Space Weather Conditions at the Time of the Galaxy 15 Spacecraft Anomaly

Report of the NOAA Tiger Team

Boulder, CO

01 June 2010

Galaxy 15 satellite. Photo Credit: Orbital Sciences

Galaxy 15
NOAA Tiger Team

At the request of the NWS/Space Weather Prediction Center (SWPC) Director the NOAA Tiger Team was formed to determine the likely space environmental conditions experienced by the Galaxy 15 spacecraft prior to and at the time of the reported anomaly. The Tiger Team was comprised of representatives from SWPC and the NESDIS National Geophysical Data Center (NGDC):

Janet Green, SWPC (co-chair)
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CIRES – Cooperative Institute for Research in Environmental Sciences

[1]Not in photograph

OUTLINE

Space Weather Conditions – 05 Apr 10

Space Weather describes changes in the interconnected system from the Sun to Earth

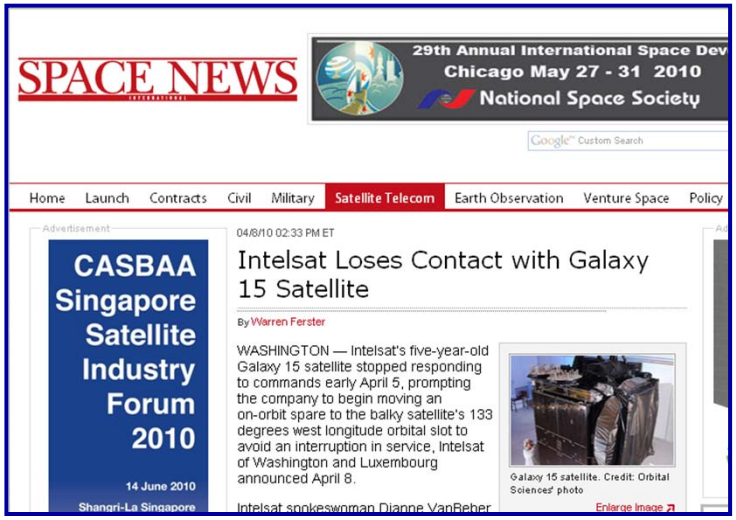
This presentation follows space weather conditions progressing from the sun to near the Galaxy 15 location showing:

1. **Events that occurred at the sun**
2. **Resulting global changes in the near-earth space environment**
3. **Local changes near Galaxy 15 in the energetic charged particles that can cause satellite charging and electronic component failure**

Summary

- ✓ **Solar activity was elevated but not remarkable**
- ✓ **Global geomagnetic activity described by the AL auroral electrojet index and K_p were extreme. Other SWx indices were more moderate**
- ✓ **Local measurements near Galaxy 15 show that a large geomagnetic substorm occurred 48 minutes prior to the anomaly. The substorm caused remarkable increases in the measured local flux of energetic particles known to cause surface or internal satellite charging**

Background (1 of 2)
Galaxy 15 Satellite Anomaly - Impacts

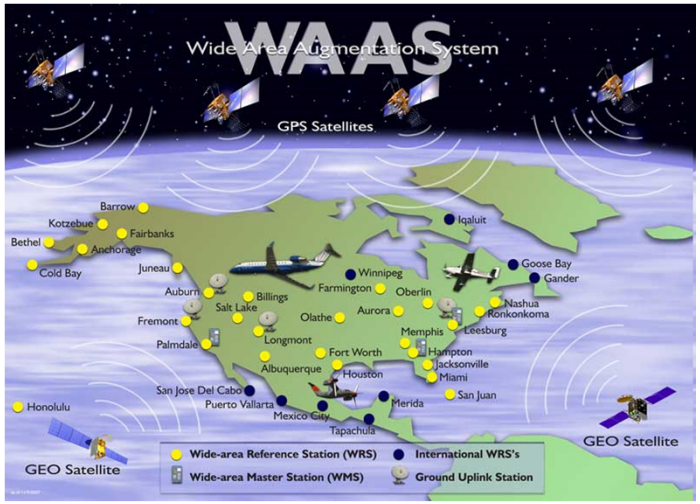


08 Apr 2010 – Intelsat reports that the Galaxy 15 stopped responding to ground commands (Anomaly time: 05 April @ 09:48 UTC)

10 Apr 2010 – FAA predicts erosion of WAAS capability due to Galaxy 15 failure

20 Apr 2010 – Orbital attributes the loss of Galaxy 15 to space weather

30 Apr 2010 – Intel reports Galaxy 15 still adrift and threatens nearby satellites (i.e. frequency interference)



Background (1 of 2)
Operational Timeline

```
:Product: 0404RSGA.txt
:Issued: 2010 Apr 04 2201 UTC
# Prepared jointly by the U.S. Dept. of Commerce, NOAA,
# Space Weather Prediction Center and the U.S. Air Force.
#
Joint USAF/NOAA Report of Solar and Geophysical Activity
SDF Number 094 Issued at 2200Z on 04 Apr 2010
IA.  Analysis of Solar Active Regions and Activity from  03/2100Z
to 04/2100Z:  Solar activity was very low. No flares were observed
during the past 24 hours. New Region 1060 (N24E58) was assigned
today and appears to be a small bipolar region.
IB.  Solar Activity Forecast:  Solar activity is expected to be very
low. However, there is a chance for an isolated C-class event during
the next three days (05-07 April).
IIA.  Geophysical Activity Summary 03/2100Z to 04/2100Z:
The geomagnetic field was mostly quiet to unsettled. However, there
was an isolated active period at mid-latitudes from 0600-0900Z which
was accompanied by storm level activity at some high latitude
stations. Solar wind speed observed by the ACE spacecraft were
elevated throughout the day, typically between 460-540 km/s. The
greater than 2 MeV electron flux at geosynchronous orbit reached
high levels during the past 24 hours.
IIB.  Geophysical Activity Forecast:  The geomagnetic field is
expected to be quiet with a chance for unsettled periods for the
first day (05 April) and partway through the second day (06 April).
An increase to mostly unsettled levels with a chance for active
periods is expected sometime late on the second day or early on the
third day (07 April) in response to a favorably positioned coronal
hole. Yesterdays halo CME appears to be primarily directed south of
the ecliptic plane. However, it is possible that the flank of the
CME could contribute to somewhat elevated activity on the third day.
III.  Event Probabilities 05 Apr-07 Apr
Class M    01/01/01
Class X    01/01/01
Proton     01/01/01
PCAF       green
IV.  Penticton 10.7 cm Flux
Observed         04 Apr 079
Predicted   05 Apr-07 Apr  080/080/085
90 Day Mean       04 Apr 083
V.  Geomagnetic A Indices
Observed Afr/Ap 03 Apr  005/008
Estimated Afr/Ap 04 Apr  010/010
Predicted Afr/Ap 05 Apr-07 Apr  005/007-007/010-012/012
VI.  Geomagnetic Activity Probabilities 05 Apr-07 Apr
A.  Middle Latitudes
Active             05/25/35
Minor storm         01/10/20
Major-severe storm    01/01/05
B.  High Latitudes
Active             10/30/40
Minor storm         05/15/30
Major-severe storm    01/01/10
_____________________
```

Operational Timeline – Universal Time (UT)

April 3, 2010

09:54 B7 solar flare (sunspot region 1059)

10:33 CME first visible

22:04 SWPC Daily Forecast issued

- *Notes Flare and Coronal Mass Ejection (CME)*
- *Geomagnetic quiet expected: 04-05 April*

April 4

22:01 Daily Forecast issued (left text)

