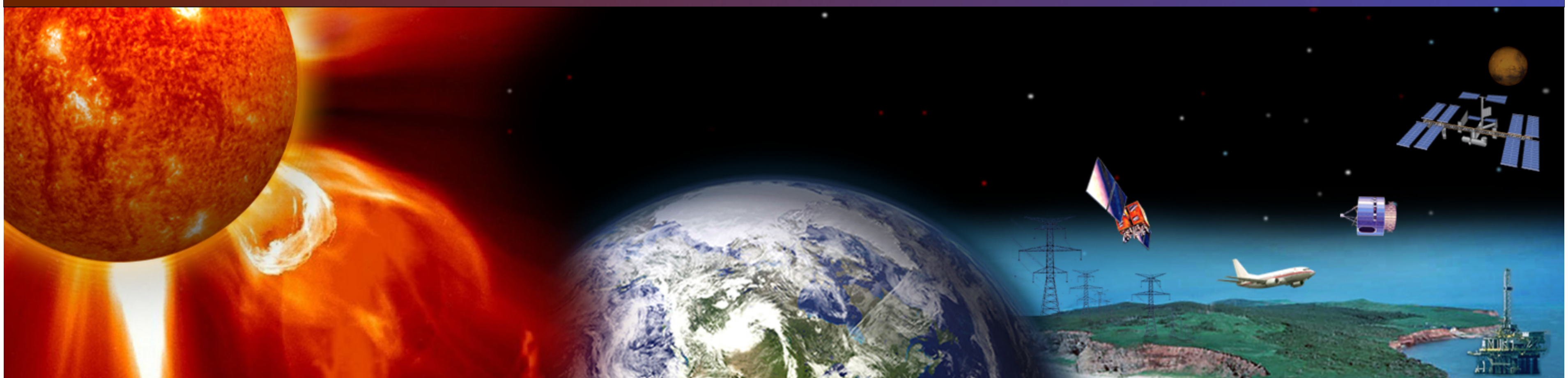
Space Weather to Space Climate: Societal Impacts



Howard J. Singer, NOAA Space Weather Prediction Center

Global Change and the Solar-Terrestrial Environment

Aspen, CO

June 13, 2010

Space Weather to Space Climate: Societal Impacts

Presentation Outline

- Introduction to Space Weather through Historical Events
- Severe Space Weather Events -- Understanding Societal and Economic Impacts (A National Research Council Workshop Report)
- Space Climatology Research:
  One example: Solar Cycle Variations in Magnetospheric Mass Density

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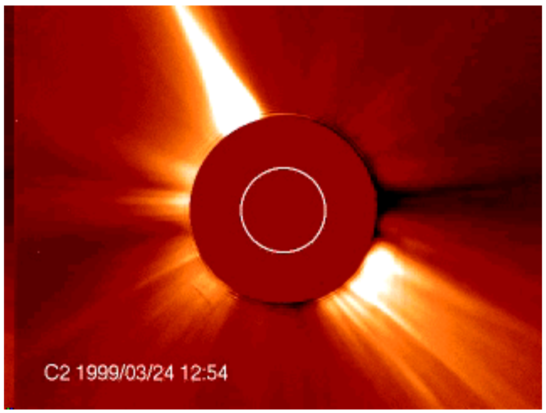
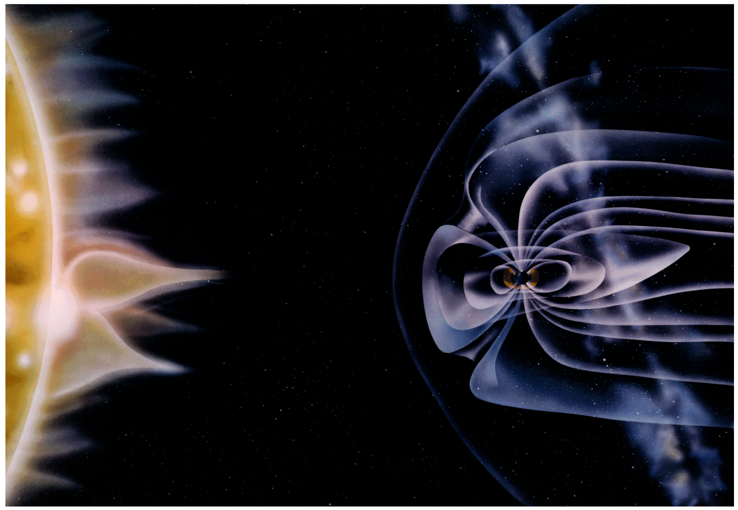
Space Weather Observations

