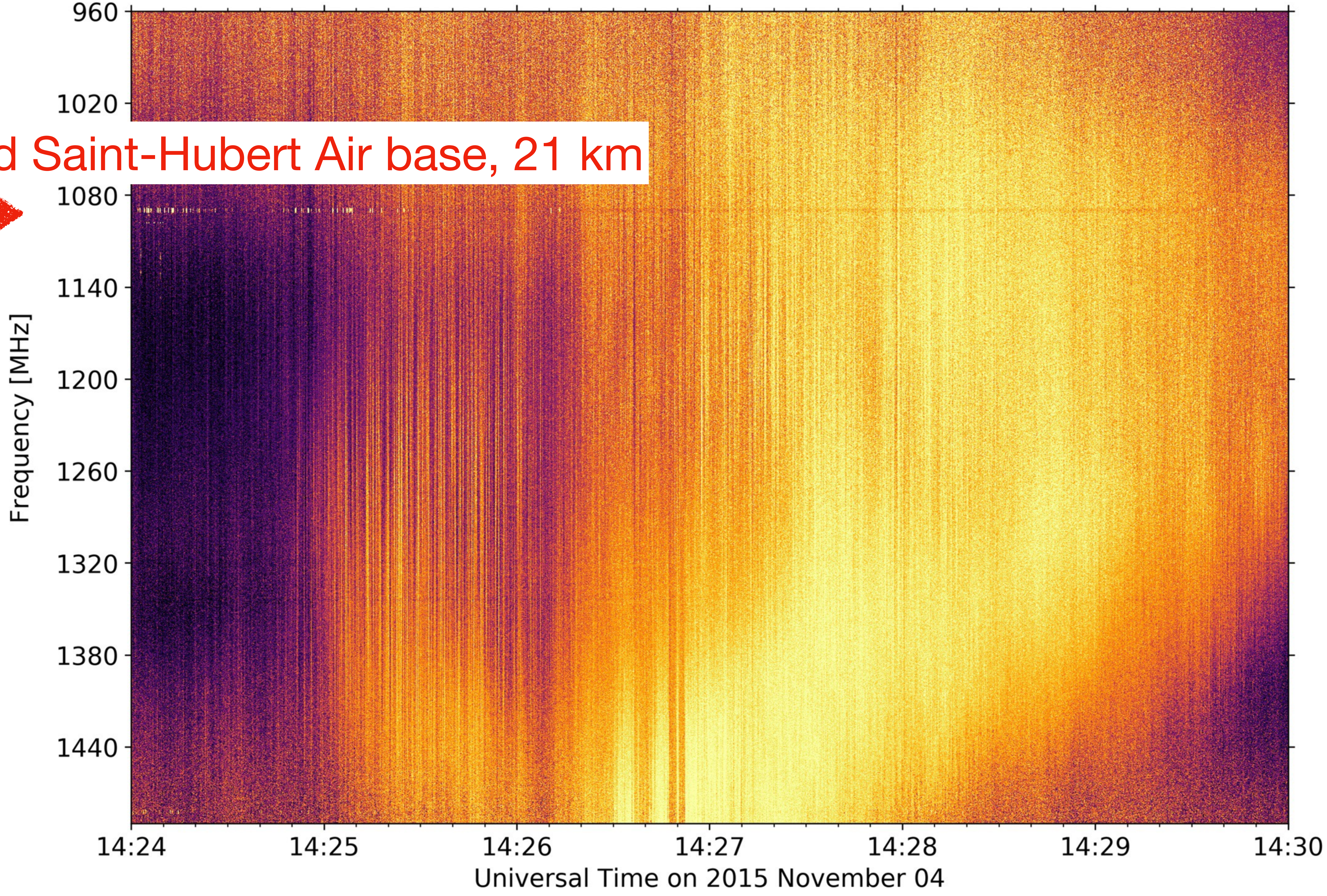
M3.7 flare peaking @1352 UT
NOAA AR 2243



In Humain

https://www.sidc.be/humain





Radar band Saint-Hubert Air base, 21 km

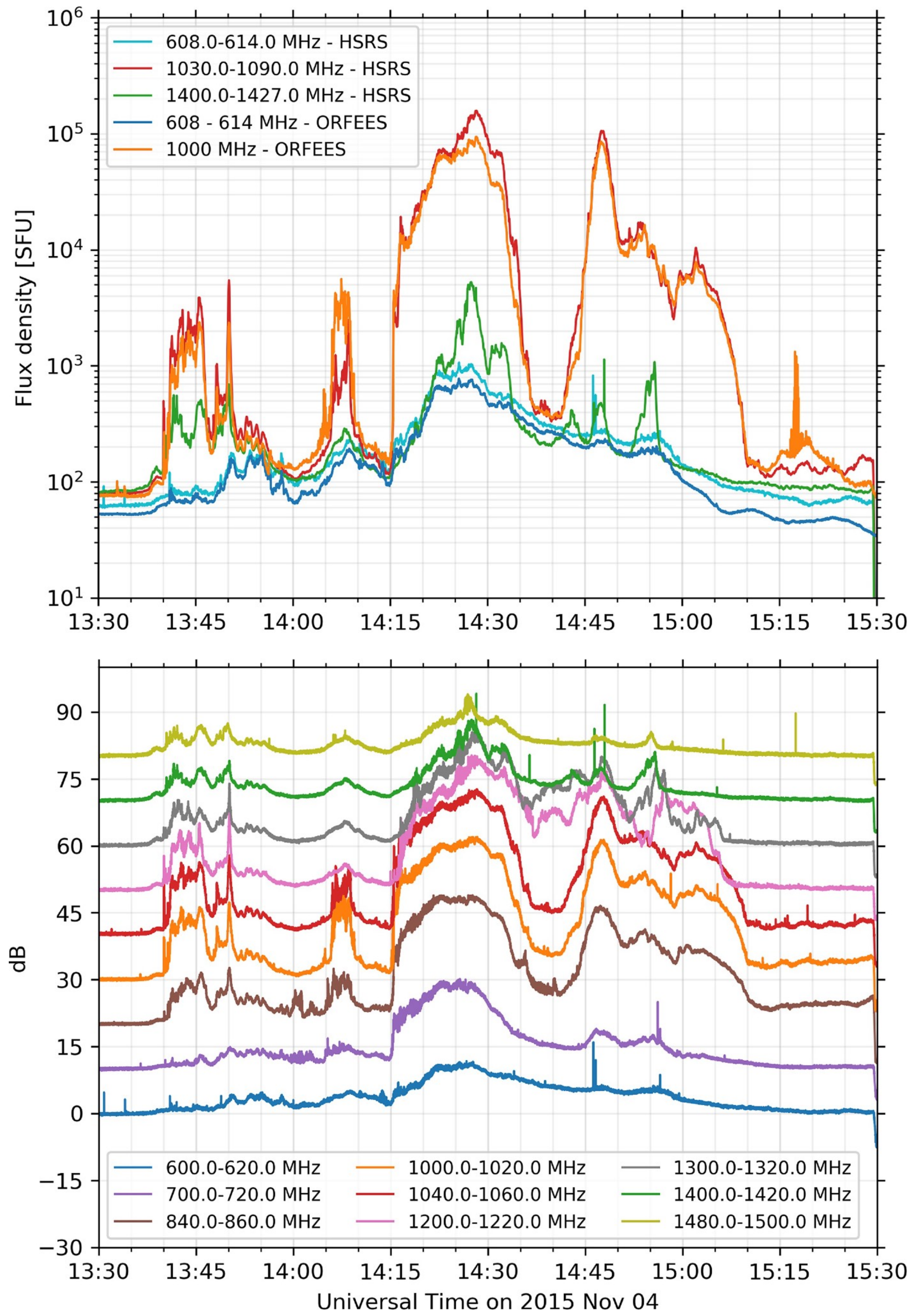
An exceptional event?

Strong magnitude

ORFEES (1000 MHz)🇫🇷	100 kSFU
Blein (1000 – 1250 MHz) 🇨🇭	123 kSFU
Humain (1060 MHz)🇧🇪	157 kSFU

But...

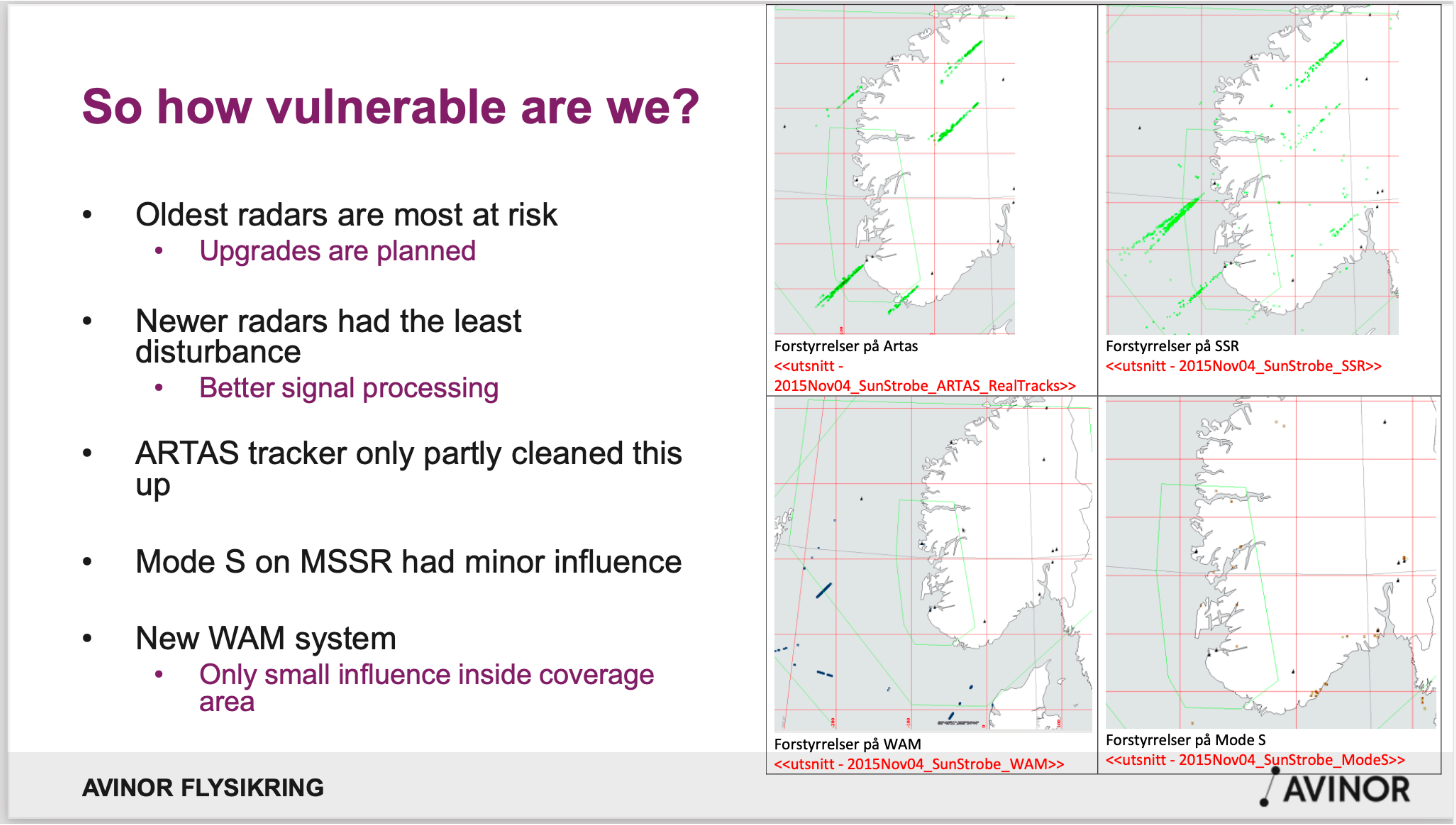
610 MHz 🇫🇷🇧🇪	820 - 1000 SFU
1415 – 1427 MHz 🇨🇭🇧🇪🇺🇸	5200 - 6300 SFU



