Space Weather Radiation Effects on GEO COMSAT Solid State Power Amplifiers

SPENVIS Workshop

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May 23, 2013

Mass: >6100 kg
Cost: $580 mil

Military COMSAT after Environmental Testing [1]

Outline

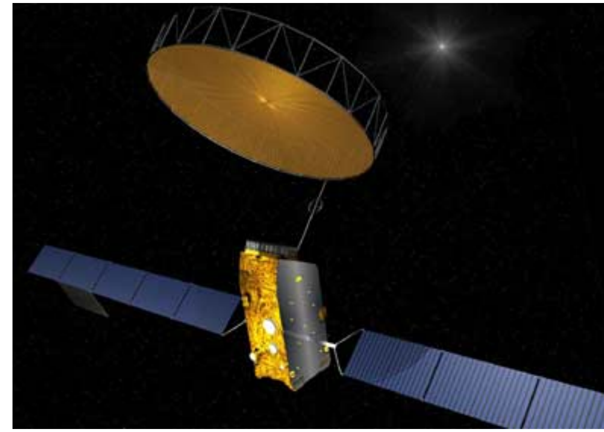
- Problem Statement
- Objectives and Research Question
- Approach
  - Data Acquisition
  - Investigation of Anomalies and…
    - Solar Cycle
    - Kp Index
    - High-energy electrons
- Future Work

Problem Statement

- In 2008, the NRC hosted a workshop – Societal & Economical Impacts of Space Weather [2]
  - Over past 20 years, ~580 spacecraft launched/attempted to GEO
- Space Weather (SW) is a constant, on-going problem
  - At GEO, SW drives design → redundancy
- To quantify how space weather effects COMSAT performance
  - Must have <u>*both*</u> space weather (SW) data and satellite telemetry
  - Obtaining satellite telemetry is difficult!

Objectives

- Team with two COMSAT companies
  - Inmarsat (London, UK) & Telenor (Norway)
  - Analyze >1 million hours of operational telemetry
  - 8 Inmarsat GEO satellites (2 unique fleets)
  - 4 Telenor GEO satellites (4 unique bus designs)



Inmarsat4 – F1 Satellite [3]

Thor 7 [4]

Trends in GEO COMSATs

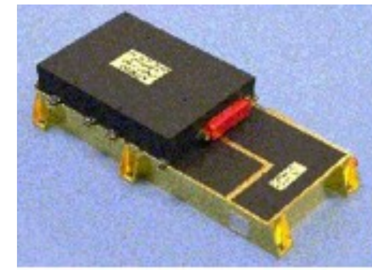
- COMSATs represent the most important application of commercial satellites today
  - Capabilities are growing to accommodate high demands of information distribution [5]
  - Higher data rates, higher band width, smaller components, increased power and efficiency, etc.
- Amplifiers consume ~85% of satellite power [6,7]
  - Control satellite performance and assure information/data is accurately transferred

1960 – Echo 1 [18]

2013 – Inmarsat I5 [19]

How does SW affect current GEO COMSAT components?

- Investigate relationship of anomalies and…
  - Low-energy electrons: Kp index
  - High-energy electrons: ~2 MeV electron flux
  - High-energy protons: 10 and 30 MeV proton flux
  - Galactic Cosmic Rays: cosmic ray intensity (CRI)
  - Local Time Index
- Investigate relationship of solar array degradation and…
  - High-energy protons: 10 and 30 MeV proton flux
  - Galactic Cosmic Rays: cosmic ray intensity (CRI)

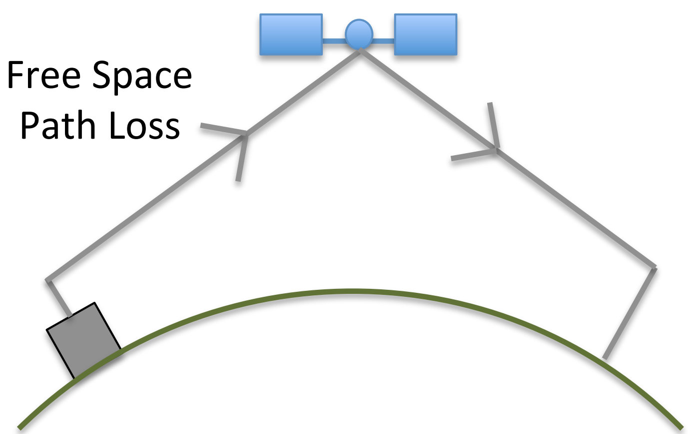


SSPA [16]

Solar Panels [4]

What are power amplifiers?

- Key components in satellite comm systems
  - Strengthen uplink signals that are weakened from free space path loss [6,8,9]
  - Amplifier units consume ~85% of the spacecraft bus power [6,7]



- Two primary types: solid state power amplifiers (SSPAs) and traveling wave tube amplifiers (TWTAs)
- Technologies experienced rapid change over past decades

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Acquiring Data – Space Weather Data and Communications Satellite Data

Geostationary Operational Environment Satellite [8] (GOES)

2 MeV Electron Flux

30 MeV Proton Flux

OMNI2 Database

Kp Index

Sunspot Number

Magnetic Field Components (Bz)

