XXII RINEM

Riunione Nazionale di Elettromagnetismo

September 3-6, 2018 Cagliari, Italy

Solar Radio Interferences on Radio Systems: A Direct Space Weather Effect

Mauro Messerotti[1,2]

[1]INAF-Astronomical Observatory of Trieste

[2]University of Trieste, Department of Physics

THANK YOU FOR YOUR ATTENTION

Presentation Outline

- Meteorology of Space and Impacts
- Solar Radio Weather and Impacts
- Solar Radio Interferences
- Solar Radio Monitoring in Italy
- Summary and Conclusions

METEOROLOGY OF SPACE AND RELATED IMPACTS

Meteorology, Weather, and Climate of Earth and Planets

- **Meteorology**

  The discipline which deals with the atmosphere and its phenomena

- **Weather**

  The physical state of the atmosphere at a specific time and place

- **Climate**

  The average state of weather on the long term

Meteorology, Weather, and Climate of Space and Planetary Environments

- **Meteorology of Space**

  The discipline which deals with the space domain and its phenomena, and their impacts on planetary environments

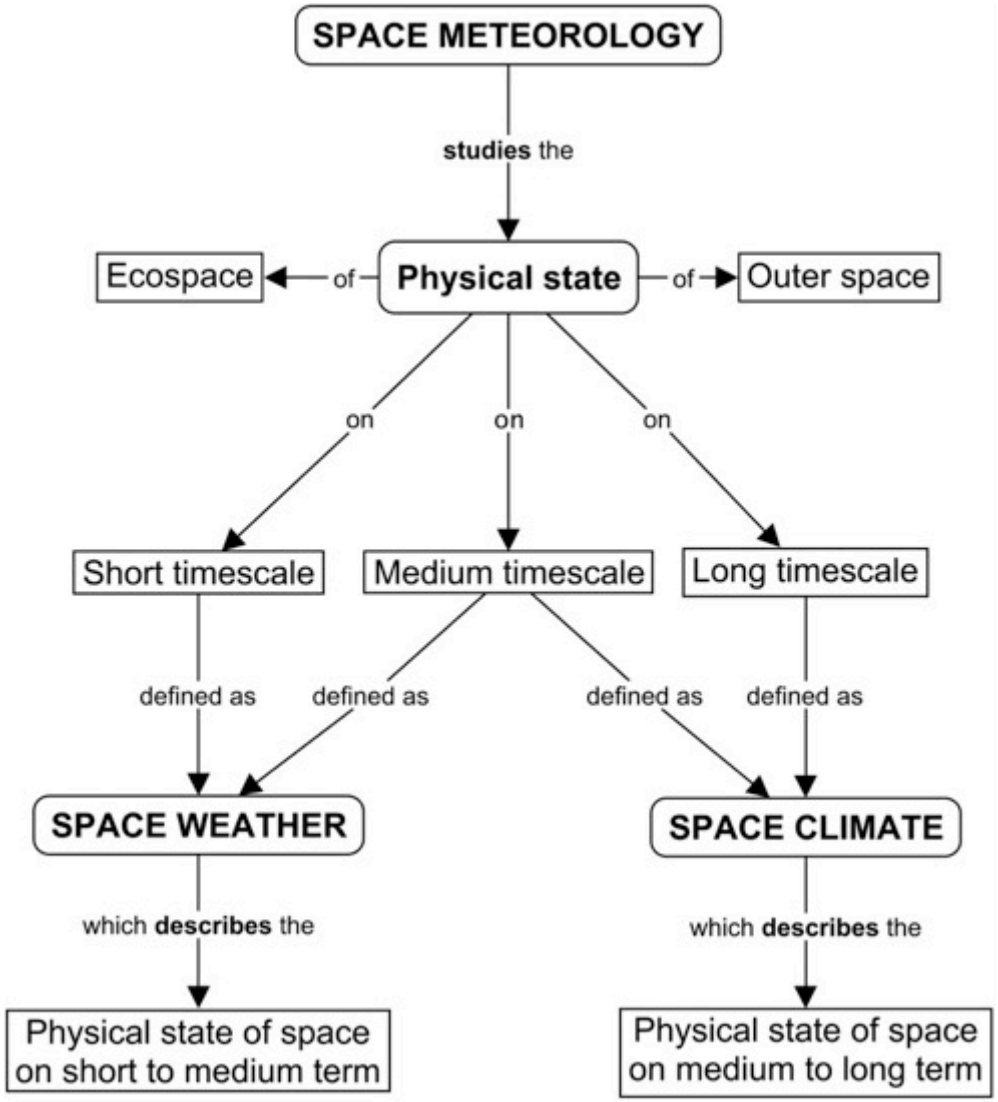
- **Space Weather**

  The physical state of the space domain at a specific time and place

- **Space Climate**

  The average state of space weather on the long term

Ontology of Meteorology of Space



This Concept Map was created with IHMC CmapTools

Messerotti, 2004

The Universe as A System of Systems

- Astrophysical systems are
  - Complex systems that exhibit a chaotic behaviour
  - Characterised by their properties in spacetime at different spatial, temporal and energy scales
  - Nonlinearly coupled to each other
- The Universe is a system of systems: no astrophysical system is decoupled by the other ones

Evolution of the Space Weather Perspective

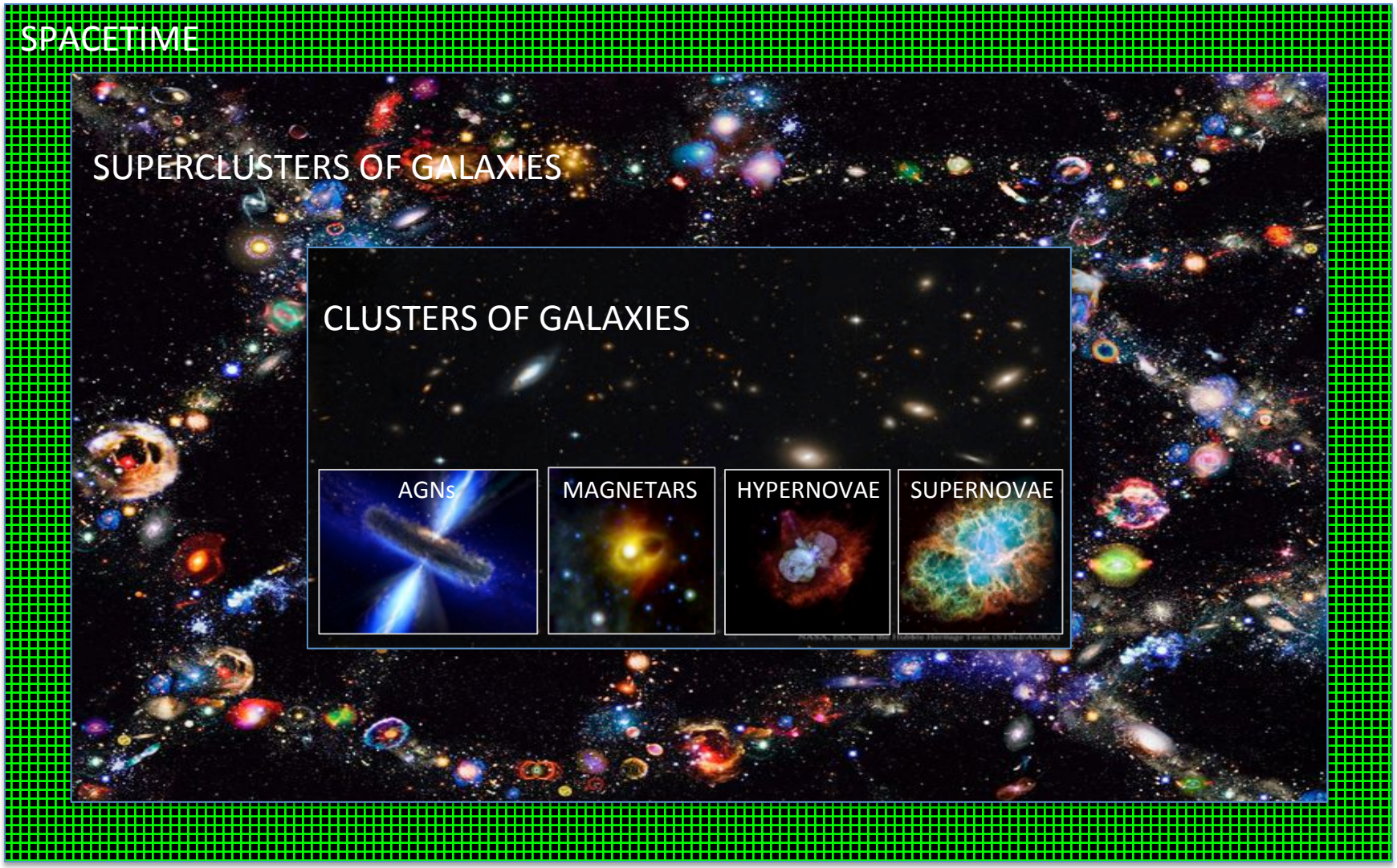
The Space Weather and Space Climate physical scenario has been progressively spanning

a. Sun-Earth
b. Sun-Earth and Planets
c. Solar System
d. Heliosphere

but will progressively and unavoidably embrace

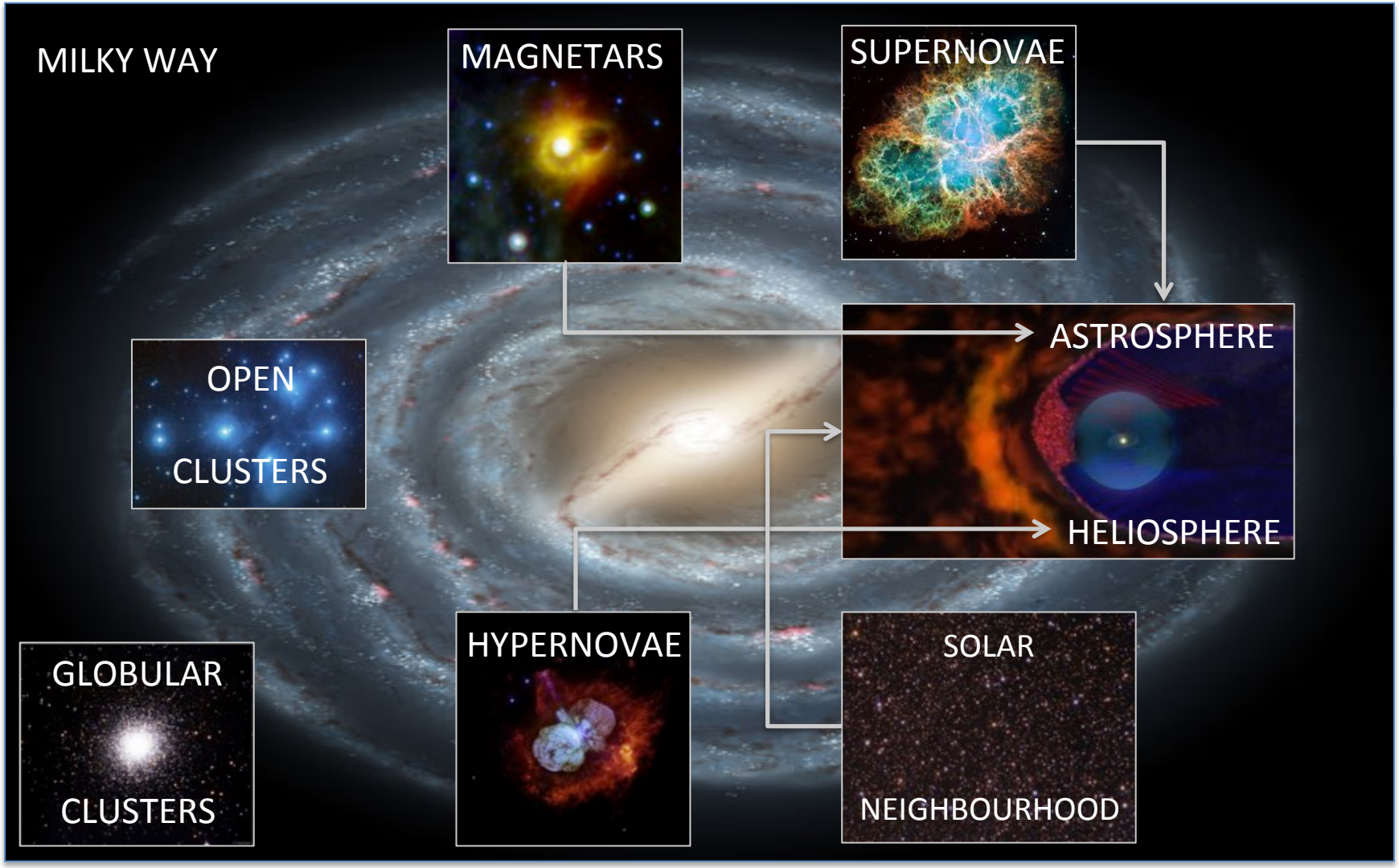
e. Our Galaxy
f. The Universe

Sources of Extragalactic Climate



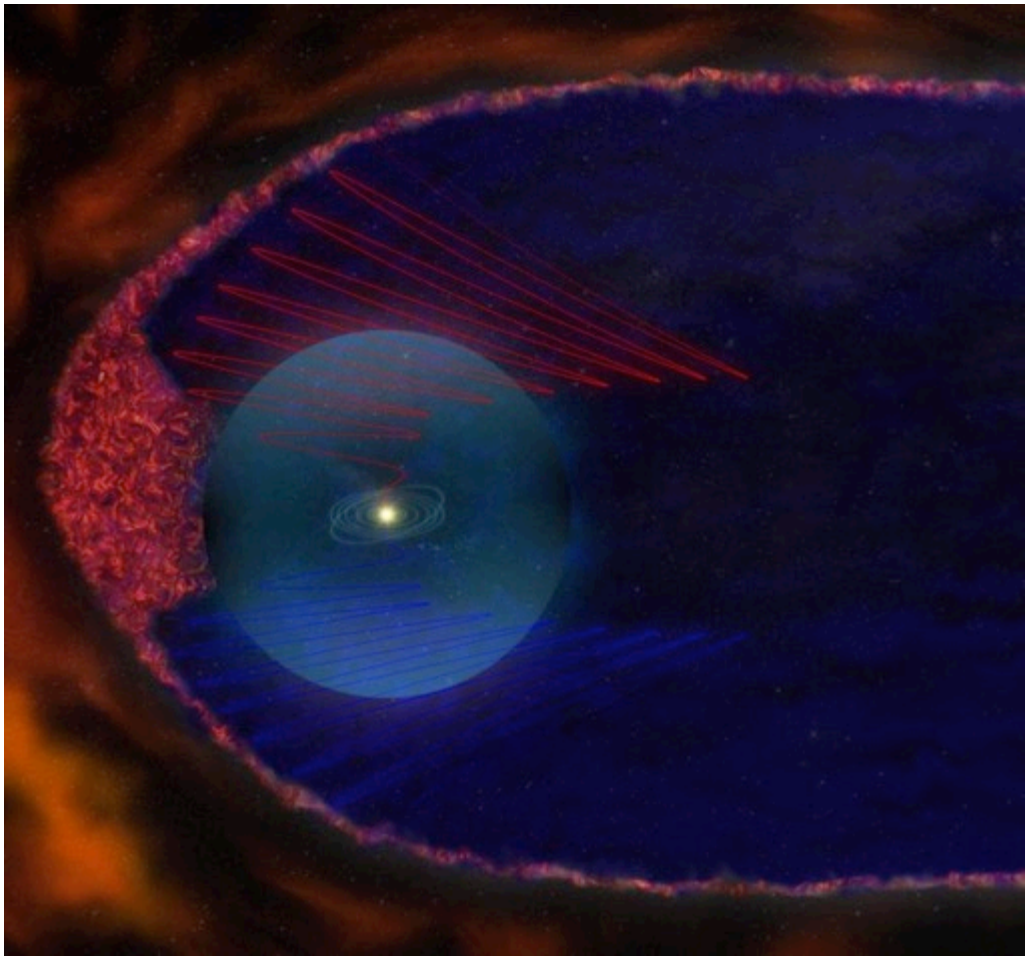
Spatial Scale: Gly-Mly **Timescale**: Ga-Ma