Space Weather observations extend from the Sun to interplanetary space, to the magnetosphere and ionosphere/upper atmosphere.





Space Weather observations support a growing and diverse user community:

- DoD, NASA, FAA, Industry, Commercial Service Providers, International …

Space Weather observations are used:

- to specify and forecast the environment
- in models (drive, assimilate, and validate)
- for research

Geomagnetic Storm Effects on Telegraph Operations September 3, 1859

***Boston (to Portland operator*).--"Please cut off your battery entirely from the line for fifteen minutes."**

***Portland*.--"Will do so. It is now disconnected."**

***Boston.*--"Mine is also disconnected and we are working with the auroral current. How do you receive my writing?"**

***Portland*.--"Better than with our batteries on. Current comes and goes gradually."**

***Boston.*--"My current is very strong at times, and we can work better without batteries, as the aurora seems to neutralize and augment our batteries alternately, making the current too strong at times for our relay magnets. Suppose we work without batteries while we are affected by this trouble?"**

***Portland*.--"Very well. Shall I go ahead with business?"**

Boston.--"Yes. Go ahead."

(Annual of Scientific Discovery, ed. by D.A. Wells, Boston, Gould and Lincoln, p414, 1860; Singer, H.J., Magnetospheric Pulsations, Model and Observations of Standing Alfven Wave Resonances, Thesis, UCLA, 1980.)

1958 Geomagnetic Storm

- On February 9, 1958 an explosive brightening was observed on the solar disk at the Sacramento Peak Observatory
- A notice was radioed to the IGY Data Center on Solar Activity at the Univ. Colorado's High Altitude Observatory in Boulder
- 28 hours later one of the greatest magnetic storms on record began
- It was the 13th most disturbed day from 1932 to the present
- Effects:
  - Toronto area plunged into temporary darkness
  - Western Union experienced serious interruptions on its nine North Atlantic telegraph cables
  - Overseas airlines communications problems

Brooks, J., The Subtle Storm, *New Yorker Magazine*, 39-77, Feb. 7, 1959.

1958 Geomagnetic Storm and Prophecy

- "The forecasters at the Central Radio Propagation Laboratory are among the most valorous of prophets, since they are called upon to make their predictions with very little in the way of scientific knowledge to guide them."

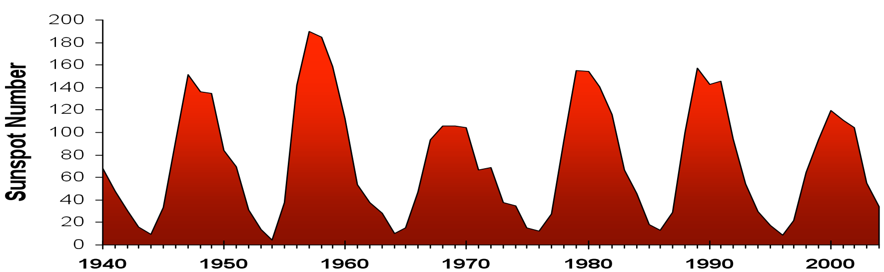
- "In future years, it may be that the Weather Bureau or some Space Age equivalent will warn us of approaching magnetic storms, just as we are now warned of approaching hurricanes,…"

- "…nobody knows what kinds of apparatus still undreamed of may come along to be thrown out of whack by their [storms] caprices."