Solar Wind Speed

10 and 30 MeV Proton Flux

Los Alamos National Labs (LANL) Data

1.8-3.5 MeV Electron Flux

Inmarsat

SSPA Current

SSPA Temp

Solar Array Current and Voltage

Total Bus Power

Single Event Upsets

Anomaly Log

Telenor

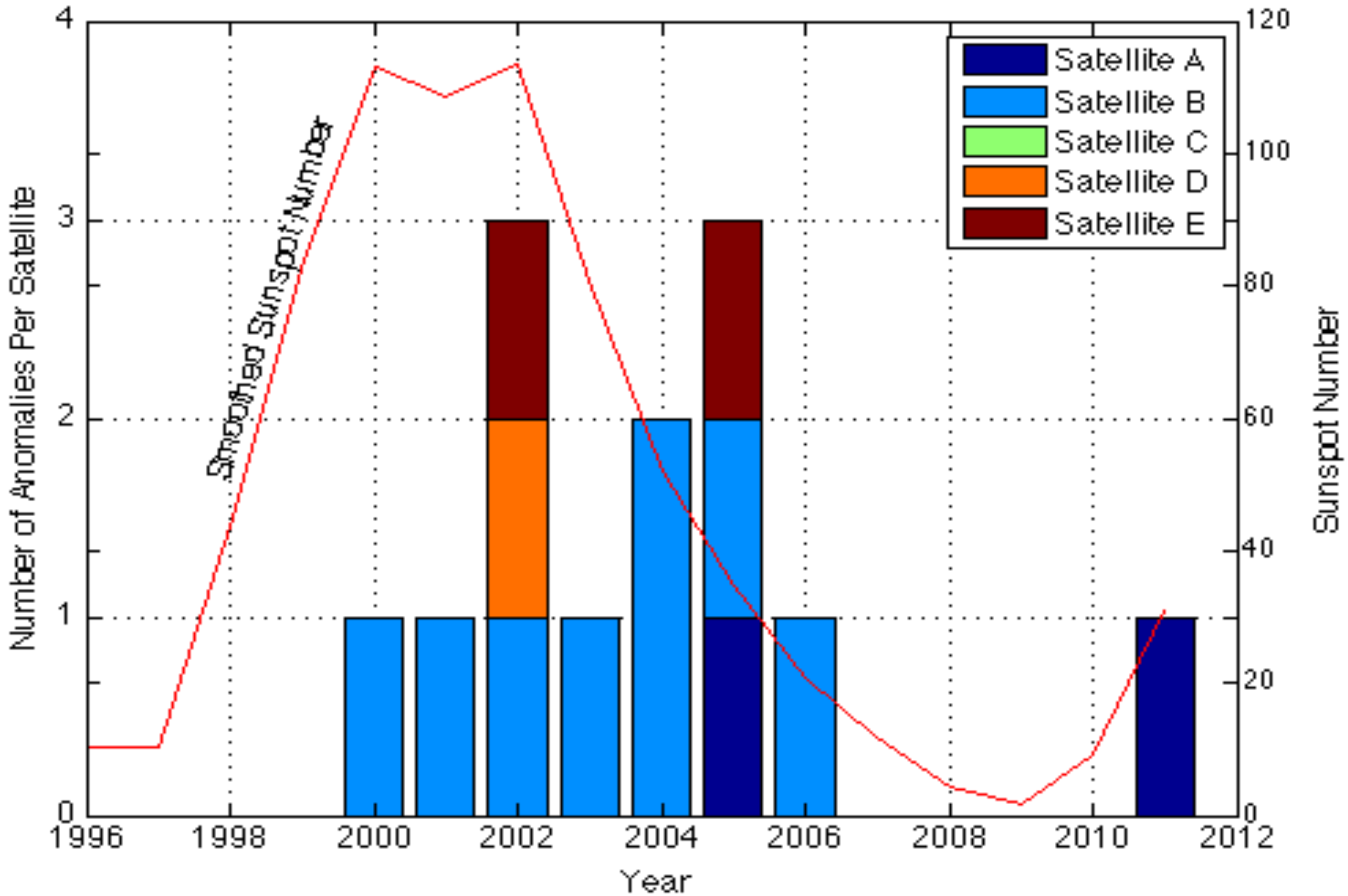
TWTA Current

TWTA Temp