- *Flank of CME may contribute to elevated activity on April 7*

April 5

05:33 Warning issued: K=4

05:44 Alert issued: K=4

08:04 Warning issued

- *Sudden Impulse (CME hits ACE @ 07:56 UT)*

09:16 Warning issued: K=5

09:17 Alert issued: K=5

09:22 Alert issued: K=6

09:48 *Galaxy 15 anomaly*

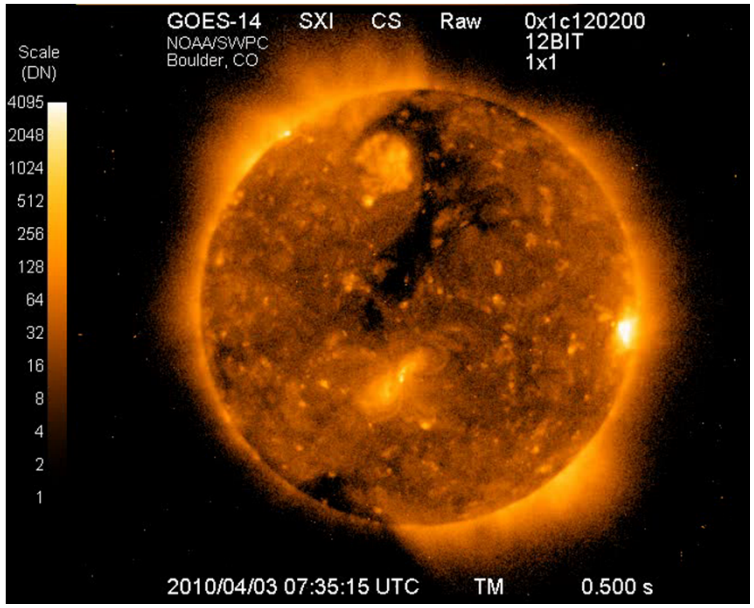
09:56 Alert issued: K=7

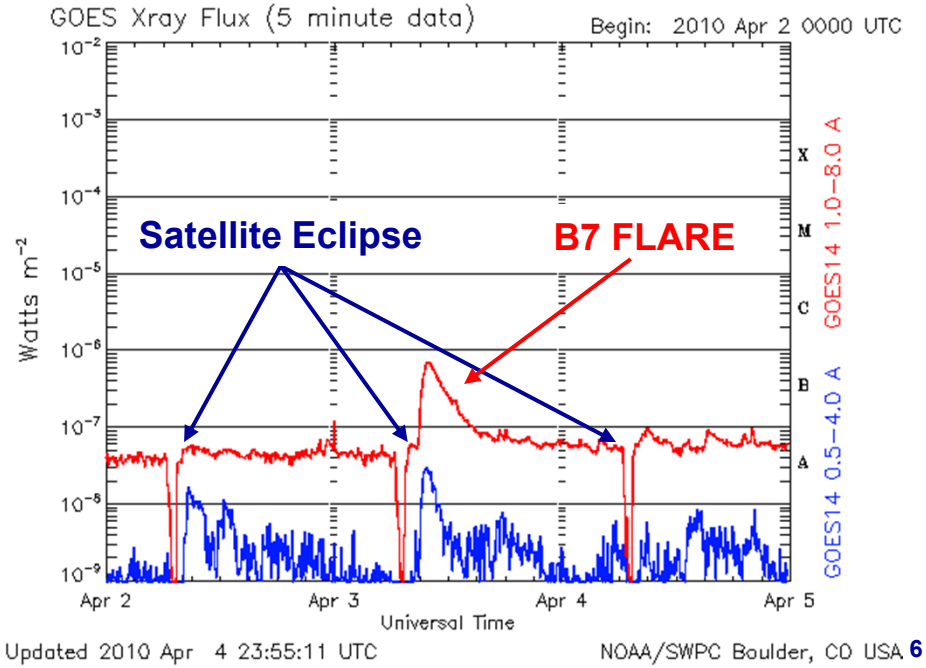
Space Weather Conditions
1. Events at the Sun (1 of 3)

Solar activity prior to the Galaxy 15 anomaly on April 05 at 9:48 was elevated but unremarkable.

On 03 April @ 9:54 UT (2 days prior to the anomaly) a solar B7 flare was observed by the NOAA GOES-14 X-Ray Sensor (XRS)

- **Flares of this intensity are not usually associated with intense space weather**
- **In solar cycle 23 there were >14,000 flares more intense than a B7-level flare**
- **There have already been 125 flares more intense than B7 in the new cycle**
- **Source of the flare was decaying active region 1059 (S22W15) with 4 sunspots**



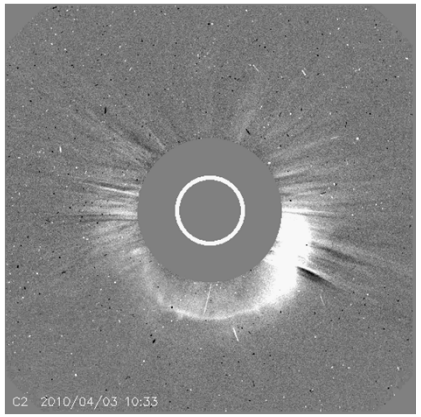


Space Weather Conditions
1. Events at the Sun (2 of 3)

April 03 @ 10:33 UT ~30 minutes after the flare an earthward directed coronal mass ejection (CME) was observed

- **SOHO/LASCO imager showed a modest partial Halo event**
- **Side view of the CME from the NASA STEREO COR2 instrument indicated that it was moving southward and only the 'edge' would graze earth**
- **Measured plane of sky speed was 512 km/s**
- **Moderate speeds and 'edge' impacts such as these typically cause weaker, shorter duration geomagnetic storms**
- **Solar cycle 23 had ~500 faster Earth directed CME's**

SOHO/LASCO

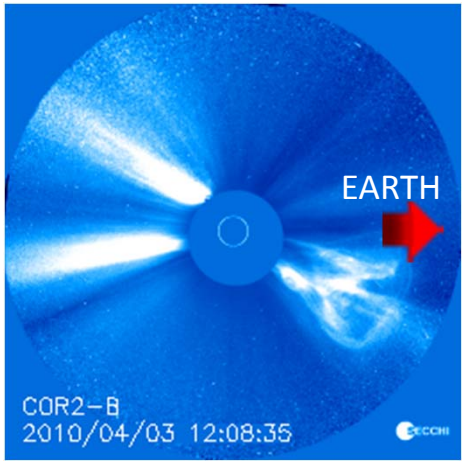


NASA/ESA

This event was classified as a moderate CME ejected from an otherwise quiet sun

- **F10.7 was 77 sfu, the sunspot count was 27 and the x-ray background was a modest 3.9×10^{-8} Watts m^{-2}**
- **At solar maximum, F10.7 is expected to be about 150 sfu and the sunspot count to be at least 3x greater**

STEREO COR2



NASA

Note: F10.7 measured in terms of solar flux units (sfu) where 1 sfu = 10^{-22} Watts m^{-2} Hz^{-1}

Sunspot counts as defined in accordance to Johann Rudolf Wolf (1816-1893) – see http://www.ngdc.noaa.gov/stp/solar/ssn.html

See http://www.swpc.noaa.gov/info/glossary.html for a discussion of x-ray background levels

Space Weather Conditions
1. Events at the Sun (3 of 3)

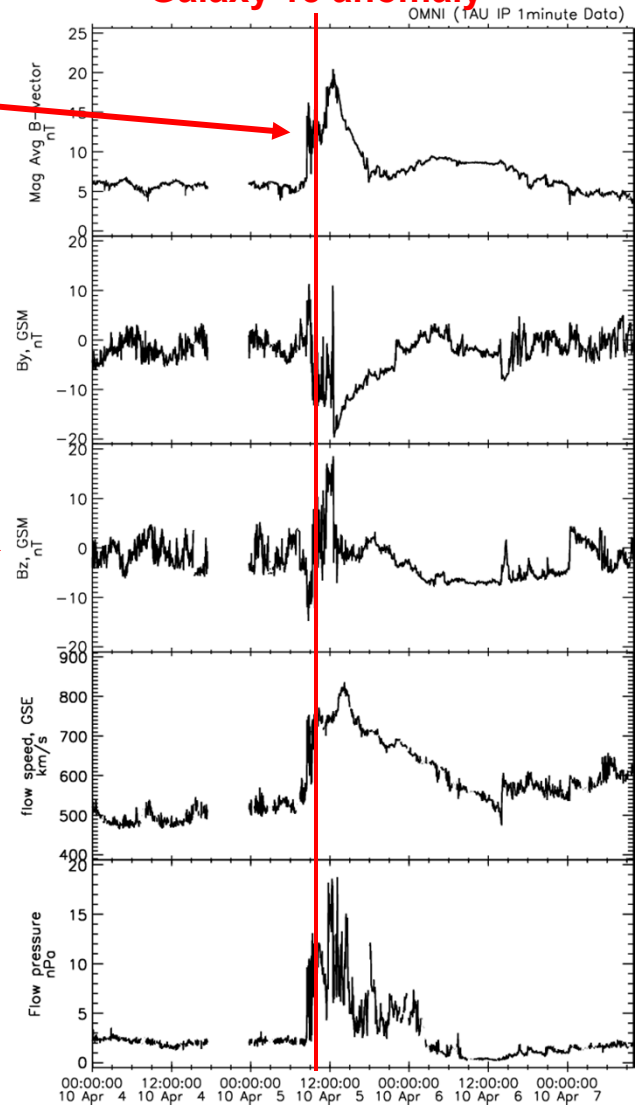
April 05 07:56 UT – Nearly 2 days after the CME lifted off from the sun, it was observed by the NASA ACE satellite upstream of earth

- **It takes ~30 minutes for the solar wind to propagate from ACE to Earth**
- **The solar wind magnetic field turned southward (negative)**
- **The solar wind speed increased from ~500 to >700 km/s**