Brooks: The Subtle Storm, *New Yorker Magazine*, 1959.

Growth of Space Weather Customers

Commercial Space Transportation
Airline Polar Flights
Microchip technology
Precision Guided Munitions
Cell phones
Atomic Clock
Satellite Operations
Carbon Dating experiments
GPS Navigation
Ozone Measurements
Aircraft Radiation Hazard
Commercial TV Relays
Communications Satellite Orientation
Spacecraft Charging
Satellite Reconnaissance & Remote Sensing Instrument Damage
Geophysical Exploration.
Pipeline Operations
Anti-Submarine Detection
Satellite Power Arrays
Power Distribution
Long-Range Telephone Systems
Radiation Hazards to Astronauts
Interplanetary Satellite experiments
VLF Navigation Systems (OMEGA, LORAN)
Over the Horizon Radar
Solar-Terres. Research & Applic. Satellites
Research & Operations Requirements
Satellite Orbit Prediction
Solar Balloon & Rocket experiments
Ionospheric Rocket experiments
Radar
Short-wave Radio Propagation



Sunspot Cycles

A few of the agencies and industries that rely on space weather services today:

- U.S. power grid infrastructure
- Commercial airline industry
- Dep. of Transportation (GPS)
- NASA human space flight activities
- Satellite launch and operations
- DoD Operations