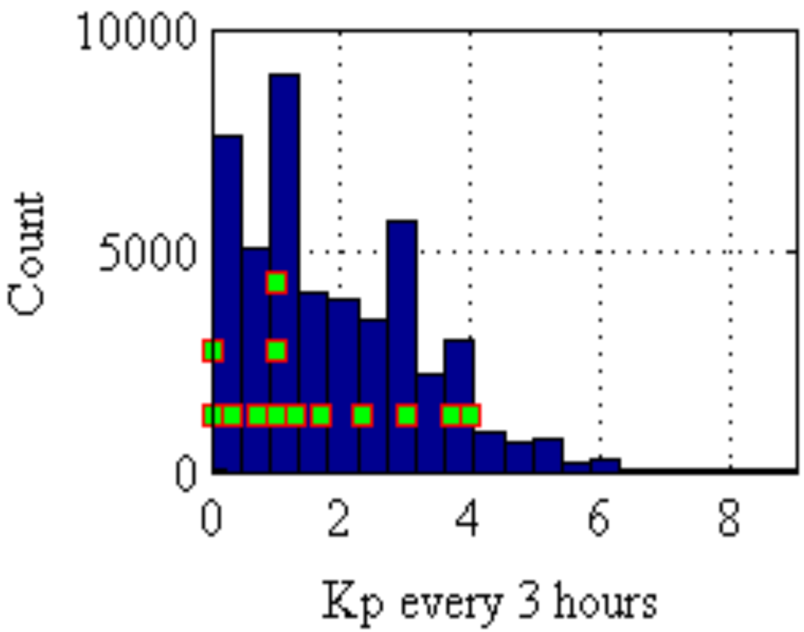
Solar Array Power

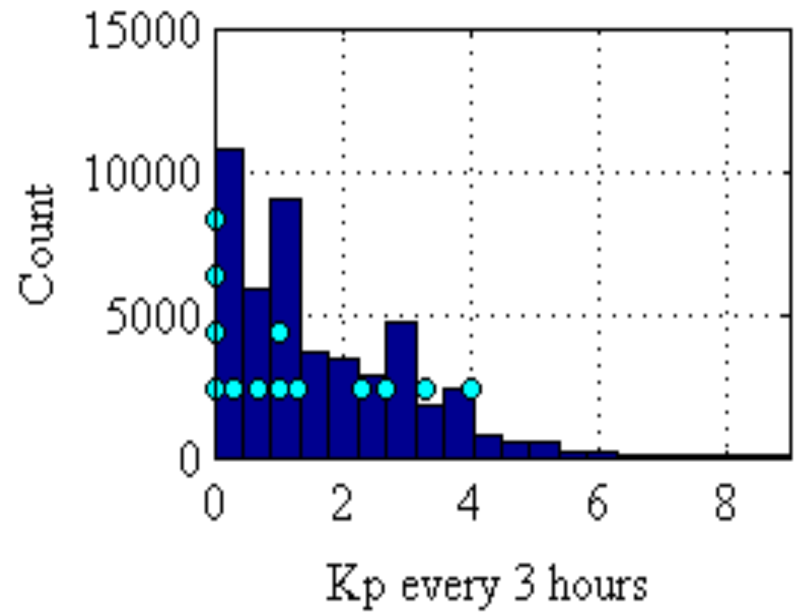
Anomaly Log

Fleet A SSPA Anomalies + Solar Cycle

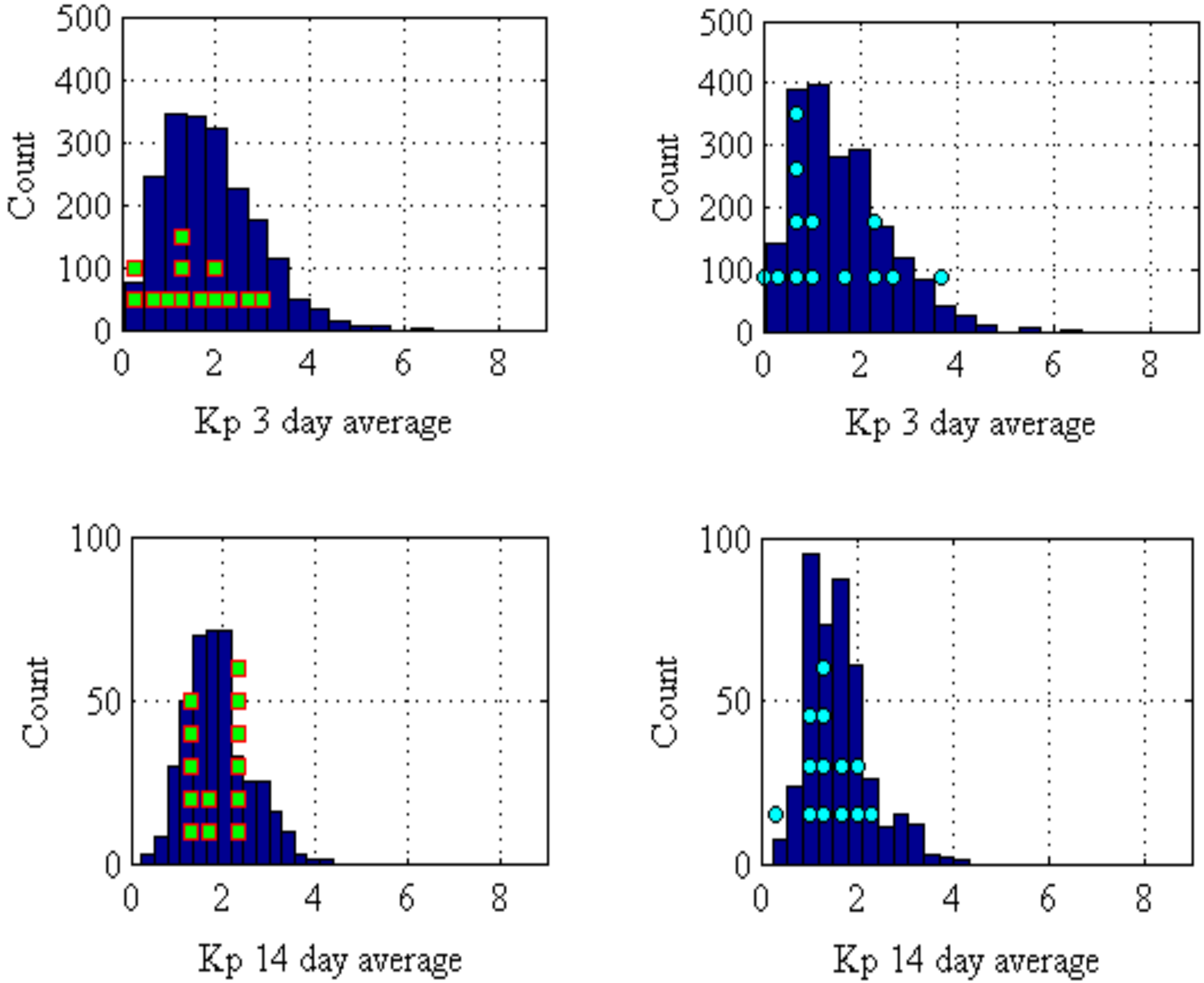


Kp Index – proxy for surface charging



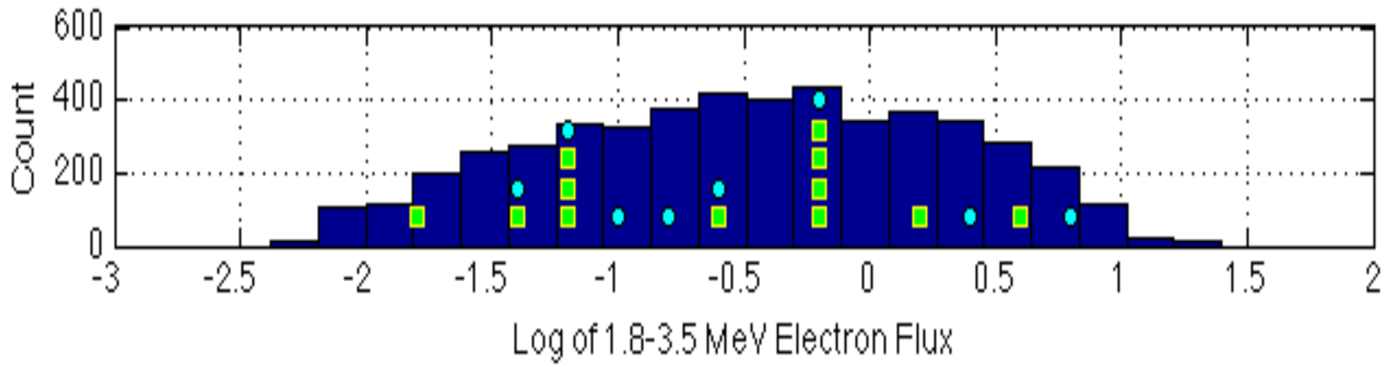


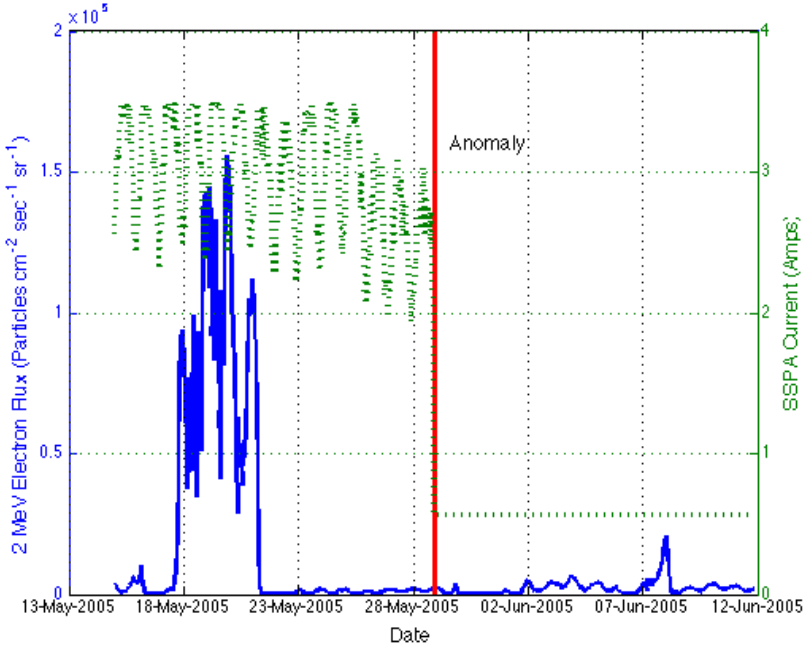
- No clear relationship with Kp
