SPACECRAFT CHARGING: THEN AND NOW

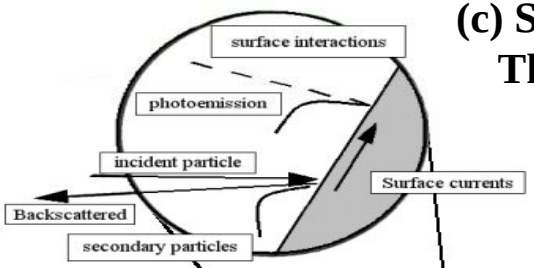
SPACECRAFT CHARGING TECHNOLOGY CONFERENCE

ALBUQUERQUE, NM
20-24 SEPTEMBER 2010

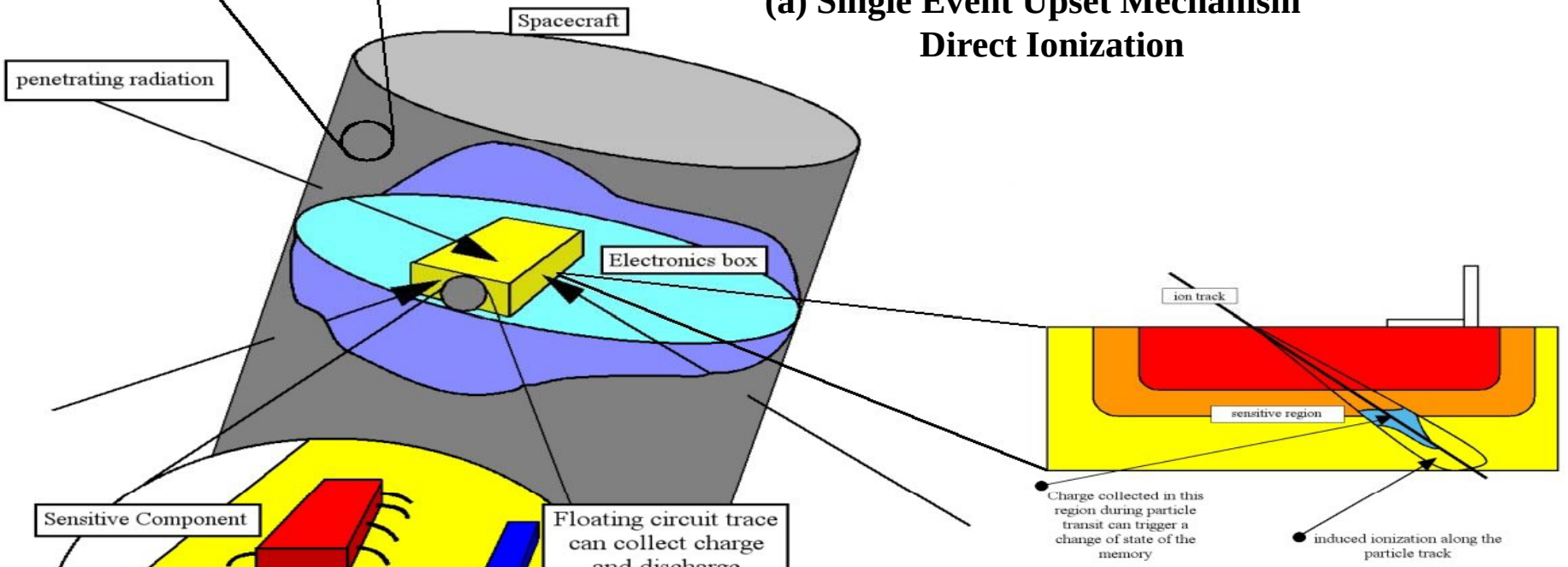
Joe H. Allen (Ret. NOAA) and Dan Wilkinson (NOAA-NGDC)

Space Environment Effects

(c) Surface Charging
Thermal Electrons



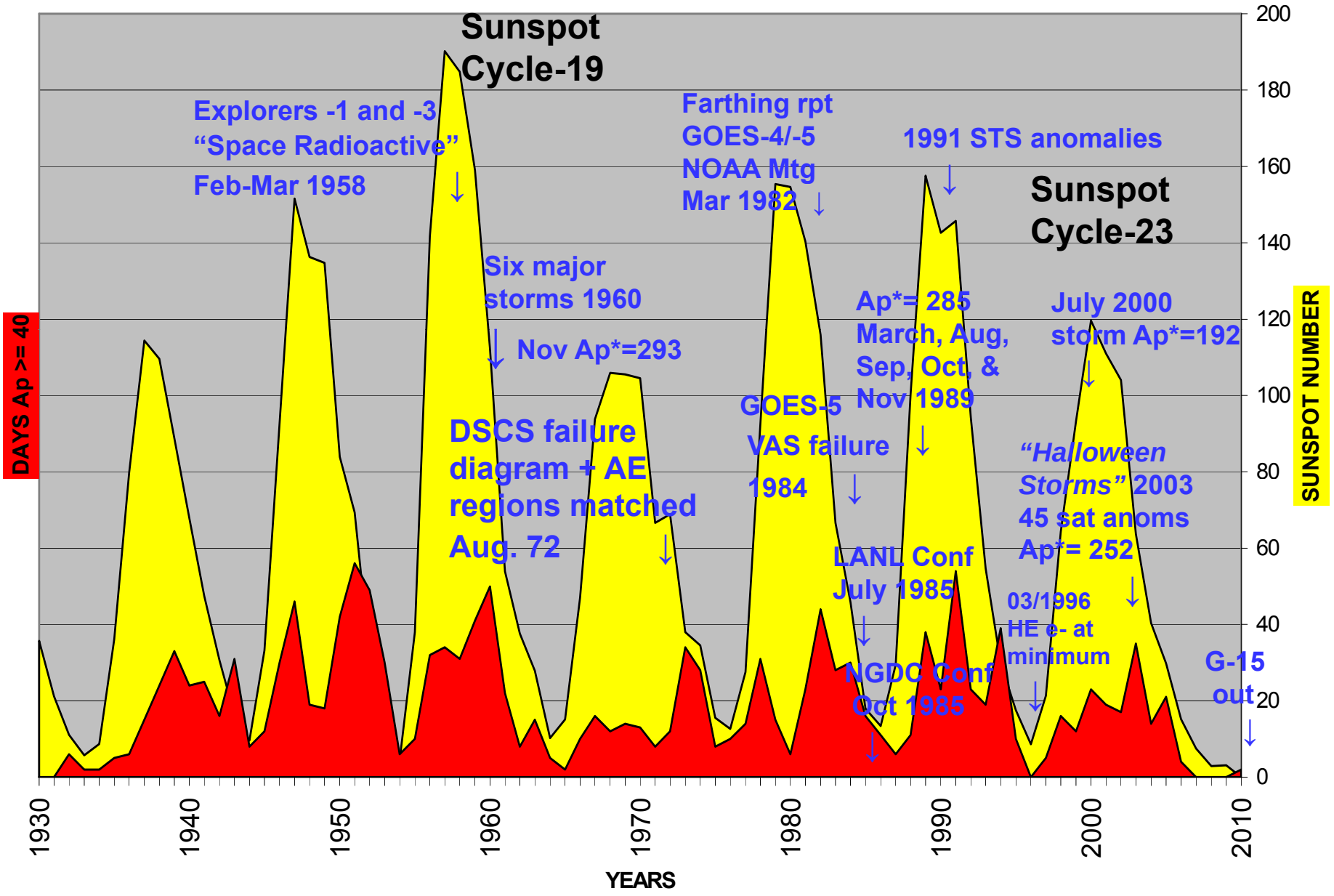
(a) Single Event Upset Mechanism
Direct Ionization

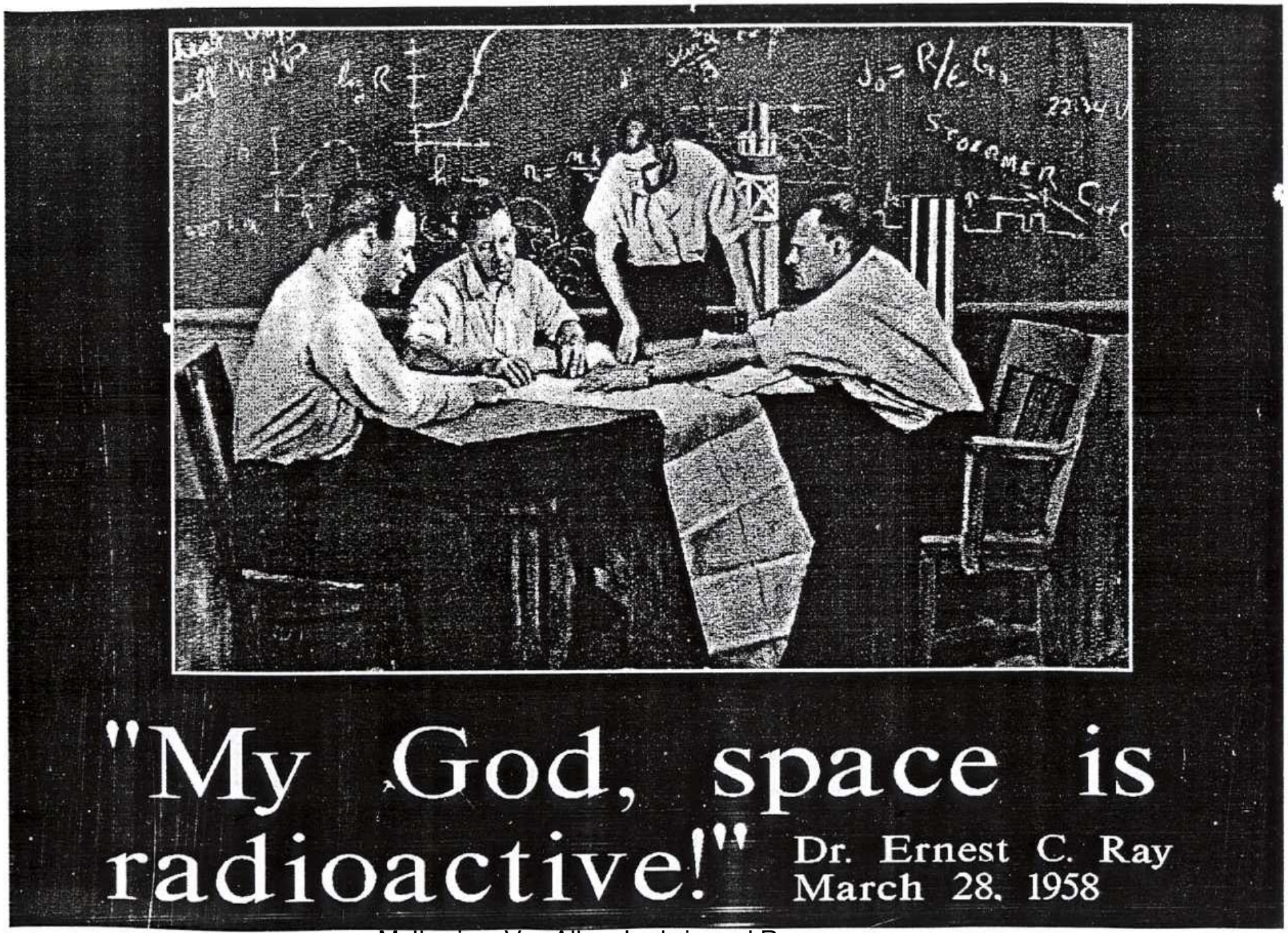


(b) Deep Dielectric Charging by
High-energy Ions or Electrons

(d) MPE disorientation
(e) dB/dT tumbling
(f) Optical disorientation
(g) Power panel output loss

Selected Satellite Anomaly Events: 1960-2010





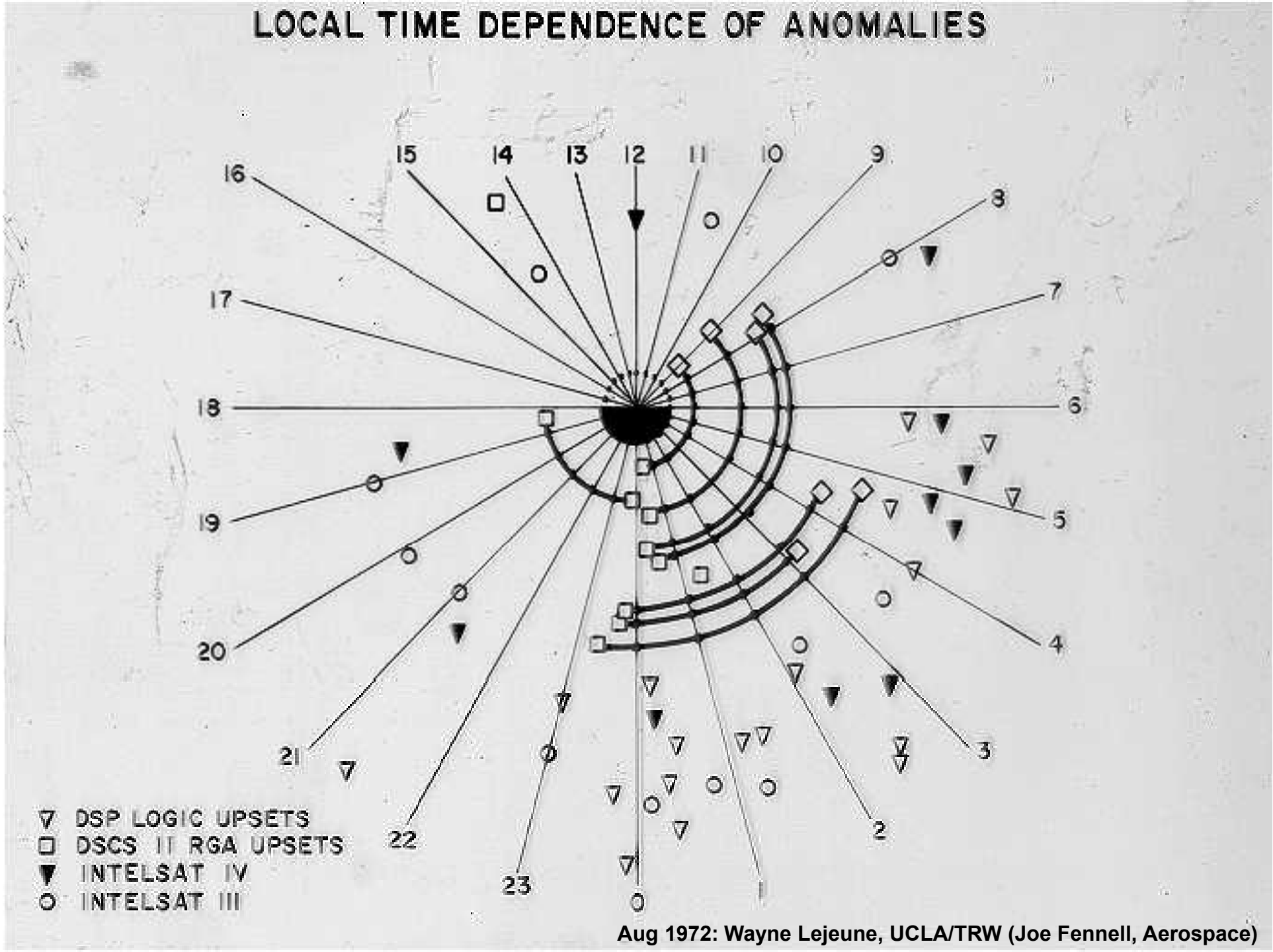
McIlwaine, Van Allen, Ludwig and Ray

Slide 4

JHA1 Carl McIlwaine, James A. Van Allen, George Ludwig, and Ernest C. Ray. Picture of a painting from a recreated scene in the University of Iowa laboratory of Van Allen's group.