Interference threshold comparison

- The interference threshold for such radars is about **-102 dBm** (6,3 . 10^{-14} W) at receiver input.
- The quiet sun level on that day was about 75 SFU (75 . 10^{-22} W.m^{-2}.Hz^{-1}), which results in a power at receiver input of **-101 dBm**
- At the peak of the burst the Sun emission level was more than 100 000 SFU, which gives at least a power at receiver input of **-68 dBm**

34 dB above interference threshold (~ 2500 times that level)



So how vulnerable are we?

- Oldest radars are most at risk
  - Upgrades are planned
- Newer radars had the least disturbance
  - Better signal processing
- ARTAS tracker only partly cleaned this up
- Mode S on MSSR had minor influence
- New WAM system
  - Only small influence inside coverage area

Forstyrrelser på Artas
<<utsnitt - 2015Nov04_SunStrobe_ARTAS_RealTracks>>

Forstyrrelser på SSR
<<utsnitt - 2015Nov04_SunStrobe_SSR>>

Forstyrrelser på WAM
<<utsnitt - 2015Nov04_SunStrobe_WAM>>

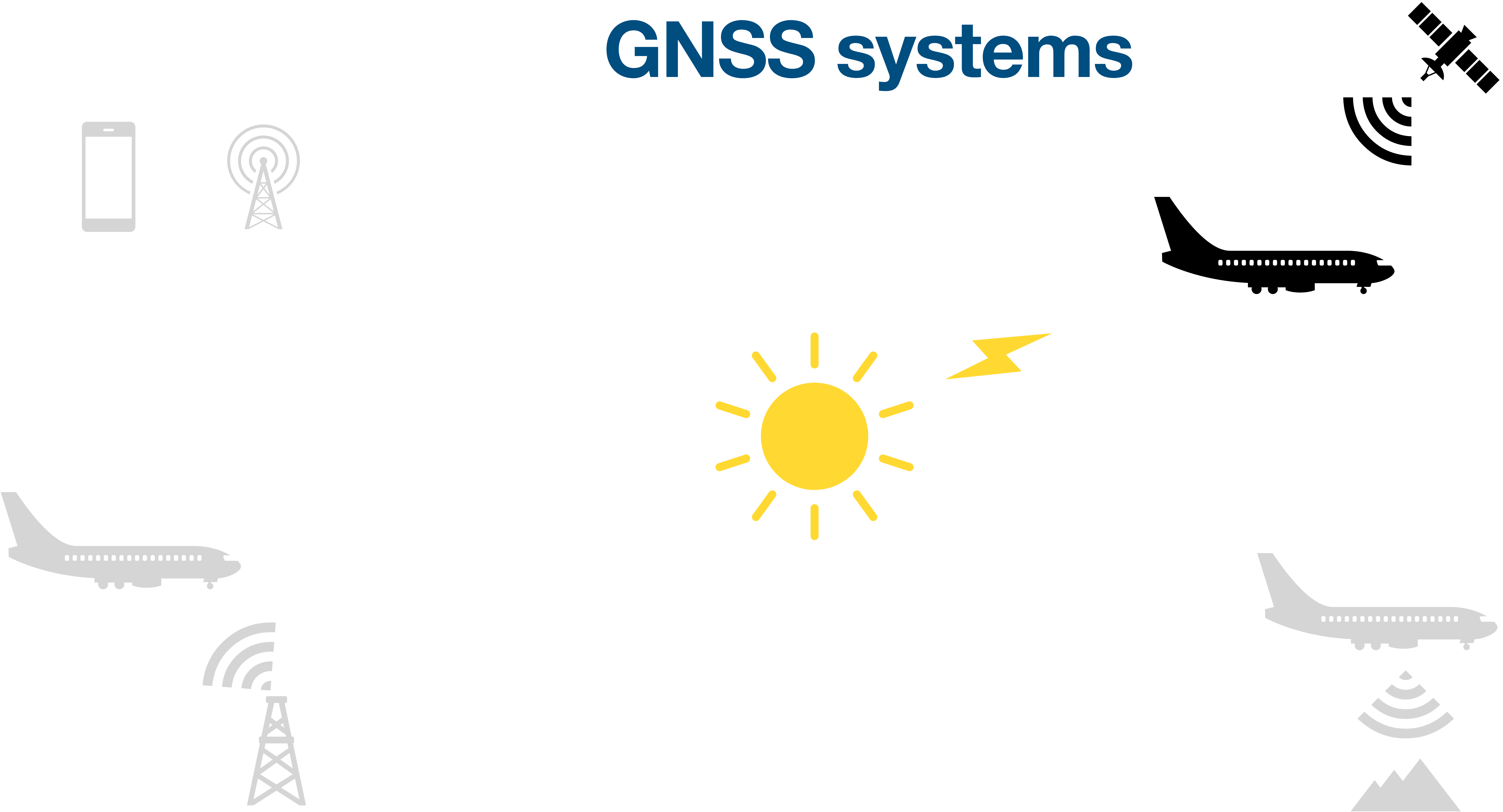
Forstyrrelser på Mode S
<<utsnitt - 2015Nov04_SunStrobe_ModeS>>

AVINOR FLYSIKRING

AVINOR

http://www.mn.uio.no/english/about/news-and-events/events/The%20Birkeland%20Anniversary/andreas-d-skjervold_150617.pdf

GNSS systems



Interference Thresholds

- Change the level of noise, decrease in C/N0 ($\Delta C/N_0$)
- Decrease in C/N0 triggers loss of locks with satellites, decrease in positioning precision, etc..
- First report: September 2005 Cerruti et al., 2006
- Dec. 2006 event (Cerruti et al., 2008; Carrano et al., 2009; Demyanov et al. 2012)

Thresholds

L1 3dB	L2 3dB codeless	L1 3dB	L2 5.2 dB	L1 signal tracking fail	L2 signal tracking fail
20000 SFU	~8000 SFU	10000 SFU	10000 SFU	10000 SFU	4000 SFU
Klobuchar, 1999	Chen et al. 2005	Cerruti et al., 2006		Demyanov et al., 2012	

GNSS

24 September 2011

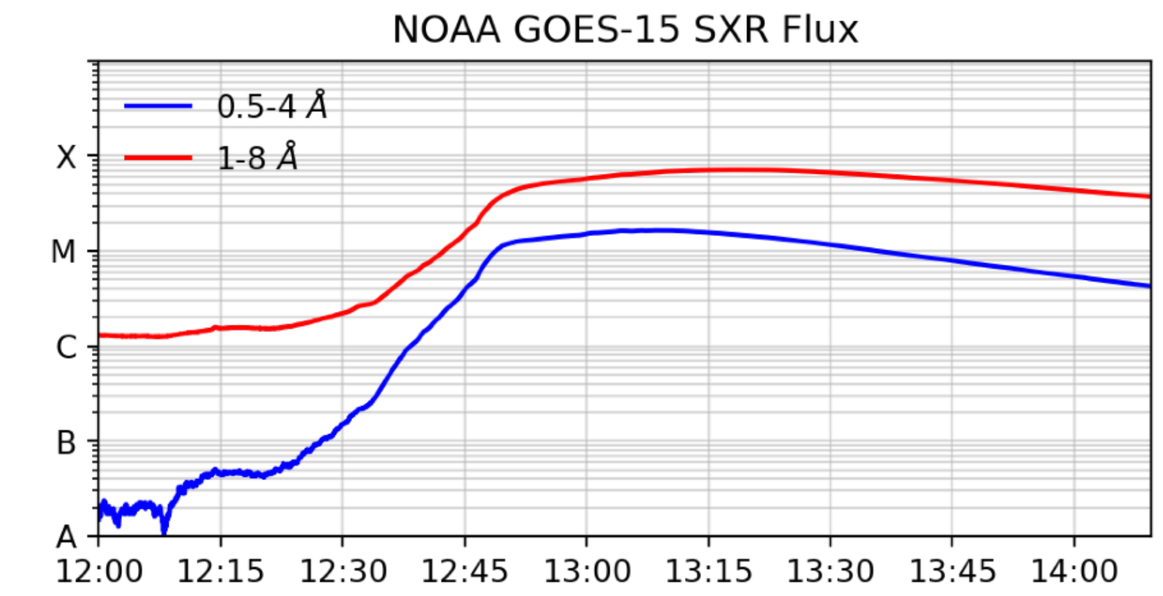
- M7.1 flare, max @ 13:20 UT
- AR 11302, Ekc, βγ