Such solar wind conditions often result in a moderate geomagnetic storm

Galaxy 15 anomaly

CME detected by ACE

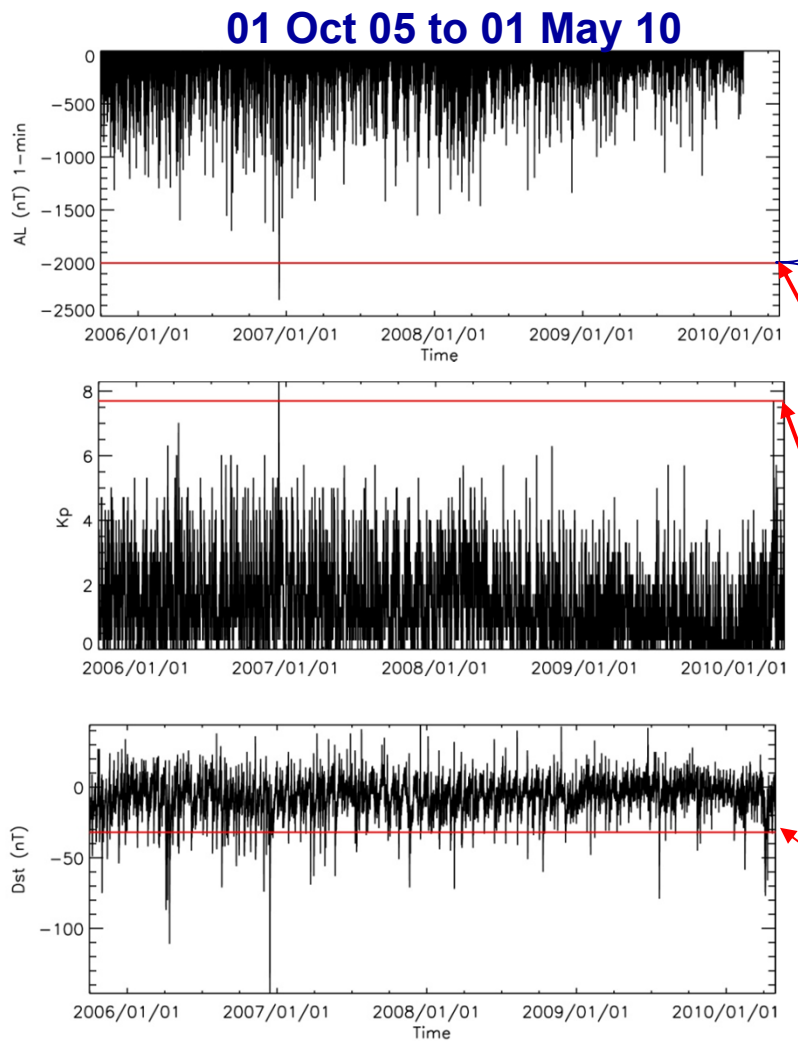


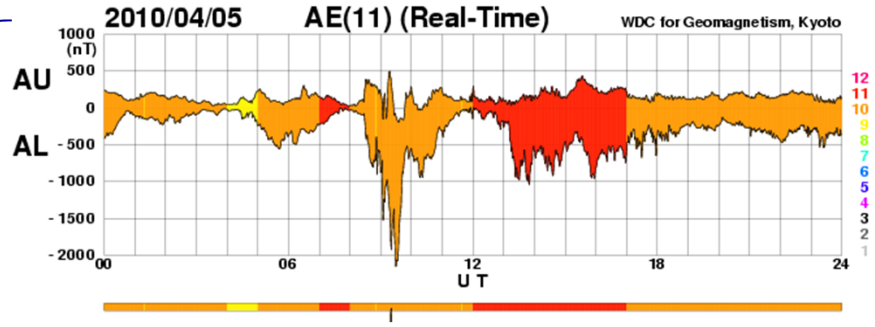
Data Source: NASA Omni

Note: ACE is the NASA Advance Composition Explorer located in a halo orbit near the L1 sun-earth Lagrangian point approximately ~1.5x10^6 km in the sunward direction. Plot shows solar wind parameters observed at ACE, time-shifted to Earth.

Space Weather Conditions
2. Global Environment At Earth (1 of 2)

Some (but not all) global geomagnetic activity indicators were extreme immediately prior to the anomaly





Currently only quick look plots are available for April

AL index was <-2000 nT prior to the anomaly. Larger values observed only once previously during Galaxy 15 lifetime (*launched: 13 Oct 05*)

K_p index reached 7.7 prior to the anomaly – larger values were observed only once previously during the Galaxy 15 lifetime

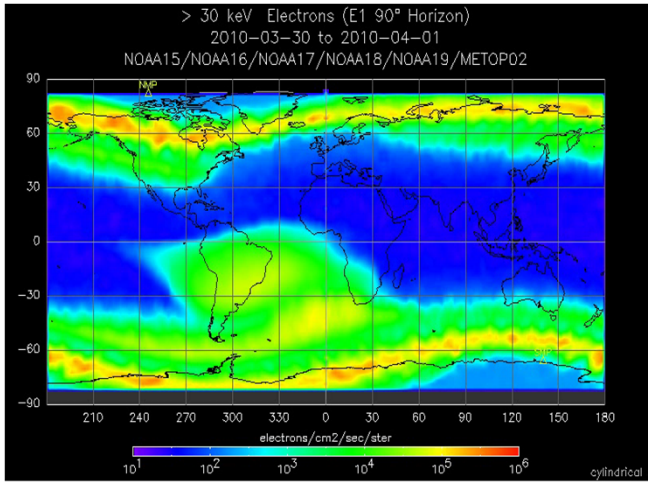
? However, Dst index reached -32 nT prior to anomaly indicating only a **moderate storm –** similar to many previously observed levels during the Galaxy 15 lifetime

Data Source: Kyoto World Data Center & German Research Centre for Geosciences

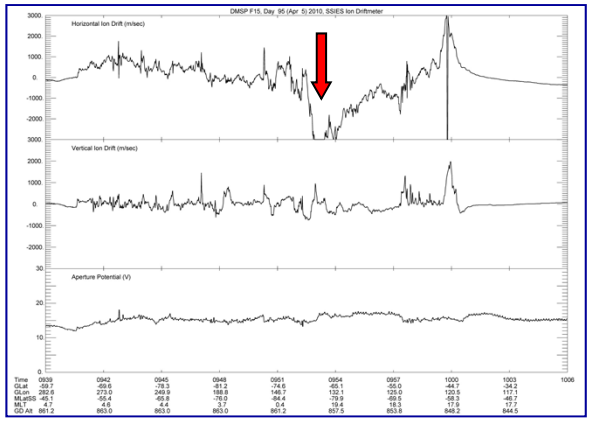
Space Weather Conditions
2. Global Environment At Earth (2 of 2)

April 5th "event" as an interval of general interest

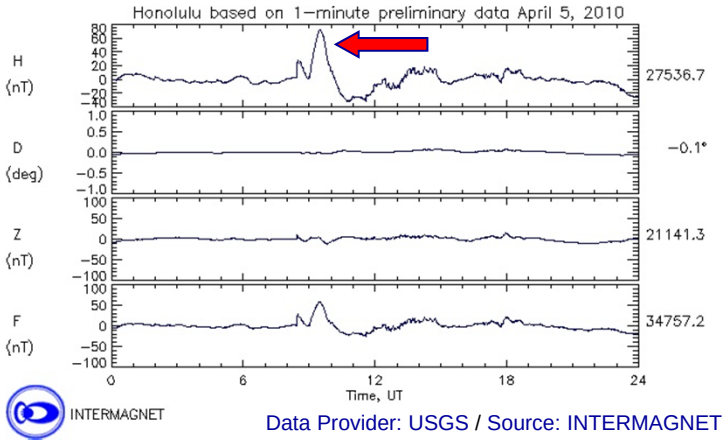
1. POES Energetic Particles (animation)