Joe Allen, 6/8/2010

LOCAL TIME DEPENDENCE OF ANOMALIES



Aug 1972: Wayne Lejeune, UCLA/TRW (Joe Fennell, Aerospace)

Noon

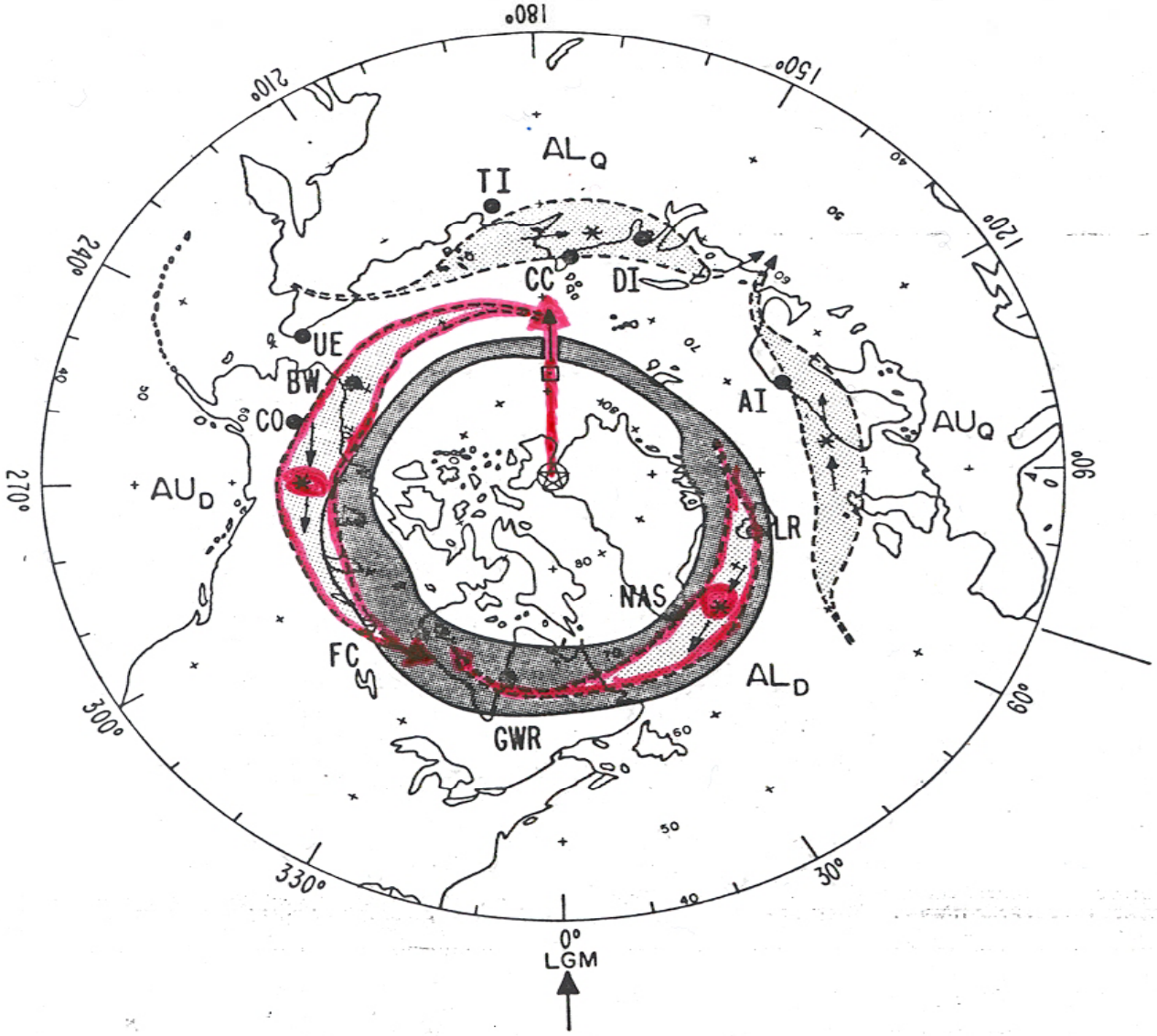
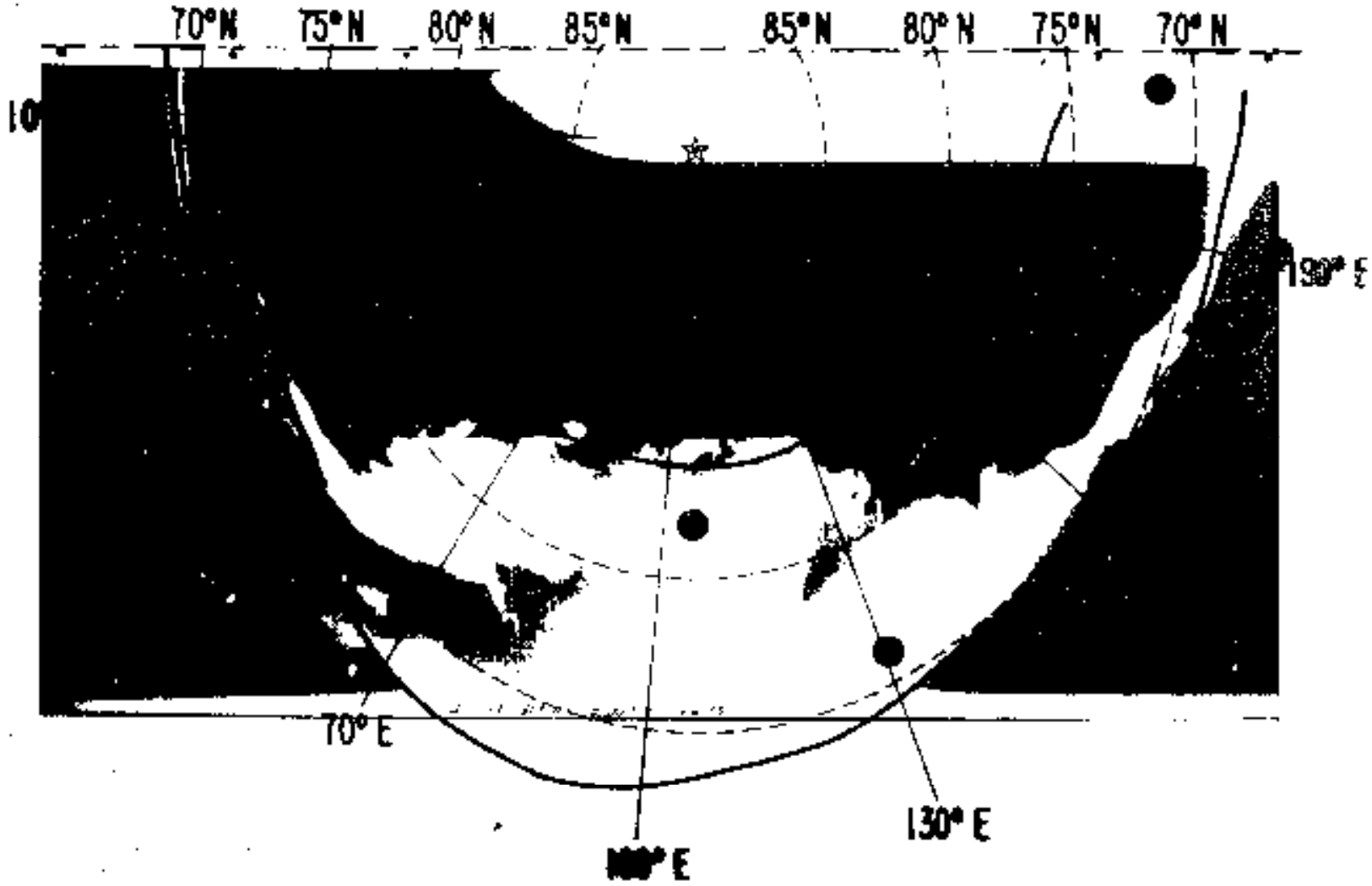
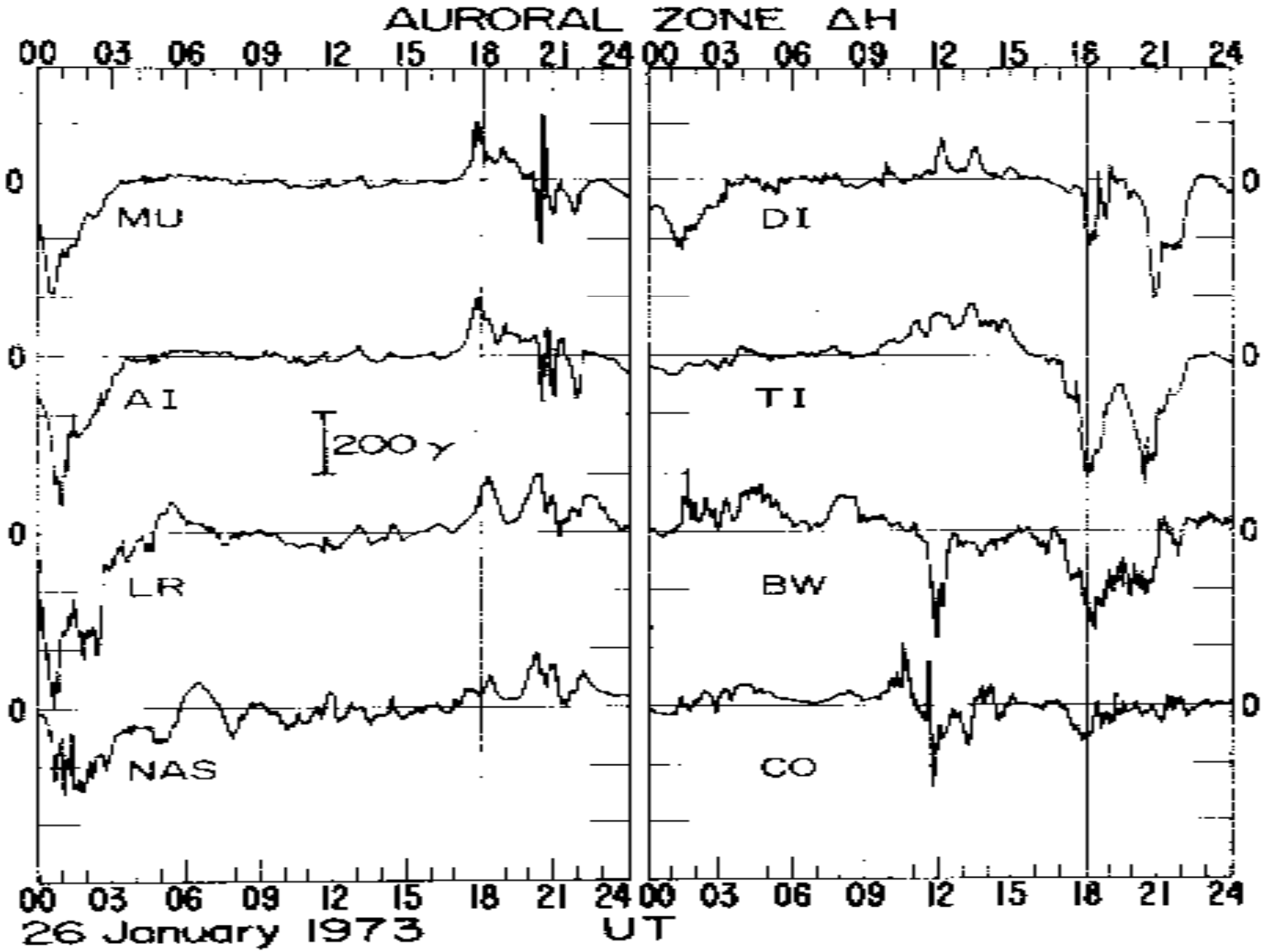


Fig. 8. Map of the Fel'dshteyn corrected auroral oval and composite ionospheric current system regions which produced *AL* and *AU* for quiet times (AL_Q, AU_Q) and disturbed times (AL_D, AU_D). The map displays the regions at the time corresponding to LGM on the 0° geomagnetic meridian (0430 UT). An asterisk marks the average location within each current region where the most frequent occurrence of maximum *H* deviations produced corresponding *AU* and *AL* indices.



5. DMSP auroral imagery for substorm interval - shows locations of critically placed magnetic observatories with superposed Feldstein auroral oval (Q=5) for January 26, 1973, auroral event over Siberia.



4. Magnetograms from auroral zone observatories recording effects of electrojets during January 26 substorm and showing time of DMSP passage relative to the disturbed H-traces. These station records would be used in deriving AE and related indices by superposition of common-scale H-traces to their common zero level giving AU as the amplitude of the upper envelope and AL as amplitude of the lower envelope of the disturbances. AE = AU - AL.