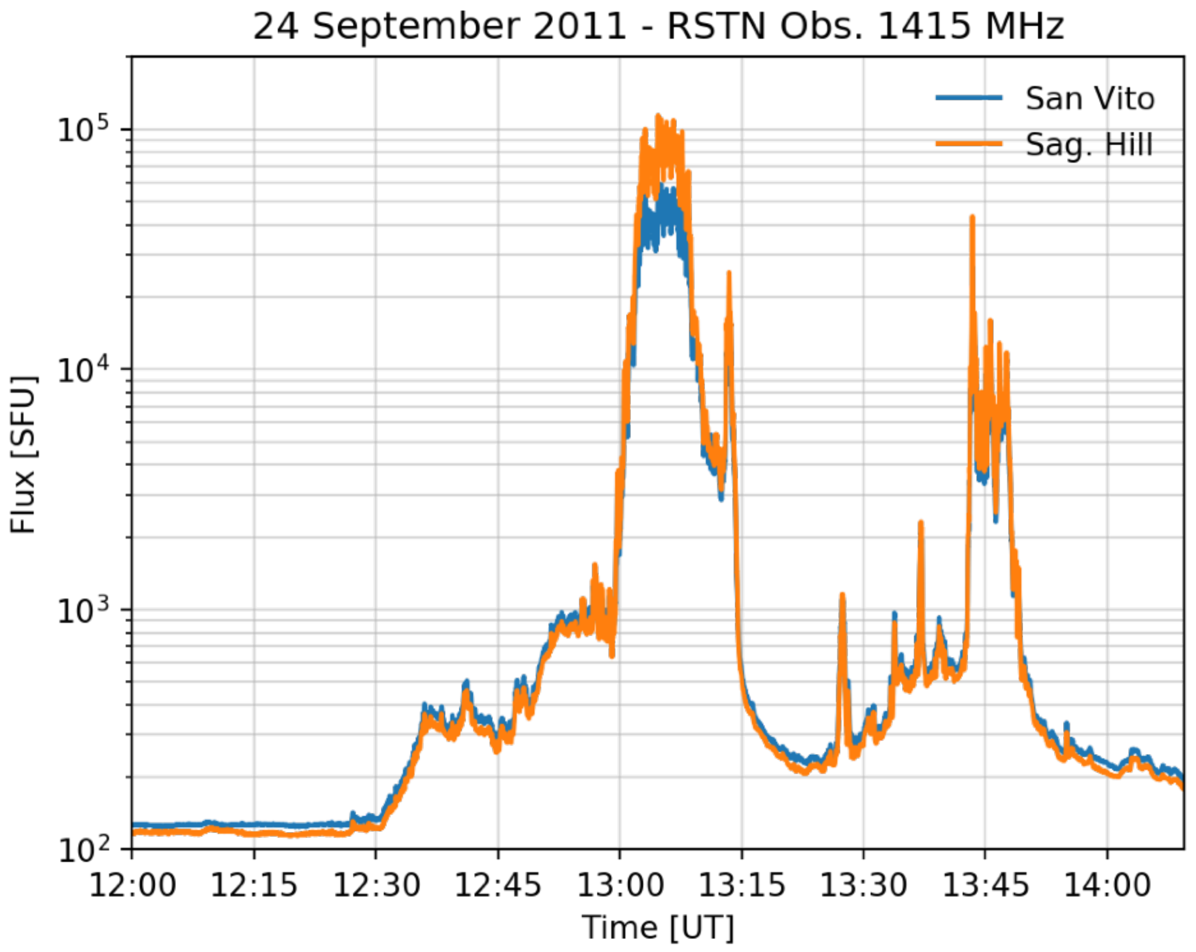
★110000 SFU @13:02 UT [Sag. Hill]

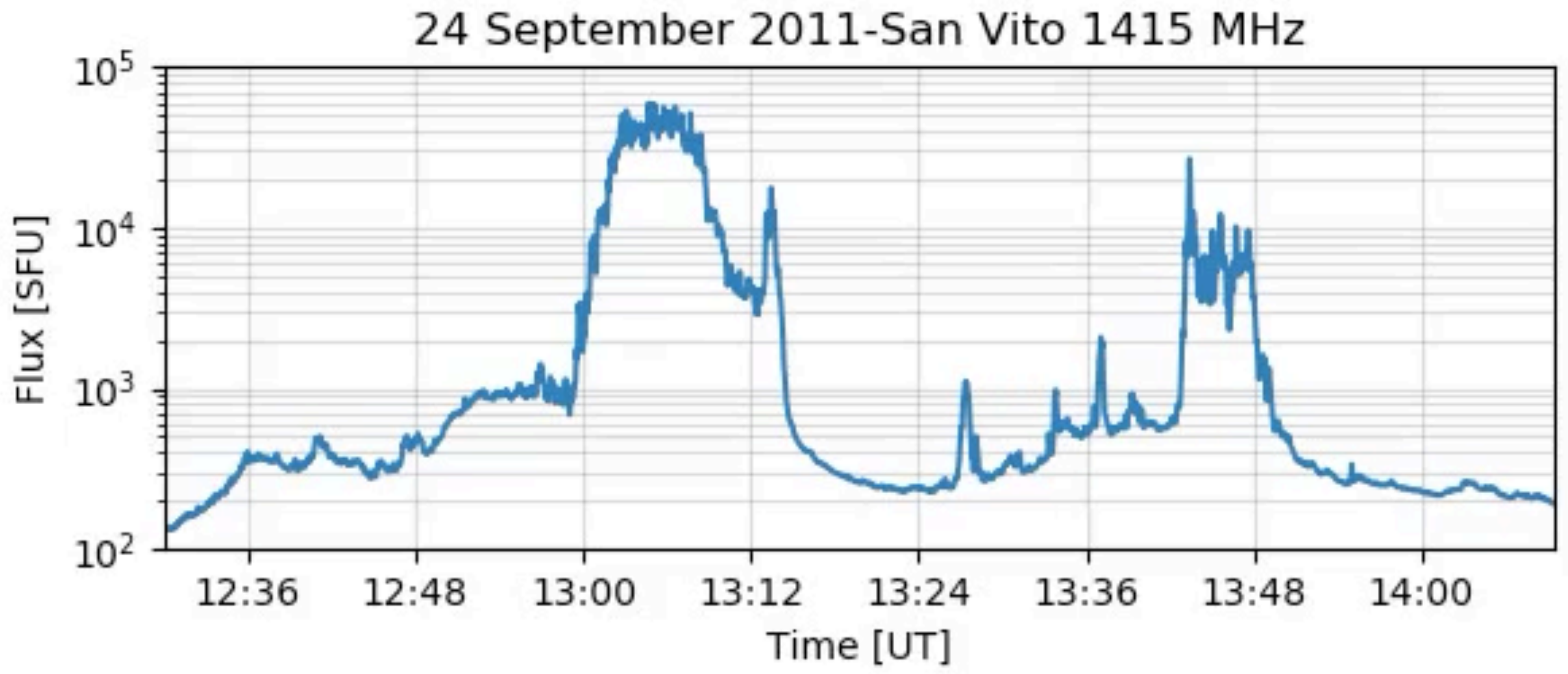
★60000 SFU [San Vito]

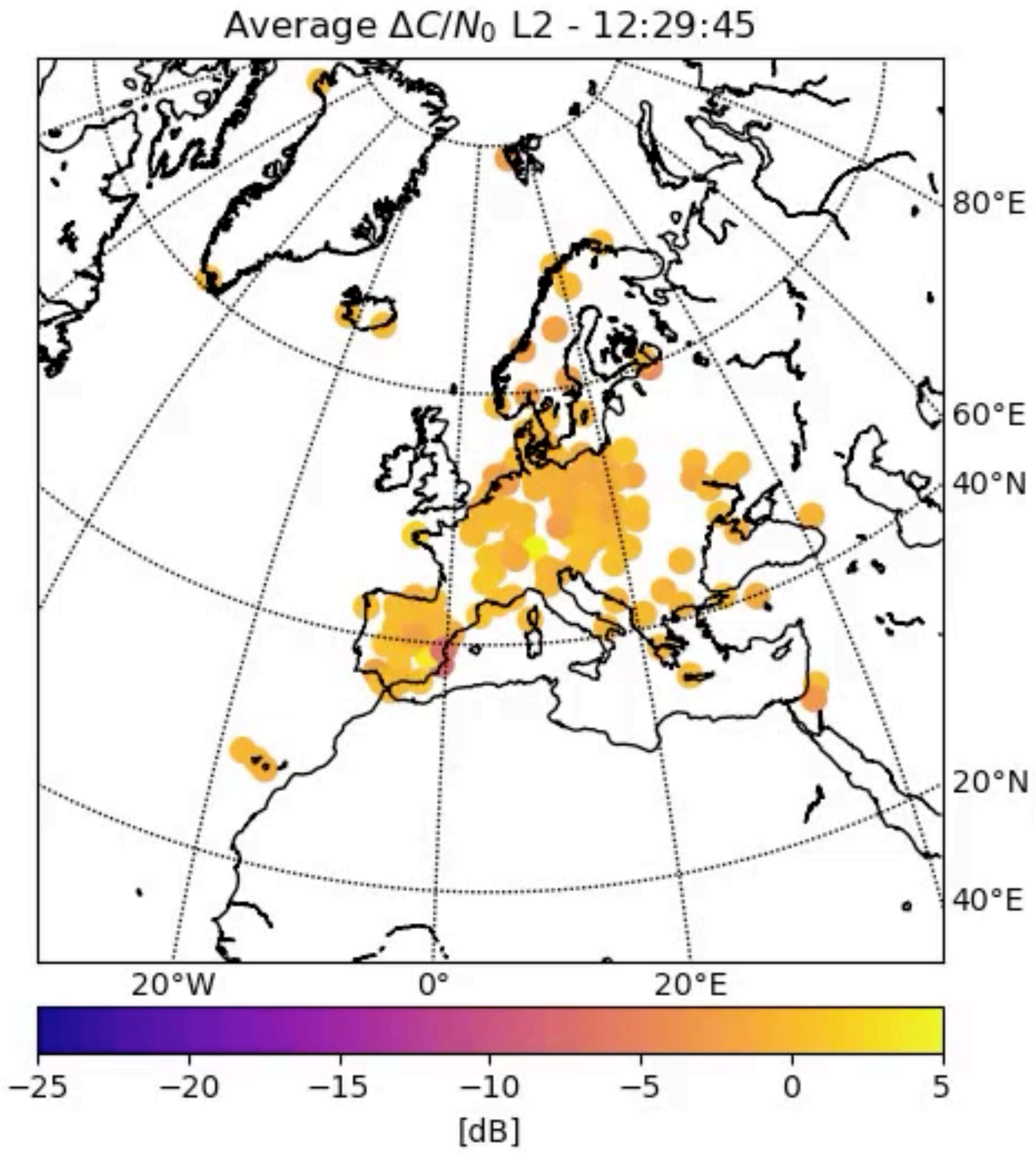
- Dm type IV burst (Bleien, Ondrejov)