DOE
Nuclear Reg Comm
Schlumberger
NY/PJM Grid

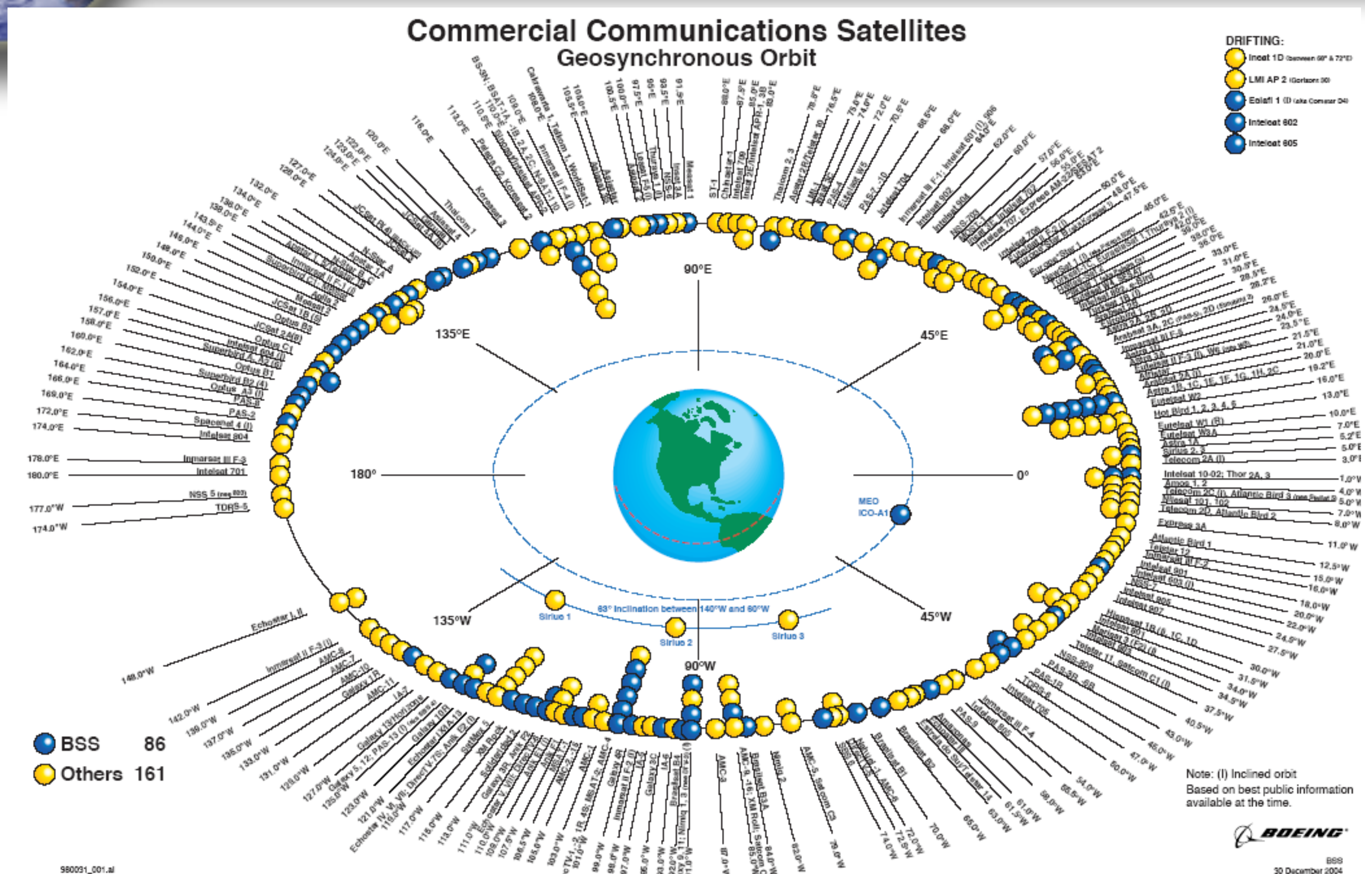
Ball
Loral
NESDIS/SOCC
Digital Globe

Boeing
Lockheed
Aerospace
Echostar

NASA
Space Command
ISS Astronauts
FAA

American
United Airlines
Northwest
Continental

Satellite Infrastructure: Relies on Space Weather Information



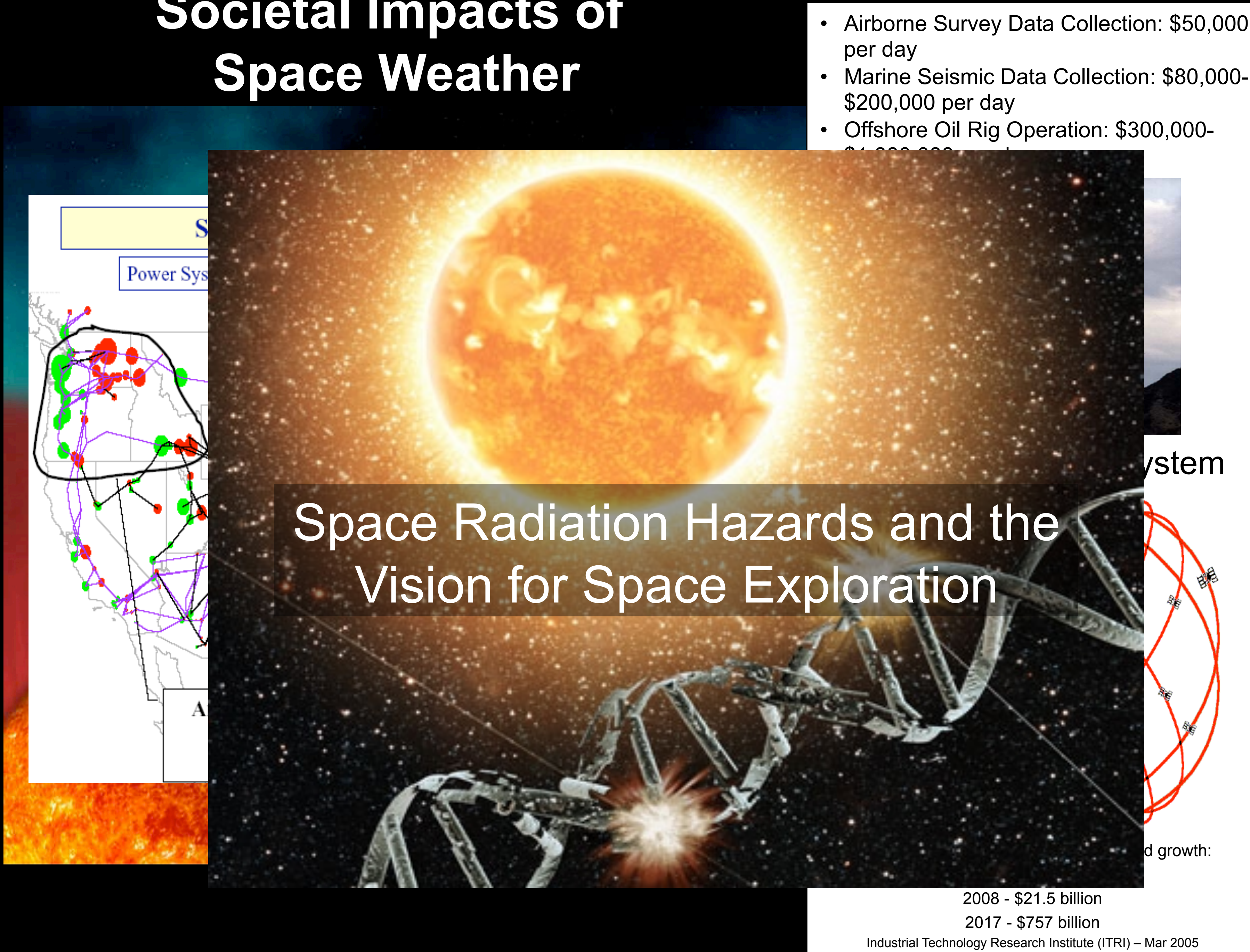
~250 S/C @ ~$300M to deploy = $75 billion dollar investment