Proceedings of a
WORKSHOP ON SATELLITE DRAG
March 13-18, 1982
Boulder, Colorado

Proceedings of a Workshop on Satellite Drag, March 13-18, 1982 Boulder, Colorado

Space Environment Services Center
Space Environment Laboratory
Boulder, Colorado
May 1982

noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / Environmental Research Laboratories

From: Harry Farthing, 99/04/28
(hfarthing@swales.com)
Visited with Dave Martin
(David.Martin@gsfc.nasa.gov)

Anomalies file

NASA

Technical Memorandum 83908

Differential Spacecraft Charging on the Geostationary Operational Environmental Satellites

Winfield H. Farthing
James P. Brown
William C. Bryant

MARCH 1982

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

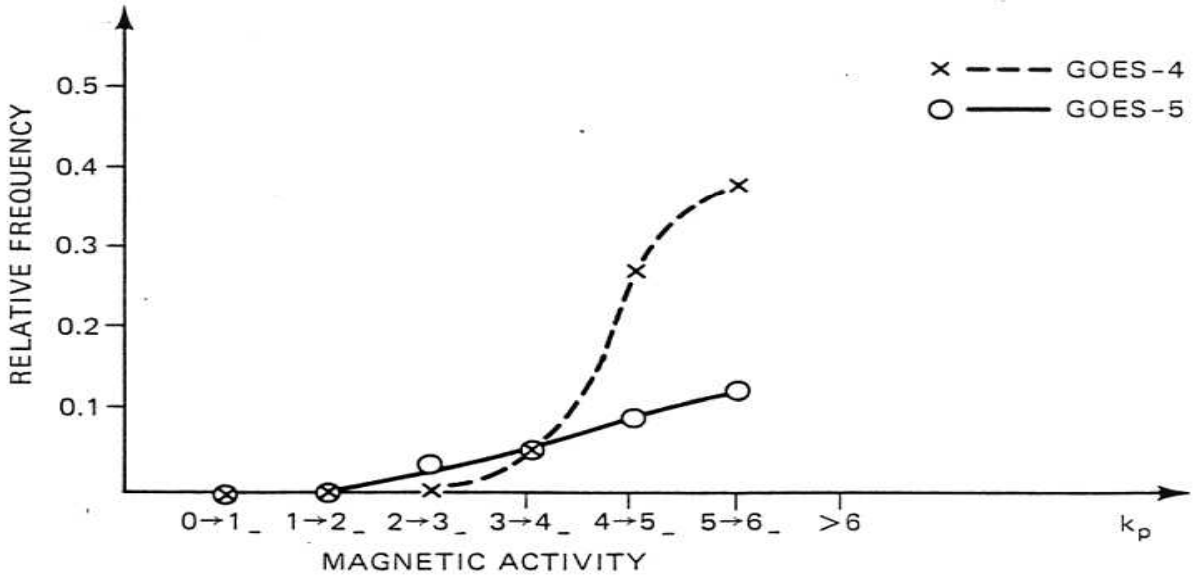


Figure 24. Relative Frequency of Anomalies

ΔT=Ta-To

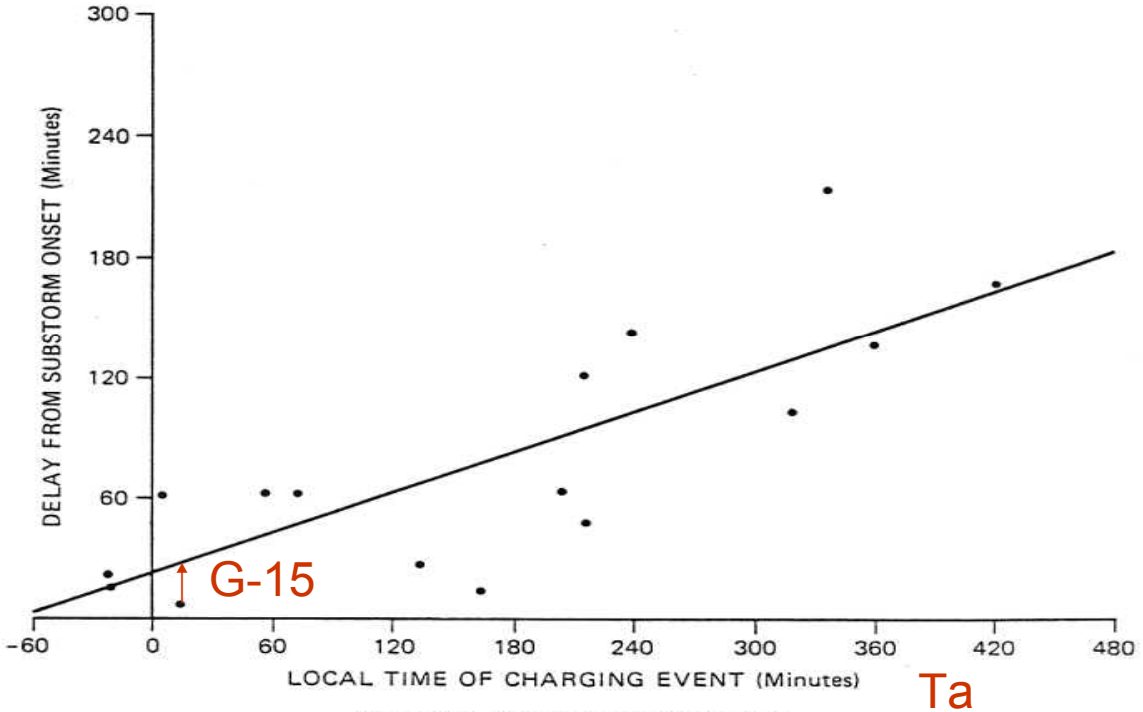


Figure 25. Plasma Drift Relationship

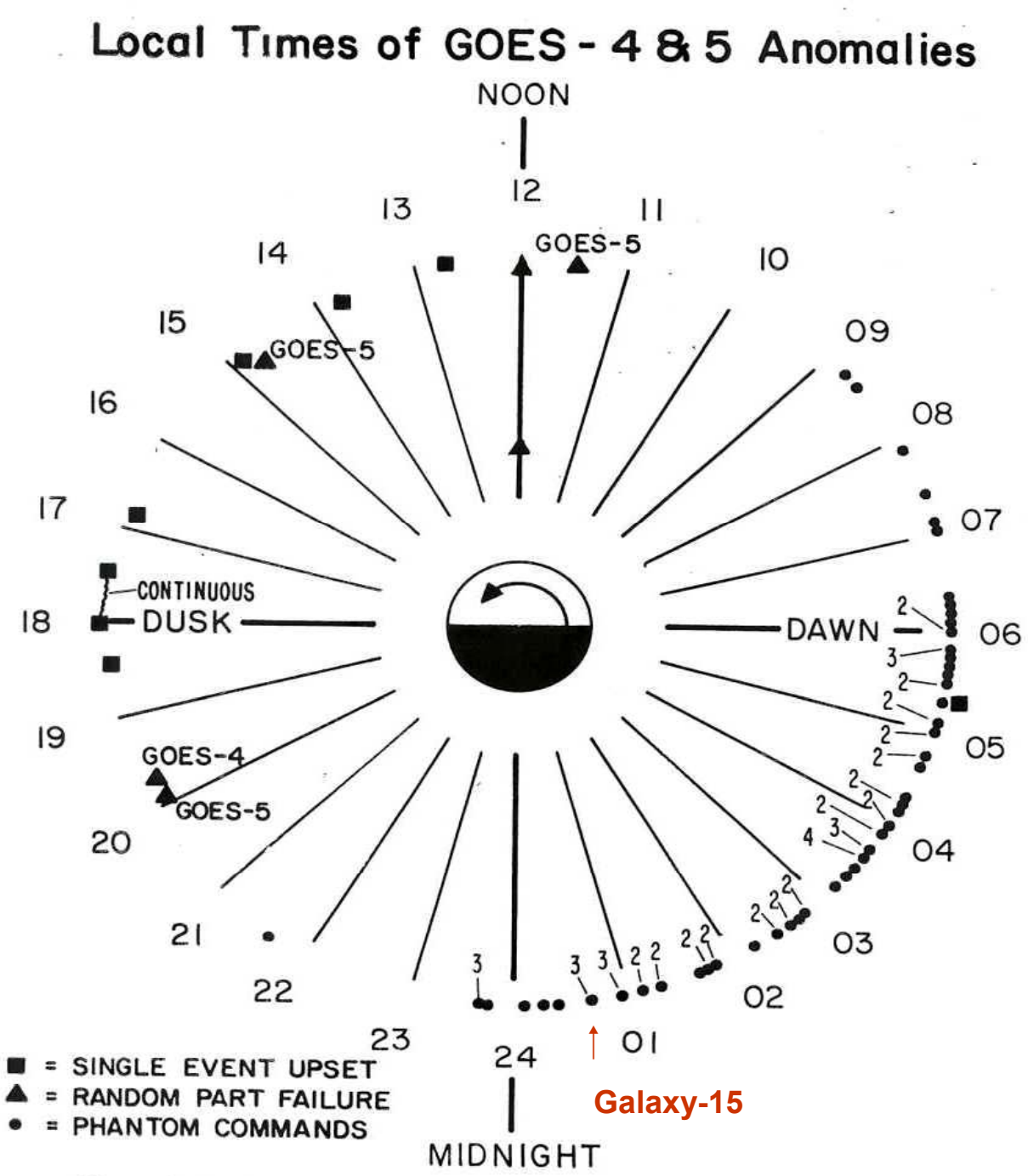
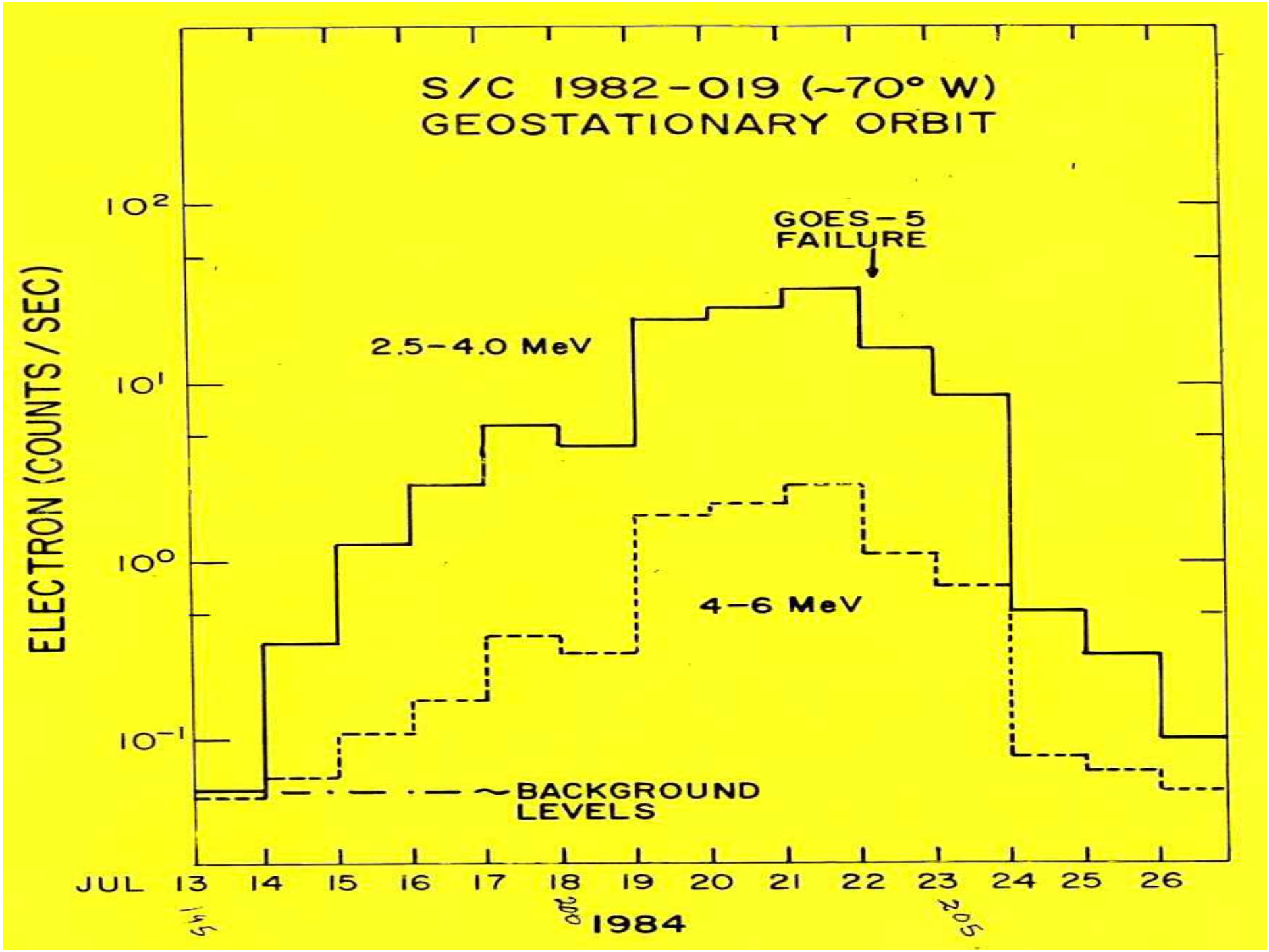
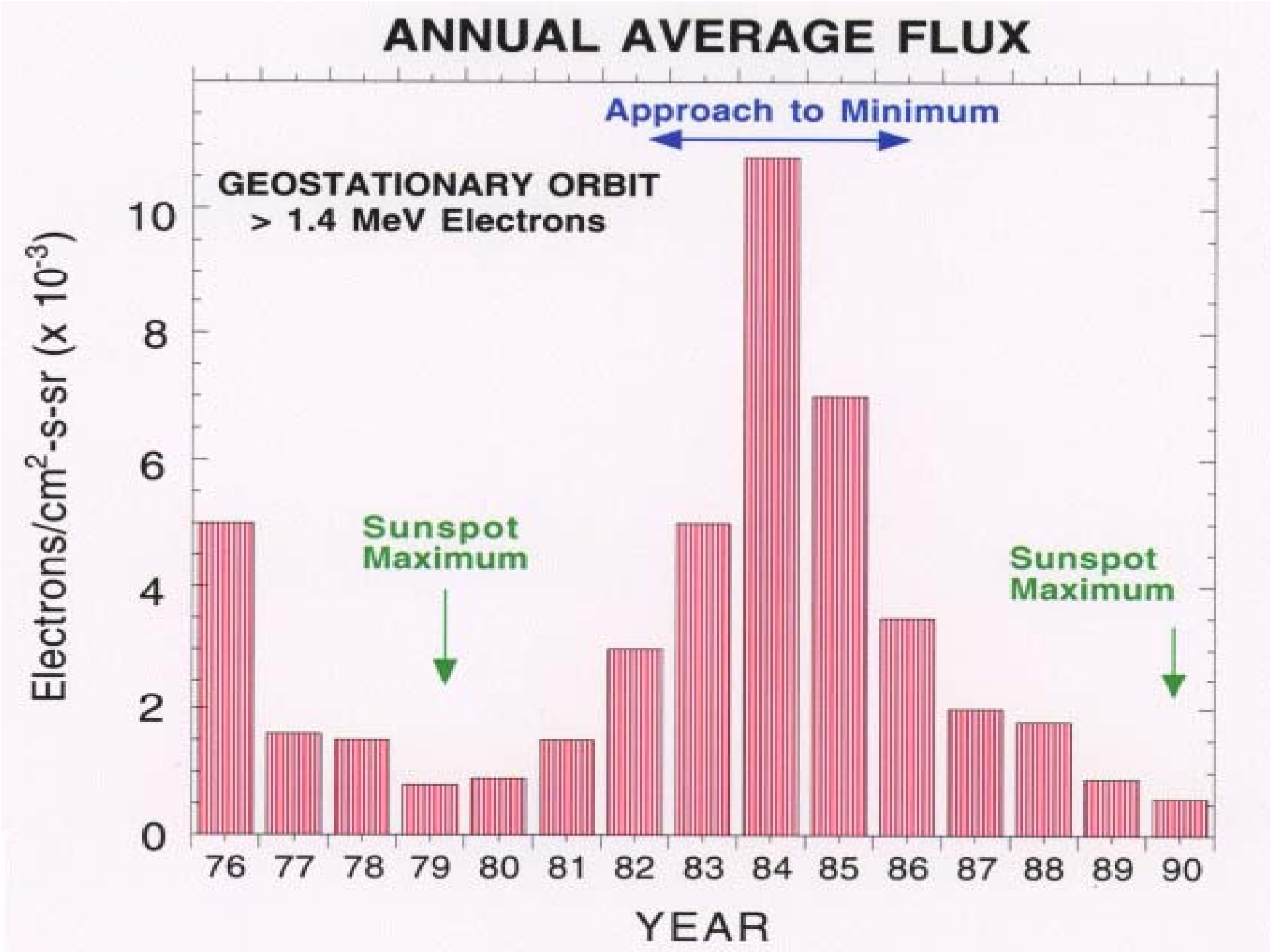
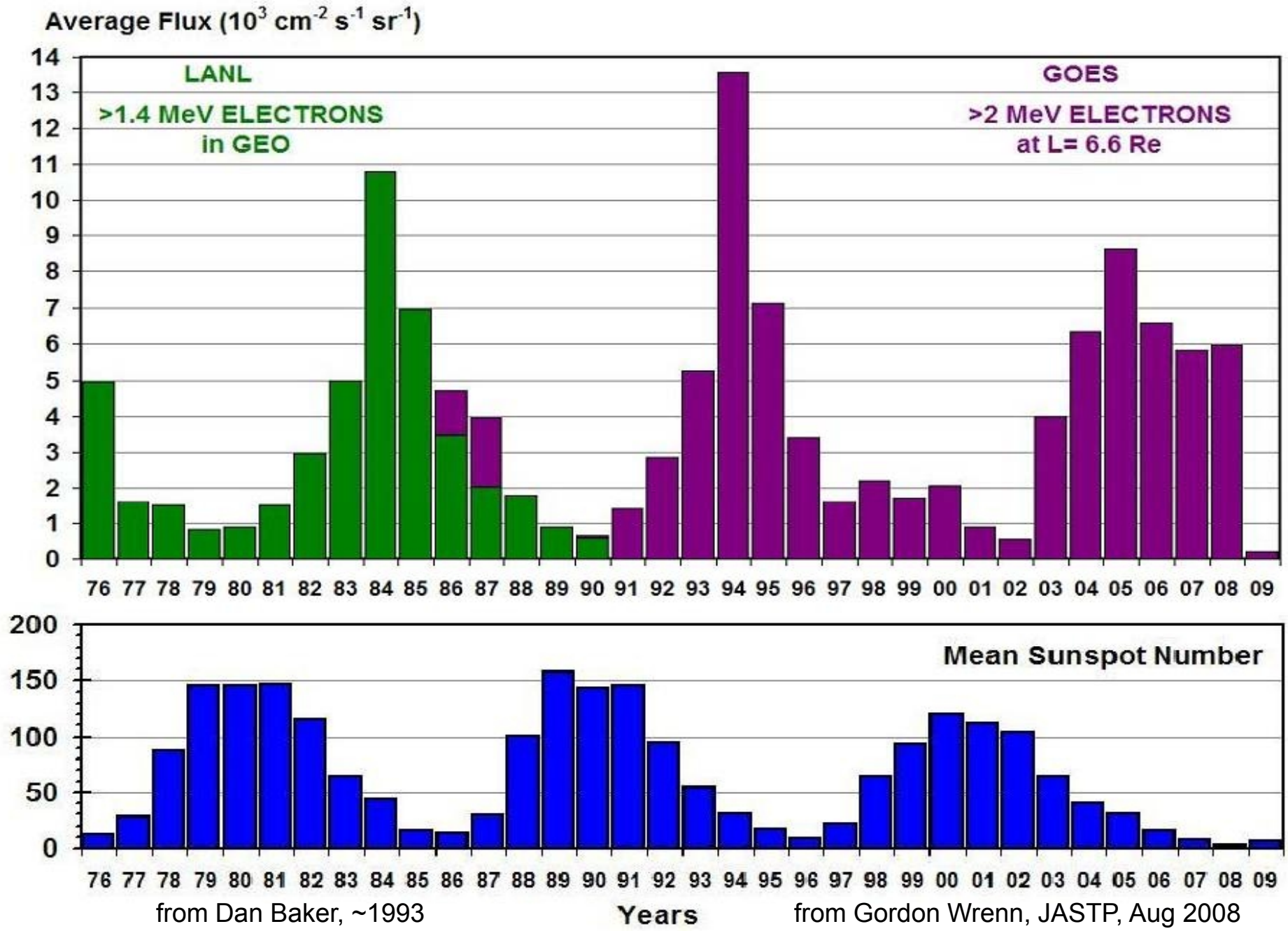