- At the time of the anomaly, Kp did not exceed 4 (scale 0-9, 9 being severe)
- 21/26 (80%) occurred when Kp was less than 2.5, 100% had a two-week average less than Kp = 2.5

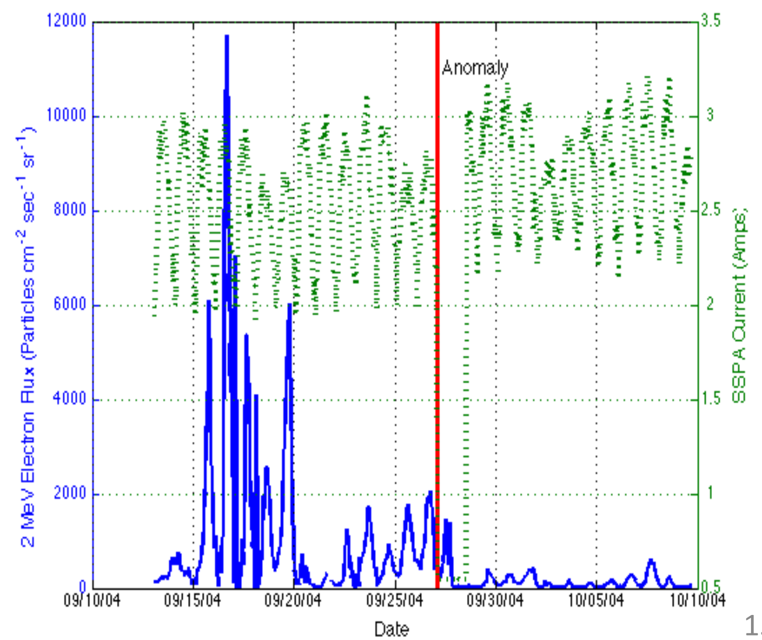


Count
Kp 3 day average
Count
Kp 3 day average
Count
Kp 14 day average
Count
Kp 14 day average