2. DMSP Convective Drifts (off-scale)

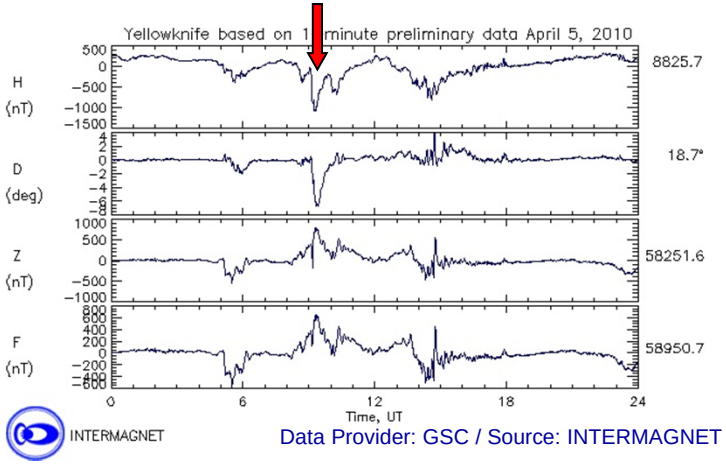


3. Magnetospheric reconfiguration?



Data Provider: USGS / Source: INTERMAGNET

4. Extreme magnetic deviations near local midnight (Galaxy 15 footprint)

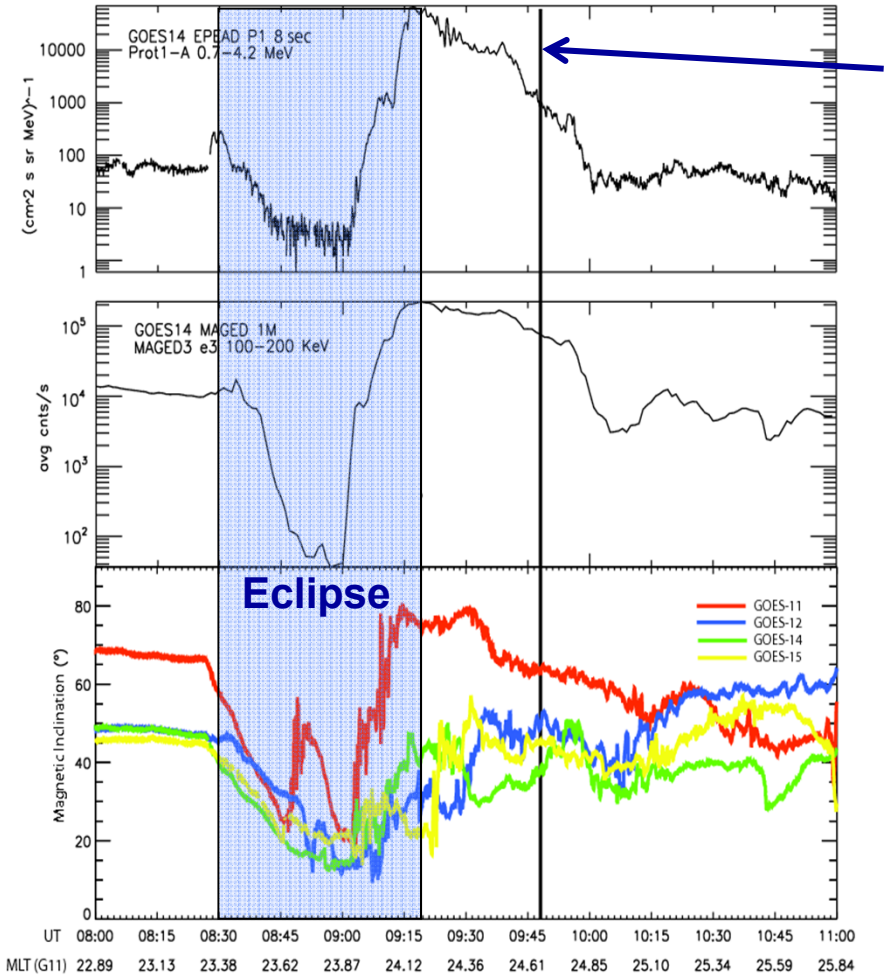


Data Provider: GSC / Source: INTERMAGNET

Space Weather Conditions

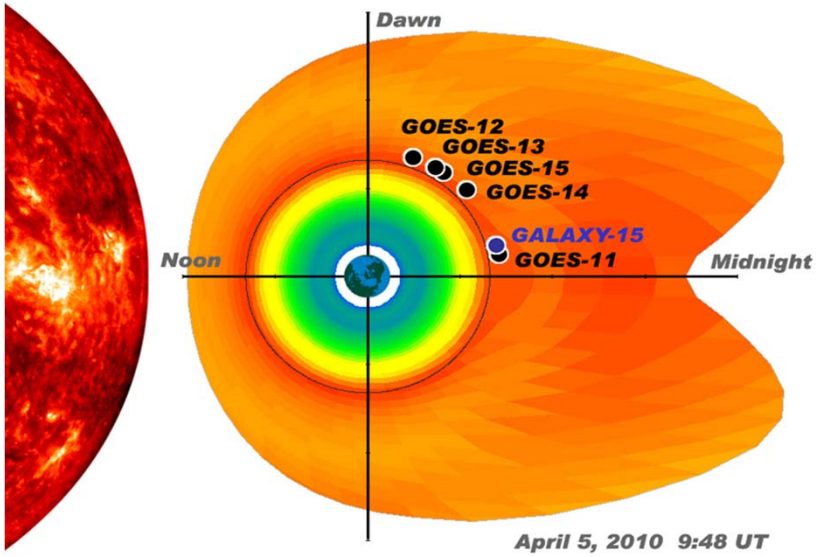
3. Local Environment At Galaxy 15 (1 of 5)

April 05 @ 09:00 UT: GOES magnetometers and particle instruments showed a major reconfiguration of the magnetosphere indicative of a substorm and injection of energetic particles into the nightside, near-earth space environment



Galaxy 15 (133 W) Anomaly 09:48 UT

Satellite Locations



Space Weather Conditions

Aside: Particle-Induced Spacecraft Anomalies

Energetic space particles are responsible for 3 known classes of satellite anomalies

Surface Charging

~0-100 keV electrons may contribute to satellite surface charging (NASA-HDBK-4002, 1999)

Internal Charging

~>100 keV electrons may penetrate through ~3 mils aluminum shielding and cause internal charging (NASA-HDBK-4002, 1999)

Single Event Upsets/Burnout/Latchup

~>5 MeV protons may penetrate through ~3 mils of aluminum shielding (NASA-HDBK-4002, 1999) and cause a temporary upset or permanent damage as it passes through an electronic component

Space Weather Conditions
Aside: GOES Sensor Availability

Satellite Series	Electrons >800 keV	Electrons 30-600 keV	Electrons 0.03-30 keV	Protons >740 keV	Protons 80-800 keV	Protons 0.03-30 keV	Magneto-meter
GOES 8-12	√			√			√
GOES 13-15	√	√		√	√		√
GOES R+	√	√	√	√	√	√	√
Use relative to spacecraft effects	**Interior charging**	**Surface and interior charging**	**Surface charging and charging signatures**	**Single event effects**	**Surface damage (e.g., solar arrays)**	**Surface charging signatures**	**Charging, orientation anomalies**

GOES 13 became the operational GOES EAST satellite on April 14, 2010 – at the time of the Galaxy 15 anomaly, SWPC was not yet receiving its data

GOES 14 Space Environment Monitor was kept on following completion of Post-Launch Test (PLT) in late 2009 in order to support GOES 15 PLT

GOES 15 has been in PLT following satellite launch in March 2010

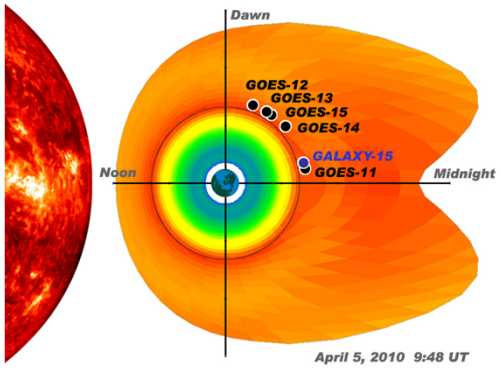
- None of the 30-800 keV electron measurements discussed herein important for this anomaly study were on an operational satellite at the time (fortunately GOES 14 & 15 PLT activities were ongoing)
- Substantial work is still required to develop this capability for real-time situational awareness and forecasting

Space Weather Conditions
3. Local Environment At Galaxy 15 (2 of 5)

Surface Charging: Electron Environment (Low-to-Medium Energy Electrons)

- **April 05 @ 9:00 – 48 minute prior to the Galaxy 15 anomaly the 40-to-475 keV electron flux increased at GOES 14 and 15**
  - **75-to-475 keV electron flux was the highest observed since GOES 14 was turned on in July 2009 and since GOES 15 was turned on in April 2010**
  - **High electron fluxes are notable although surface charging potentials cannot be accurately estimated without lower energy (<40 keV) particle measurements and detailed modeling of their interactions with specific satellite surface materials**
  - **Note: Future GOES-R instruments will measure low energy electrons and protons within the energy range 30 eV to 30 keV**

Satellite Locations

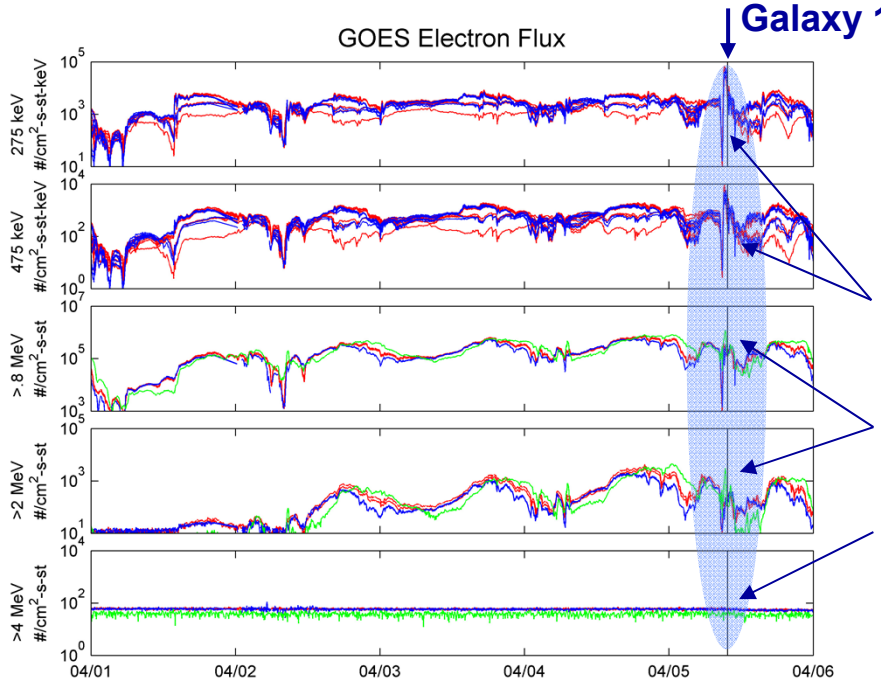


Note: Multiple curves for each GOES satellite correspond to different telescope "look" directions