C/N0 degradation


NOAA GOES-15 SXR Flux


24 September 2011 - RSTN Obs. 1415 MHz

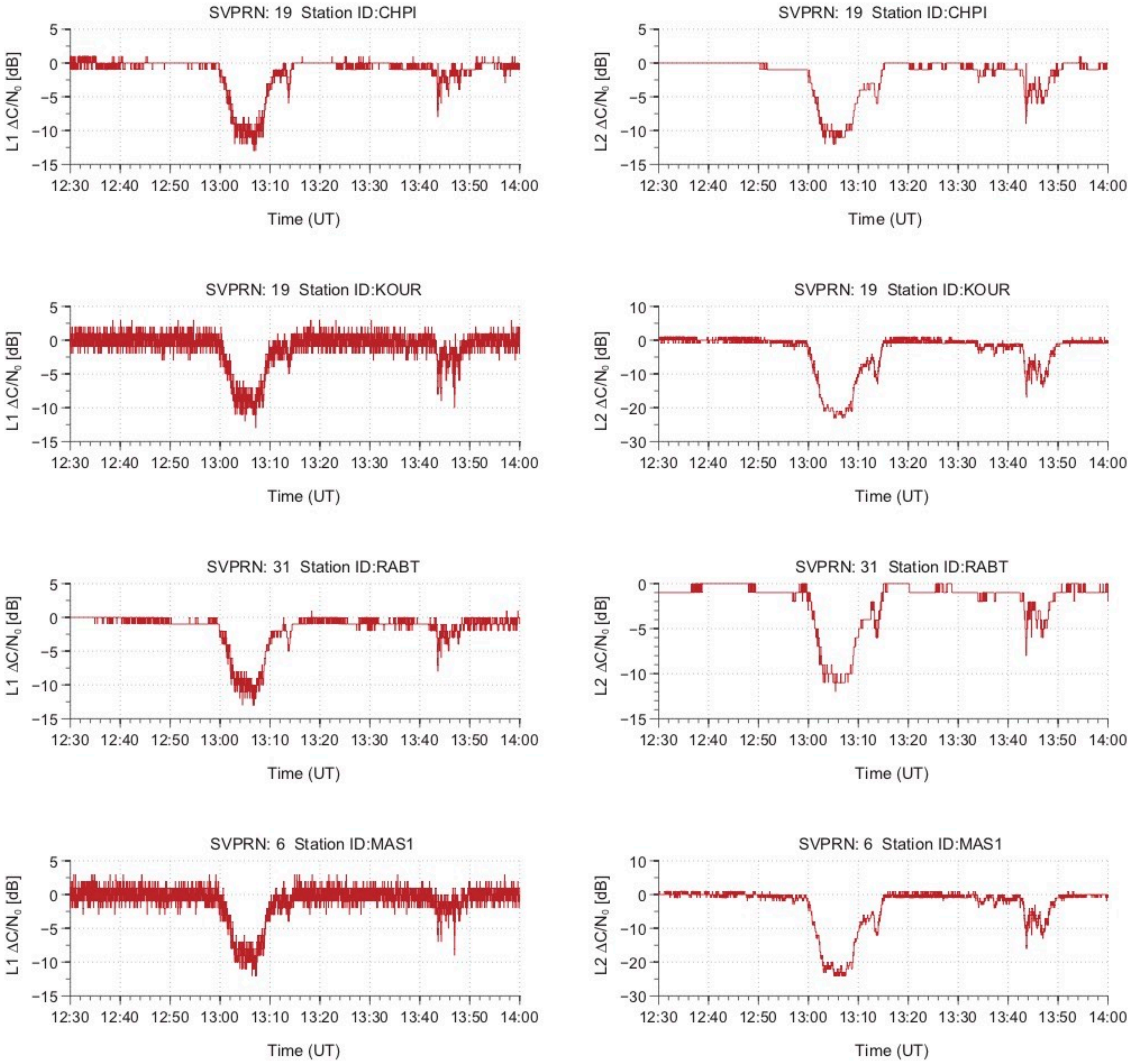

24 September 2011-San Vito 1415 MHz


Average $\Delta C/N_0$ L2 - 12:29:45

C/N0 DEGRADATION

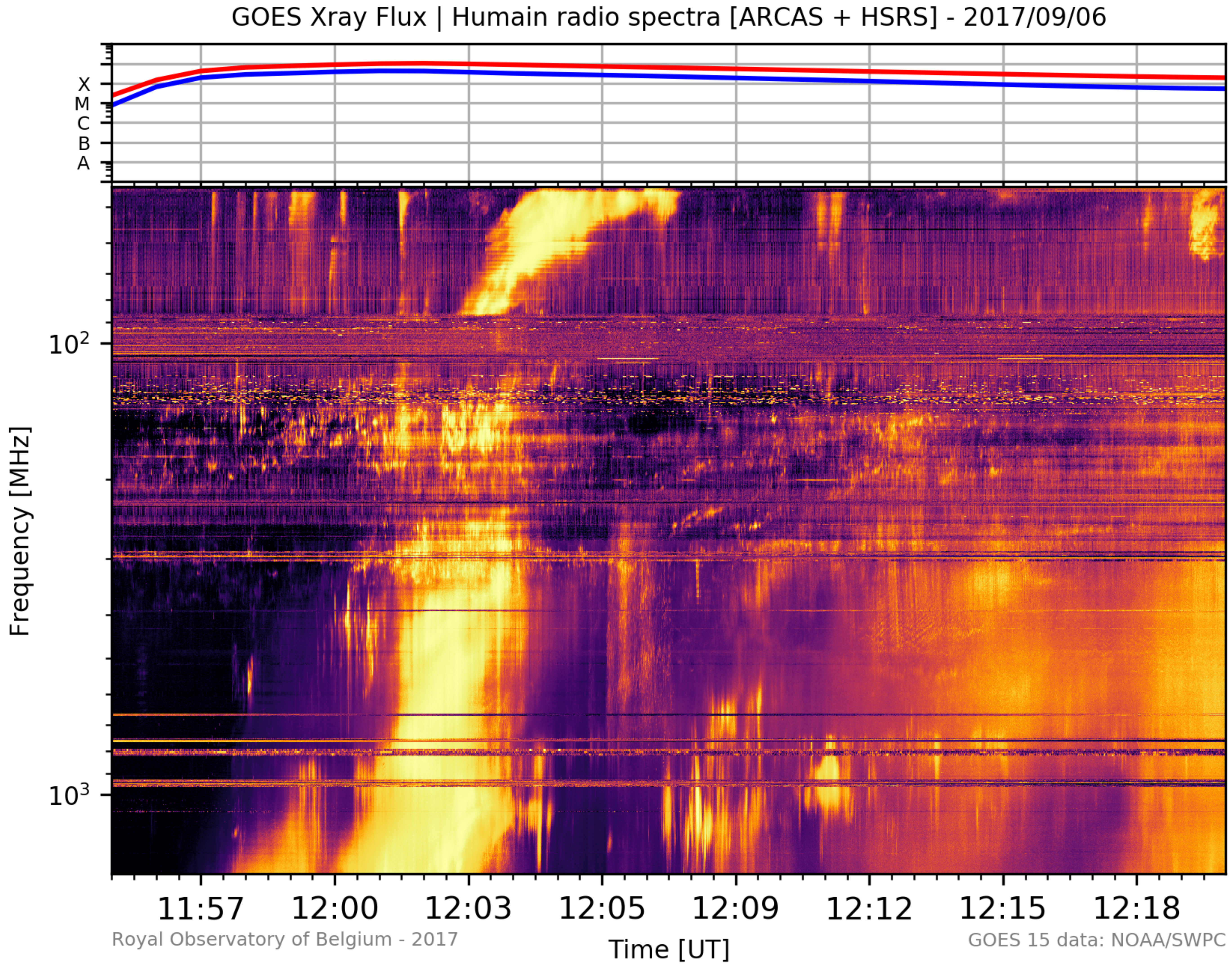
L1 1575 MHz

L2 1228 MHz