Sources of Galactic Climate in The Galaxy



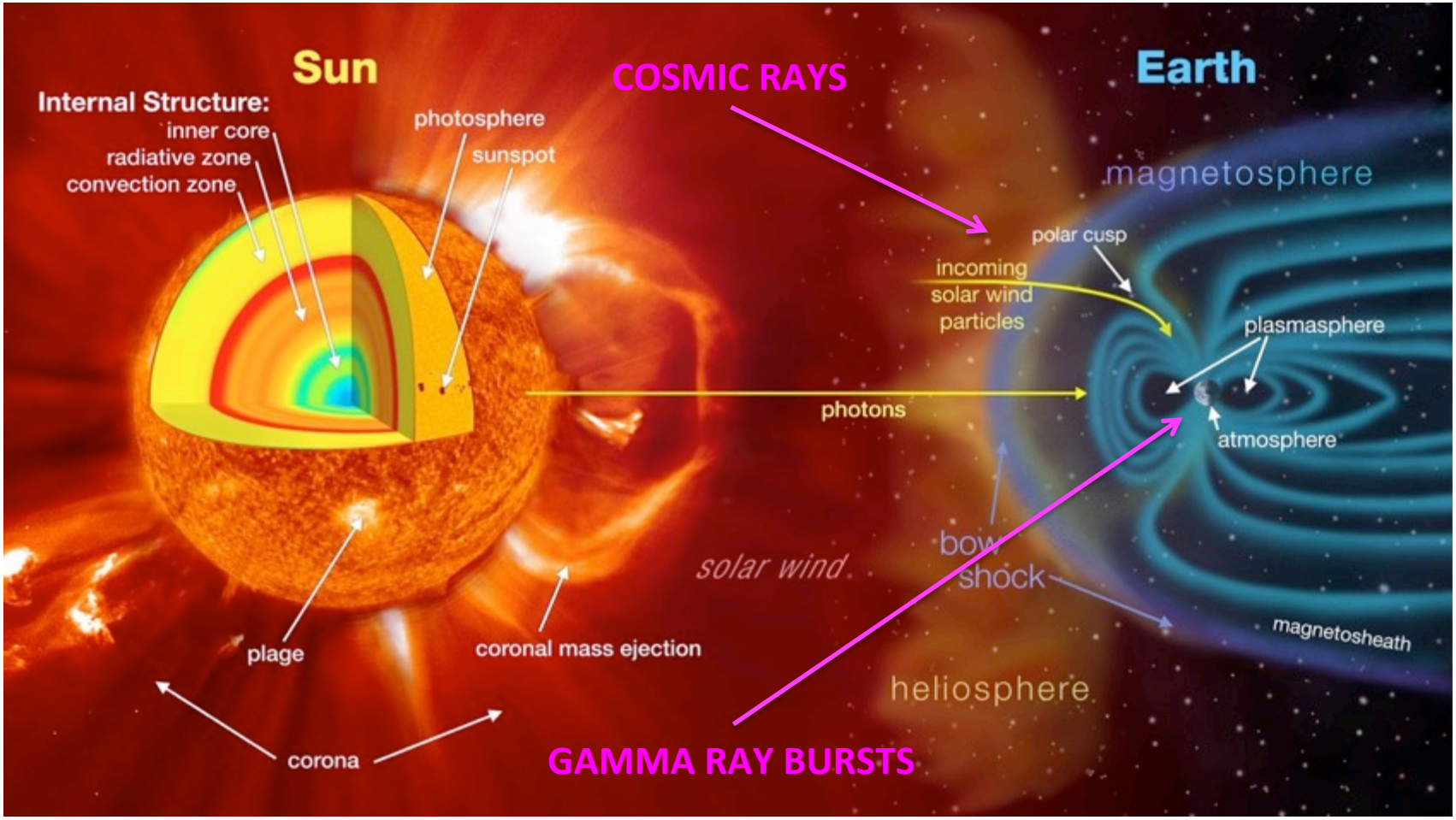
Spatial Scale: 10^5- 1 ly **Timescale**: Ga-Ma

Heliospheric Weather and Climate



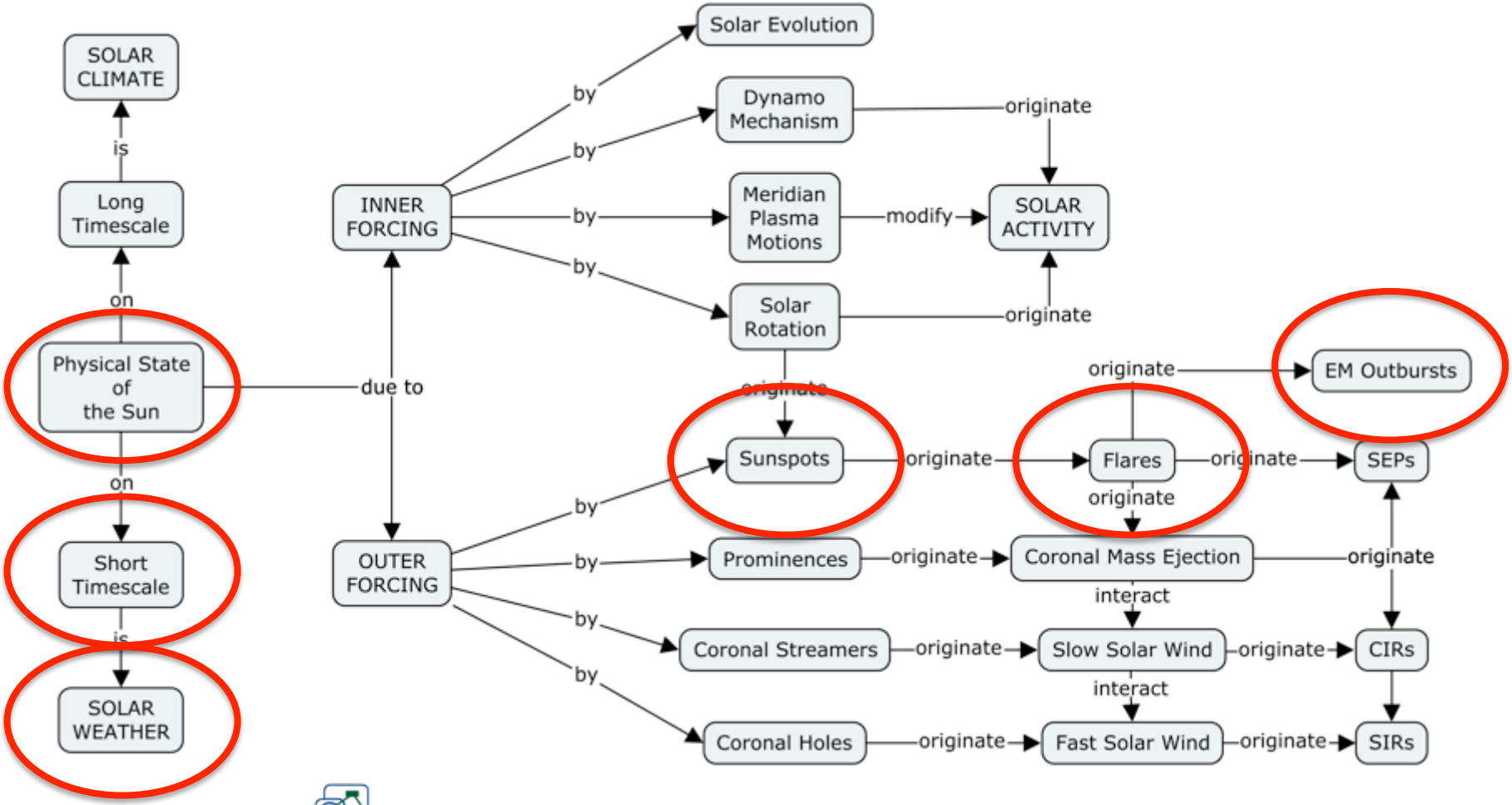
Spatial Scale: 100- 1 AU **Timescale**: Ga-1 yr

Heliospheric and Solar Weather and Climate Coupling With Geospace Weather and Climate



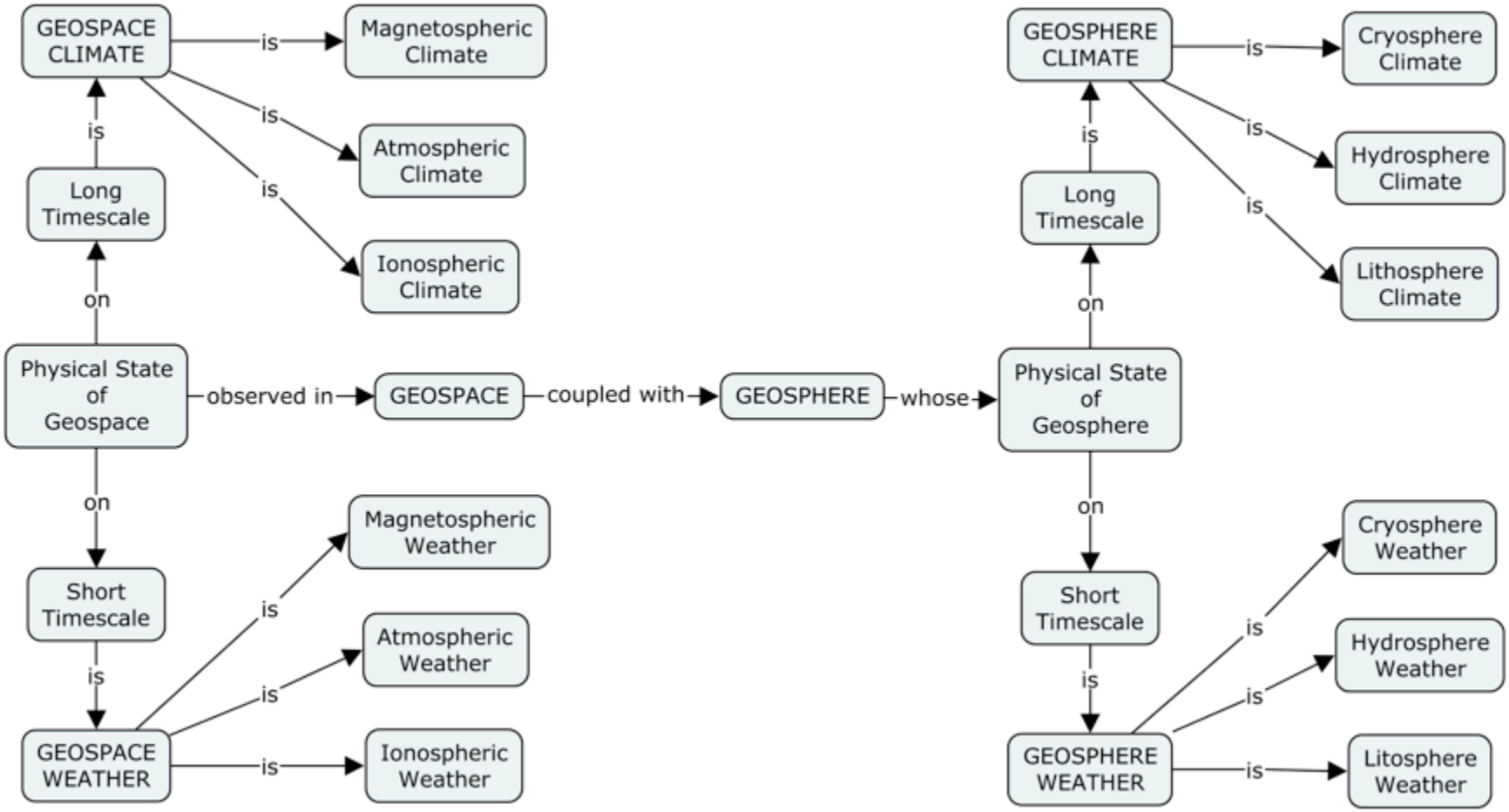
Spatial Scale: 1 AU-1 cm **Timescale**: Ga-0.1 ms

Definition of Solar Weather and Climate



Messerotti, 2017

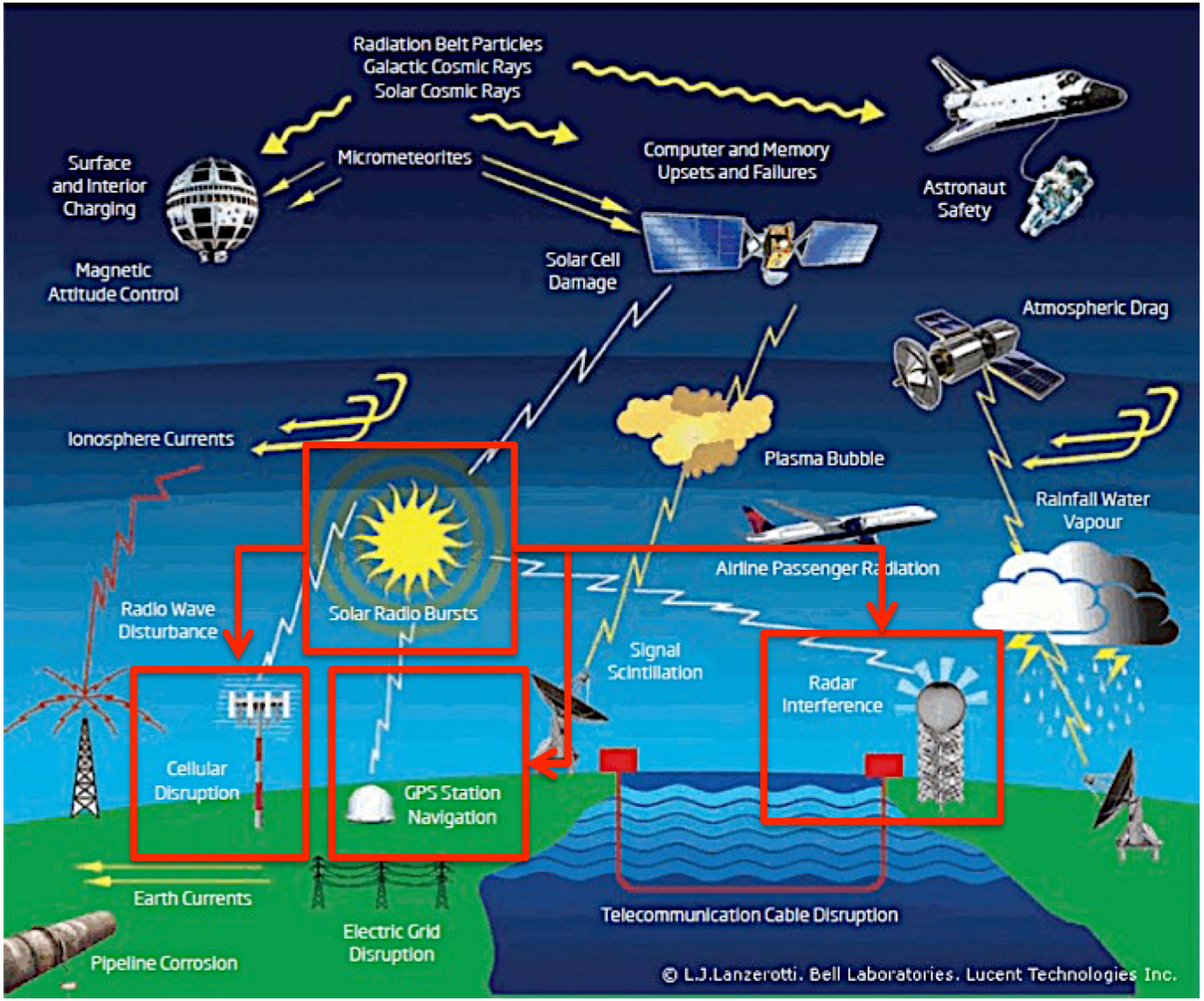
Definition of Geospace Weather and Climate