SSPA Anomalies and High Energy Electron Flux



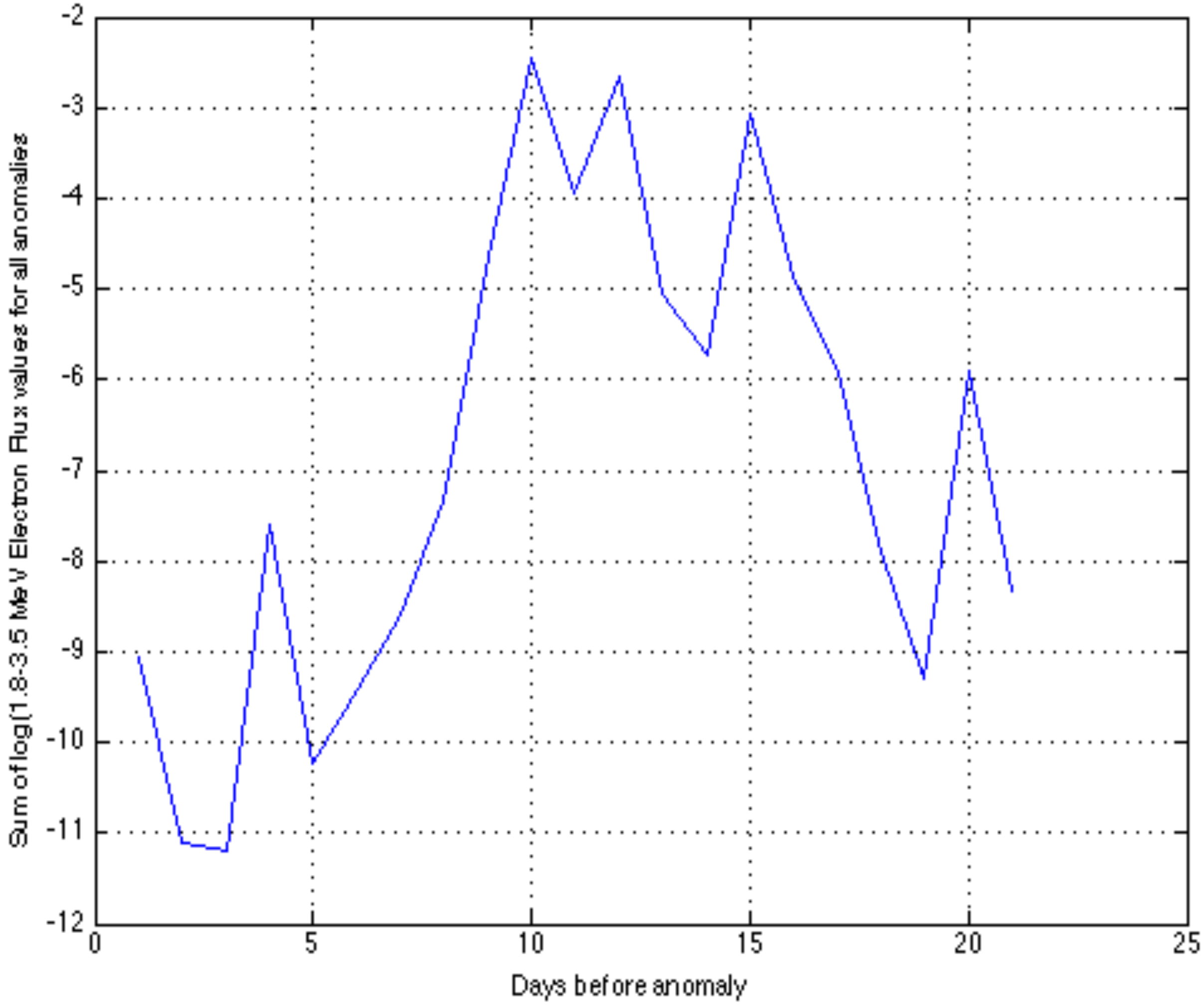




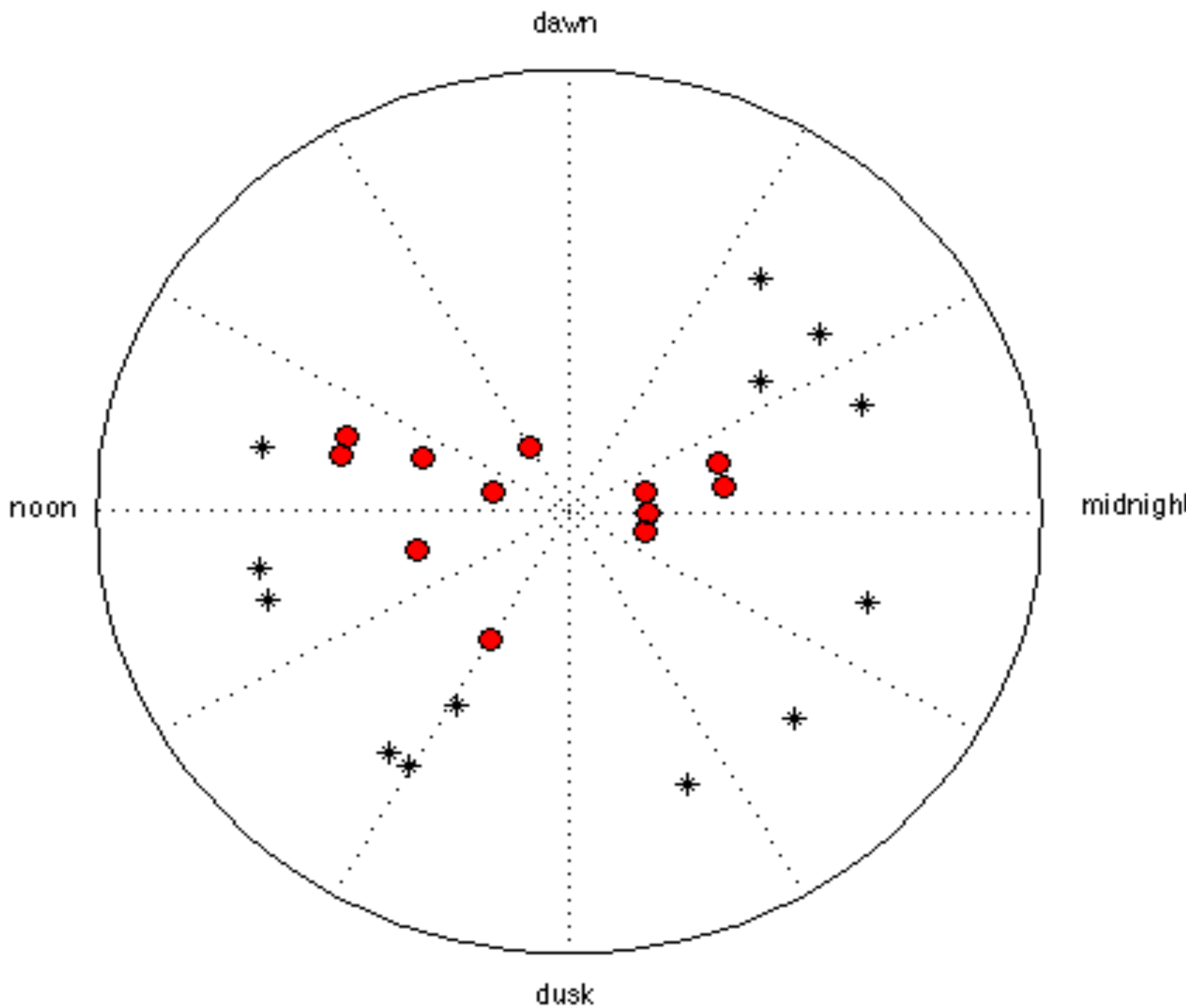
Not claiming high energy electrons CAUSE anomalies, yet…

- 11/26 (40%) anomalies occurred two weeks after elevated $\log_{10}$(1.8-3.5 MeV electron flux)
  - Elevated → >1 standard deviation of $\log_{10}$(1.8-3.5 MeV electron flux) from 1996-2009
- Frequency analysis suggests 15% likelihood for an a given day (1st of the month) to have elevated $\log_{10}$(1.8-3.5 MeV electron flux) 2-weeks before