Space Weather Conditions
3. Local Environment At Galaxy 15 (3 of 5)

Internal Charging: Electron Environment (Medium-to-High Energy Electrons)

- **April 05 @ 9:00 – 48 minutes prior to the anomaly 275-475 keV electron flux increased at GOES 14 and 15**
  - **Flux of 275-475 keV electrons was the highest observed since GOES 14 was turned on in July 2009 and GOES 15 since April 2010 (GOES 11 does not measure electrons below .8 MeV**
  - **Flux of >.8 MeV electrons measured by GOES 11, 14 and 15 did not increase above prior levels**
  - **Internal charging is still commonly inferred from the >.8 MeV alone because the lower energy data was not operationally available on satellites prior to GOES 13**



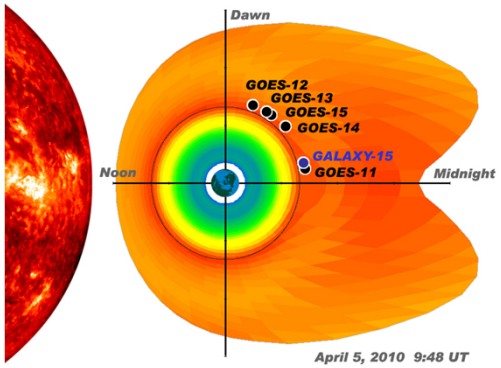
GOES 14 -----
GOES 15 -----
GOES 11 -----

Flux increase
(275 keV / 475 keV)

Moderate increase
(>.8 MeV / >2 MeV)

No increase
(>4 MeV)

Satellite Locations

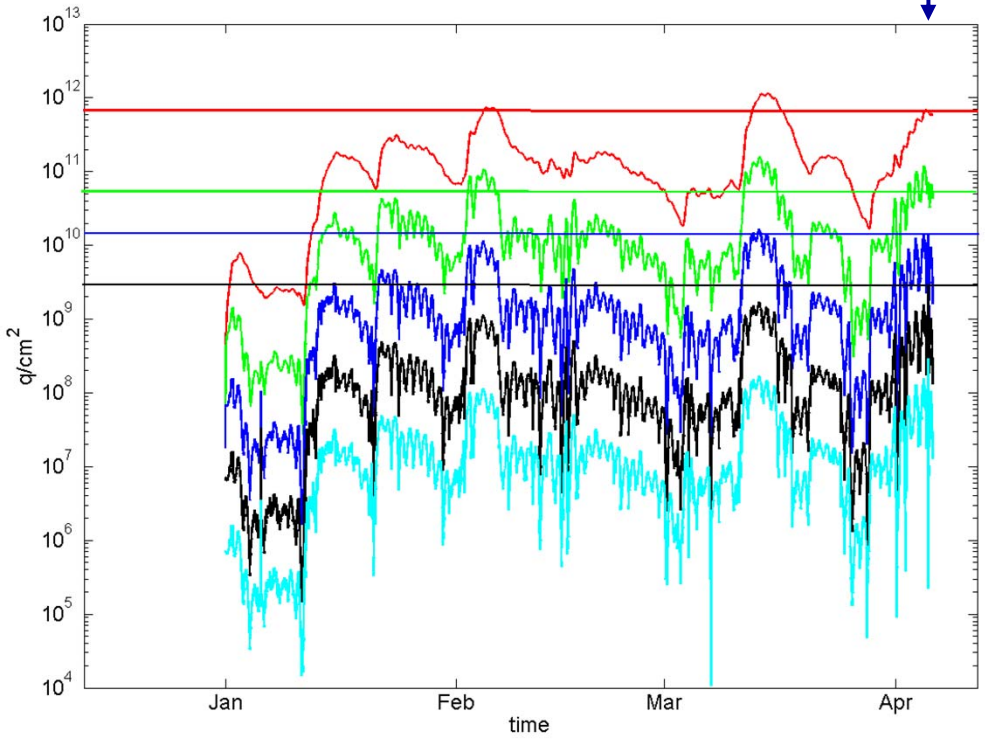


Space Weather Conditions

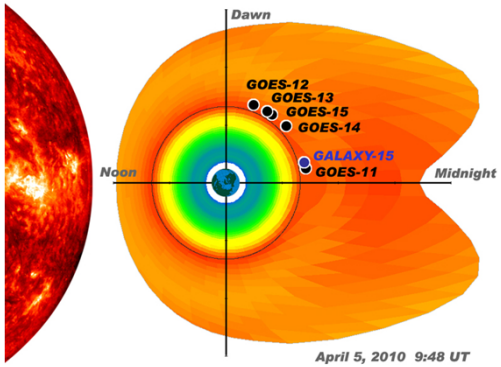
3. Local Environment At Galaxy 15 (4 of 5)

Internal Charging: Electron Environment (Additional Considerations)

- **As a rule of thumb an accumulated charge of 10^{10} to 10^{11} q/cm^2 can induce internal discharges within spacecraft (Note: "q" refers to an electronic charge)**
  - **On April 5th the accumulated charge calculated at GOES 14 using the measured >350 keV electron flux prior to the anomaly can be calculated for different dielectric discharge time constants**
  - **Dielectric time constants, τ, for typical dielectric material range from 10 to 10^5 s (Garrett and Whittlesey, 2000)**



Satellite Locations

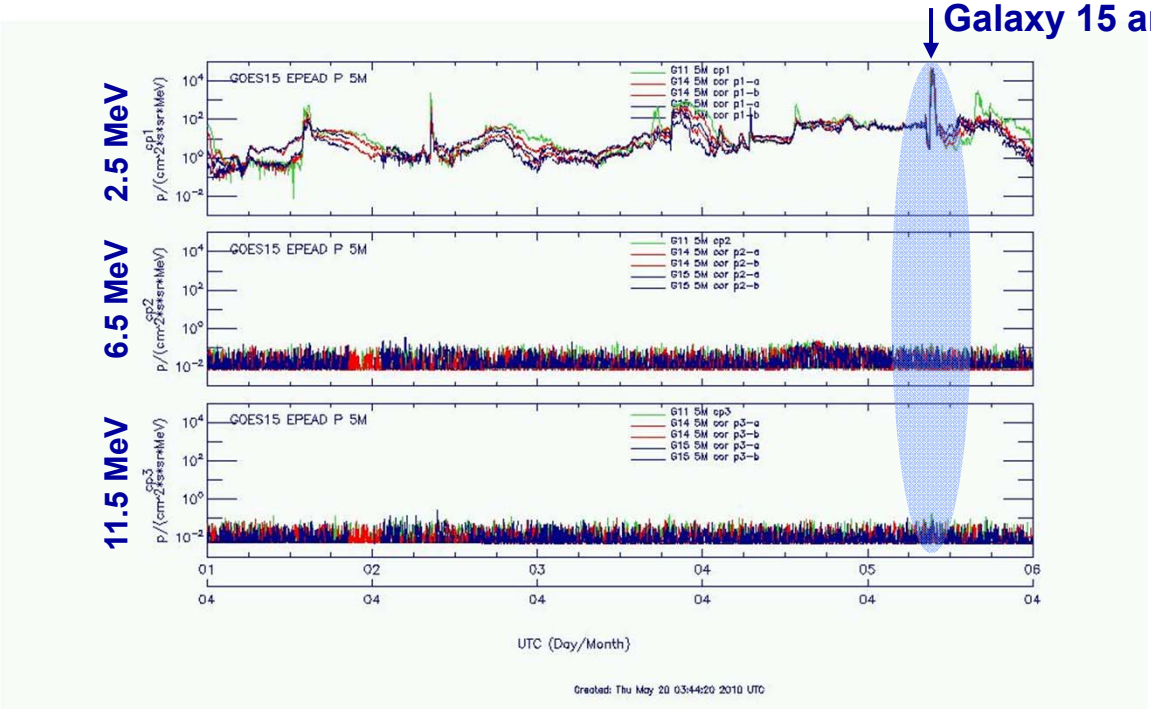


Space Weather Conditions

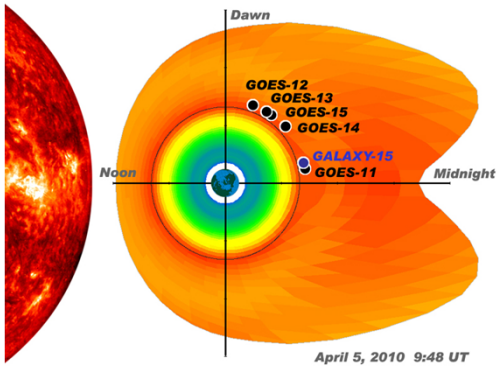
3. Local Environment At Galaxy 15 (5 of 5)