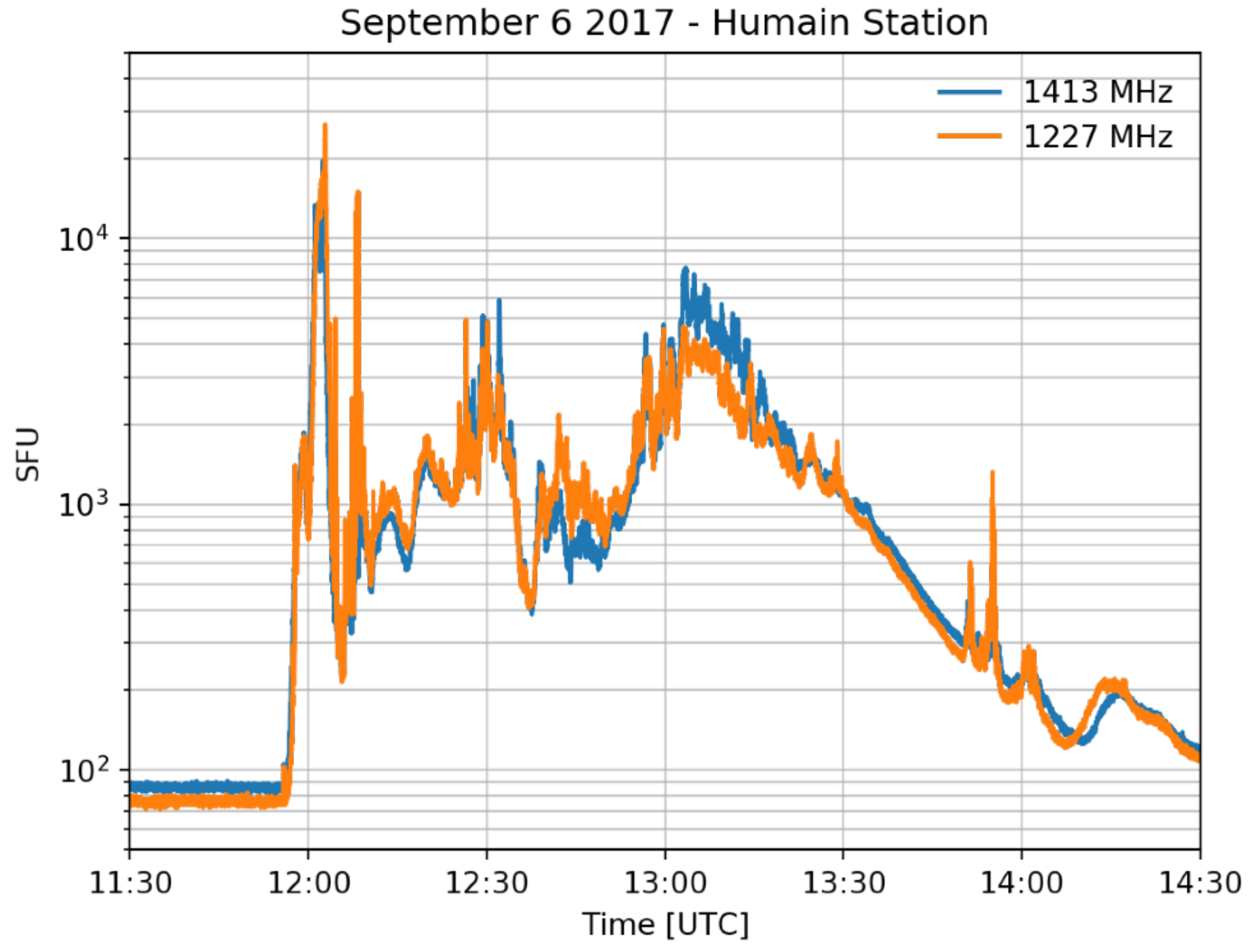
Muhammad et al., 2015

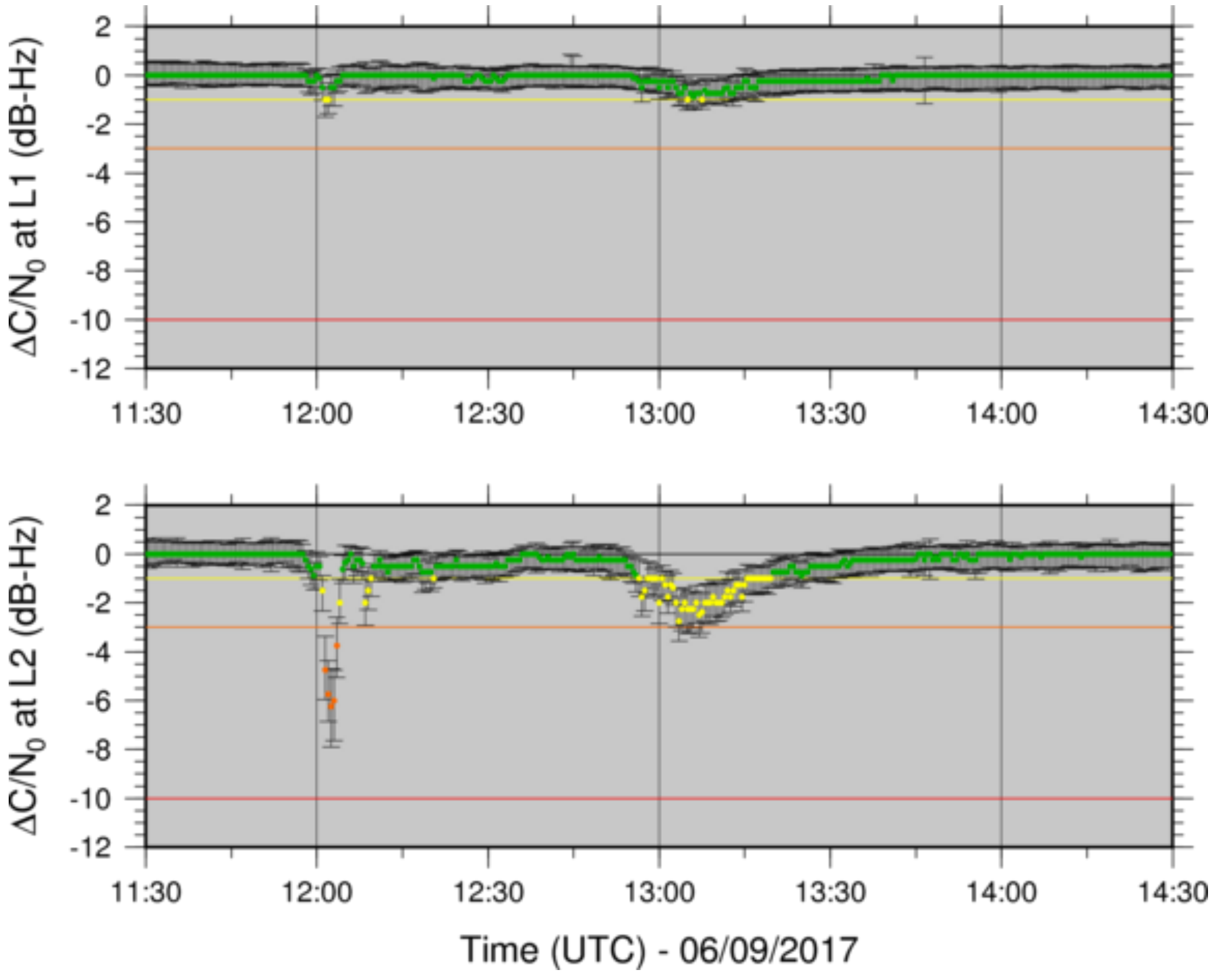
September 6 2017



Complex dm type IV + fine structures

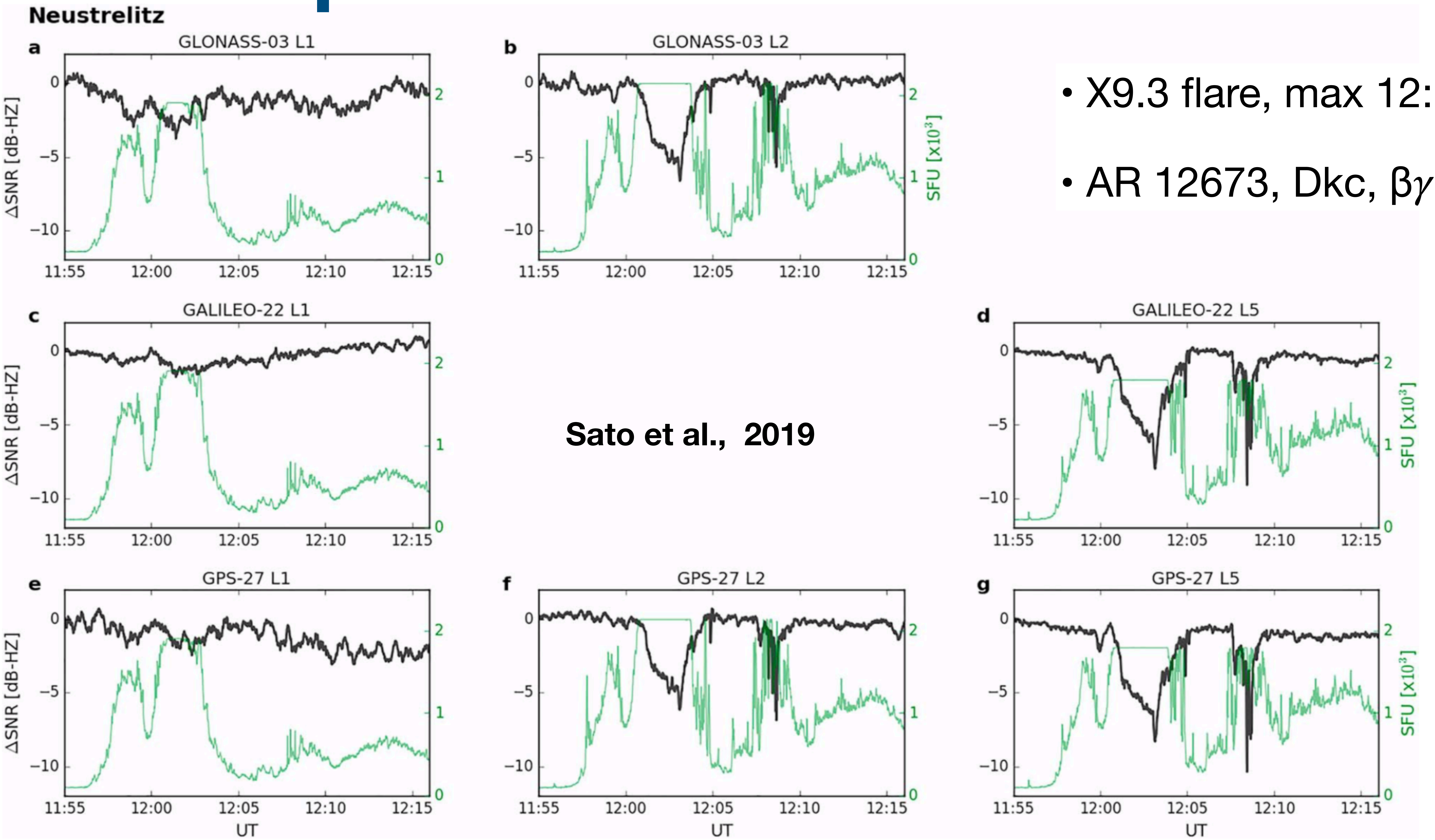
Flux density > 20 kSFU @ L2





Chevalier & Bergeot

September 6 2017



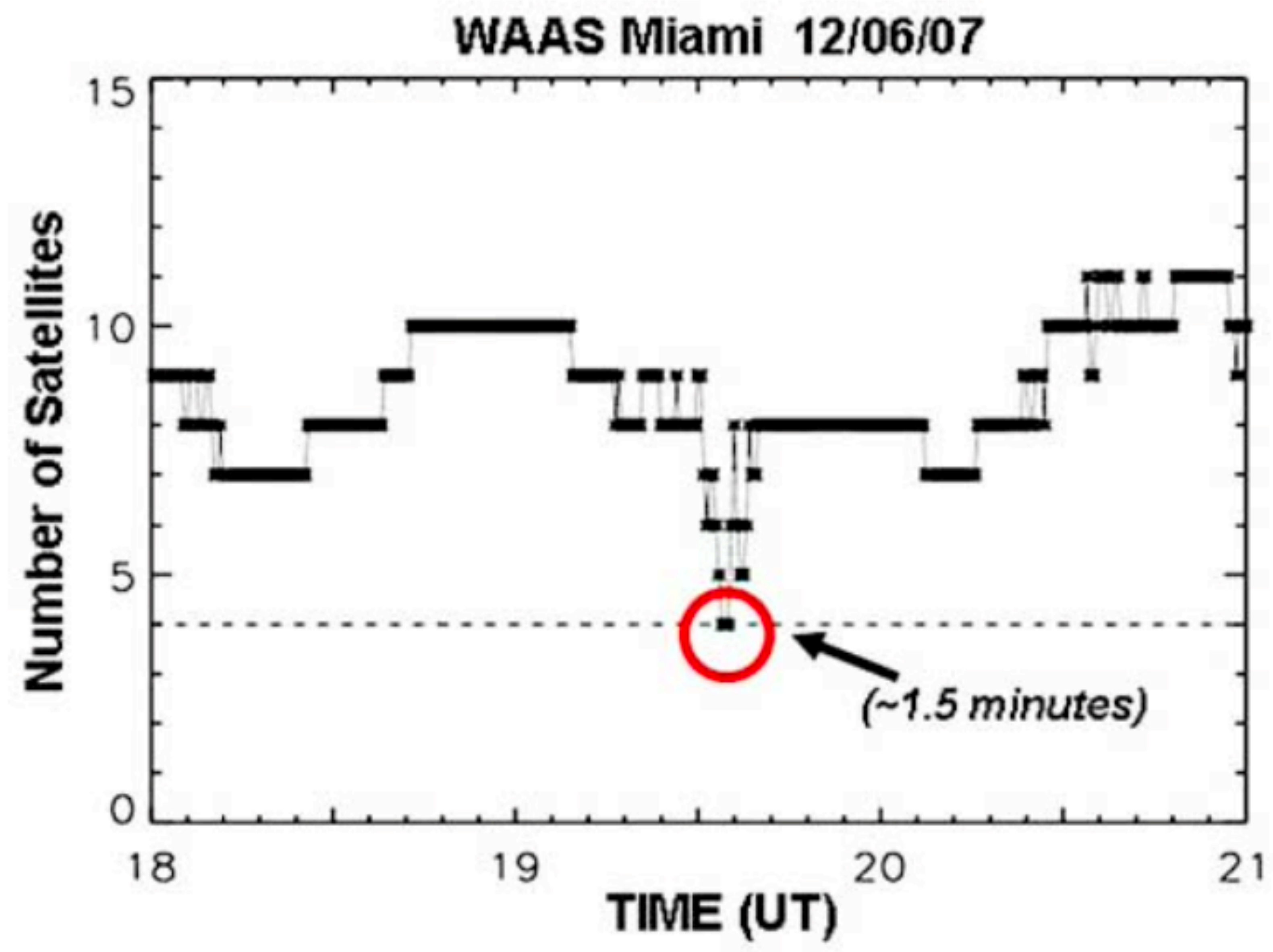