- Monte Carlo simulation of 26 random anomalies suggests only 2/26 (<8%) likelihood to occur 2 weeks after an anomaly.

Epoch Analysis of High-Energy Electrons 2 Weeks before Anomalies



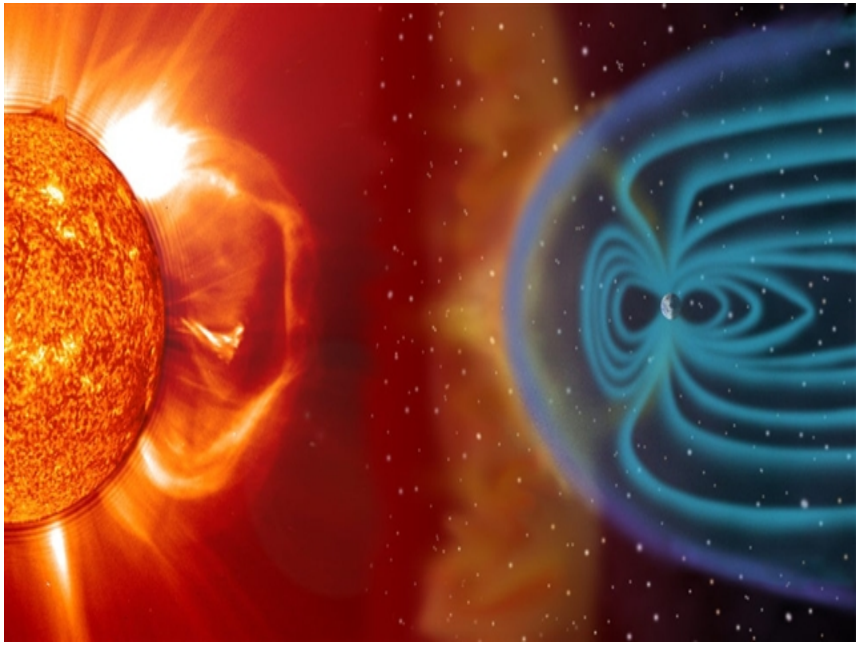
Local Time of SSPA Anomalies



Current Findings – SW Effects on Inmarsat Anomalies

Twenty-six SSPA anomalies between 1996-2012

- Fleet A anomalies occur in declining phase of solar cycle
  - Enhanced electron flux
- 11/26 anomalies occur 1-2 weeks after enhanced electron flux
- No obvious relationship with Kp, proton flux, or local time