Revenues ~ $100M/yr per S/C = >$250 billion revenue stream

Operate 24/7 for 10-15 years

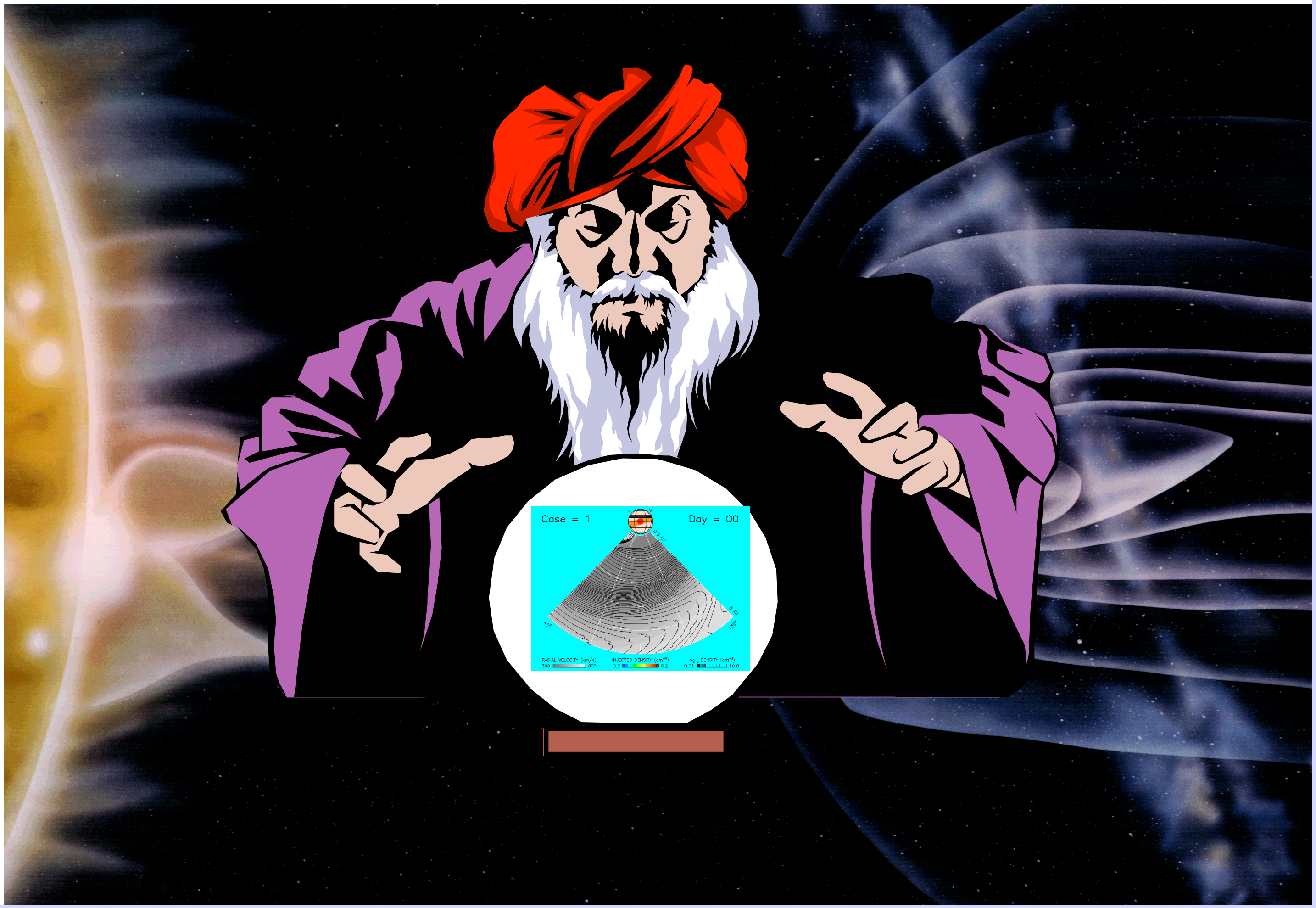
adapted from M. Bodeau (Boeing)