This Concept Map was created with IHMC CmapTools

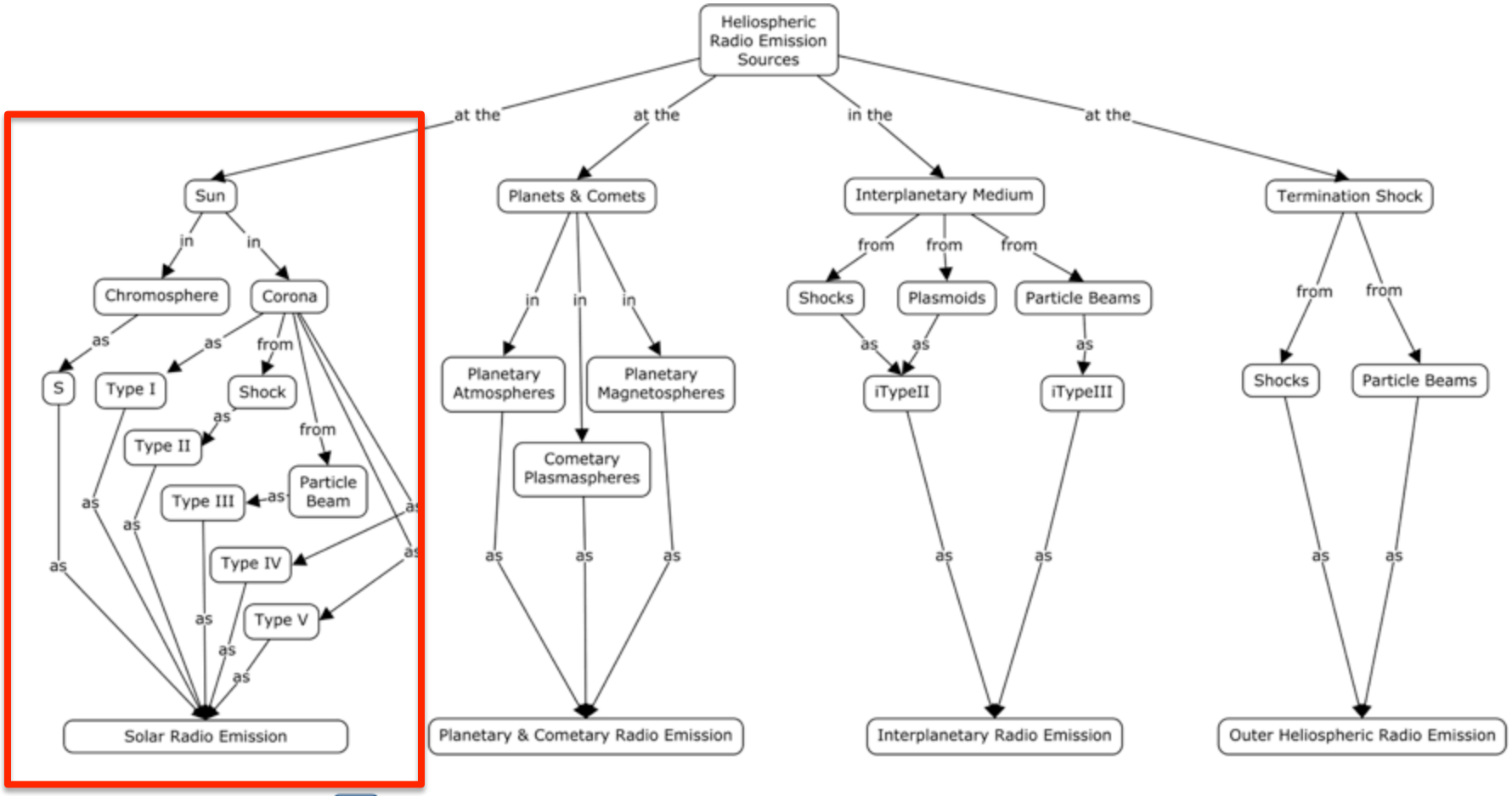
Messerotti, 2017

Synopsis of SWx Impacts



RADIO EMISSIONS RELEVANT TO SPACE WEATHER

Radio Emission Sources in Heliosphere



This Concept Map was created with IHMC CmapTools

Messerotti, 2009

Solar Radio Physics

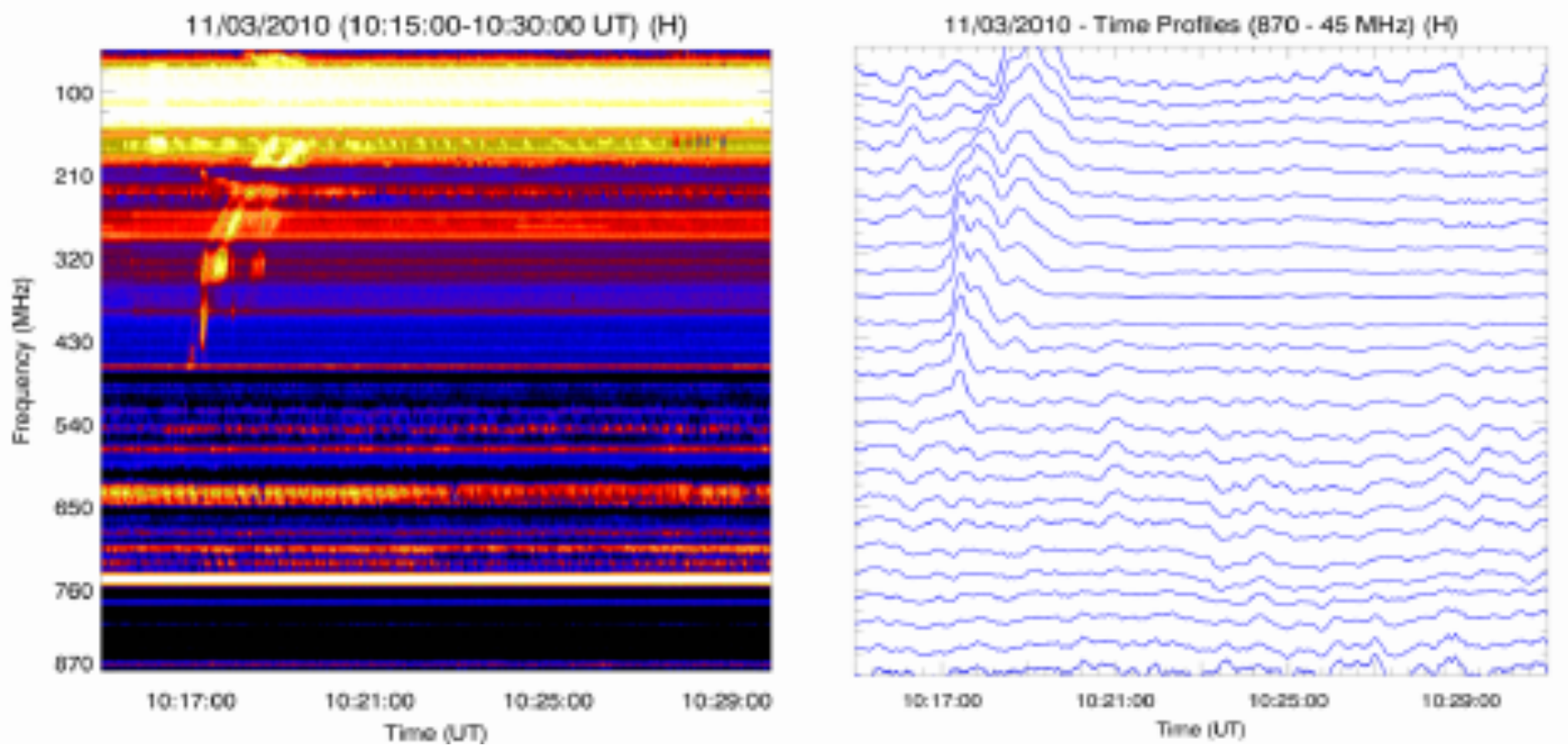
In the framework of Space Weather:

- **Radio physics of solar radio emissions:**
  a. Provides key information on solar energetic processes
  b. Allows to estimate their direct geoeffectivity as radio interferences
  c. Allows to use them as precursors and proxies of energetic particle events
- **Solar Radio Spectrography and Imaging** provide a wealth of physical information on plasma processes

Solar and Heliospheric Radio Weather Monitoring

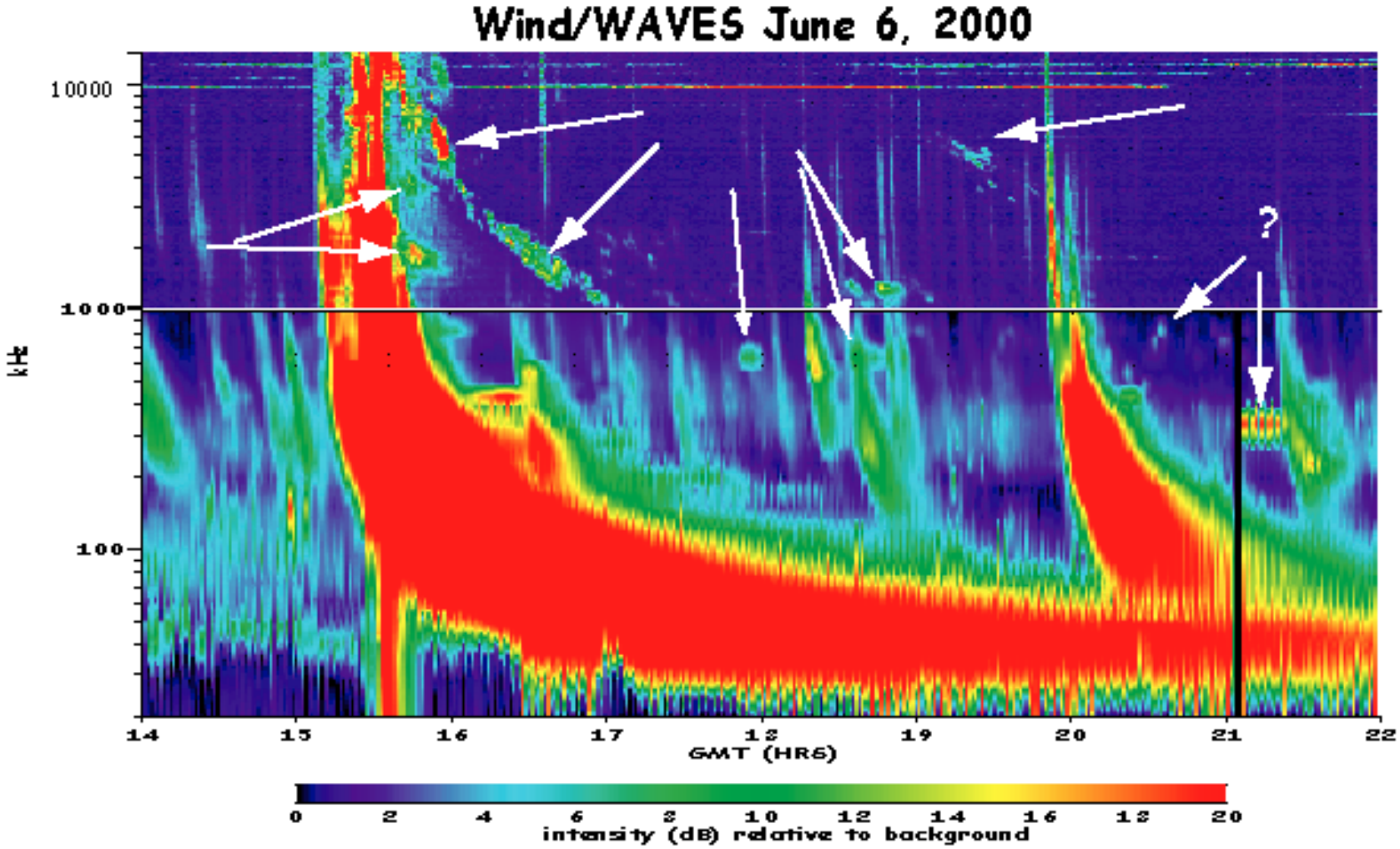
- Diachronic radio observations are a must to adequately sample the physical parameter hyperspace
  - S(t; f; {x, y, z}), Radio Flux Density
  - P(t; f; {x, y, z}), Circular Polarisation
- This requires dedicated radio instruments
  - Ground-based (network) and space-based (fleet)
  - Extended spectral coverage
  - Multichannel radio polarimeters — 1-D DATA
  - Polarimetric radio spectrographs — 2.5-D DATA
  - Polarimetric radio heliographs — 4-D DATA