The Space Environment [16]

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Future Work

- Validate Inmarsat amplifier anomaly analysis with Telenor satellite fleet
  - Kp distribution, high-energy electrons, LT, etc.
- How are galactic cosmic rays related to amplifier anomalies?
- Better understanding of solar array telemetry and degradation – galactic cosmic rays
- ***Incorporate SPENVIS and Geant4 tools into this analysis!***

References

[1] Military COMSAT image - http://www.spacemankind.com/pr/2009/09/16/s5-second-aehf-comm-sat-completes-major-environmental-test-at-lockheed.aspx

[2] “Severe Space Weather Events – Understanding Societal and Economic Impacts Workshop” *National Research Council*. National Academy of Sciences. <http://www.nap.edu/catalog/12507.html>.

[3] Inmarsat 4 Picture – http://space.skyrocket.de/doc_sdat/inmarsat-4.html

[4] Thor7 Imagehttp://www.ssloral.com/html/pressreleases/pr20110620.html

[5] SSPA Image http://www.astrium.eads.net/en/equipment/l-band-sspa.html

[6] Aloisio et al. (2010), “R&D Challenges for Broadband Satcomms in 2020”, 1EEE International Vacuum Electronics Conference, 18-20 May 2010.

[7] Strauss, R. (1993), Orbital Performance of Communication Satellite Microwave Power Amplifiers (MPAs), *International Journal of Satellite Communications,* 11, 279-285.

[8] Illoken, E. (1987), TWT Reliability in Space, *Aerospace and Electronic Systems Magazine,* IEEE, 2(7), 22-24.

[9] Robbins et al. (2005), Performance and reliability advances in TWTA high power amplifiers for communications satellites. In *Military Communications Conference, 2005. MilCOM 2005,* 1887-1890.

[10] Kaliski, M. (2009), “Evalution of the Net Steps in Satellite High Power Amplifier Technology: Flexible TWTAs and GaN SSPAs”, IEEE International Vacuum Electronics Conference, 28-30 April 2009.

[11] Echo 1 image – http://www.space.com/8973-1st -communication

-satellite-giant-space-balloon-50-years.htm

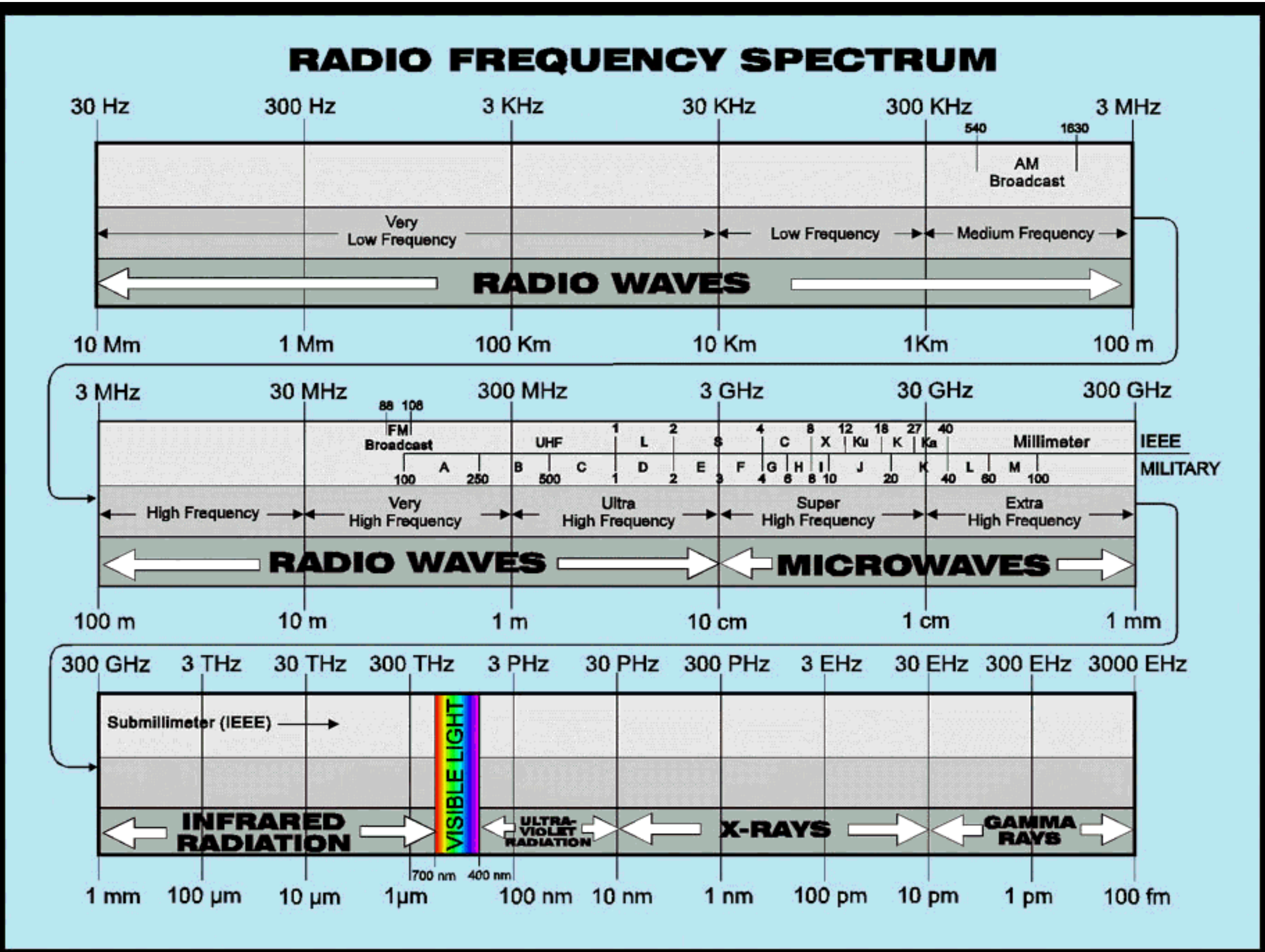
[12] Inmarsat 5 image – space.skyrocket.de