Single Event Upsets / Latchups / Burnouts: Proton Environment

- **April 05 @ 9:00 – GOES 11, 14 and 15 measured increased proton flux limited to the 2.5 MeV channel**
  - **Flux increase was notable although GOES 11 measured numerous events with higher flux rates over the lifetime of Galaxy 15**
  - **Protons with energies >5 MeV required to penetrate typical spacecraft shielding (3 mils Al)**
  - **GOES 11, 14 & 15 measured no increase in the 6.5 MeV and 11.5 MeV channels**



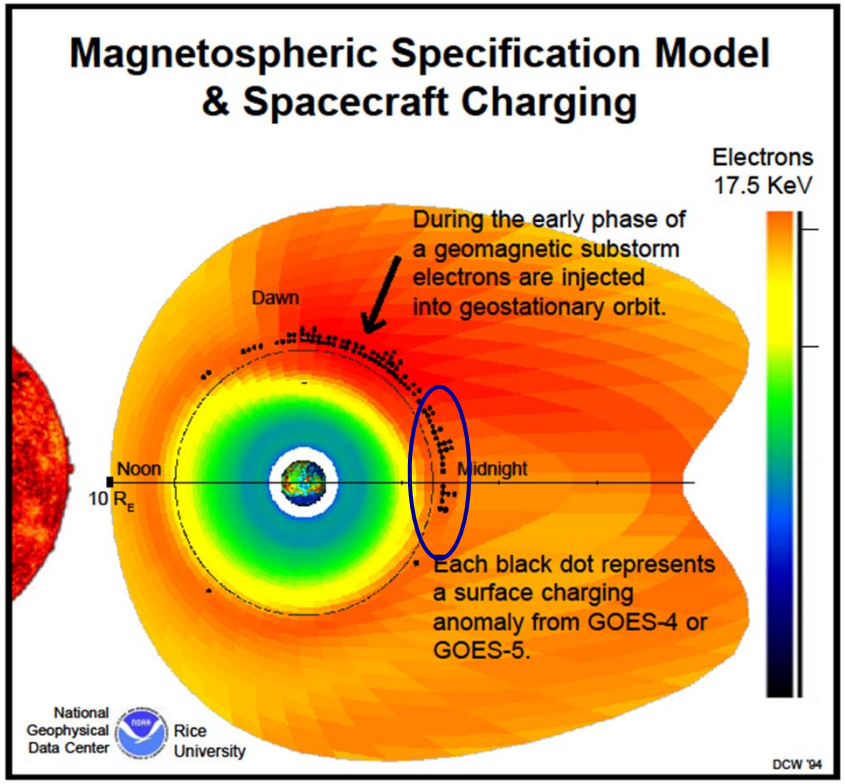
Satellite Locations



Space Weather Conditions
Galaxy 15 Anomaly (05 Apr 2010 0948 UT)

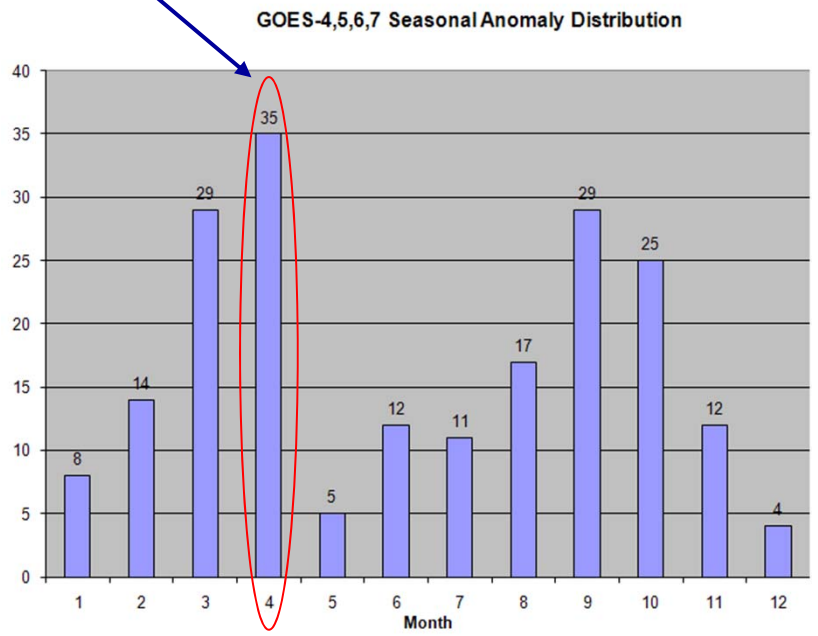
Statistical Distribution of Spacecraft Anomalies

GALAXY 15 anomaly occurred in the midnight to dawn local time sector, where anomalies are most likely to be observed.



GALAXY 15 anomaly occurred near equinox which is the time of year where anomalies are most likely to occur

Around equinox is also the time of year where geosynchronous spacecraft encounter eclipse periods and elevated geomagnetic activity



Summary
SWx Conditions for Galaxy 15 – 05 Apr 10

Conclusions:

- Energetic particle flux measurements (protons & electrons) in the GEO space environment near midnight and on the dawn flanks for 05 April 2010 are available for use in Galaxy 15 anomaly investigations
- Measured electron fluxes at low to moderate energies are consistent with increased risk factors for surface and internal spacecraft charging
- Measured high-energy proton fluxes are not consistent with increased risk of single-event upsets, latchups and burnouts by sensitive electronic components

1. W.F. Denig et al., Space Weather Conditions at the Time of the Galaxy 15 Spacecraft Anomaly *(submitted for presentation)*
2. J.C. Green et al., Satellite charging applications from the particle and field instruments on the NOAA satellites *(submitted for presentation)*
3. J.V. Rodriguez et al., GOES-R Moments and Spacecraft Charging Algorithm and Application to Anomaly Studies *(submitted for presentation)*