Figure 6: Satellite local times of GOES-4 and -5 anomalies for 1981-1983.


S/C 1982-019 (~70° W)
GEOSTATIONARY ORBIT
GOES-5
FAILURE
2.5-4.0 MeV
4-6 MeV
~BACKGROUND
LEVELS
ELECTRON (COUNTS/SEC)
10^2
10^1
10^0
10^{-1}
JUL 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1984

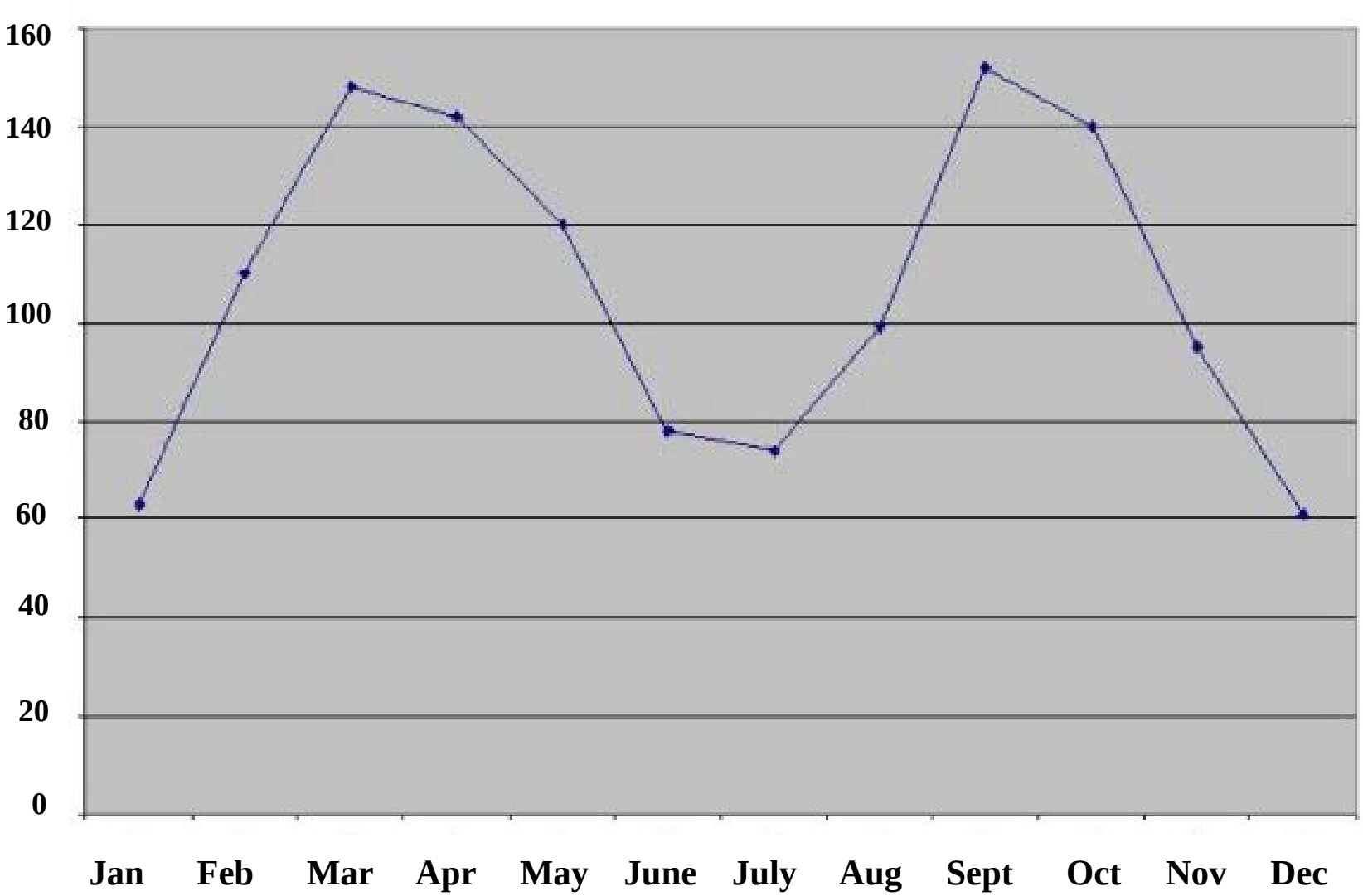

ANNUAL AVERAGE FLUX
Approach to Minimum
GEOSTATIONARY ORBIT
> 1.4 MeV Electrons
Sunspot Maximum
Sunspot Maximum
Electrons/cm²-s-sr (x 10⁻³)
0
2
4
6
8
10
76 77 78 79 80 81 82 83 84 85 86 87 88 89 90
YEAR



from Dan Baker, ~1993

from Gordon Wrenn, JASTP, Aug 2008

Cumulative Monthly Magnetic Storms: 1932-2001
Ap* ≥ 40



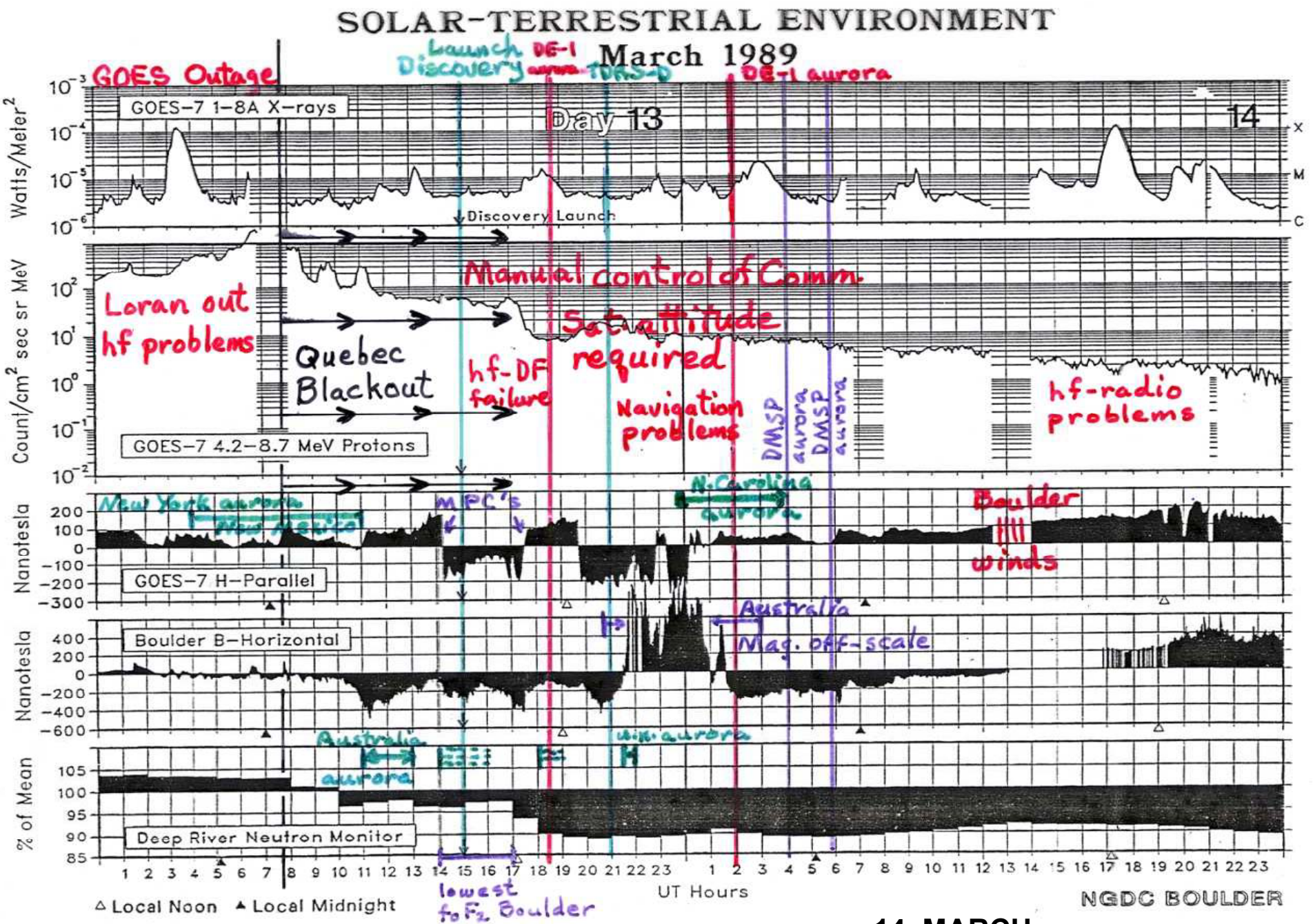
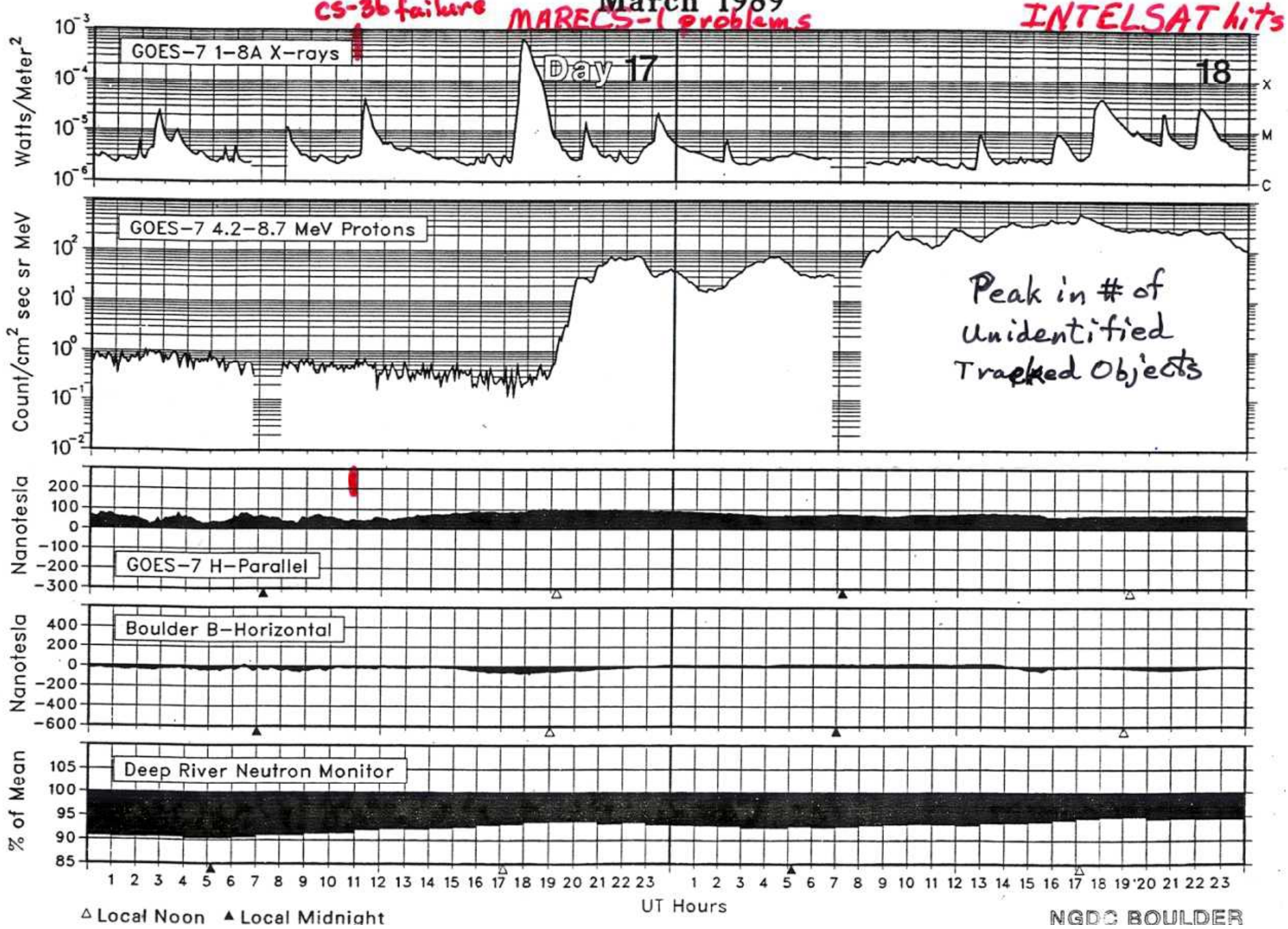