[13] Space Environment Image sohowww.nascom.nasa.gov/spaceweather/.

[14] Electromagnetic Energy Spectrum Image – donsnotes.com/tech/em-spectrum.html

[15] Wertz, J.R. and W.J. Larson, Space Mission Analysis and Design (SMAD) 3rd Edition.

[16] Butt Y, 2009 *Nature 4* **60** 701

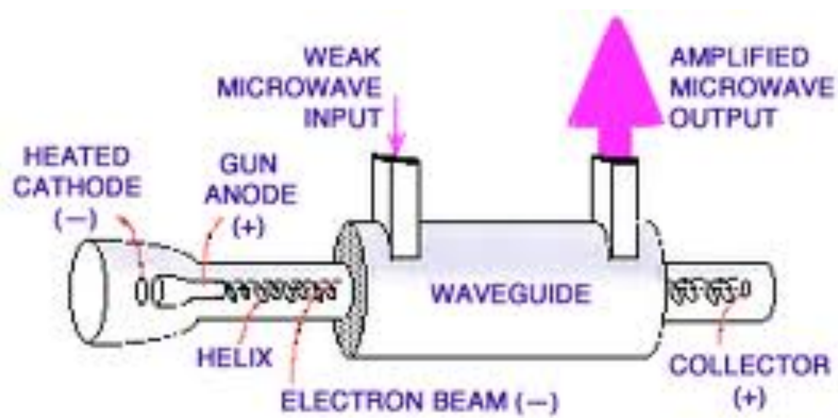


RADIO FREQUENCY SPECTRUM
30 Hz
300 Hz
3 KHz
30 KHz
300 KHz
3 MHz
540
1630
AM Broadcast
Very Low Frequency
Low Frequency
Medium Frequency
RADIO WAVES
10 Mm
1 Mm
100 Km
10 Km
1Km
100 m
3 MHz
30 MHz
300 MHz
3 GHz
30 GHz
300 GHz
88 108
FM Broadcast
UHF
1 L 2 S 4 C 8 X 12 Ku 18 K 27 Ka 40
Millimeter
IEEE
100 A 250 B 500 C 1 D 2 E 3 F 4 G 6 H 8 I 10 J 20 K 40 L 60 M 100
MILITARY
High Frequency
Very High Frequency
Ultra High Frequency
Super High Frequency
Extra High Frequency
RADIO WAVES
MICROWAVES
100 m
10 m
1 m
10 cm
1 cm
1 mm
300 GHz
3 THz
30 THz
300 THz
3 PHz
30 PHz
300 PHz
3 EHz
30 EHz
300 EHz
3000 EHz
Submillimeter (IEEE)
INFRARED RADIATION
VISIBLE LIGHT
ULTRA-VIOLET RADIATION
X-RAYS
GAMMA RAYS
700 nm
400 nm
1 mm
100 µm
10 µm
1µm
100 nm
10 nm
1 nm
100 pm
10 pm
1 pm
100 fm

TWTAs vs. SSPAs

TWTA Technology

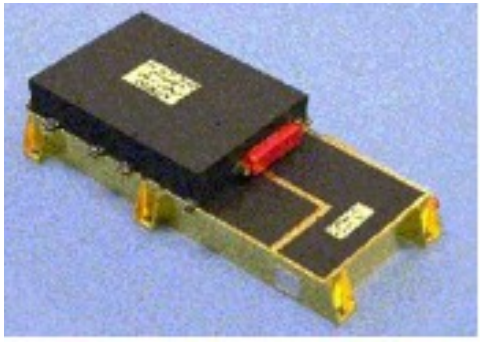
- Traveling wave tube (TWT) and electrical power conditioner (EPC)
- Used for high power + high freq.
- Provide better efficiency [10]
- 1992-2006 69% COMSATS used TWTAS [11]



TWTA [12]

SSPA Technology

- Field effect transistor (FET) and EPC [6]
- More reliable and safe
- Less complex and cheaper [13,14]
- Historically used at L + S band
- Competitive in 1980s, new GaN technology is increasing market popularity [9]



SSPA [16]