Solar Radio Spectrum With Coronal Type II Burst

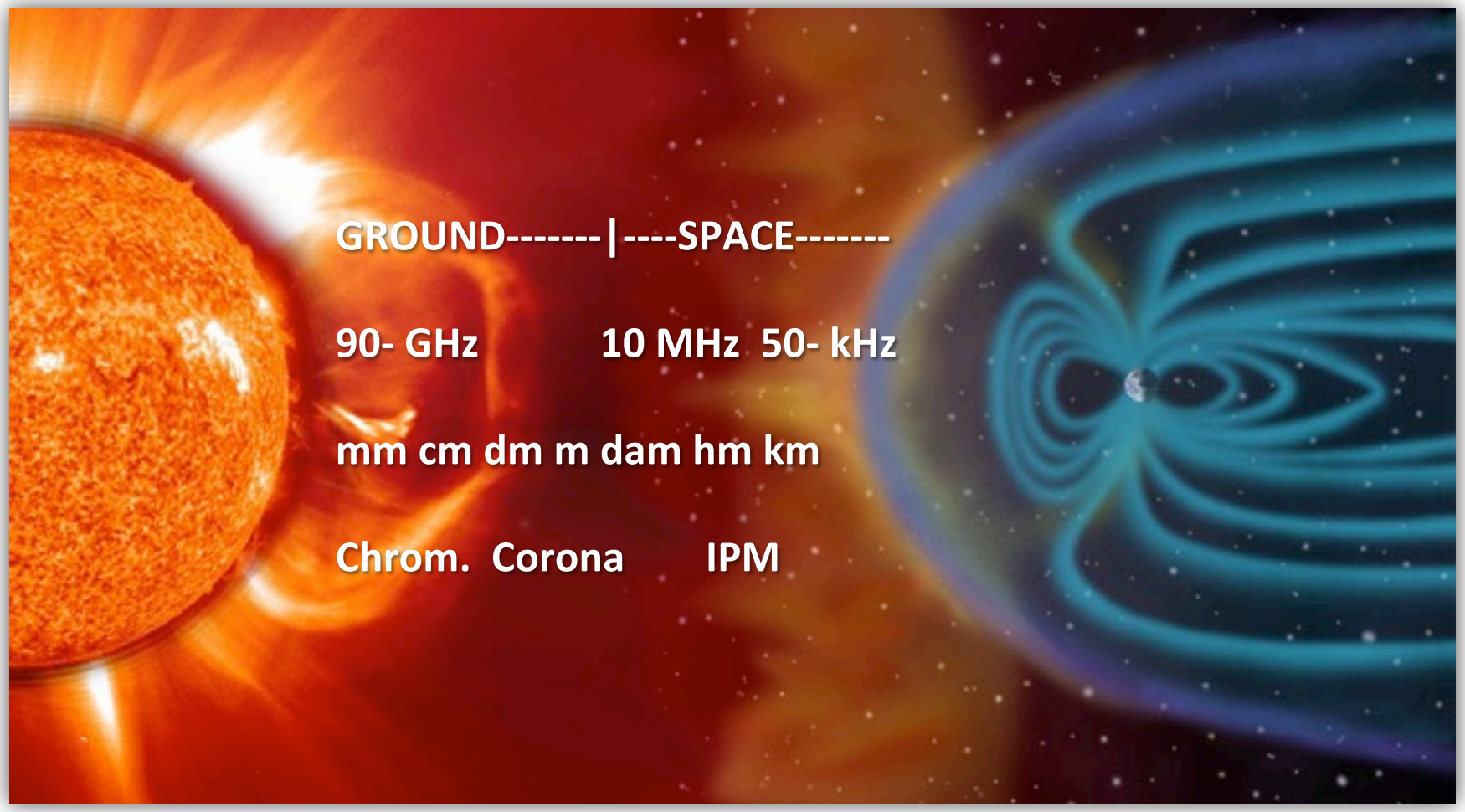


Silva et al., 2012

Radio Spectrum
With Interplanetary Type II Burst

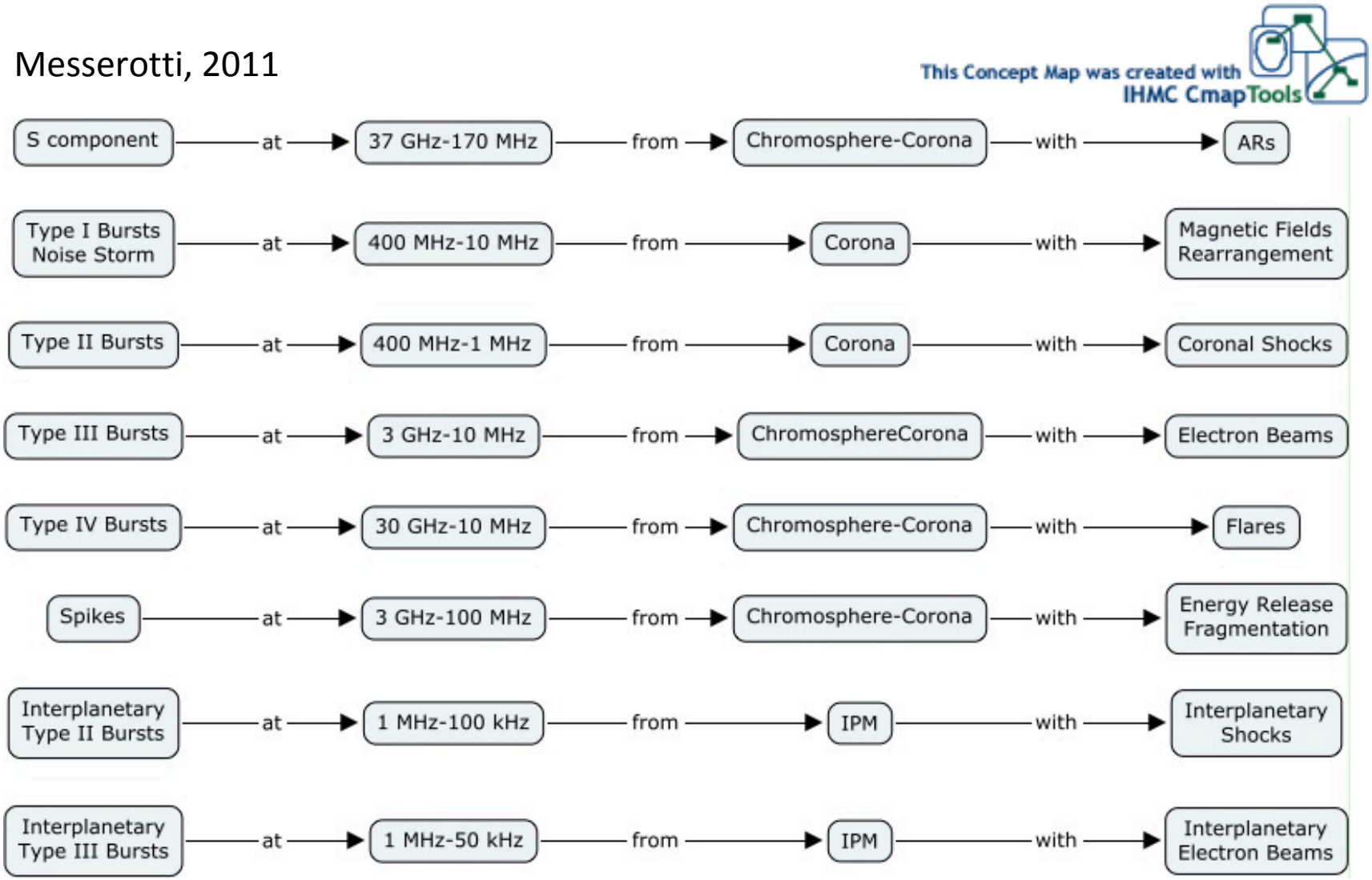


Approximate Location of Radio Emissions @ $f \gtrsim f_{pe}(r) \sim \sqrt{n_e(r)}$

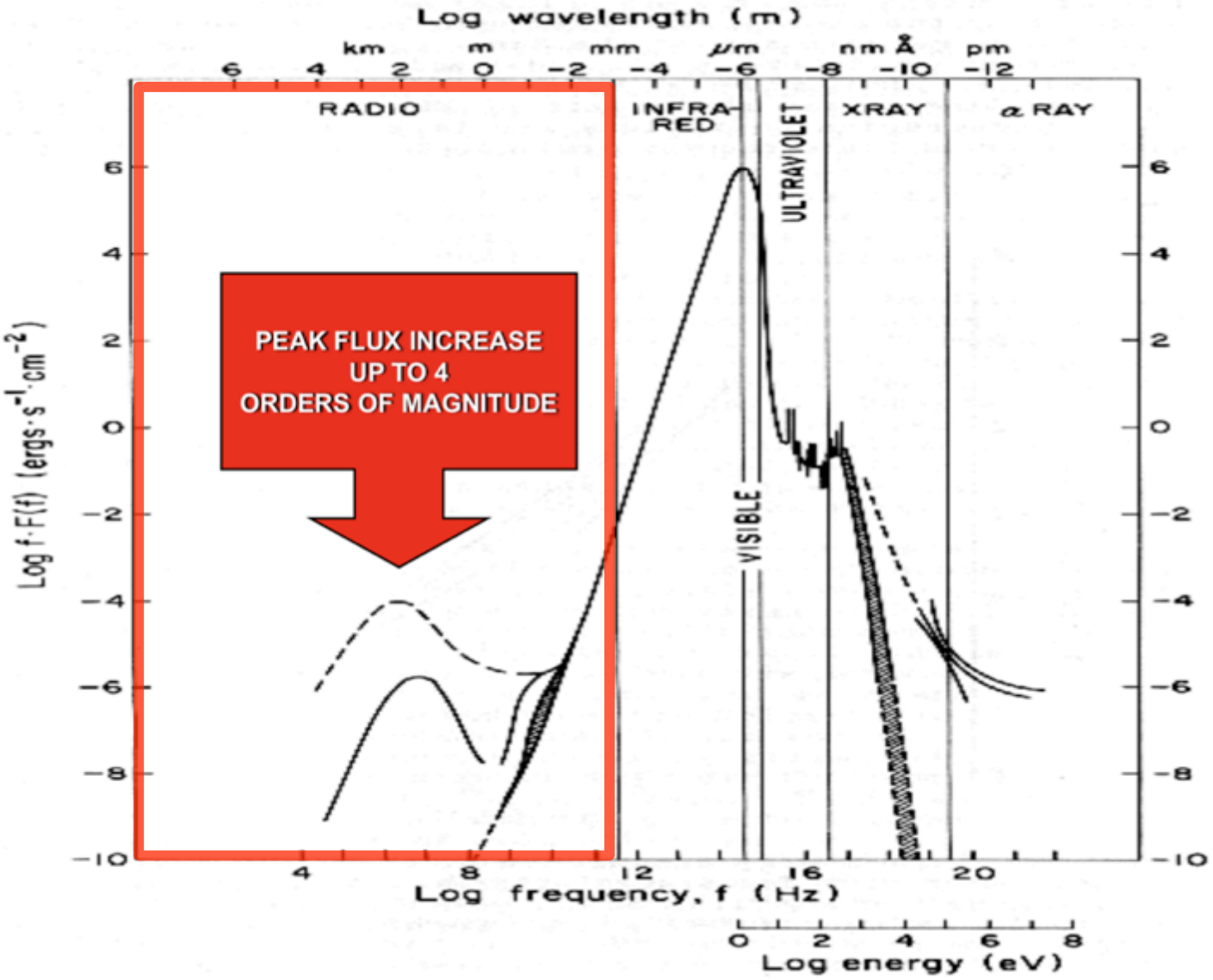


Solar and IP Radio Emissions

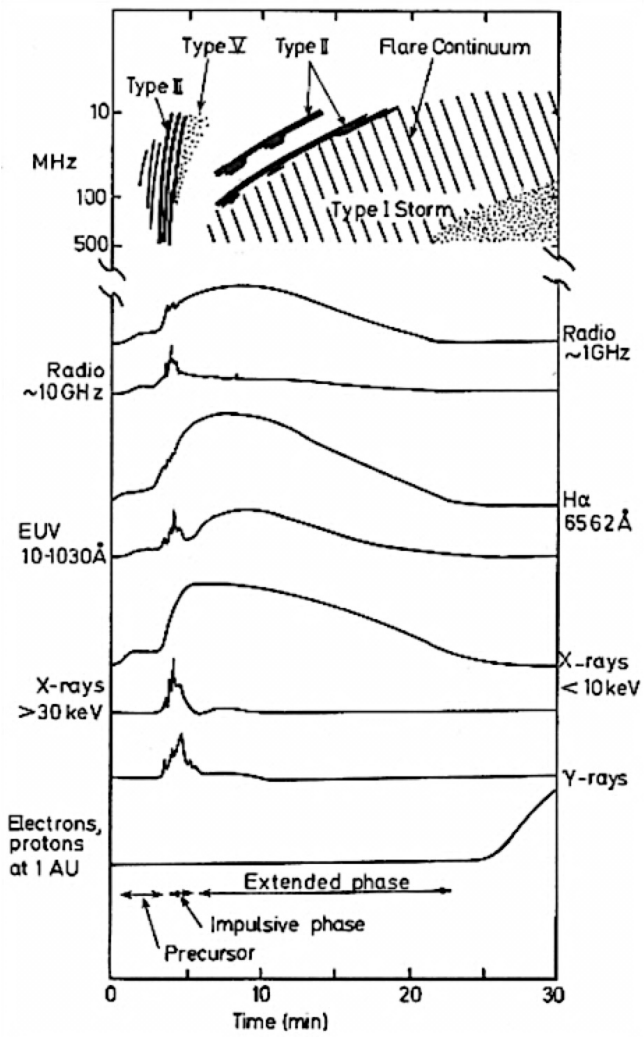
Messerotti, 2011



Solar Radiation Spectrum



Timing of Solar Radio Bursts With Respect to Solar Flares



McLean & Labrum, 1985

SOLAR RADIO WEATHER AND SOLAR RFI'S

Solar Radio Weather Definition

- **SOLAR RADIO WEATHER** REFERS TO THE PHYSICAL STATE OF THE SUN AS AN ENSAMBLE OF RADIO SOURCES

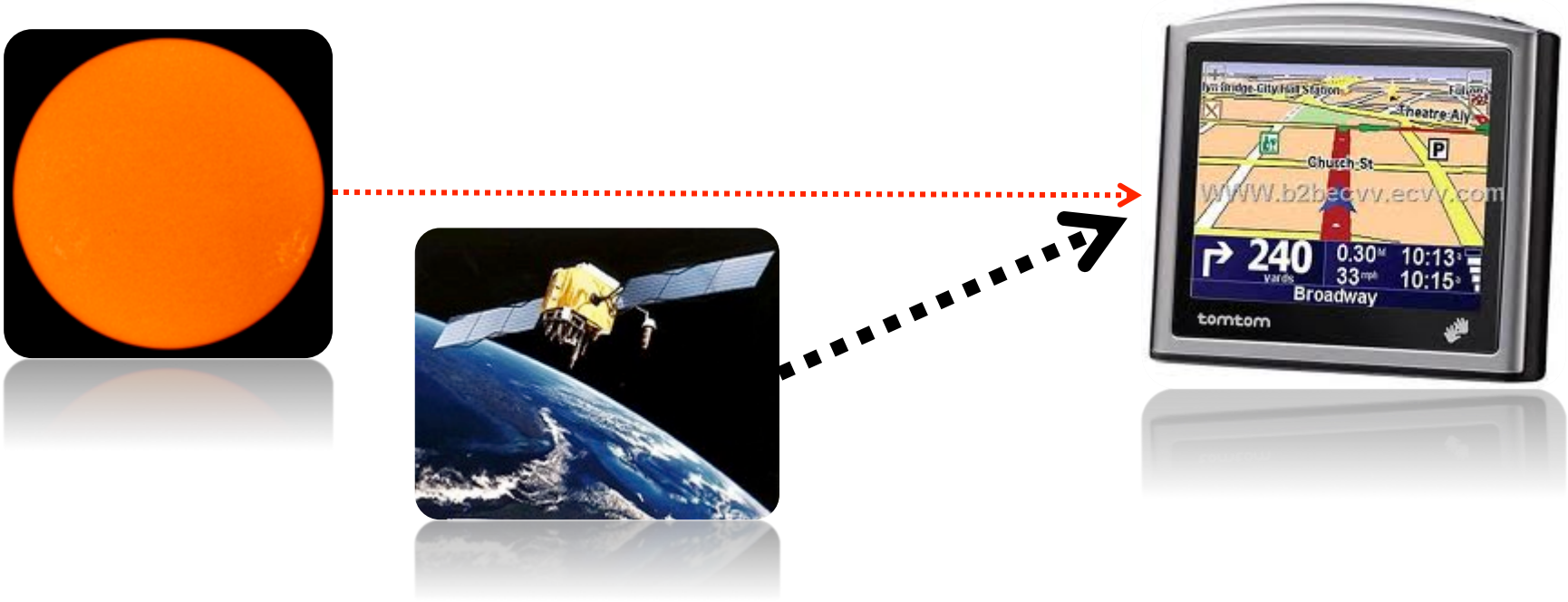
Solar Radio Frequency Interferences

- The Sun is a source of radio emissions that are
  - Non-directional
  - Broadband
- Solar radio noise can
  - Increase by several orders of magnitude during outbursts
  - Persist at high levels for minutes to hours
- Increased solar radio noise can interfere with
  - HF communications (MIL)
  - Mobile communications (GSM, UMTS)
  - Global Navigation Satellite Systems (GNSS)
  - GNSS Augmentation Systems (WAAS, EGNOS)
  - Radars
  - SATCOM's

DIRECT SOLAR RADIO WEATHER IMPACTS

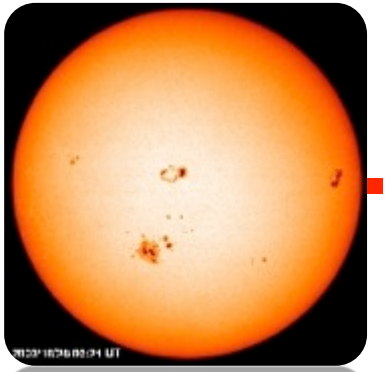
EFFECT OF SOLAR RADIO WEATHER ON GPS SIGNAL RX'S

Quiet Radio Sun



- **VERY LOW SOLAR RADIO EMISSION LEVEL**
- GPS RADIO SIGNAL FROM SATELLITES
- **HIGH SIGNAL-TO-NOISE RATIO @ RECEIVER**
- STANDARD POSITION ACCURACY

Active Radio Sun



- **VERY HIGH SOLAR RADIO EMISSION LEVEL**
- GPS RADIO SIGNAL FROM SATELLITES
- **LOW SIGNAL-TO-NOISE RATIO @ RECEIVER**
- HIGH POSITION ERROR TO TOTAL LOSS OF LOCK
- ALL SUNLIT EARTH'S HEMISPHERE AFFECTED