Societal Impacts of Space Weather



Forecasting Space Weather

Forecasting Space Weather



The Economic And Societal Impacts of Space Weather

NRC Study figures adapted from and courtesy of Daniel N. Baker

Task

An ad hoc committee of the Space Studies Board (SSB) of the National Academies was tasked to convene a workshop to assess the Nation's current and future ability to manage space weather events and their societal and economic impacts.

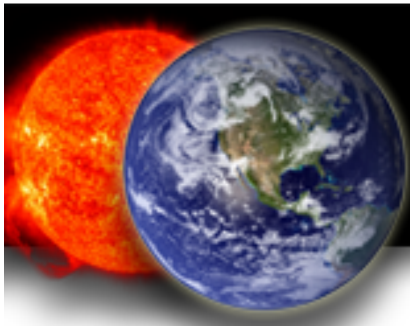
- What are the socioeconomic consequences to the Nation of severe space weather events?
- How likely are very intense space weather storms and what might be the consequences of such events?
- Are there specific ground- or space-based sensors or other approaches that might mitigate or avoid the effects of future severe space weather events?

Anticipated Benefits

- **Economic Impacts analysis would provide:**
  - Better guidance for policy makers on investment in SWx systems
  - Better rationale for Agency budgeting
  - Better understanding of “high-payoff” forecasts
  - Clearer guidance for future human exploration
  - Improved societal appreciation for SWx risks