Sato et al., 2019

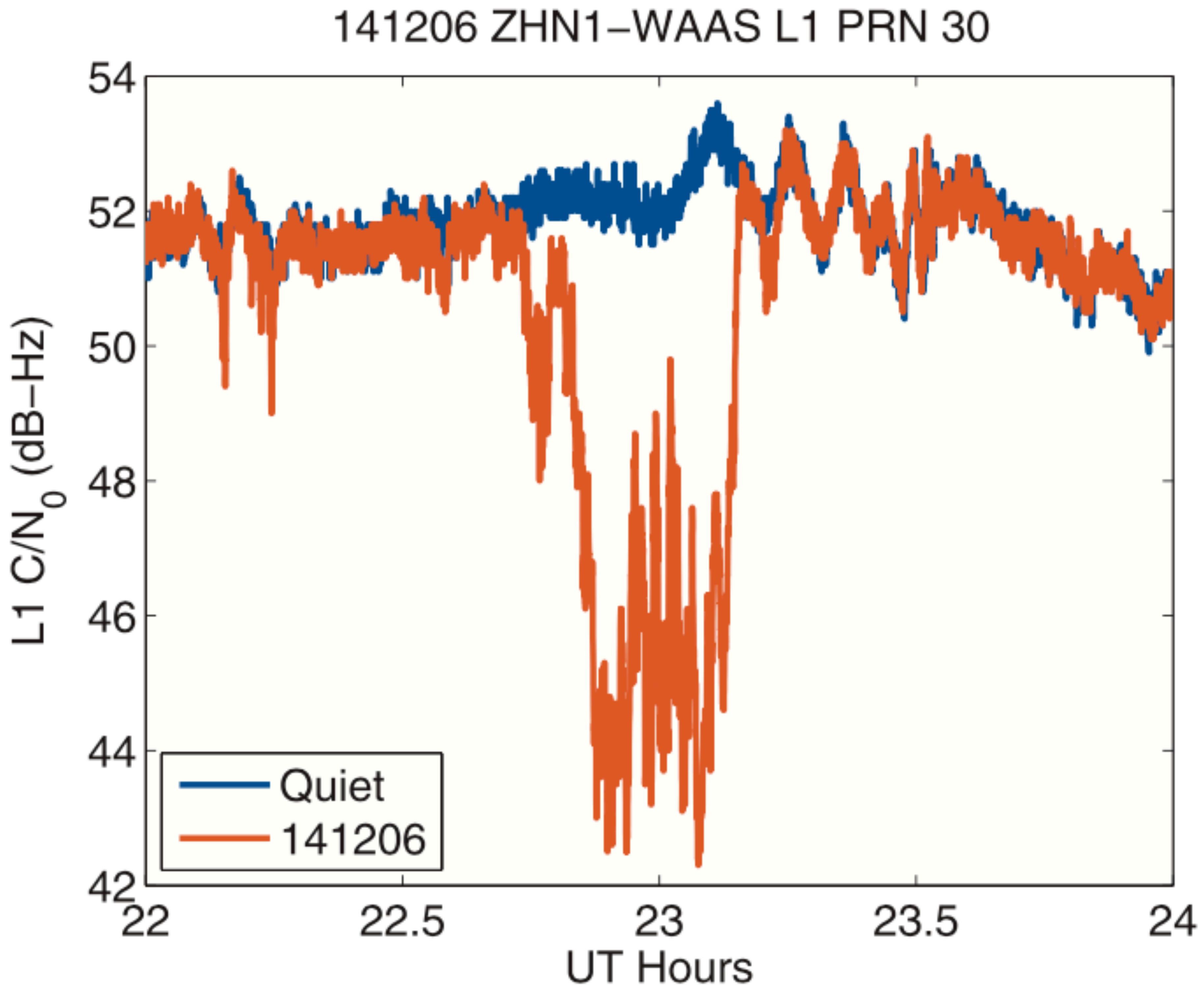
- X9.3 flare, max 12:02 UT
- AR 12673, Dkc, $\beta\gamma\delta$

Impact on WAAS/EGNOS systems

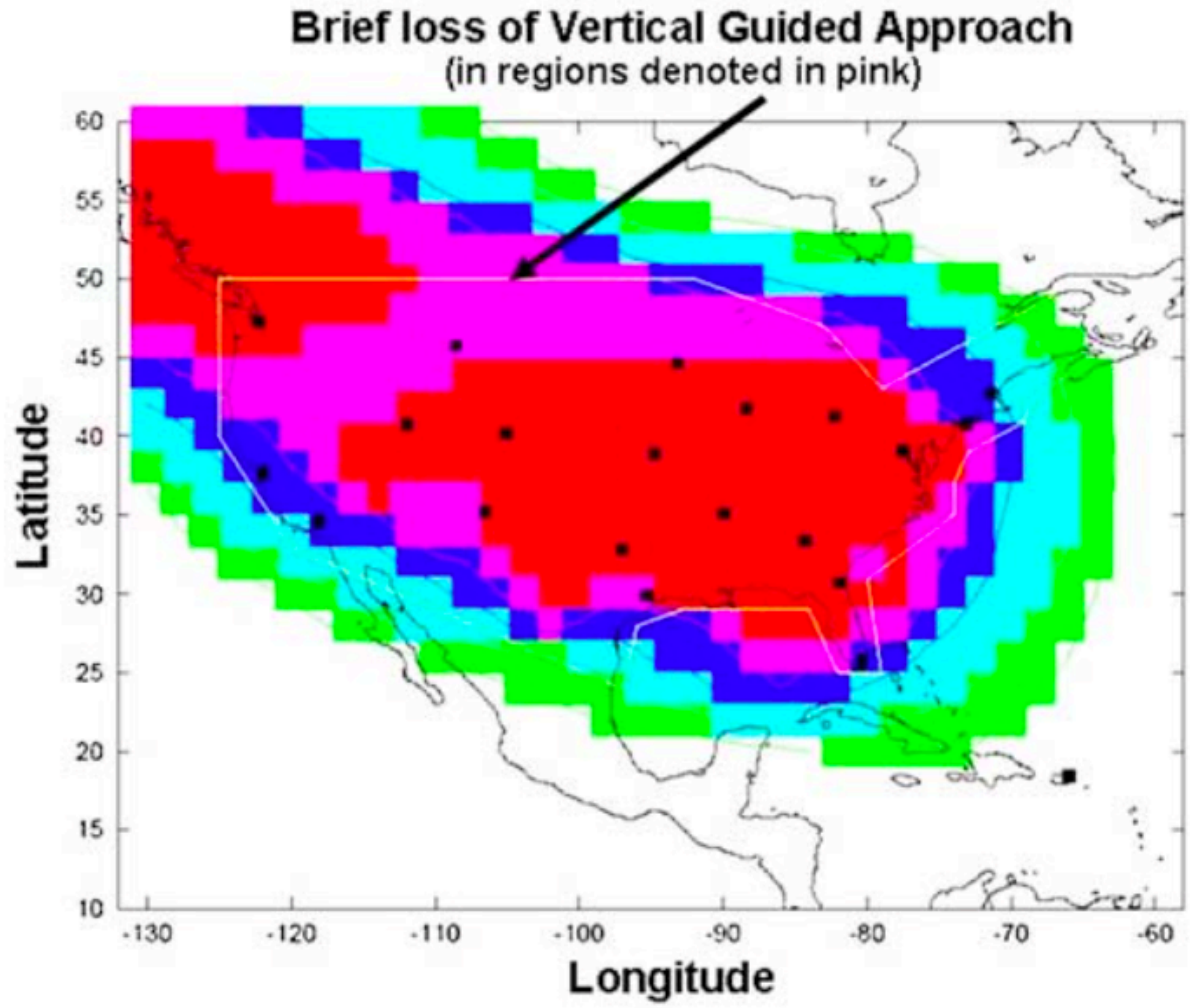
December 6 2006 event

- X6 flare producing an intense SRB (type IV) at 1415 MHz (10^6 SFU - RHCP)