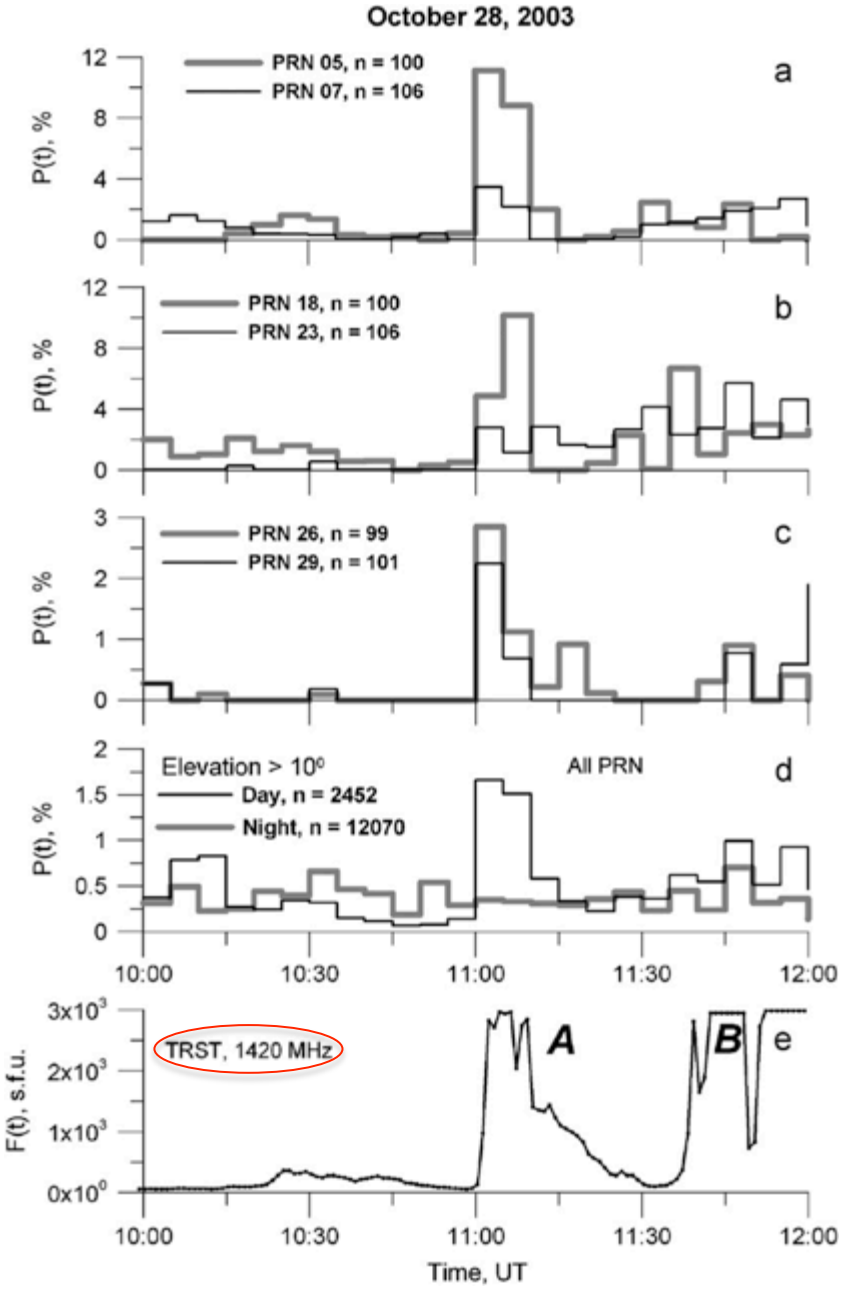
Effects of SRBs on GPS Receivers

- Cerruti et al. (2006):
  - **Observed** reduced carrier-to-noise ratio in sunlit GPS receivers over the duration of SRB (8,700 SFU RHCP → 2.3 dB loss; 2005.09.07)
  - Estimated L1 C/N_0 fade of 3 dB and L2 C/N_0 fade of 5.2 dB for commonly used GPS antennas with a gain of 4 dBic, from a SRB of 10,000 SFU
  - SRB's are a potential threat to life-critical systems based on a Global Navigation Satellite System (GNSS): a 80,000 SFU SRB can determine a 12 dB fade at L1 and a 26.2 dB fade on the L2 channel → loss of lock in semi-codeless receivers.
- Possibly 4,000-12,000 SFU Chen et al. (2005)

Powerful solar radio bursts as a global and free tool for testing satellite broadband radio systems, including GPS–GLONASS–GALILEO (Afraimovich et al., JASTP 70, 1985, 2008)

- Investigated failures in the global positioning system (GPS) performance produced by solar radio bursts with unprecedented radio flux density during the X6.5 and X3.4 solar flares on 6 and 13 December 2006, respectively
- Significant experimental evidence was found that high-precision GPS positioning on the Earth's entire sunlit side was partially disrupted for more than 10–15 min on 6 and 13 December 2006

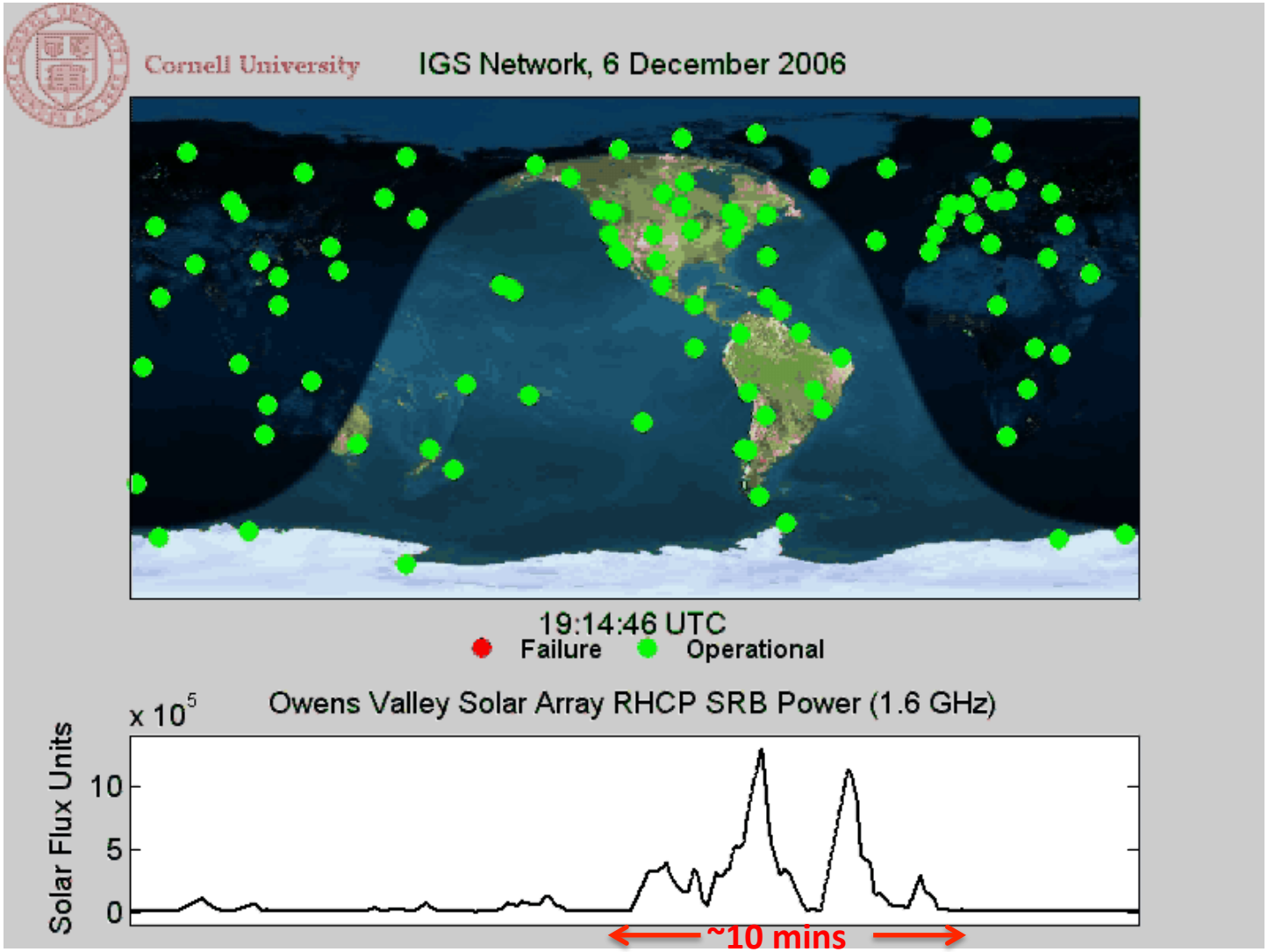
GPS Failures on 28 October 2003



GPS phase slips during the solar flare on 28 October 2003 in the sunlit hemisphere. The relative density P(t) of L1–L2 phase slips for all (d) and individual GPS satellites (a), (b), and (c). The flux F(t) of RHCP radio emission (1420 M Hz) registered by the Trieste Solar Radio Spectrograph (e).

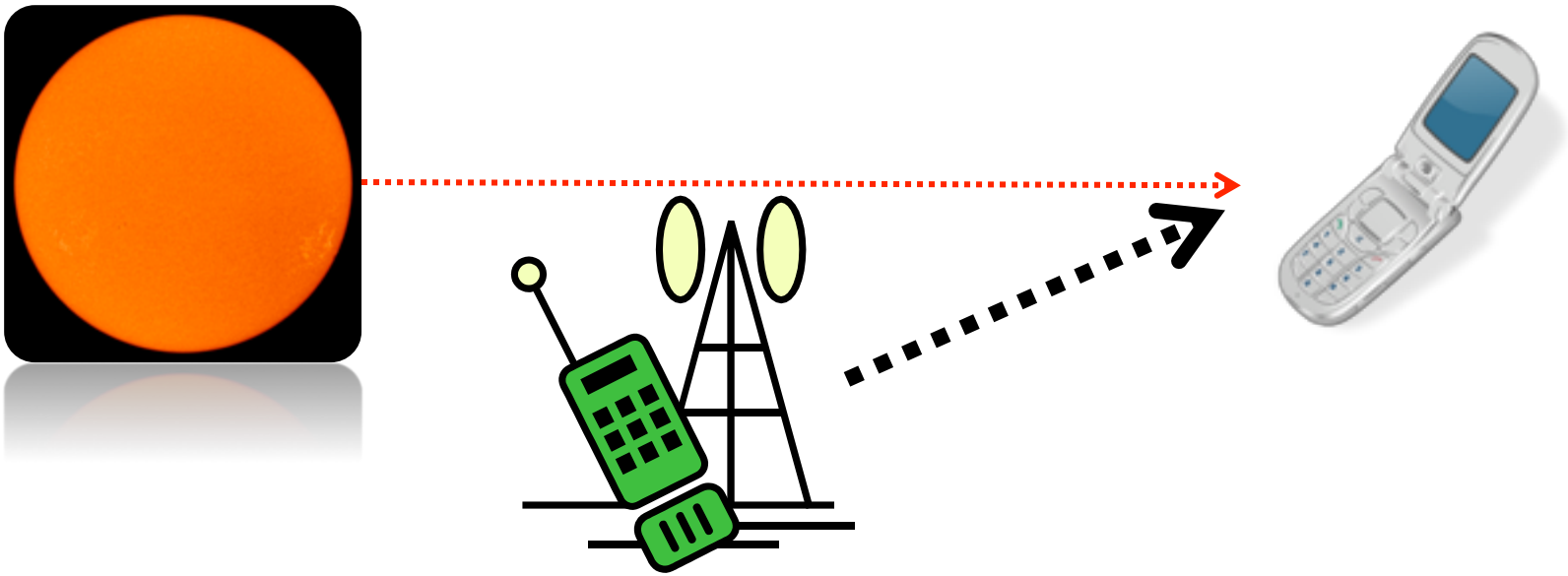
Afraimovich et al., 2008

Solar Radio Burst Impact on GPS on 6 Dec. 2006



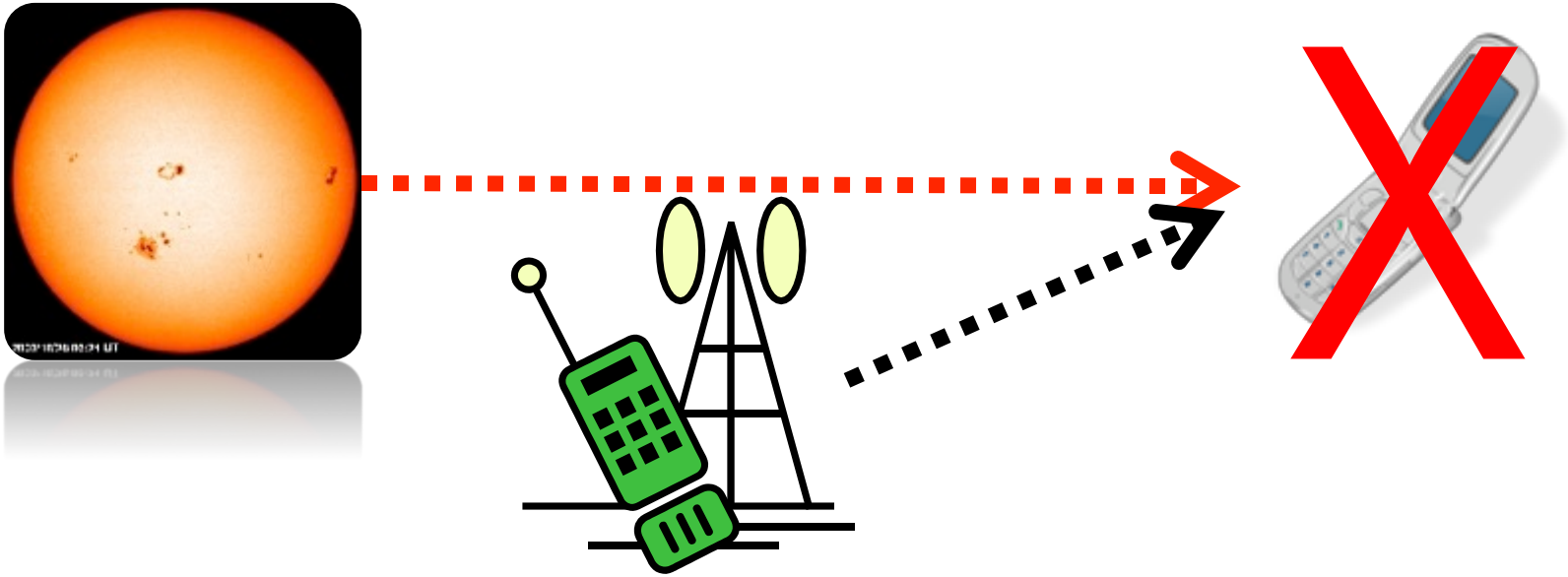
EFFECT OF SOLAR RADIO WEATHER ON MOBILE COM'S

Quiet Radio Sun



- **VERY LOW SOLAR RADIO EMISSION LEVEL**
- RADIO SIGNAL FROM CELL REPEATER
- **HIGH SIGNAL-TO-NOISE RATIO @ RECEIVER**
- STANDARD COMMUNICATION QUALITY
- GEOMETRY KEY CONDITION

Active Radio Sun



- **VERY HIGH SOLAR RADIO EMISSION LEVEL**
- RADIO SIGNAL FROM CELL REPEATER
- **LOW SIGNAL-TO-NOISE RATIO @ RECEIVER**
- LOSS OF LOCK AND COMMUNICATION DROP
- GEOMETRY KEY CONDITION

Effects of SRBs on Wireless Systems

- Bala et al. (2002):
  - For a cellular base station operating at 900 MHz , the equivalent solar flux (thermal noise=solar noise level) F_{eq} ~ 960 SFU → more than twice the thermal noise power.
  - For a base station operating at 2.4 GHz, F_{eq} ~ 6,000 SFU.
  - The bit error rate (ber) changes rapidly with the S/N power ratio. (0.75 dB change → 10x in ber)
  - Assuming an SRB effectivity threshold of 1,000 SFU, the statistics over 4 decades indicates a probability of interference every 10-20 days on average per year, modulated by the solar cycle
- Lanzerotti et al. (2002); Nita et al. (2004)