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SWx Impacts on Spacecraft

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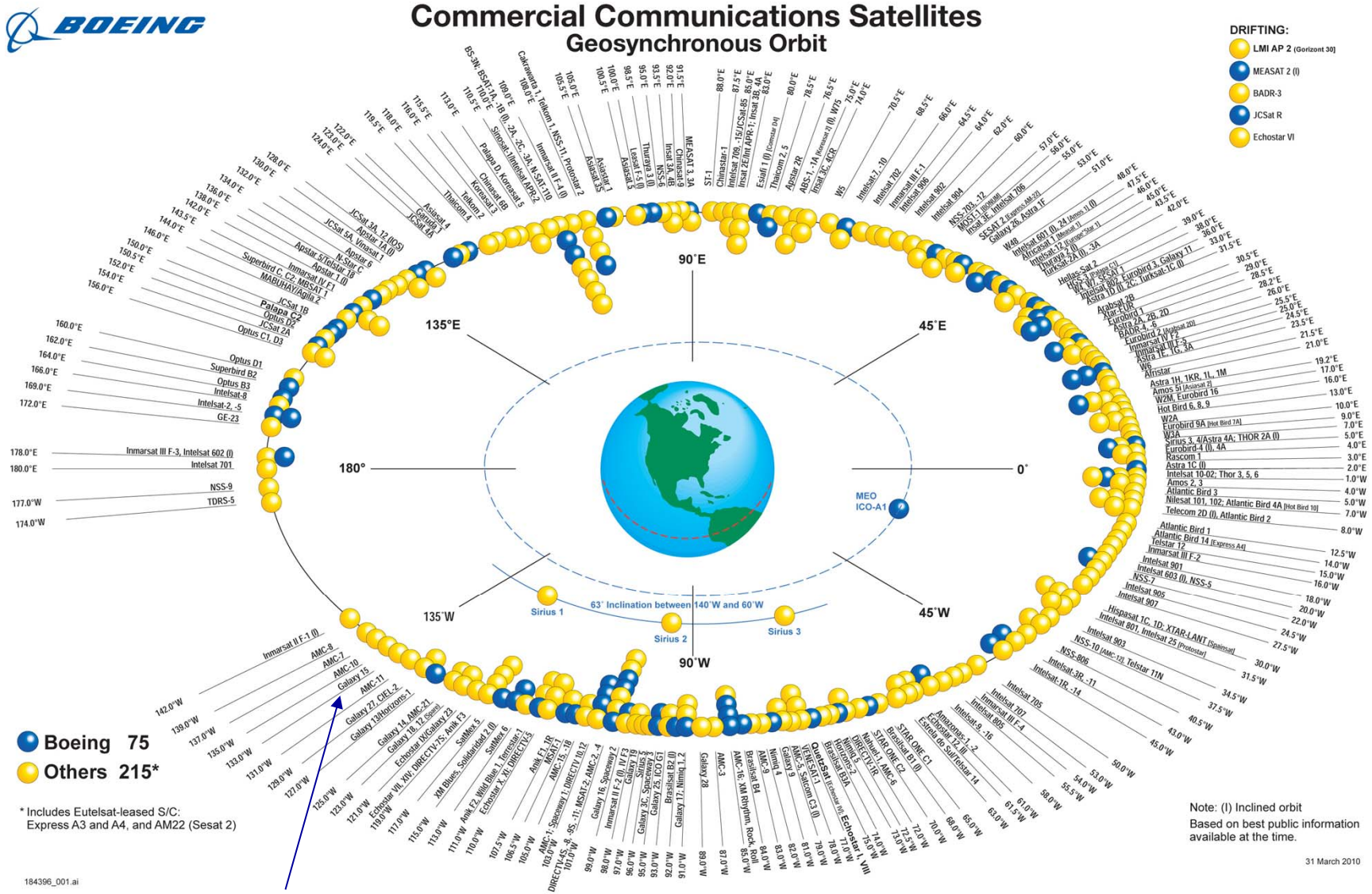
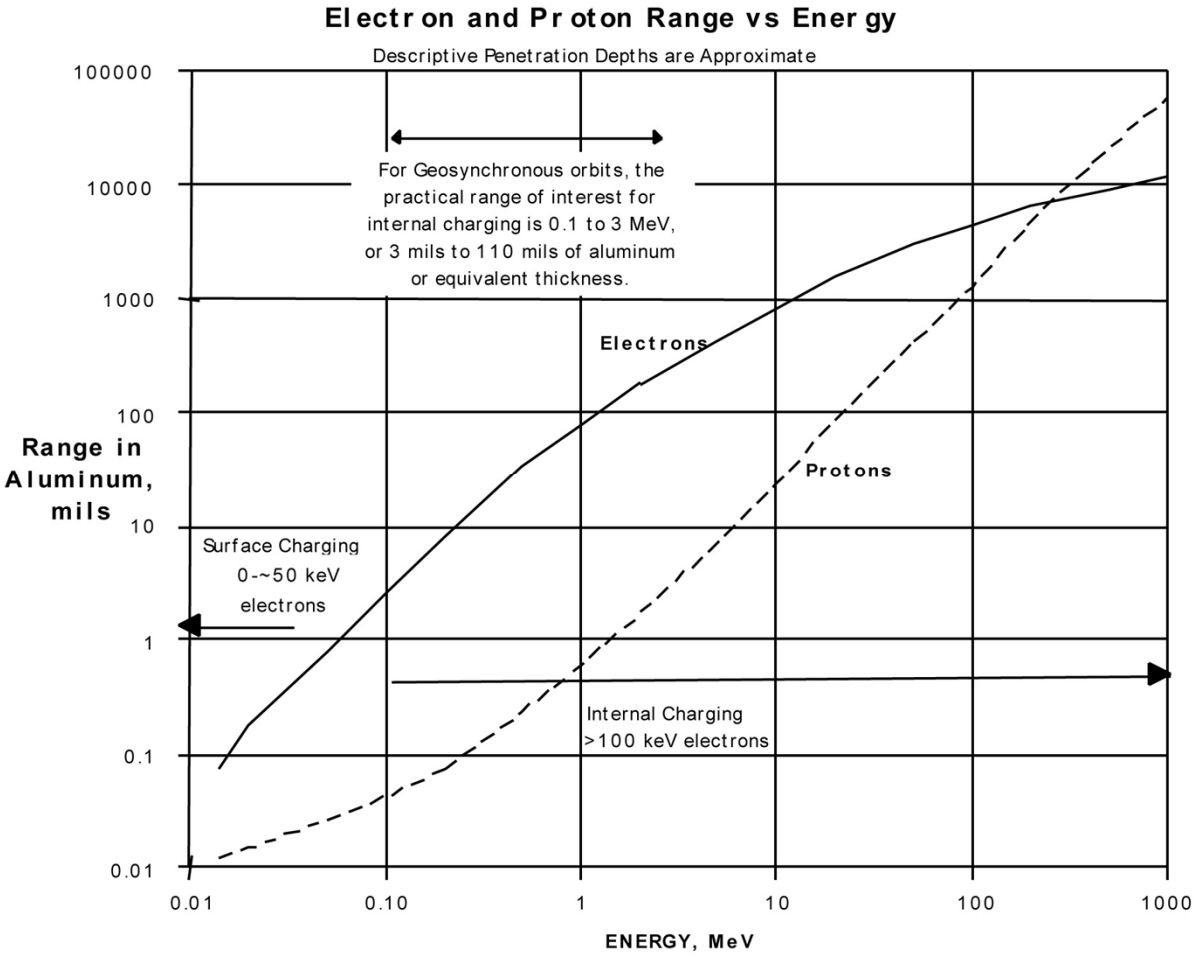
QUESTIONS?

BACKUP SLIDES

Boeing Corporation
Commercial Communication Satellites



NASA-HDBK-4002
Electron/Proton Penetration Depths (Al)

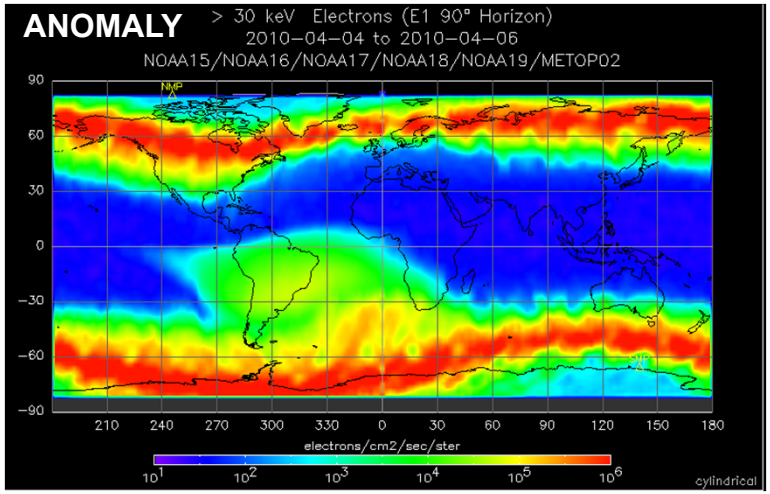


Extracted from page 6 of NASA-HDBK-4002, "Avoiding Problems Caused by Spacecraft On-Orbit Internal Charging Effects

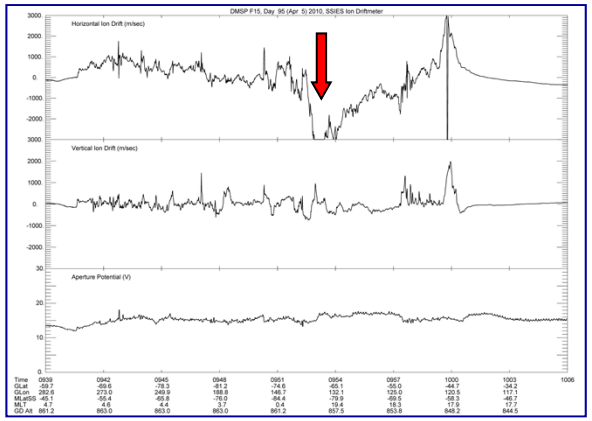
Space Weather Conditions
2. Global Environment At Earth (2 of 2)

April 5th "event" as an interval of general interest

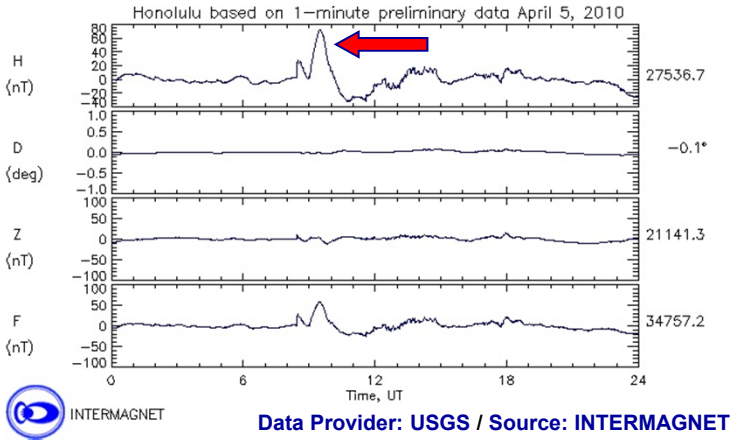
1. POES Energetic Particles (still)