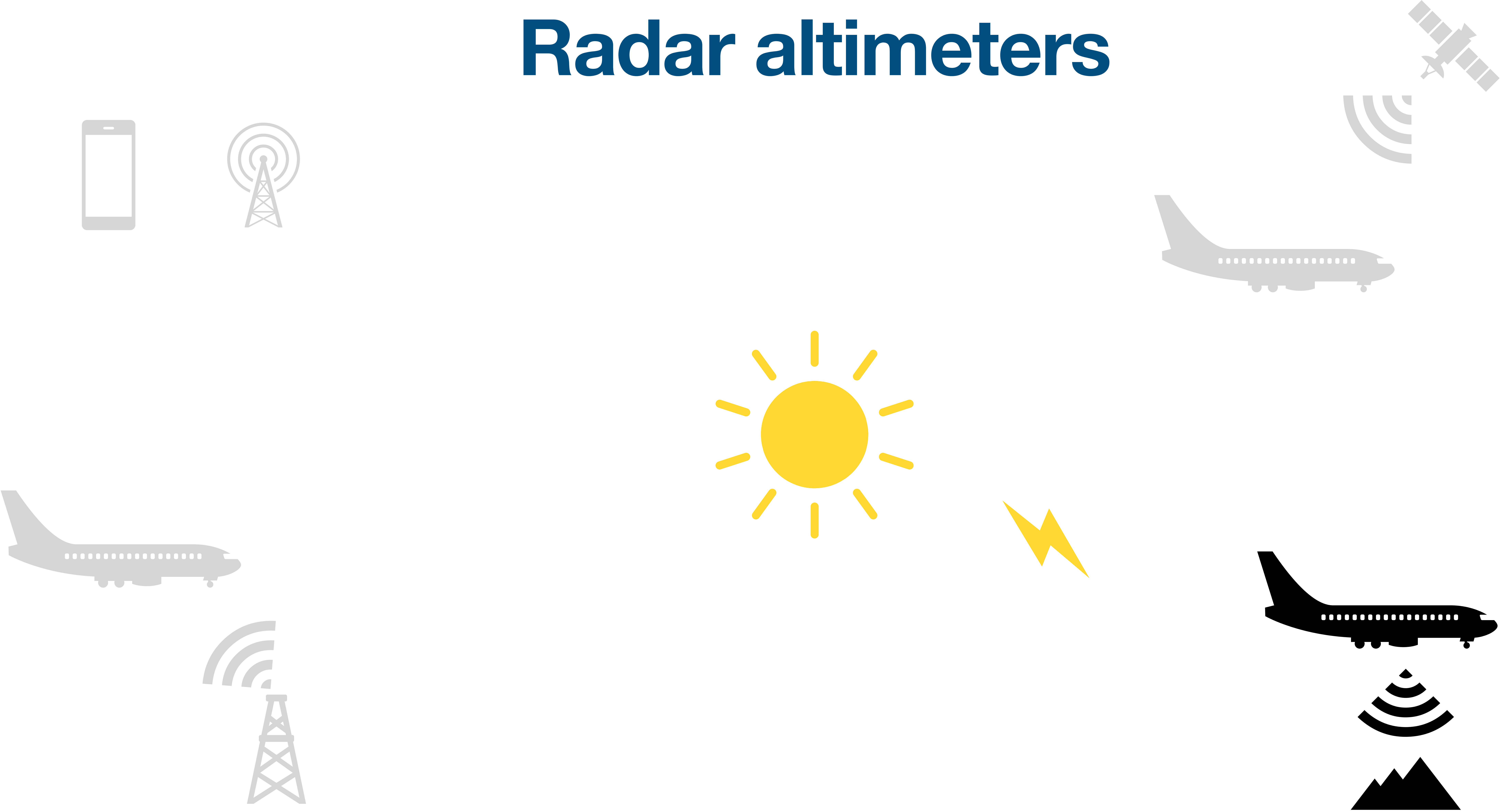




Cerruti et al., 2008



Radar altimeters

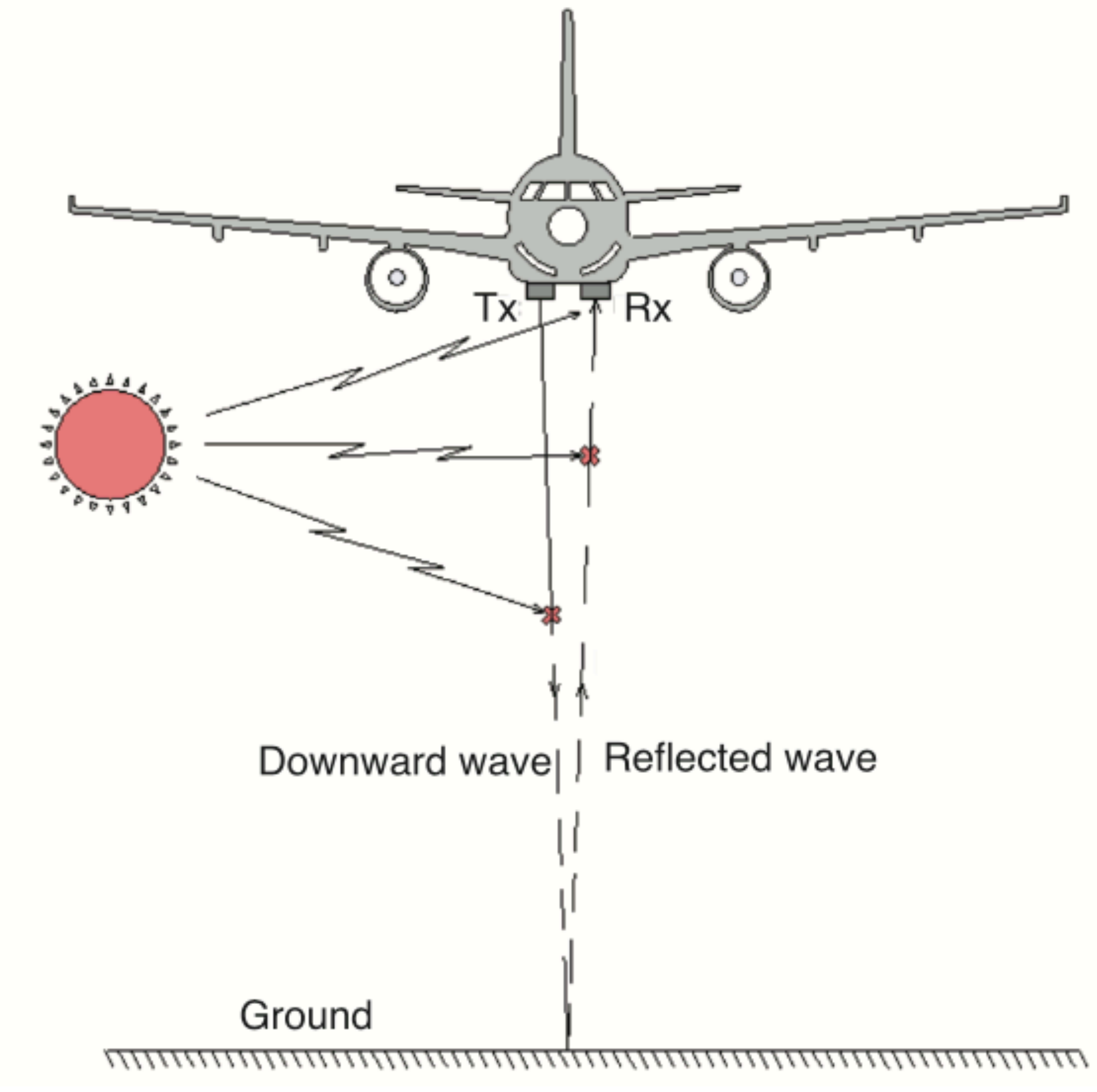


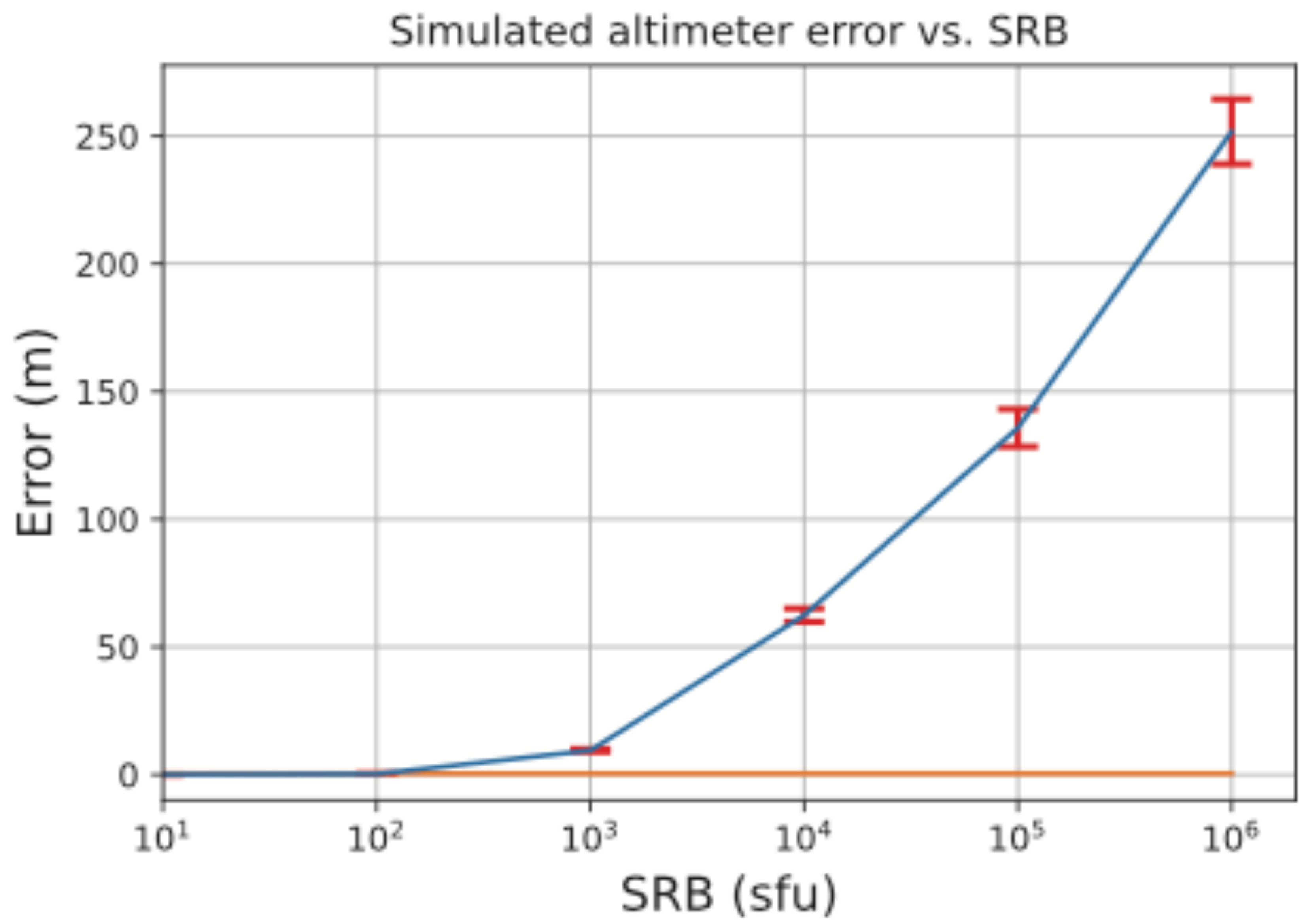
Radar altimeter

Estimated susceptibility

- Measurement of height Above Ground Level
- 4.2 - 4.4 GHz
- Devices on the plane belly

Mc Kee et al., 2023





Should we worry ?