SOLAR-TERRESTRIAL ENVIRONMENT
March 1989
GOES Outage
Launch Discovery
DE-1 aurora
TDRS-D
DE-1 aurora
Day 13
14
GOES-7 1-8A X-rays
Watts/Meter²
Discovery Launch
Manual control of Comm
Satellite attitude required
Loran out hf problems
Quebec Blackout
hf-DF failure
Navigation problems
DMSP aurora
DMSP aurora
hf-radio problems
GOES-7 4.2-8.7 MeV Protons
Count/cm² sec sr MeV
New York aurora
New Mexico
MPC's
N. Carolina aurora
Boulder winds
GOES-7 H-Parallel
Nanotesla
Australia
Mag. off-scale
Boulder B-Horizontal
Nanotesla
Australia aurora
U.K. aurora
Deep River Neutron Monitor
% of Mean
lowest foF2 Boulder
UT Hours
△ Local Noon ▲ Local Midnight
NGDC BOULDER
13 MARCH
14 MARCH

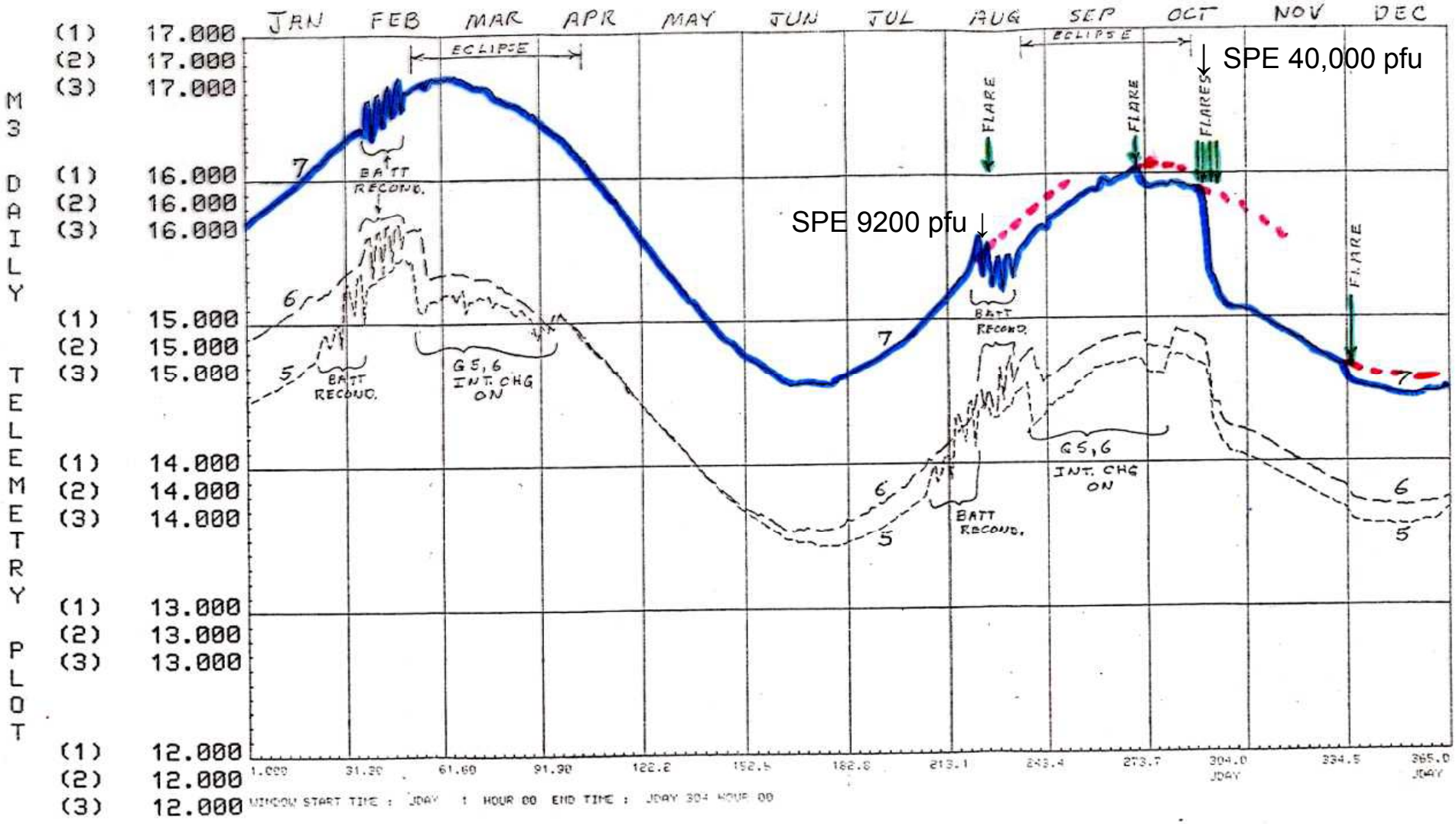
Figure 1(b)

SOLAR-TERRESTRIAL ENVIRONMENT

March 1989

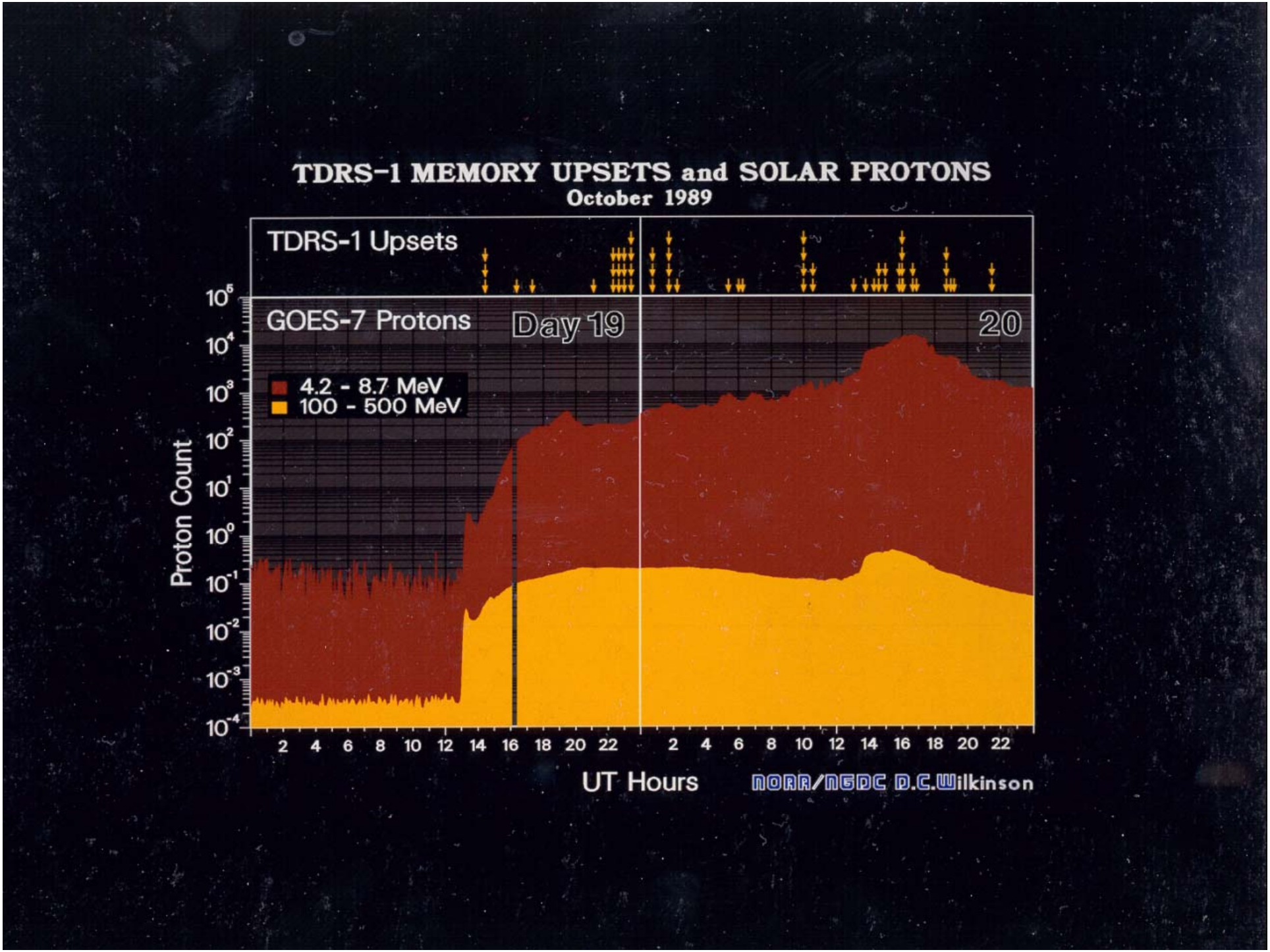


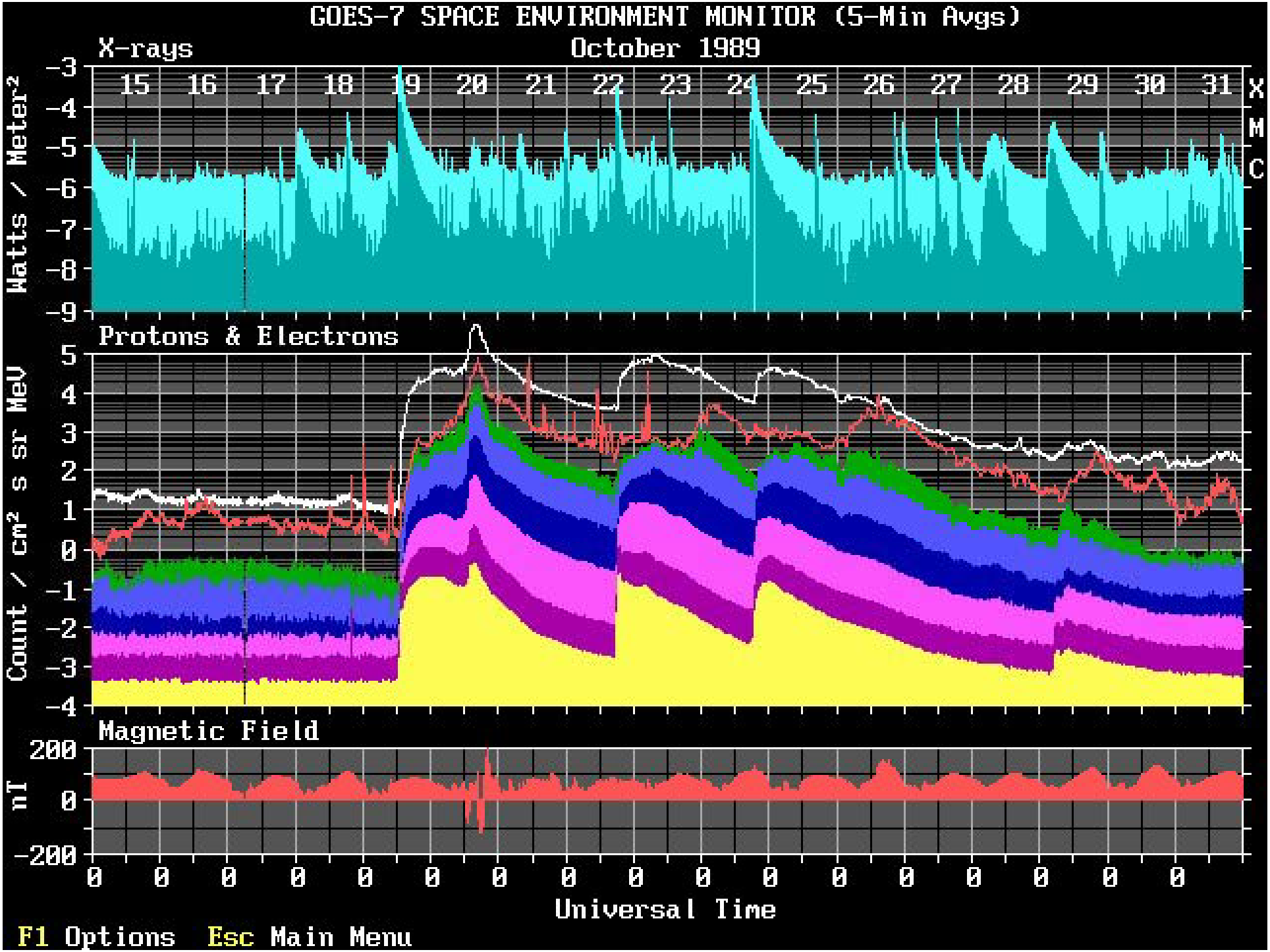
1989



(1) BSOLRPNC GOS7 49 ARRAY I AMPS SOLID LINE DAILY MEAN
(2) BSOLRPNC GOS6 49 ARRAY I AMPS DOTTED LINE DAILY MEAN
(3) BSOLRPNC GOS5 49 ARRAY I AMPS LONG DASHED LINE DAILY MEAN

GOES-5, 6, 7 SOLAR ARRAY CURRENT

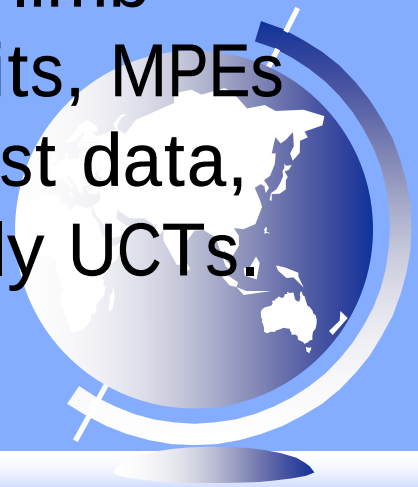

TDRS-1 MEMORY UPSETS and SOLAR PROTONS
October 1989
TDRS-1 Upsets
GOES-7 Protons
Day 19
20
4.2 - 8.7 MeV
100 - 500 MeV
Proton Count
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
2 4 6 8 10 12 14 16 18 20 22
2 4 6 8 10 12 14 16 18 20 22
UT Hours
NOAA/NGDC D.C.Wilkinson


GOES-7 SPACE ENVIRONMENT MONITOR (5-Min Avgs)
X-rays
October 1989
15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
Watts / Meter²
-3 -4 -5 -6 -7 -8 -9
X
M
C
Protons & Electrons
Count / cm² s sr MeV
5 4 3 2 1 0 -1 -2 -3 -4
Magnetic Field
nT
200 0 -200
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Universal Time
F1 Options Esc Main Menu

Space Weather Selected Events

Aug 1972; Seasonal 1985-1991; March 1989

- Aug 1972 - Strong solar flare with high energy protons affected communications satellites.
- 1985-1991 - TDRS-1 RAM hits, many protons
- Mar 1989 - TDRSS-D launch problems, POES tumbling, Japanese CS-3B hits, POES limb sensor hits, GEO pointing, MARECS hits, MPEs affect orientation, Japanese GMS-3 lost data, Drag hurt SMM and caused 6,000 daily UCTs.