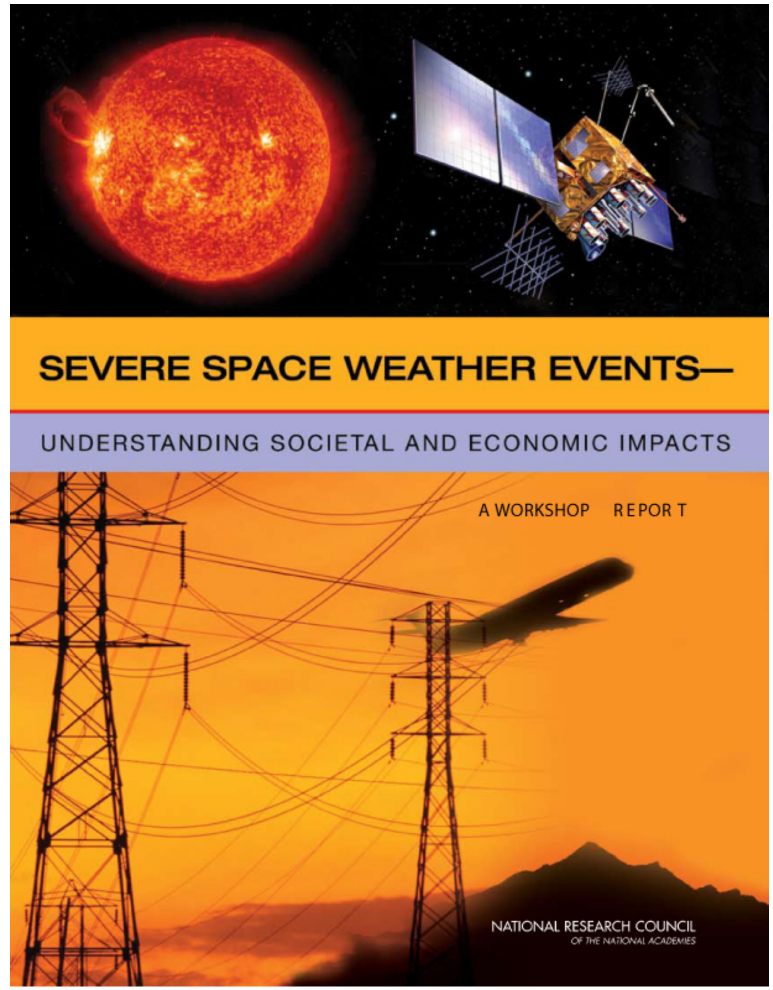
Committee on the Societal and Economic Impacts of Severe Space Weather Events

- DANIEL N. BAKER, University of Colorado at Boulder, Chair
- ROBERTA BALSTAD, Center for International Earth Science Information Network, Columbia University
- J. MICHAEL BODEAU, Northrop Grumman Space Technology
- EUGENE CAMERON, United Airlines, Inc.
- JOSEPH F. FENNELL, Aerospace Corporation
- GENENE M. FISHER, American Meteorological Society
- KEVIN F. FORBES, Catholic University of America
- PAUL M. KINTNER, Cornell University
- LOUIS G. LEFFLER, North American Electric Reliability Council (retired)
- WILLIAM S. LEWIS, Southwest Research Institute
- JOSEPH B. REAGAN Lockheed Missiles and Space Company, Inc. (retired)
- ARTHUR A. SMALL III, Pennsylvania State University
- THOMAS A. STANSELL, Stansell Consulting
- LEONARD STRACHAN, JR., Smithsonian Astrophysical Observatory
- Staff
- SANDRA J. GRAHAM, Study Director
- THERESA M. FISHER, Program Associate
- VICTORIA SWISHER, Research Associate
- CATHERINE A. GRUBER, Assistant Editor



The Societal and Economic Impacts of Severe Space Weather Events: A Workshop

- Workshop details
  - May 22-23, 2008 in DC
  - Approximately 80 attendees from academia, industry, government, and industry associations
    - Association reps aggregated data and helped avoid concerns about proprietary or competition-sensitive data
  - Analyses in specific areas; e.g., GPS, power industry, aviation, military systems, human and robotic exploration beyond low-Earth orbit
  - Econometric analysis of value of improved SpaceWx forecasts



[http://www.nap.edu/catalog.php?record_id=12507]