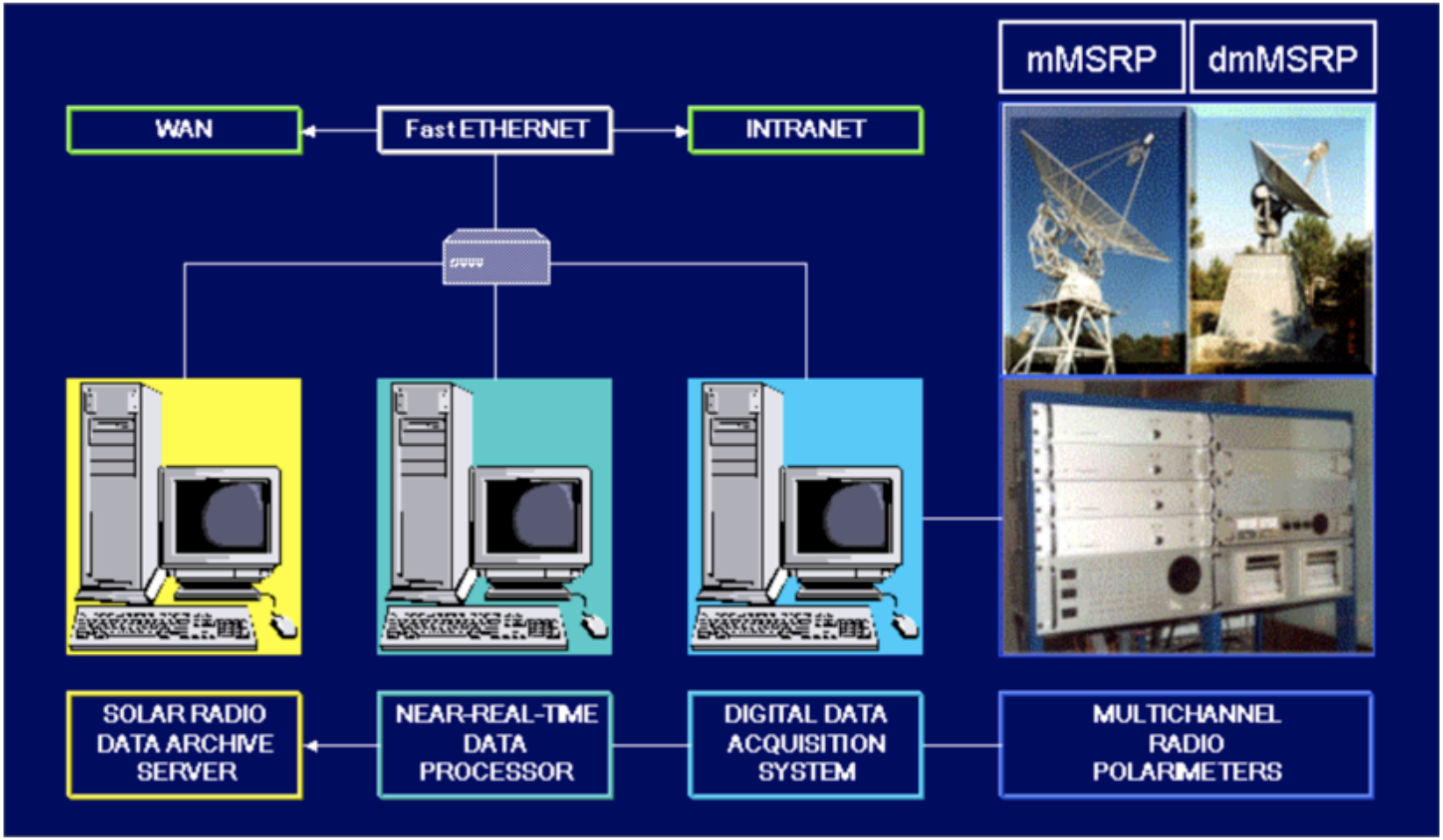
SOLAR RADIO MONITORING IN ITALY

THE FORMER TRIESTE SOLAR RADIO SYSTEM (TSRS)

TSRS at a Glance

- TSRS (Trieste Solar Radio System)
  - MMSRP (237, 327, 408, 610 MHz)
  - DMMSRP (1420, 2695 MHz)
  - Flux density + Circular polarization
  - High time resolution (1 ms – 0.1 ms)
- Continuous coronal radio surveillance
- Radio indices published on the net in NRT
- SOLRA (SOLar Radio Archive) updated in NRT

TSRS Architecture



TSRS NRT Data Products

- High time res. calibrated data files (1kHz; 10min; FITS)
- High time res. uncalibrated data files (1kHz; 10min; BIN)

- 1-sec average calibrated data file (1 Hz; WD; FITS)
- 1-sec average calibrated data file (1 Hz; WD; BIN)

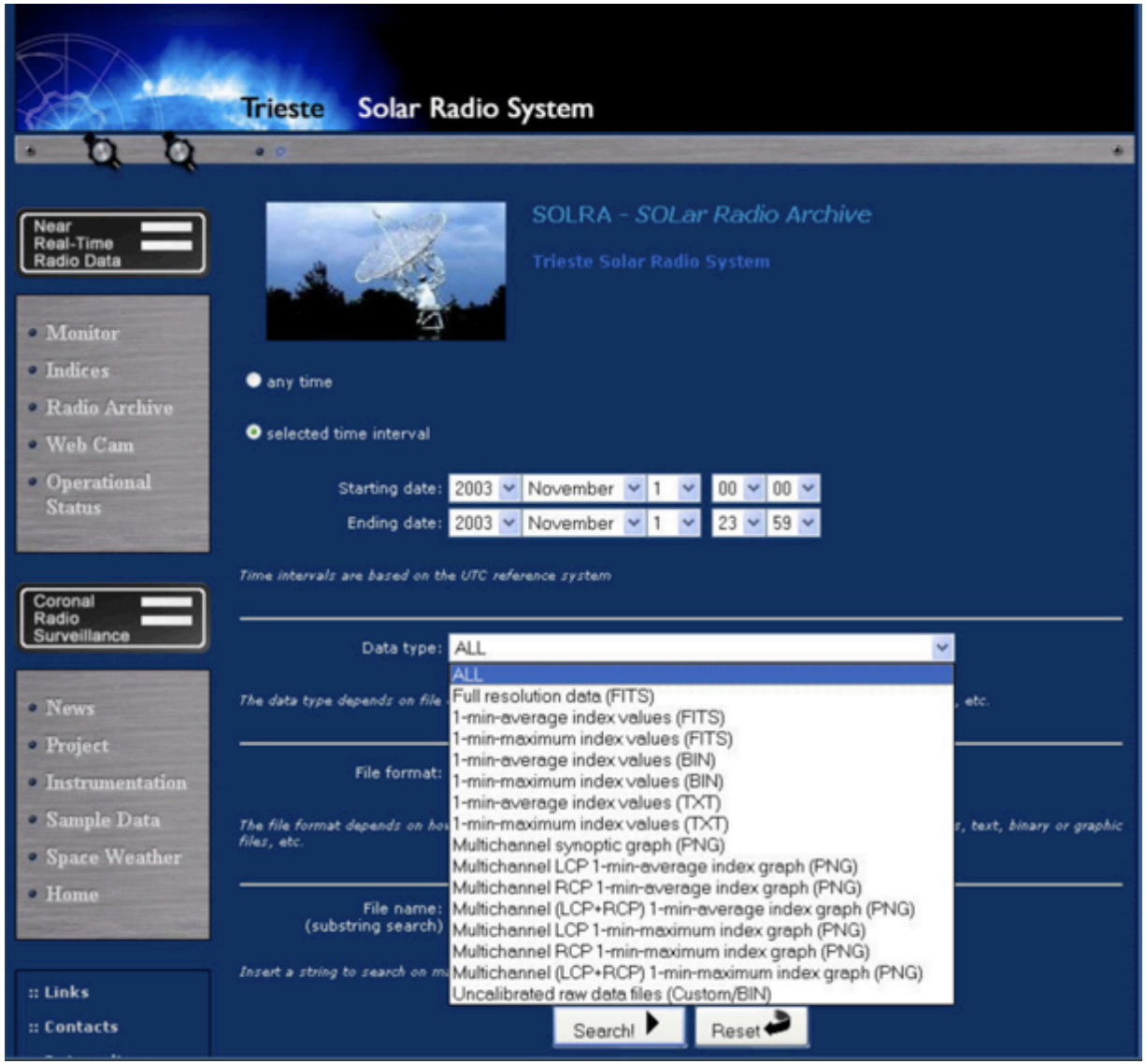
- 1-sec max. calibrated data file (1 Hz; WD; FITS)
- 1-sec max calibrated data file (1 Hz; WD; BIN)

- 1-sec median S+CP multichannel graph (WD; PNG)

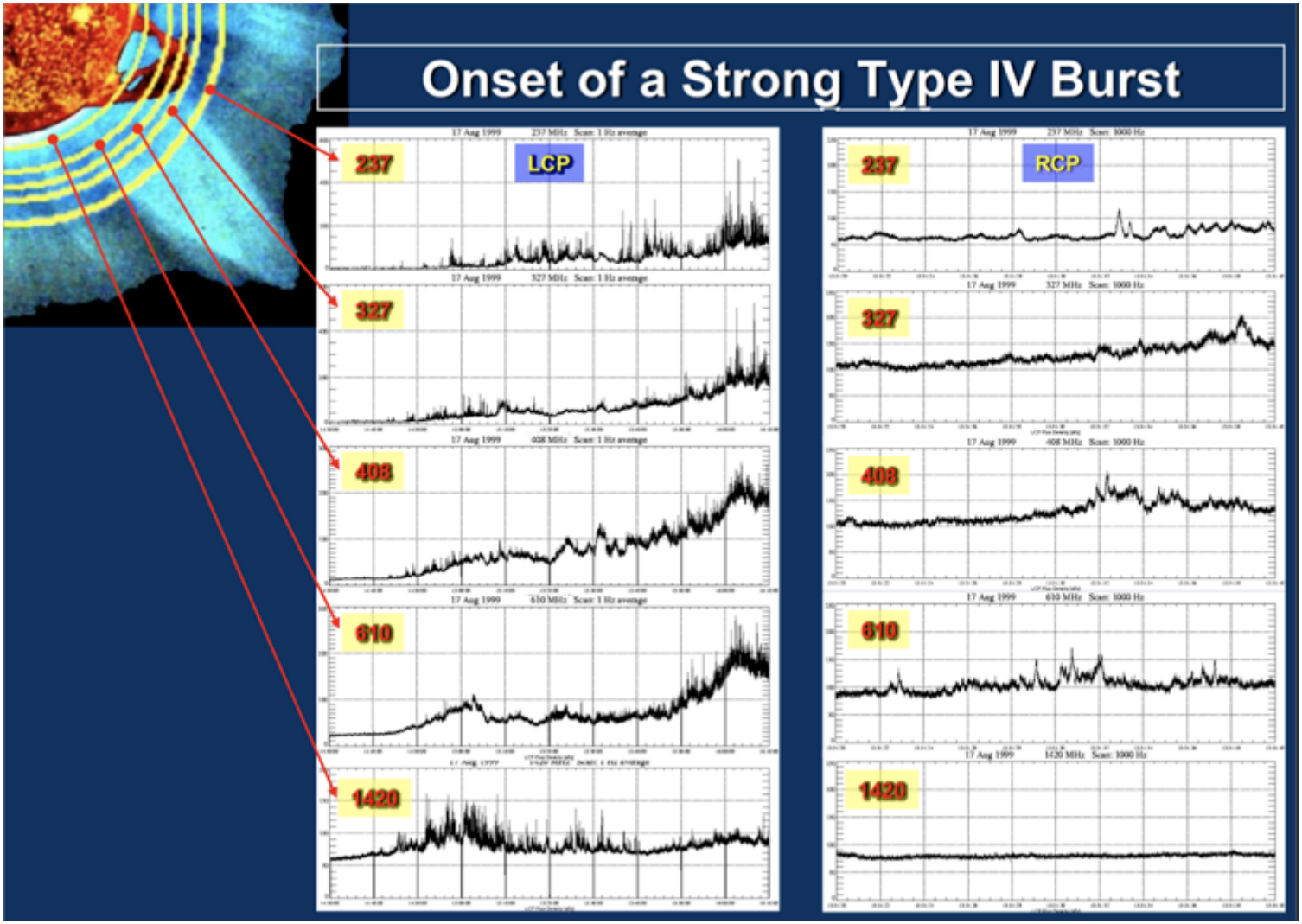
TSRS NRT Radio Indices

- 1-min average radio index
  - whole day index values in text format (WD; TXT)
  - whole day LCP multichannel graph (WD; PNG)
  - whole day RCP multichannel graph (WD; PNG)
  - whole day (LCP+RCP) multichannel graph (WD; PNG)
- 1-min maximum radio index
  - whole day index values in text format (WD; TXT)
  - whole day LCP multichannel graph (WD; PNG)
  - whole day RCP multichannel graph (WD; PNG)
  - whole day (LCP+RCP) multichannel graph (WD; PNG)

TSRS NRT Radio Archive



Multichannel Radio Polarimetry of a Strong Type IV Burst



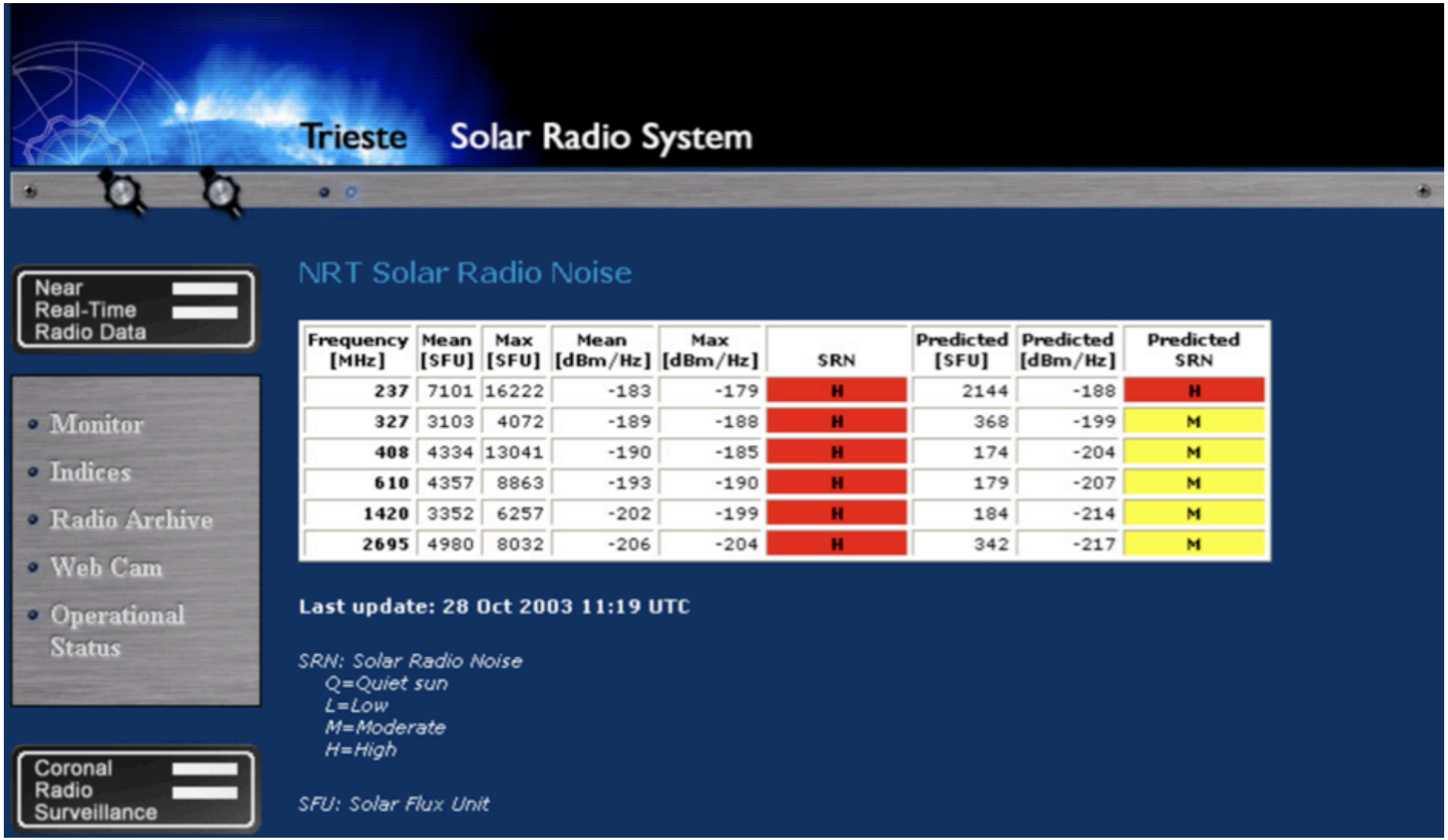
THE HALLOWEEN STORM ON 28 OCTOBER 2003


Trieste Solar Radio System
Monitor
Indices
Radio Archive
Web Cam
Operational Status
Coronal Radio Surveillance
News
Project
Instrumentation
Sample Data
Space Weather
Italiano
:: Links :: Contacts :: Data policy :: Disclaimer :: Credits
NRT Solar Radio Noise
Freq [MHz] 237 327 408 610 1420 2695
SRN H H H H H H
predicted H M M M M M
Last update: 28 Oct 2003 11:19 UTC
Details
INAF
esa
SWENET