Space Weather Selected Events

March 1989 continued:

- Commercial radio interrupted for 2 weeks.
- LORAN inoperable during 6-13 March; HF radio could not be used to alert for problems
- US Navy MARS out worldwide
- Ionosphere “invisible” below 50 MHz but ham operators and police radio systems strong.
- VLBI strong signal at > 140 MHz.
- GPS surveys discarded: US, RSA, Canada, and Australia.

Space Weather Selected Events

March 1989 continued:

- Hydro-Quebec James Bay Power Station failure on 13-14 March; Ap*=285 (#3).
- Scandinavian power grid shut down in central and southern Sweden.
- Local power failures across USA - Tokyo Elect Power Co transformer burned out; power company engineer heard “groans”.
- NE US nuclear power stations’ security.
- Pipeline corrosion in Australia.
- Atlantic & Pacific undersea cable voltages.

Space Weather Selected Events
August 12-20, 1989

- Lost Solar Panel Power: GOES-5, 6, 7; Telecommunications satellites; others
- Star sensor locks lost at GEO and LEO
- GOES-6 lost half telecomm capability
- Increased SEUs on many satellites
- Canadian ground communications problems

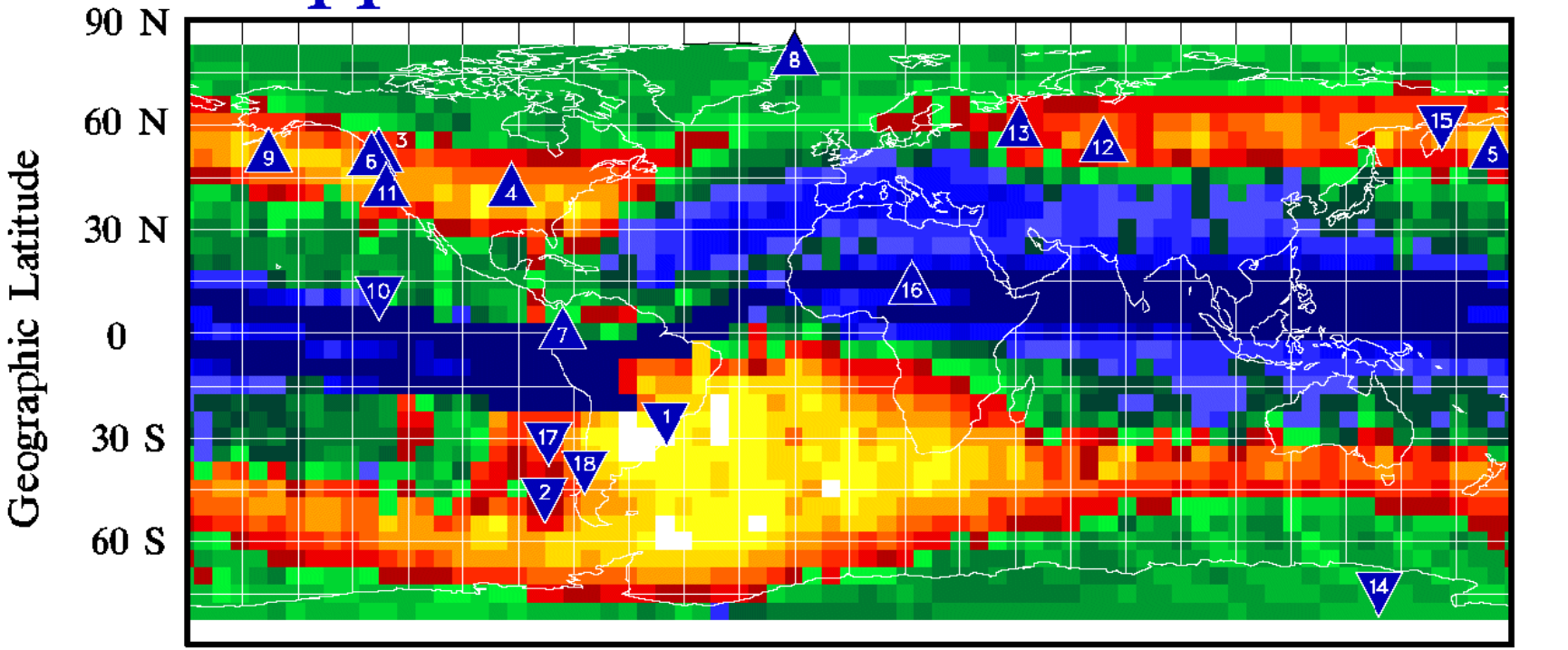
Space Weather Selected Events

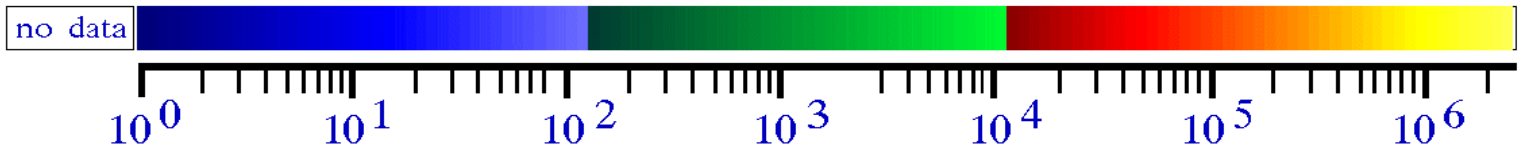
September 29-30, 1989

- Largest GLE in 33 years (satellite era)
- Solar power panel loss GOES-5, -6
- Magellan photo-sensitive damage enroute to Venus
- GEO telecomm (13) 46 hits reported
- TDRSS-1 53 RAM hits
- SEUs on GOES-5, -6

NOAA-10 March 11-20, 1989

Trapped >300 KeV Electron Flux per cm^2-s-sr





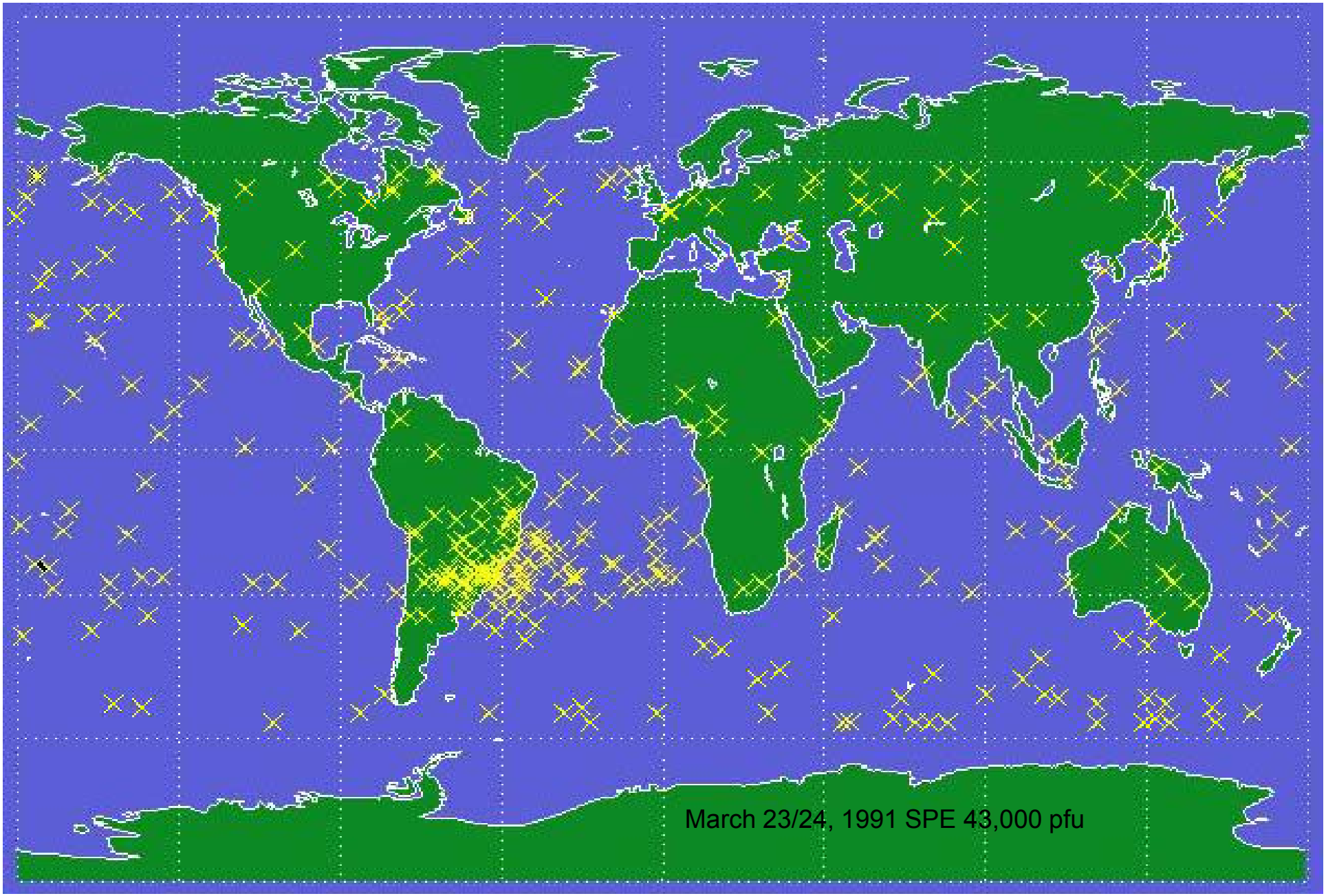
NOAA-11 Anomalies: ▲ Ascending ▼ Descending

Anomalies span 88/09 - 90/08.

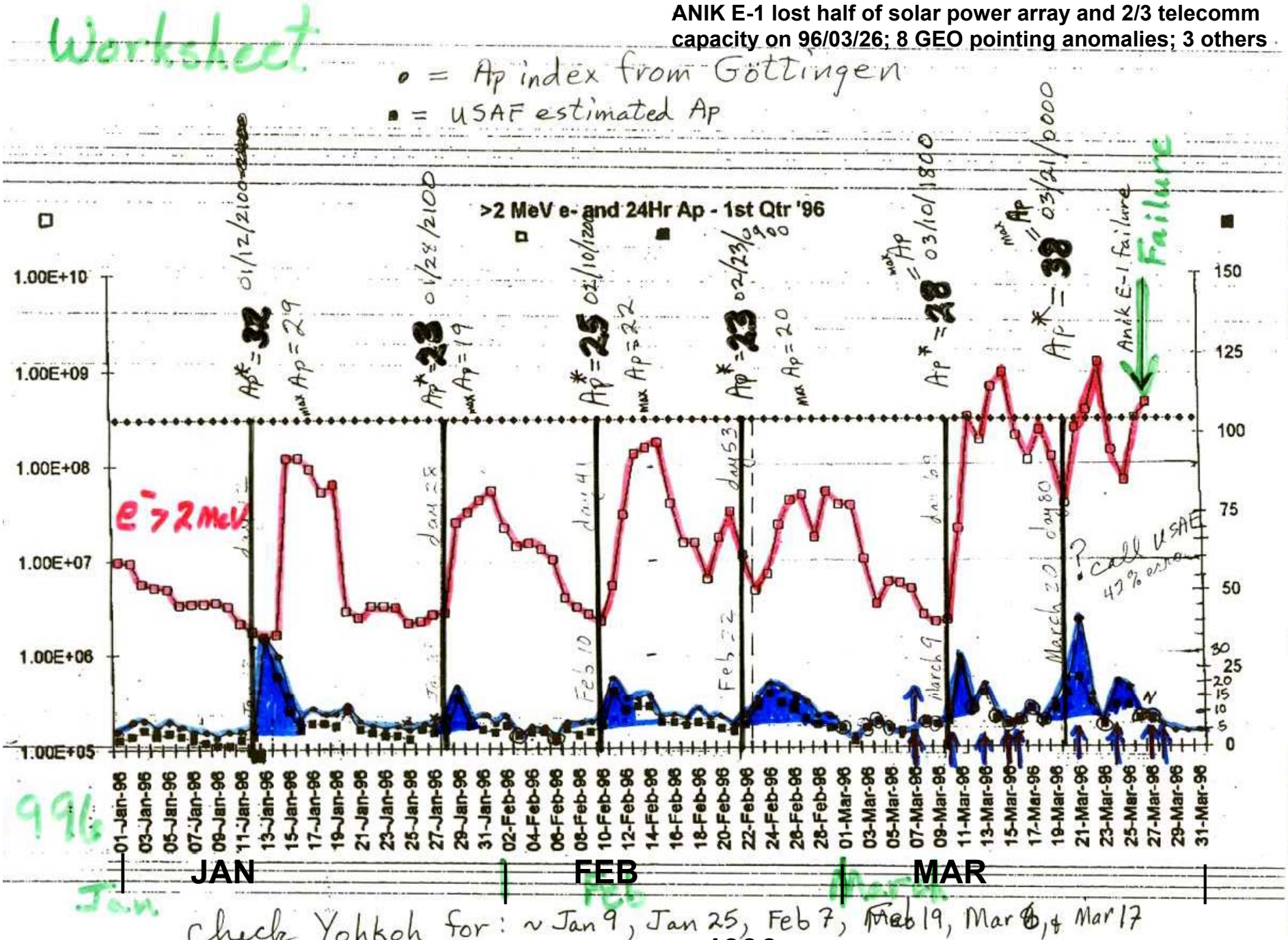
March 11-20 1989 is a "worst case" environment.