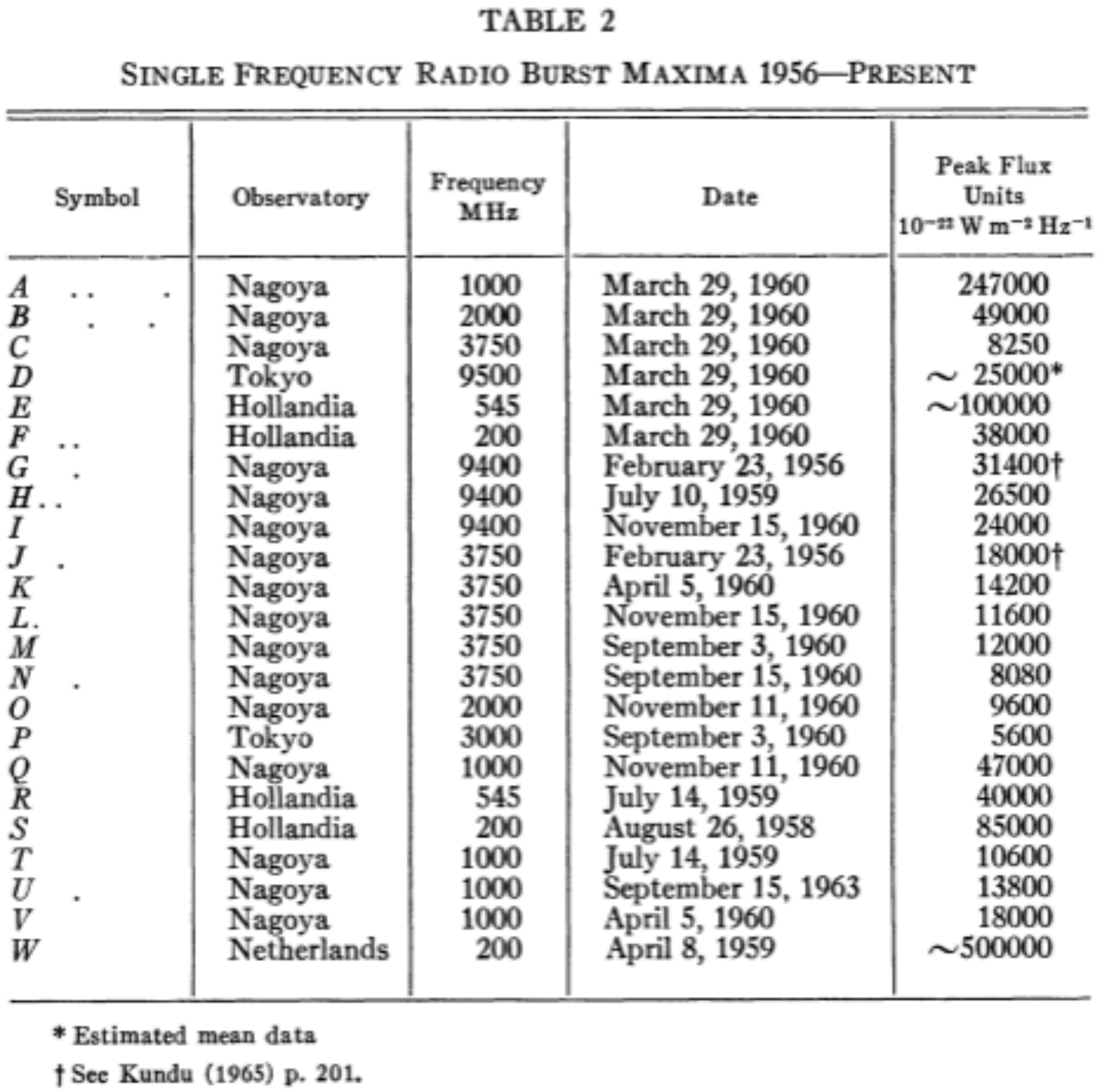


TABLE 2

SINGLE FREQUENCY RADIO BURST MAXIMA 1956—PRESENT

Symbol	Observatory	Frequency MHz	Date	Peak Flux Units 10^{-22} W m^{-2} Hz^{-1}
A	Nagoya	1000	March 29, 1960	247000
B	Nagoya	2000	March 29, 1960	49000
C	Nagoya	3750	March 29, 1960	8250
D	Tokyo	9500	March 29, 1960	~ 25000*
E	Hollandia	545	March 29, 1960	~100000
F	Hollandia	200	March 29, 1960	38000
G	Nagoya	9400	February 23, 1956	31400†
H	Nagoya	9400	July 10, 1959	26500
I	Nagoya	9400	November 15, 1960	24000
J	Nagoya	3750	February 23, 1956	18000†
K	Nagoya	3750	April 5, 1960	14200
L	Nagoya	3750	November 15, 1960	11600
M	Nagoya	3750	September 3, 1960	12000
N	Nagoya	3750	September 15, 1960	8080
O	Nagoya	2000	November 11, 1960	9600
P	Tokyo	3000	September 3, 1960	5600
Q	Nagoya	1000	November 11, 1960	47000
R	Hollandia	545	July 14, 1959	40000
S	Hollandia	200	August 26, 1958	85000
T	Nagoya	1000	July 14, 1959	10600
U	Nagoya	1000	September 15, 1963	13800
V	Nagoya	1000	April 5, 1960	18000
W	Netherlands	200	April 8, 1959	~500000

* Estimated mean data

† See Kundu (1965) p. 201.

Castelli, 1968

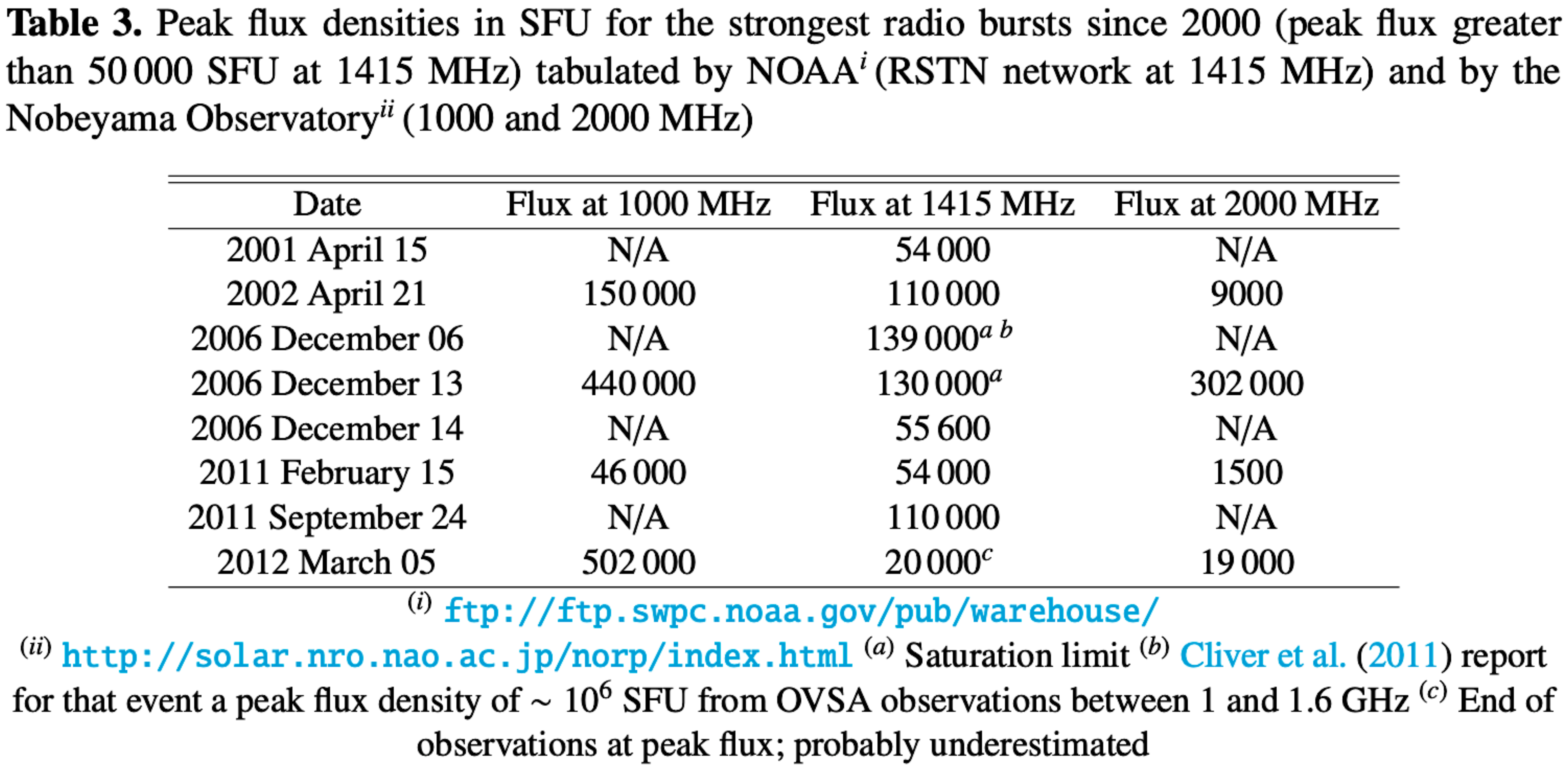


Table 3. Peak flux densities in SFU for the strongest radio bursts since 2000 (peak flux greater than 50 000 SFU at 1415 MHz) tabulated by NOAA[i] (RSTN network at 1415 MHz) and by the Nobeyama Observatory[ii] (1000 and 2000 MHz)

Date	Flux at 1000 MHz	Flux at 1415 MHz	Flux at 2000 MHz
2001 April 15	N/A	54 000	N/A
2002 April 21	150 000	110 000	9000
2006 December 06	N/A	139 000[a b]	N/A
2006 December 13	440 000	130 000[a]	302 000
2006 December 14	N/A	55 600	N/A
2011 February 15	46 000	54 000	1500
2011 September 24	N/A	110 000	N/A
2012 March 05	502 000	20 000[c]	19 000

(i) `ftp://ftp.swpc.noaa.gov/pub/warehouse/`

(ii) `http://solar.nro.nao.ac.jp/norp/index.html` (a) Saturation limit (b) Cliver et al. (2011) report for that event a peak flux density of ~ 10^6 SFU from OVSA observations between 1 and 1.6 GHz (c) End of observations at peak flux; probably underestimated

Our own study, 2018

In conclusion

- Long duration and intense radio bursts (type IV) are to be monitored
- ATC radar and GNSS (WAAS/EGNOS) systems used by the aviation industry are susceptible to interferences from Solar Radio Bursts
- Radar altimeters may be susceptible
- These systems may be degraded during critical parts of flights (landing, traffic around airports etc...)
- Communication services are also susceptible to be interfered with (we would like to hear from users !)
- Awareness of operators and pilots is critical