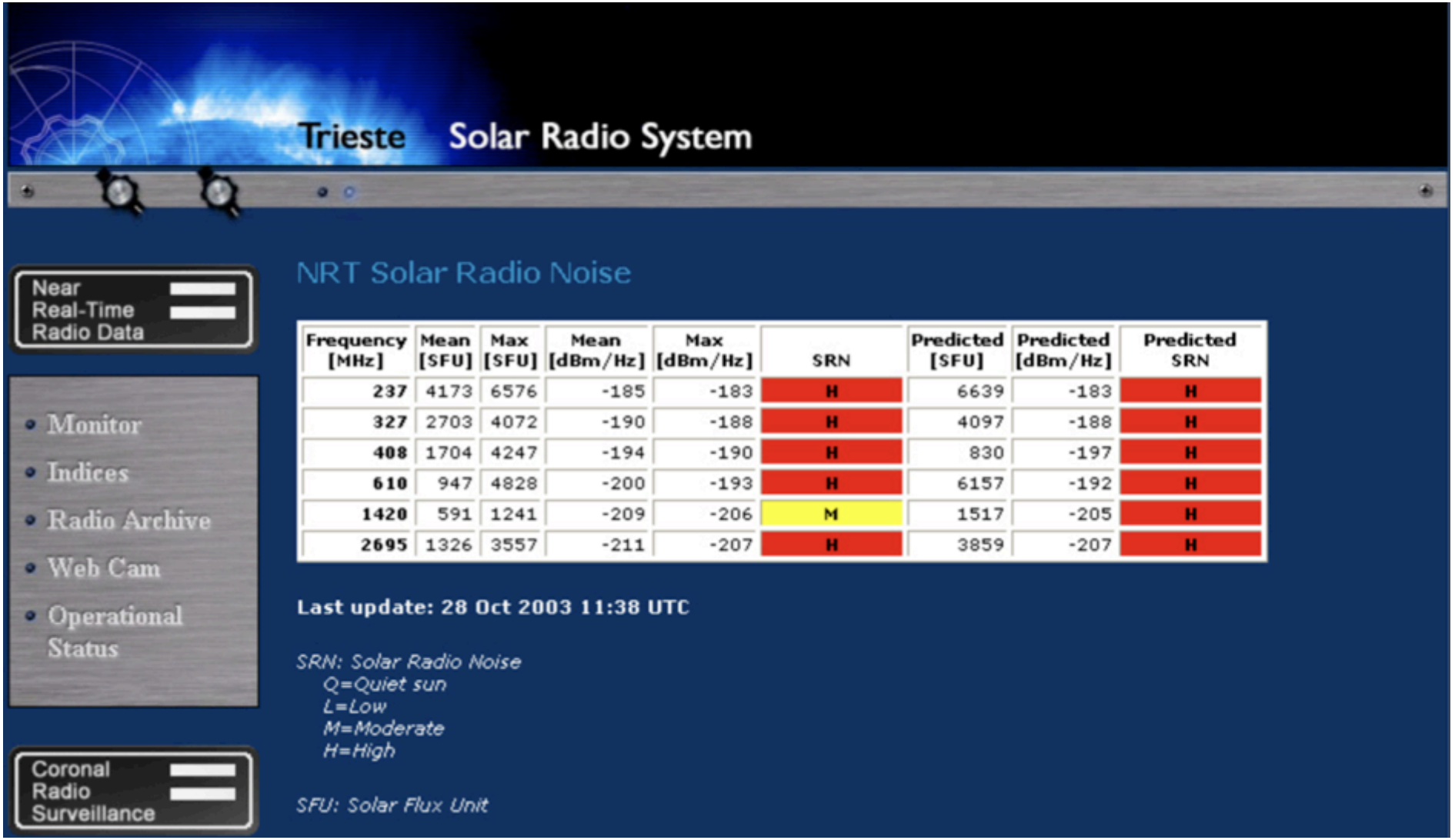

Trieste Solar Radio System
Monitor
Indices
Radio Archive
Web Cam
Operational Status
Coronal Radio Surveillance
News
Project
Instrumentation
Sample Data
Space Weather
Italiano
:: Links :: Contacts :: Data policy :: Disclaimer :: Credits
NRT Solar Radio Noise
Freq [MHz] 237 327 408 610 1420 2695
SRN H H H H M H
predicted H H H H H H
Last update: 28 Oct 2003 11:38 UTC
Details
INAF
esa
SWENET


Trieste Solar Radio System
Monitor
Indices
Radio Archive
Web Cam
Operational Status
Coronal Radio Surveillance
News
Project
Instrumentation
Sample Data
Space Weather
Italiano
:: Links :: Contacts :: Data policy :: Disclaimer :: Credits
NRT Solar Radio Noise
Freq [MHz] 237 327 408 610 1420 2695
SRN H H H H M M
predicted H H H H M M
Last update: 28 Oct 2003 13:58 UTC
Details
INAF
esa
SWENET

NRT Solar Radio Noise



NRT Solar Radio Noise



NRT Solar Radio Noise

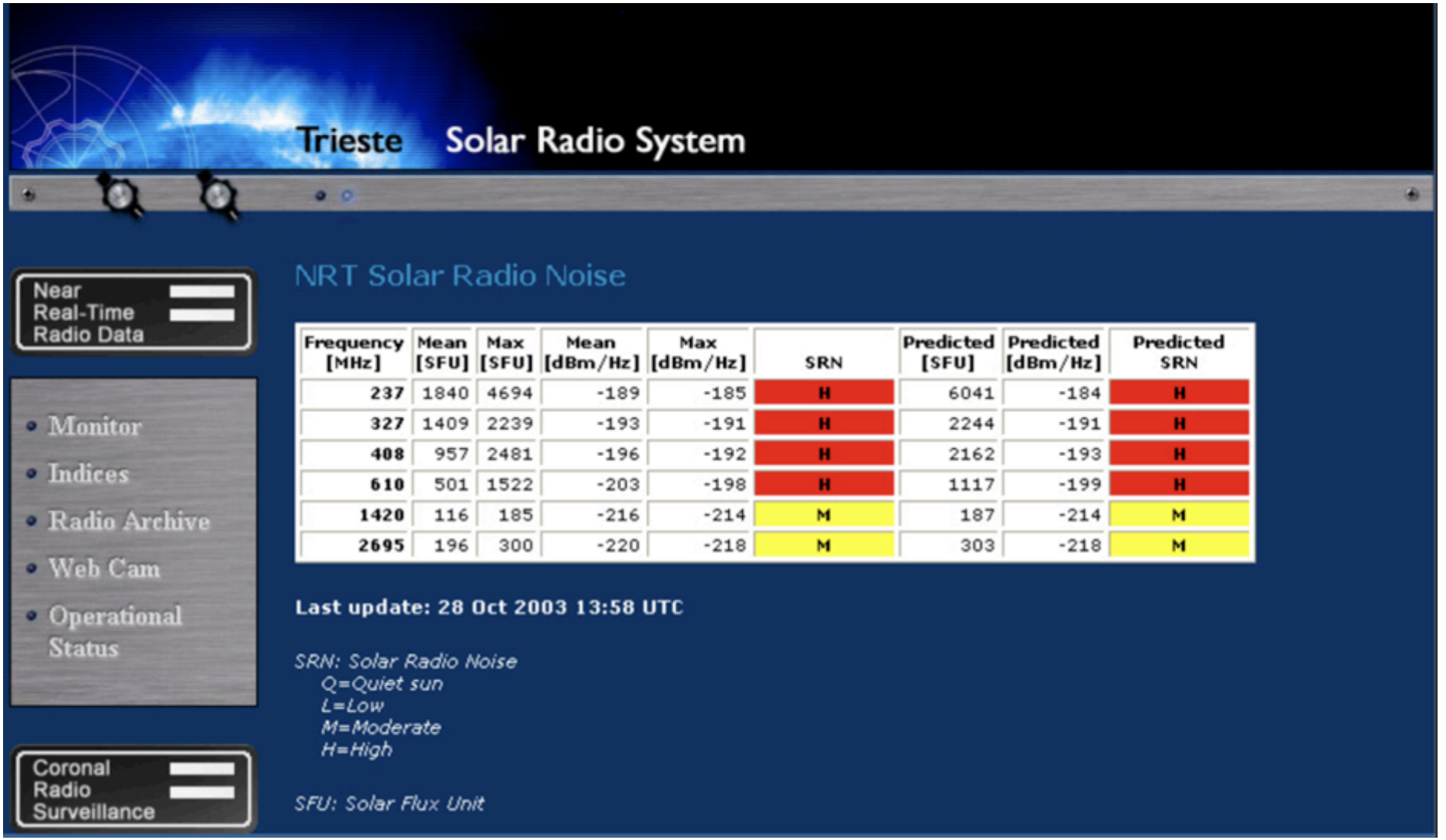
Frequency [MHz]	Mean [SFU]	Max [SFU]	Mean [dBm/Hz]	Max [dBm/Hz]	SRN	Predicted [SFU]	Predicted [dBm/Hz]	Predicted SRN
237	4173	6576	-185	-183	H	6639	-183	H
327	2703	4072	-190	-188	H	4097	-188	H
408	1704	4247	-194	-190	H	830	-197	H
610	947	4828	-200	-193	H	6157	-192	H
1420	591	1241	-209	-206	M	1517	-205	H
2695	1326	3557	-211	-207	H	3859	-207	H

Last update: 28 Oct 2003 11:38 UTC

SRN: Solar Radio Noise
Q=Quiet sun
L=Low
M=Moderate
H=High

SFU: Solar Flux Unit

NRT Solar Radio Noise



NRT Solar Radio Noise

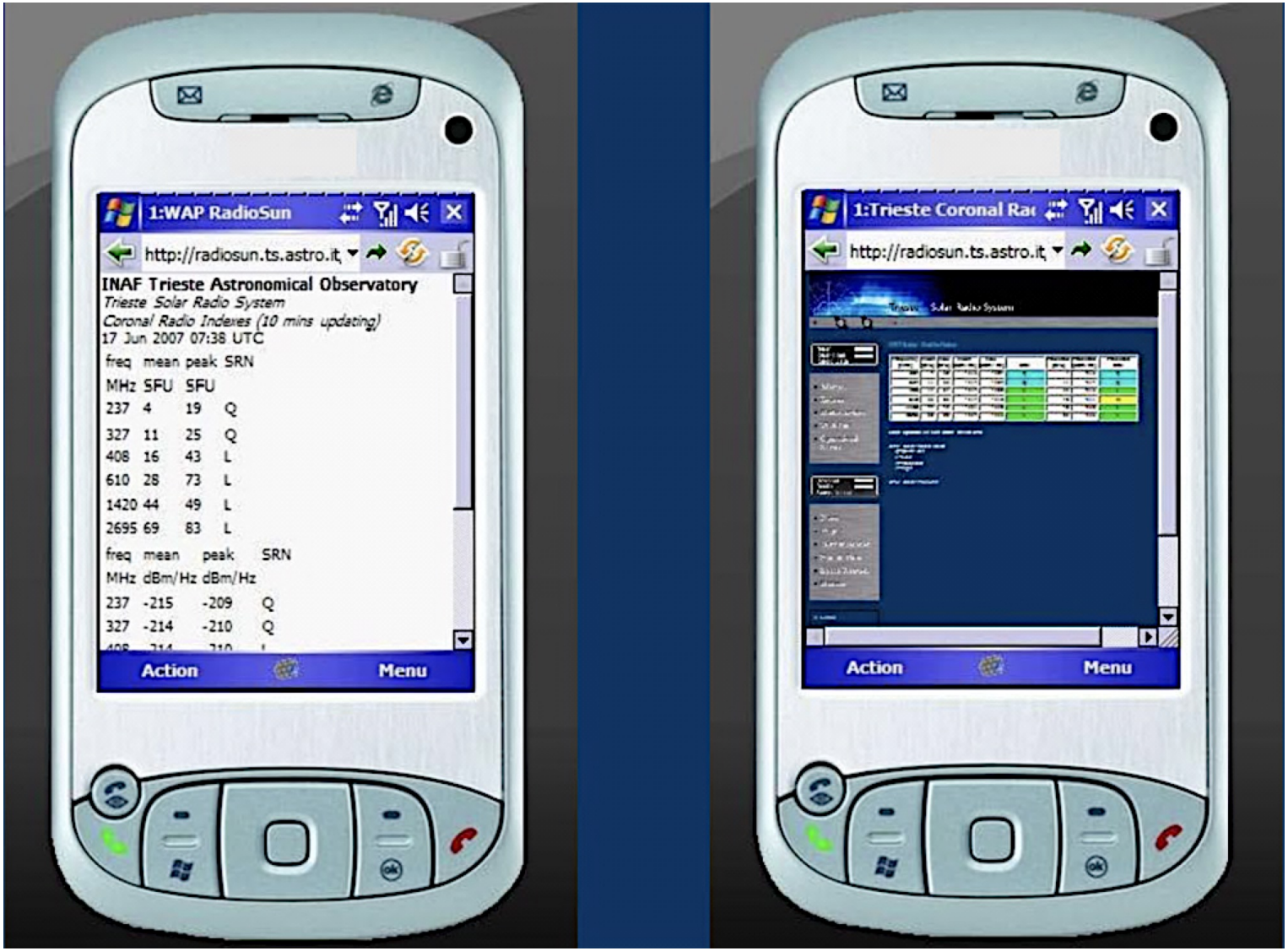
Frequency [MHz]	Mean [SFU]	Max [SFU]	Mean [dBm/Hz]	Max [dBm/Hz]	SRN	Predicted [SFU]	Predicted [dBm/Hz]	Predicted SRN
237	1840	4694	-189	-185	H	6041	-184	H
327	1409	2239	-193	-191	H	2244	-191	H
408	957	2481	-196	-192	H	2162	-193	H
610	501	1522	-203	-198	H	1117	-199	H
1420	116	185	-216	-214	M	187	-214	M
2695	196	300	-220	-218	M	303	-218	M