Sauer (SEL) / Wilkinson (NGDC)

COMPUTER ANOMALIES: STS-37, -39, -43, & -44 1991 Missions

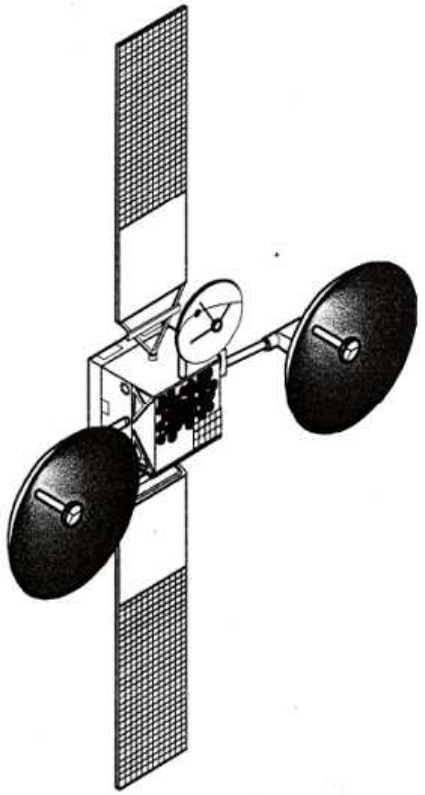


ANIK E-1 lost half of solar power array and 2/3 telecomm capacity on 96/03/26; 8 GEO pointing anomalies; 3 others



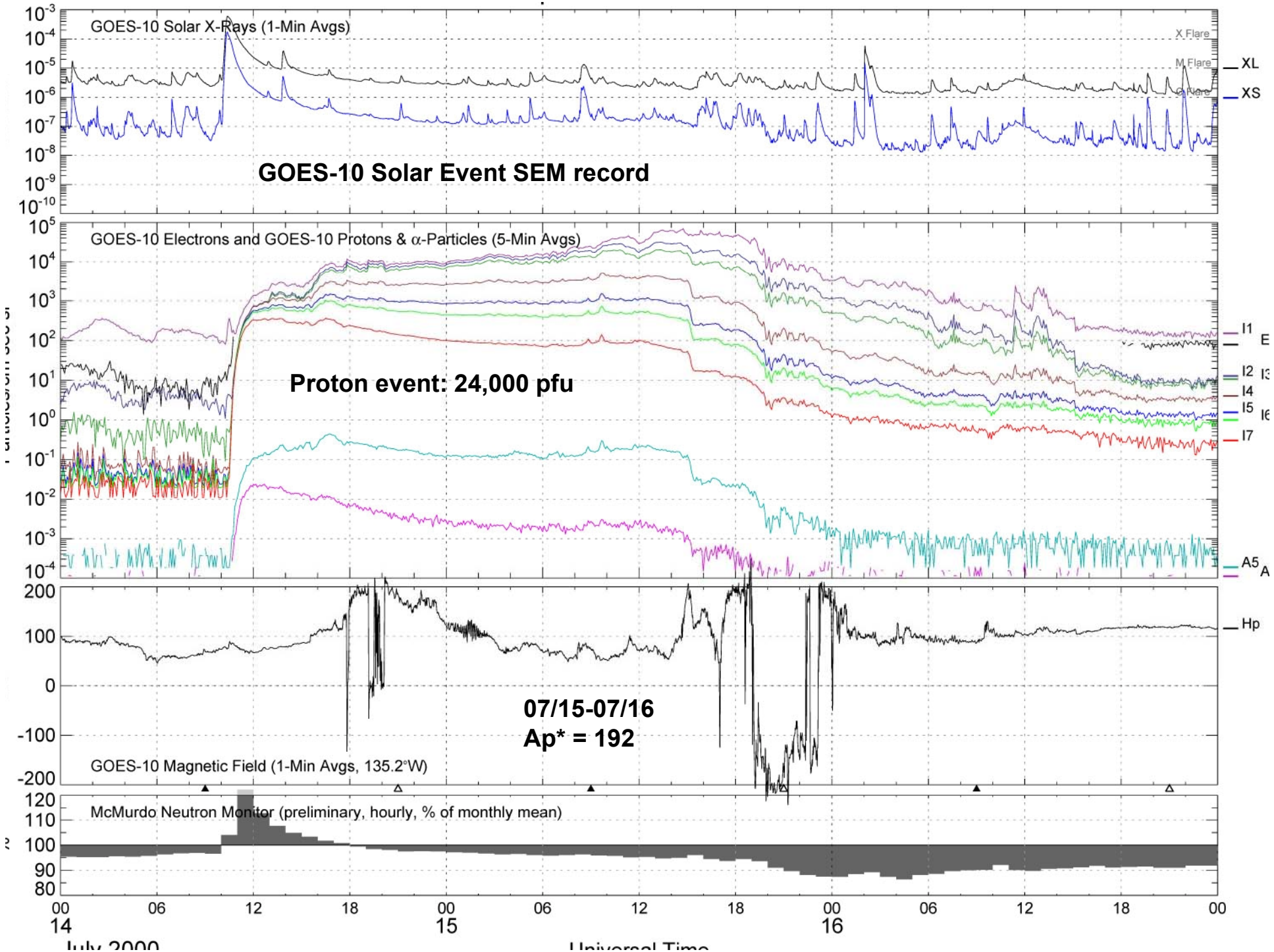
Redesigns
(Some Mission Loss)

These systems had extensive SWx problems and follow-ons required redesign



DMSP F2 - 1977 chronic charging on one component
METEOSAT F1 11/77 extensive charging
GPS Blk I- clock failures
GPS - 6/13/80 solar array tracking
GOES-4 81/82 ungrounded radiator
HEO signal degradations - subassembly redesigned
TDRSS-1 4/83 attitude control system
Telecom 1A- 8/84 ungrounded thermal shielding
CLAS - extensive loss of data/noise
SUPERBIRD-1 12/90 - SEU affecting attitude control led to hardened microprocessors
MARECS-A 3/91 continuous safeing
TEMPO 4/97 New technology - increased power,use of GaAs, solar panel problems

from Marsha Korose


GOES-10 Solar X-Rays (1-Min Avgs)
X Flare
M Flare
C Flare
XL
XS
GOES-10 Solar Event SEM record
GOES-10 Electrons and GOES-10 Protons & α-Particles (5-Min Avgs)
Proton event: 24,000 pfu
I1
E
I2
I3
I4
I5
I6
I7
A5
A
Hp
07/15-07/16
Ap* = 192
GOES-10 Magnetic Field (1-Min Avgs, 135.2°W)
McMurdo Neutron Monitor (preliminary, hourly, % of monthly mean)
00 06 12 18 00 06 12 18 00 06 12 18 00
14 15 16
July 2000
Universal Time

Satellite Anomalies: 14-16 July 2000

Proton Event, 24,000 pfu & Geomagnetic Storm, Ap*=192

- **ASCA** (Advanced Satellite for Cosmology and Astrophysics) – lost attitude fix resulting in solar array misalignment and power loss, satellite probably lost
- **GOES-8 & -10** – SEM Electron sensor problems, power panels
- **ACE** (Advanced Composition Explorer) – Temporary SW and other sensor problems
- **WIND** – Permanent (25%) loss of primary transmitter power & Temporary loss of Sun and star sensors
- **SOHO** (also **YOHKOH** & **TRACE**) – High energy protons obscure solar imagery
- **GEO** and **LEO** Satellites – S/C orientation problems during MPE
- **GEO** Satellites lost ~0.1 amp output from solar arrays

Date	Satellite	from Satellite News Digest Problem(s)
4 May 2002	DirecTV 3	SCP failure
21 Apr 2002	Genesis *	Star tracker blinded 4 times during solar storm (high energy protons)
21 Apr 2002	Nozomi *	Hit by solar storm, loss of most communications, one instrument damaged
16 Apr 2002	Globalstar	Over the past 13 months, 7 of the company's satellites experienced anomalies and were taken out of service
11 Apr 2002	Telstar 6	Satellite reportedly out of control for 3 hours, possibly hit by a meteoroid or space debris
12 Mar 2002	TDRS-I	Loss of pressurisation in one fuel tank while in transfer orbit, may not reach final orbit
Jan 2002	Echostar III	Failure of another transponder pair; 32 of 44 transponders left
15 Dec 2001	Yohkoh	Safe mode during solar eclipse, unexpected spin, loss of control
10 Dec 2001	FUSE	y-axis reaction wheel stops working; spacecraft in safe mode
7 Dec 2001	Arabsat 3A	Permanent loss of several transponders
25 Nov 2001	FUSE	x-axis reaction wheel stops working
23 Oct 2001	Echostar VI	Loss of two solar array strings (of a total of 112) announced
Sep 2001	BeppoSAX	Last of six gyroscopes fails. Satellite now operates in gyroless mode
Sep 2001	Genesis	Thermal control problem caused by faulty radiator
Sep 2001	Echostar V	Third TWTA switched off, replaced with spare
Sep 2001	(various)	Boeing announces power degradation on 702 model solar arrays
6 Sep 2001	PAS-7	Sudden loss of 25 percent of power, to be declared "Constructive Total Loss"
Aug 2001	Echostar V	Thruster anomaly, short interruption of service
14 Aug 2001	Globalstar	Globalstar announces loss of two satellites during 2001
11 Aug 2001	TDRS-8	Boeing announces performance shortfall on Multiple-Access phased array antenna
July 2001	Echostar V	Loss of one momentum wheel, short interruption of service
11 June 2001	Ekspress 2	Loss of attitude control, undisclosed reason. Spacecraft probably lost
April 2001	GSAT	Satellite runs out of fuel after unexpected contingency
April 2001	Echostar VI	Series of anomalous events resulting in a temporary interruption of service

ANOMALIES RELATED TO FALL 2003 SOLAR ACTIVITY

X17/4B flare - 29,500 pfu proton event - Ap*=252

Oct. 23: *Genesis* solar wind satellite at L1 entered safe mode. Normal operations resumed on Nov. 3.

Oct. 24: Airlines rerouted polar flights due to bad HF/VHF communication.

***Midori-2* Earth-observing satellite failed, probably lost; Safe mode, Power dropped, Telemetry lost (23:55).**
***Stardust* comet mission went into safe mode due to read errors; recovered.**
***Chandra* X-ray astronomy satellite observations halted due to high radiation levels (09:34EDT). Restarted Oct. 25.**
***GOES-9, 10 and 12* had high bit error rates (9 and 10); magnetic torquers disabled (12) due to activity.**

Oct. 25: *RHESSI* solar satellite had spontaneous rest of CPU (10:42).

Oct. 26: *SMART-1* had auto shutdown of engine due to increased radiation level in lunar transfer orbit (19:23).

Oct. 27: *NOAA-17* AMSU-A1 lost scanner.
***GOES-8* X-ray Sensor turned itself off and could not be recovered.**

Oct. 28 - 30: Astronauts on *Intl. Space Station* went into service module for radiation protection.
FAA issued first-ever alert on radiation doses received by airplane passengers above 25K ft.
[instrument on *Integral* satellite went into safe mode because of increased radiation.
***Chandra* observations halted again autonomously. Later resumed.**

Power system failure in Malmo, Sweden (Oct. 30, 21:07 LT).

***ACE & Wind* solar wind satellites lost plasma observations;**

Electron sensors of *GOES* satellite in geosynchronous orbit saturated.
***Chandra* observations halted again on Oct. 28 autonomously due to radiation. Resumed Nov. 1.**

***Kodama* data relay satellite in geosynch.; Safe mode, signals noisy, Recovery unknown (Oct. 29)**

***DMSP F16 SSIES* sensor lost data twice, on Oct. 28 and Nov. 3; Recovered.**
Microwave sounder lost oscillator; Switched to redundant system.

***RHESSI* satellite had 2 more spontaneous resets of CPU (28, 17:40; 29, 03:32).**

***CHIPS* satellite computer went offline on Oct. 29 and contact lost with the spacecraft for 18 hr. When contacted the S/C was tumbling; recovered successfully. Offline for a total of 27 hrs.**

***CDS* instrument on *SOHO* spacecraft at the L1 point commanded into Safe mode for 3 days (Oct. 28-30).**

Mars *Odyssey* spacecraft entered Safe mode and MARIE instrument had a temperature red alarm leading it to be powered off (Oct. 28). During downloading on Oct. 29, S/C had a memory error that was corrected with a cold reboot on Oct. 31. The twin *Mars Explorer Rover* spacecraft both entered "Sun Idle" mode due to excessive start tracker events. Stable and will wait for recovery.

***SIRTF*, in orbit drifting behind Earth, turned off science experiments and went to Earth pointing due to high proton fluxes (Oct. 28). 4 days of operations lost.**
***X-ray Timing Explorer* science satellite Proportional Counter Assembly (PCA) experienced high voltages and the All Sky Monitor autonomously shut off (Oct. 29). On Oct. 30 both instruments recovered, but PCA again shut down. PCA recovery delayed into November.**

***Microwave Anisotropy Probe* spacecraft star tracker reset and backup tracker autonomously turned on (Oct. 28). Prime tracker recovered.**

Two ultraviolet experiments on *GALEX* science satellite had excess charge so high voltages turned off. Detectors will remain off until later in Nov.

Despun platform on *Polar* satellite went "out of lock" 3 times but recovered automatically each time. Some of the 4 *Cluster* spacecraft had processor resets but recovered.

NASA's Earth Sciences Mission Office directed all instruments on 5 spacecraft be turned off or safed due to Level 5 storm prediction (Oct. 29). Satellites affected: *AQUA, Landsat, TERRA, TOMS, TRMM.*

Wisconsin & New York: High current levels in transmission lines.