2. DMSP Convective Drifts (off-scale)

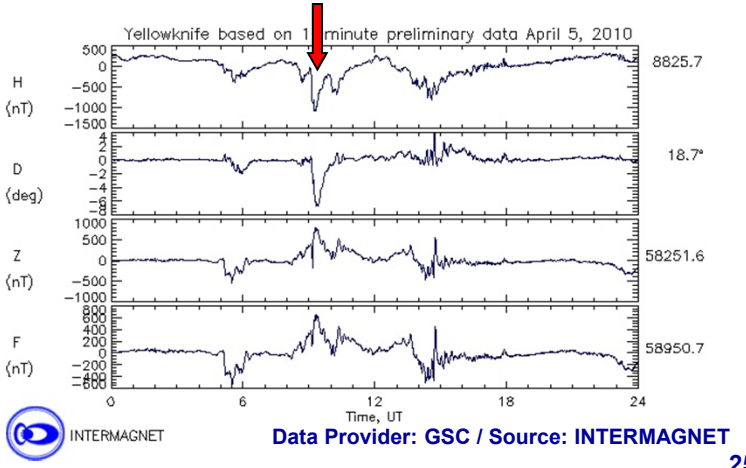


3. Magnetospheric reconfiguration?



Data Provider: USGS / Source: INTERMAGNET

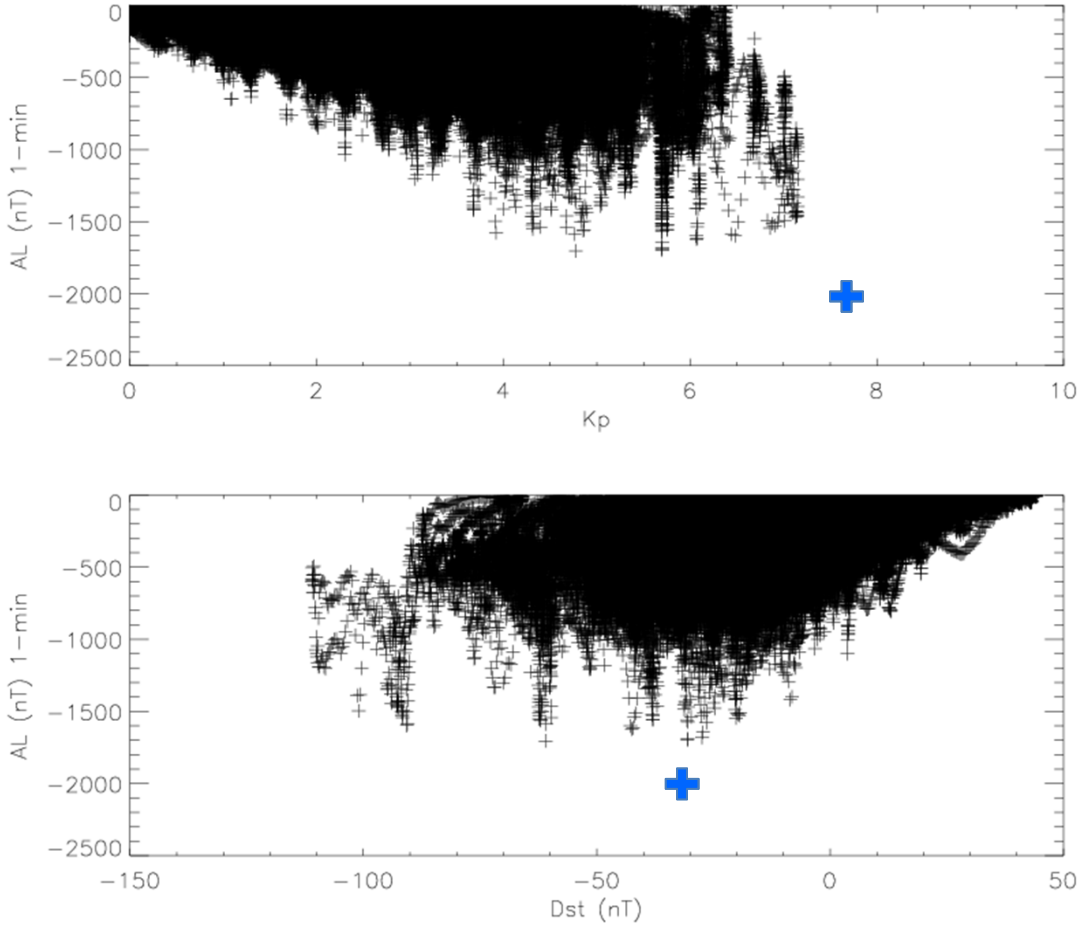
4. Extreme magnetic deviations near midnight (Galaxy 15 footprint)



Data Provider: GSC / Source: INTERMAGNET

Space Weather Conditions
Global Environment At Earth (extra-1)

01 Oct 2005 to 01 Feb 2010

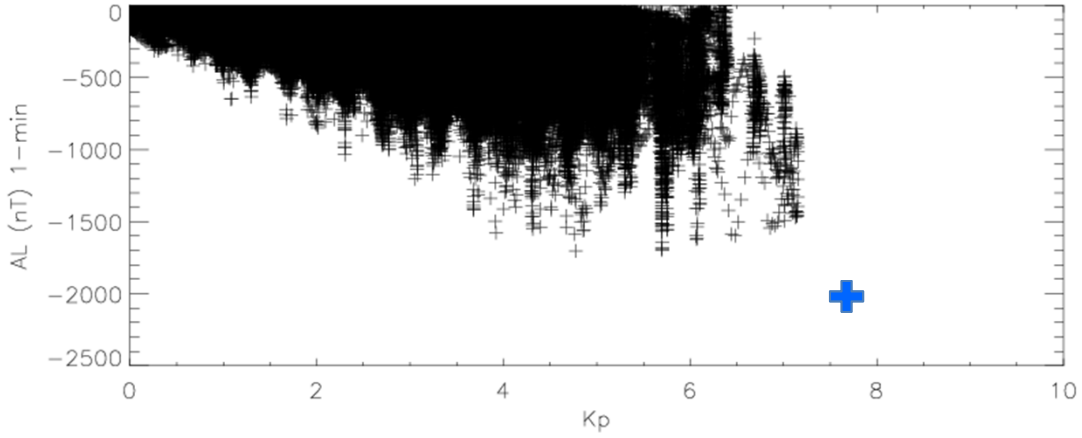


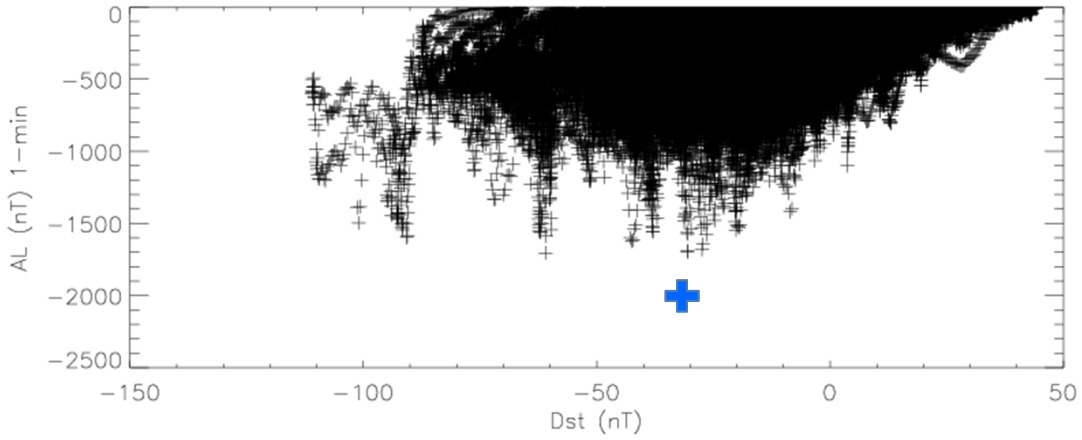
- **Kp and Dst versus 1-min AL**
- **The AL index was unusually extreme compared to the corresponding values of Kp and Dst**
- **The Al index captures reconfigurations of Earths magnetic field on the nightside where Galaxy 15 was located**
- **These magnetic field reconfigurations or sub-storms often inject particle radiation associated with anomalies**

Note: Blue crosses represent values at 09:30 UT, 5 April 2010 (closest to 09:48 UT anomaly time), where Dst =-32 nT, Kp~7.7 and AL was <= -2000 nT (from quick-look plot).

Space Weather Conditions
Global Environment At Earth (extra-2)

01 Oct 2005 to 01 Feb 2010





- **Same as "extra-1" – Kp and Dst versus 1-min AL with data from active day period 14-15 Dec 2006 removed**
- **The AL index was unusually extreme compared to the corresponding values of Kp and Dst**
- **The Al index captures reconfigurations of Earths magnetic field on the nightside where Galaxy 15 was located**
- **These magnetic field reconfigurations or sub-storms often inject particle radiation associated with anomalies**

Note: Blue crosses represent values at 09:30 UT, 5 April 2010 (closest to 09:48 UT anomaly time), where Dst =-32 nT, Kp~7.7 and AL was <= -2000 nT (from quick-look plot).