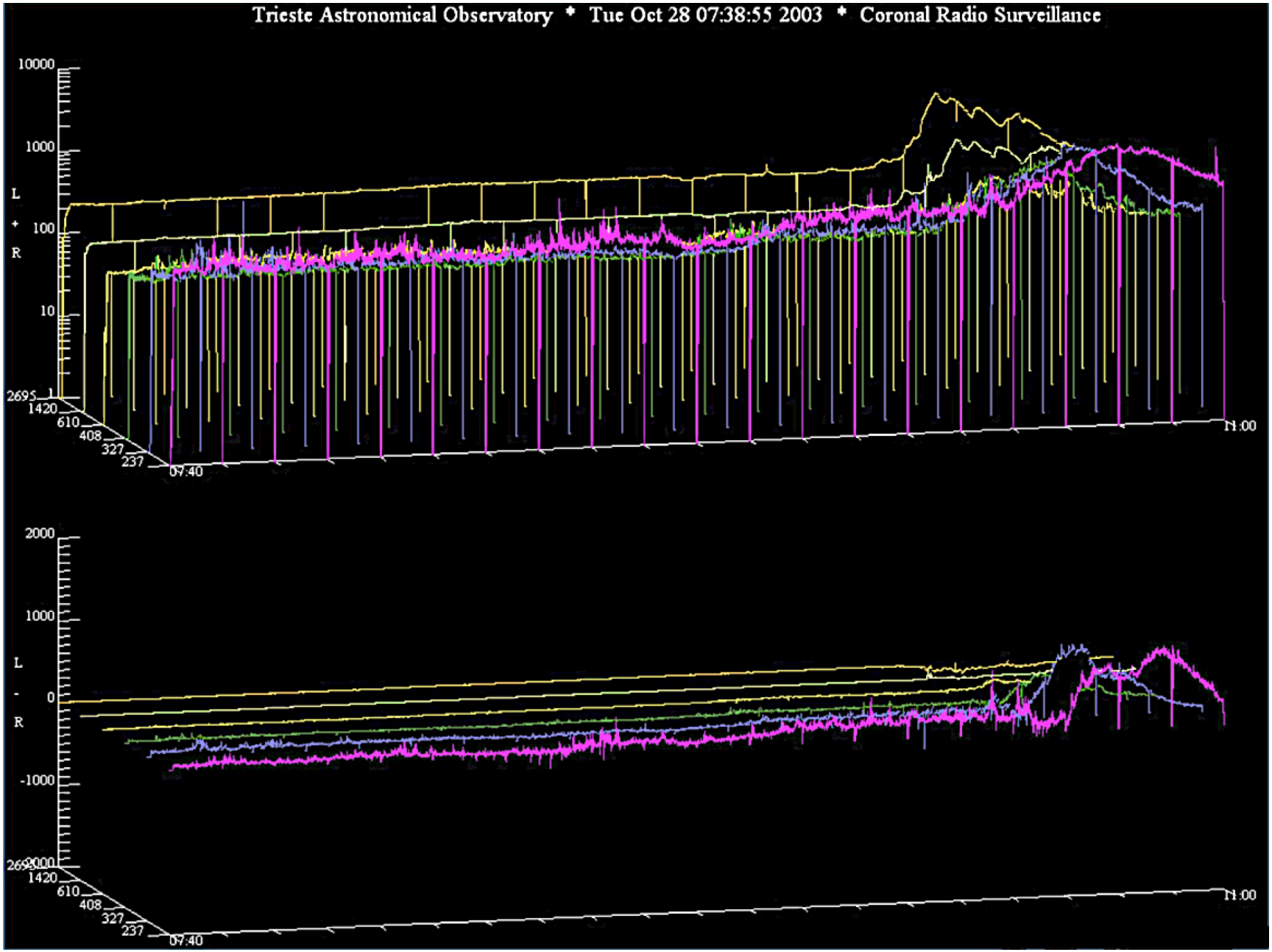
Last update: 28 Oct 2003 13:58 UTC

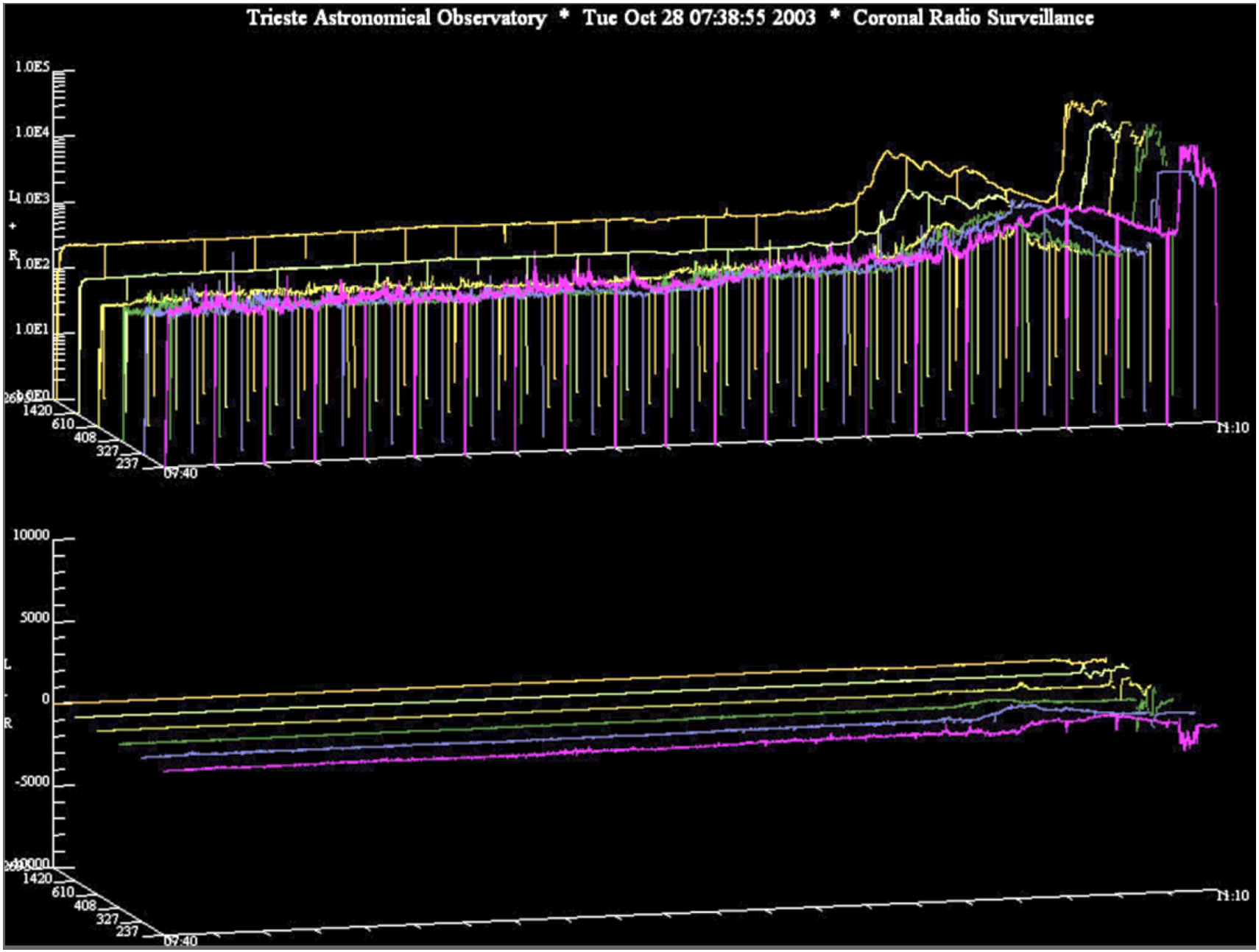
SRN: Solar Radio Noise
Q=Quiet sun
L=Low
M=Moderate
H=High

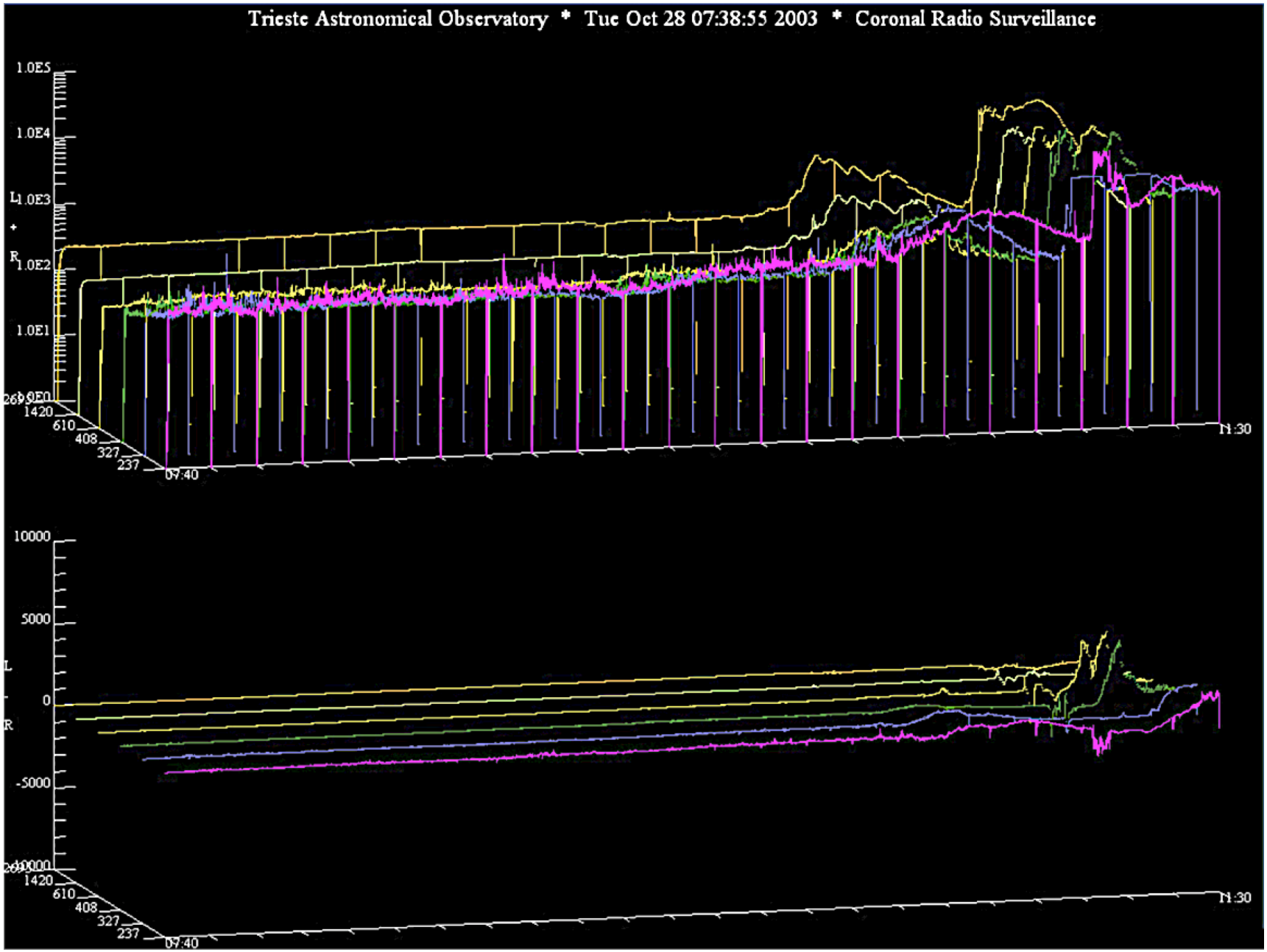
SFU: Solar Flux Unit

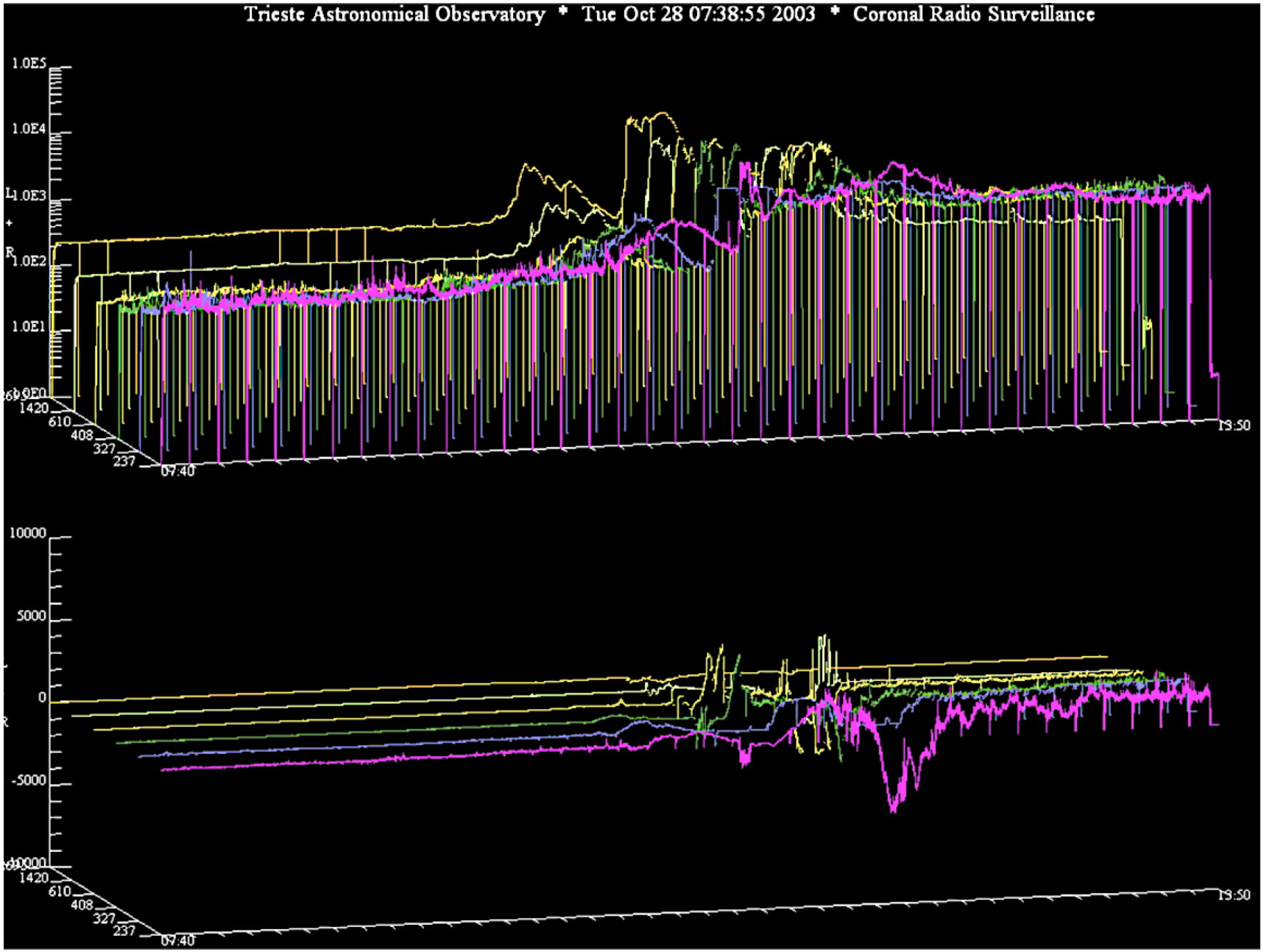
TSRS NRT Data on Mobile Phones




Trieste Astronomical Observatory • Tue Oct 28 07:38:55 2003 • Coronal Radio Surveillance
10000
1000
L
+
R
100
10
2695
1420
610
408
327
237
07:40
11:00
2000
1000
L
-
R
0
-1000
2695
1420
610
408
327
237
07:40
11:00


Trieste Astronomical Observatory * Tue Oct 28 07:38:55 2003 * Coronal Radio Surveillance
1.0E5
1.0E4
1.0E3
1.0E2
1.0E1
1420
610
408
327
237
09:40
N:10
10000
5000
0
-5000
1420
610
408
327
237
09:40
N:10


Trieste Astronomical Observatory * Tue Oct 28 07:38:55 2003 * Coronal Radio Surveillance
1.0E5
1.0E4
1.0E3
1.0E2
1.0E1
1420
610
408
327
237
07:40
N:30
10000
5000
0
-5000
1420
610
408
327
237
07:40
N:30


Trieste Astronomical Observatory • Tue Oct 28 07:38:55 2003 • Coronal Radio Surveillance
1.0E5
1.0E4
1.0E3
1.0E2
1.0E1
1.0E0
1420
610
408
327
237
07:40
13:50
10000
5000
0
-5000
-10000
1420
610
408
327
237
07:40
13:50

Solar Radio Observations in Trieste

- 1969 Start on 19 January 1969 (under USAF contract)
- 1997 System updated for SWx (TSRS)
- 2010 Unrecoverable stop for an extreme lightning stroke
- 2013 Installation of a Callisto radio spectrograph
- 2017 Project cancelled and insurance money diverted by INAF-Astronomical Observatory of Trieste despite of national and international support expressions (ASI, ESA, NASA, NOAA, NICT, etc.) [because I am the last solar radio astronomer in Trieste, homeland of cosmology, and will retire in a few years]
- 2018 Project approved and funded by INAF-Science Directorate, National Division for Radio Astronomy, upon new operational scenarios
- 2019 Q1 Expected start of new system for SWx (TSRS 2.0)

Phoenix, Aberdeen Bestiary, 12th Century

THE NEW TRIESTE SOLAR RADIO SYSTEM (TSRS 2.0) REBIRTH

TSRS 2.0
A Solar Radio Polarimeter for SWx

Funded by INAF-Science Directorate, National Division for Radio Astronomy in the framework of the INAF Space Weather National Programme

- High time resolution
- Circular Polarisation
- Data Calibration
- NRT Operations in:
  - L band (1.35-1.45 GHz)
  - 2800 MHz (10.7 cm)
  - C band (3-4 GHz)
  - Ku band (11.5-12.5 GHz)
  - Ka band (22-23 GHz)
- In support of:
  - INAF SunDish Network
  - ASI Fiducial GPS Network
  - ESA SSA-SWE Network
  - LOFAR SWx applications
  - SKA Heliophysics applications
  - Solar Orbiter/Metis Coronagraph

Summary and Conclusions

- Intense SRB's can severely interfere with radio communications
- Experimental evidences prove that HF, VHF, UHF, SHF COM's, Radars, GNSS, Augmentation Systems, Wireless COM's can be significantly affected
- Diachronic monitoring by dedicated solar radio polarimeters is a must for detection
- INAF TSRS 2.0 was designed to play a unique role in this framework and will operate in support of the INAF single-dish solar radio observations

THANK YOU
FOR YOUR ATTENTION!