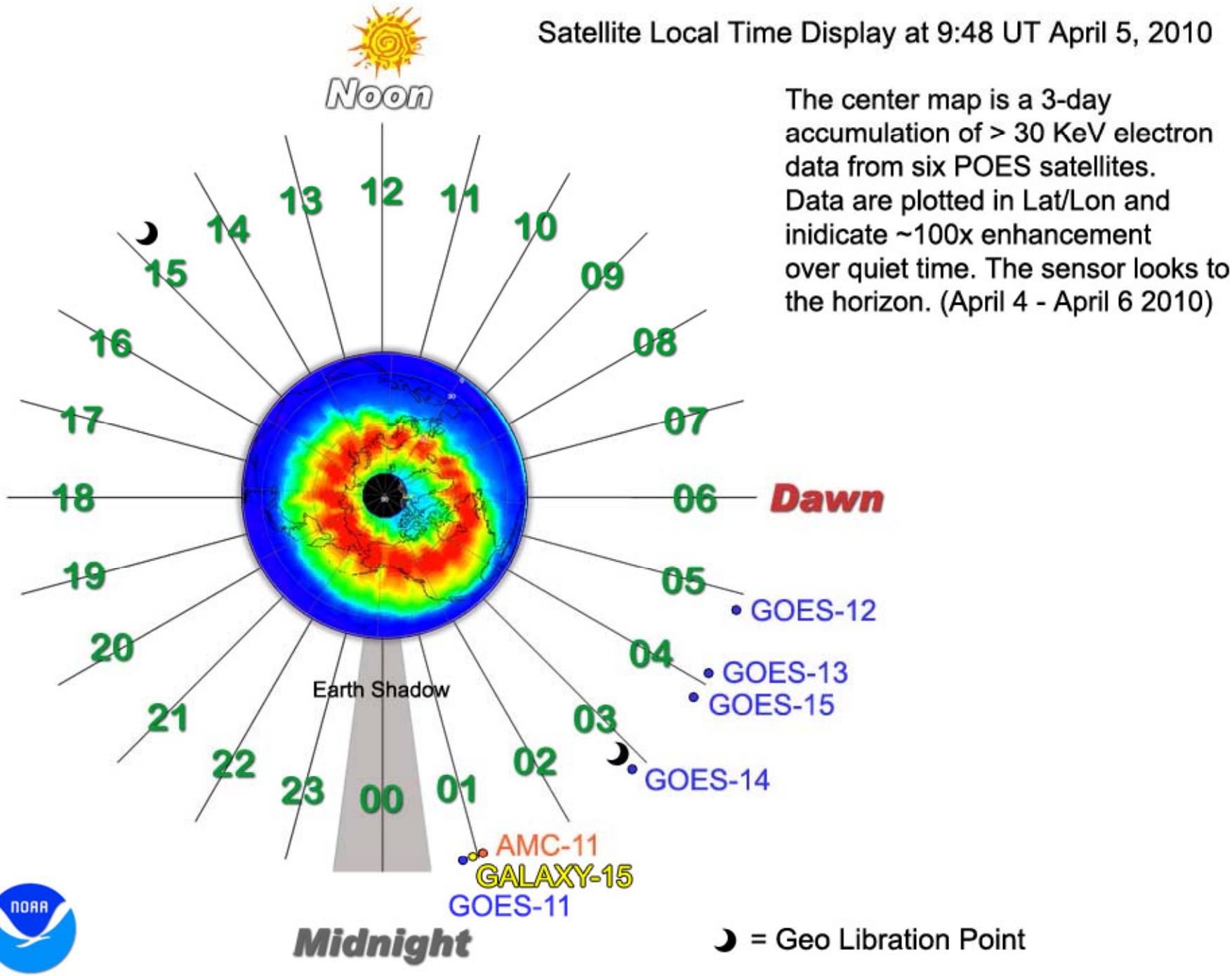
Changes prohibited to airplane routes N of 57deg lat. Some U.S. flights rerouted.
British trans-Atlantic routes moved south.

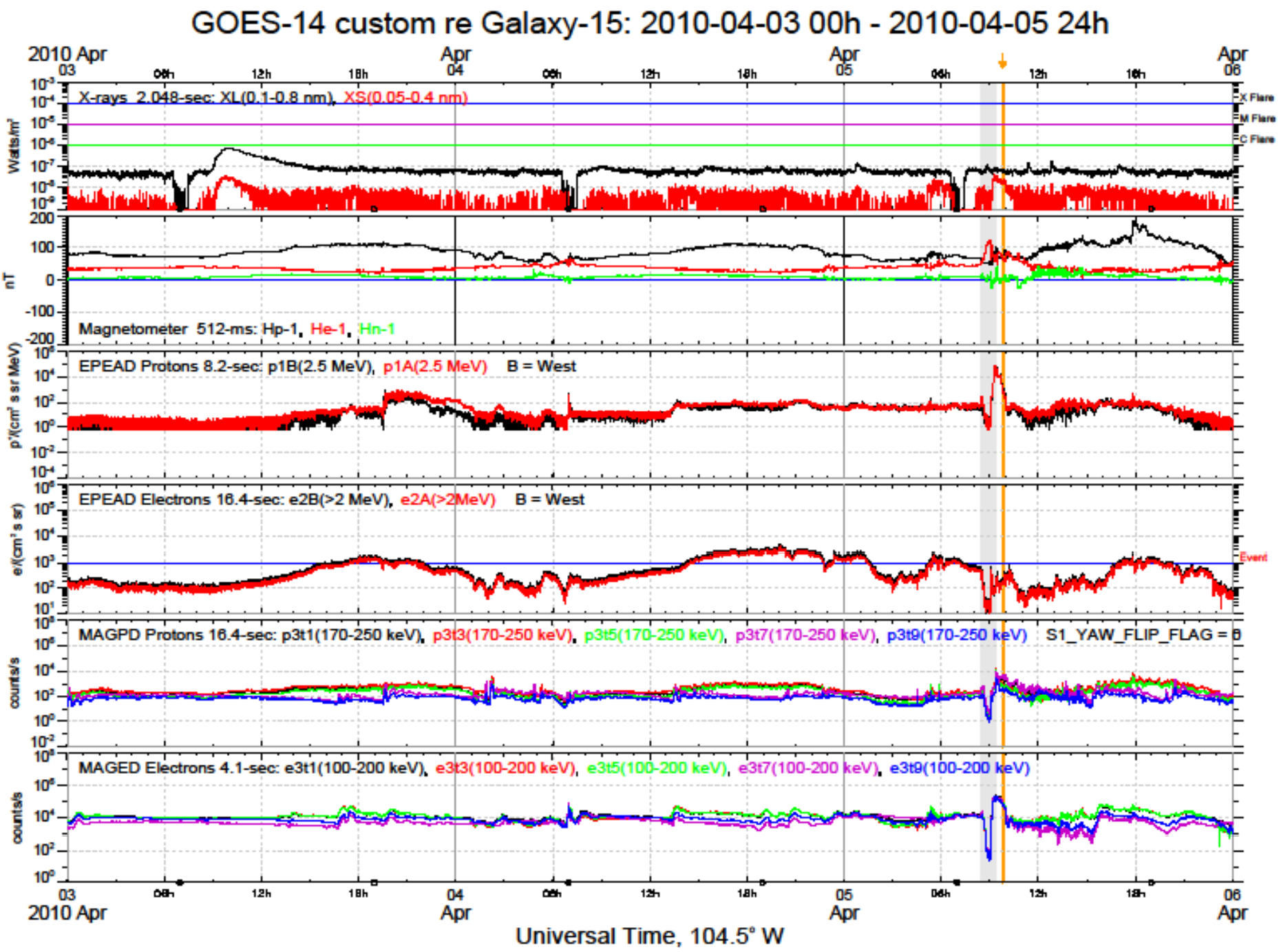
WAAS service interrupted in CONUS; High latitude GPS receiver outages
Military communications impacted (HF/UHF SATCOM)/OTH/Classified users
Loran C station in Newfoundland had interference.

Nov. 2: *Chandra* observations halted again autonomously due to radiation.
Resumption of observations will be delayed for days.

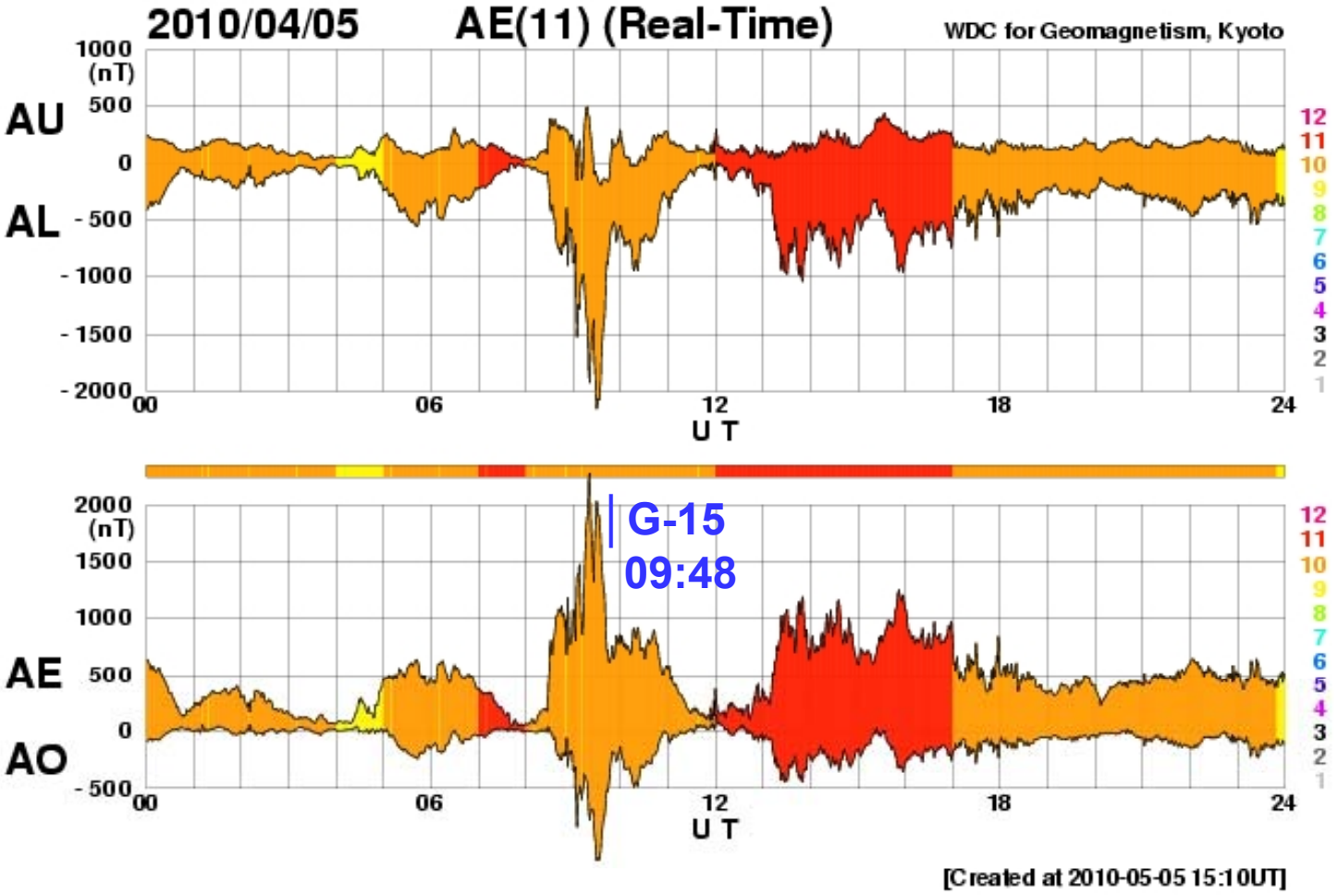
Nov. 6: *Polar* TIDE instrument reset itself and high voltage supplies were disabled; recovered within 24 hr.

Mars *Odyssey* spacecraft commanded out of Safe mode; operations nominal.


Satellite Local Time Display at 9:48 UT April 5, 2010
The center map is a 3-day accumulation of > 30 KeV electron data from six POES satellites. Data are plotted in Lat/Lon and inidicate ~100x enhancement over quiet time. The sensor looks to the horizon. (April 4 - April 6 2010)
Noon
12
13
11
14
10
15
09
16
08
17
07
18
06
Dawn
19
05
GOES-12
20
04
GOES-13
GOES-15
Earth Shadow
21
03
22
02
GOES-14
23
00
01
AMC-11
GALAXY-15
GOES-11
Midnight
= Geo Libration Point
NOAA


GOES-14 custom re Galaxy-15: 2010-04-03 00h - 2010-04-05 24h
2010 Apr
03
04
05
06
Apr
X-rays 2.048-sec: XL(0.1-0.8 nm), XS(0.05-0.4 nm)
Watts/m²
X Flare
M Flare
C Flare
nT
Magnetometer 512-ms: Hp-1, He-1, Hn-1
EPEAD Protons 8.2-sec: p1B(2.5 MeV), p1A(2.5 MeV) B = West
p⁺/(cm² s sr MeV)
EPEAD Electrons 16.4-sec: e2B(>2 MeV), e2A(>2MeV) B = West
e/(cm² s sr)
Event
MAGPD Protons 16.4-sec: p3t1(170-250 keV), p3t3(170-250 keV), p3t5(170-250 keV), p3t7(170-250 keV), p3t9(170-250 keV) S1_YAW_FLIP_FLAG = 0
counts/s
MAGED Electrons 4.1-sec: e3t1(100-200 keV), e3t3(100-200 keV), e3t5(100-200 keV), e3t7(100-200 keV), e3t9(100-200 keV)
counts/s
Universal Time, 104.5° W

Kyoto real-time AE(11)



CONCLUSIONS-1

- **Sunspot cycle decline and minimum years are ideal for “killer electrons” at GEO and lower orbit altitudes charging surface and interior.**
- **Sunspot cycle maximum years are ideal for energetic proton and heavier ion events that cause SEUs and sensor optics & power panel degradation.**
- **Major magnetic storms may happen at any time and cause spectacular effects on satellites, technology and humans.**

CONCLUSIONS-2

- **Every satellite (or object) in orbit is a probe of the Space Environment from which to learn.**
- **The history of satellites should be the basis for learning what causes operational problems.**
- **Combining space environment data with satellite histories is necessary.**
- **Solar Cycle # 23 still may be highly active. Are we any more ready today?**
- **What about cycle # 24? Can engineering cope?**

CONCLUSIONS-3

- SATELLITE GALAXY-15 PASSED THROUGH MIDNIGHT ECLIPSE JUST BEFORE GOES-11 WHICH MEASURED AN ORDER OF MAGNITUDE DECREASE AND THEN TWO ORDERS INCREASE OF >2MeV ELECTRONS AND A POSITIVE PULSE OF SOME 3~4 ORDERS OF MAGNITUDE >1MeV PROTONS. THOSE CHANGES ALSO SHOULD HAVE HAPPENED AT G-15.

- DURING THE POSITIVE PARTICLE PULSES, GOES-11'S MAGNETOMETER RECORDED ~100 nT POSITIVE Hp PULSE, SIMILAR TO A MAGNETOPAUSE COMPRESSION BUT WITHOUT A CROSSING.

- PRELIMINARY AE(11) INDICES PEAKED AT ~09:20 UT AT THE PEAK OF THE FIRST SUB-STORM INJECTION