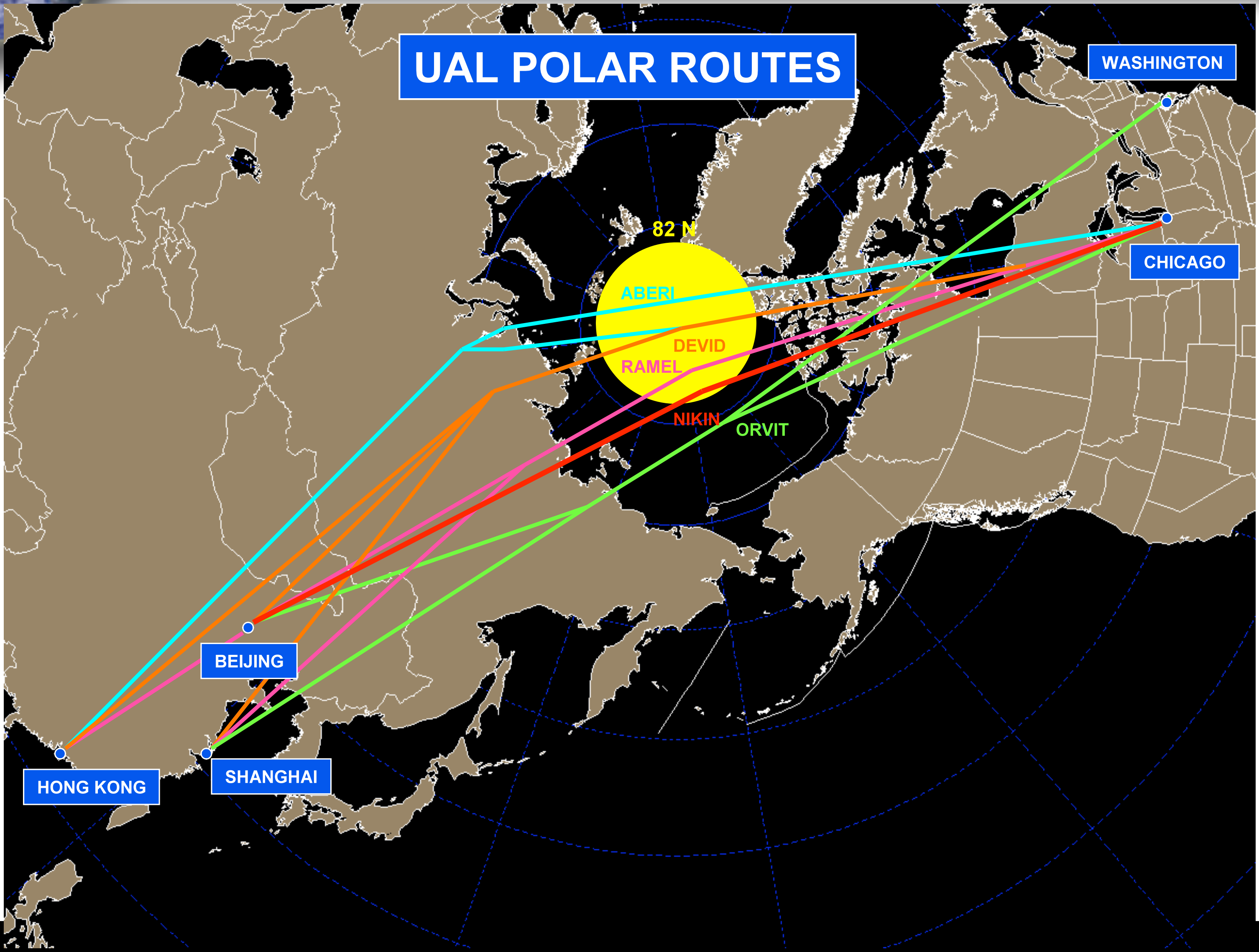
What Were Goals and Some Outcomes?

- Identify decisions that can be improved using a reliable forecast
- Differences with and without forecast (the expected value of a forecast)
- When best design decisions are made
- Economic impact of events
  - Repair damaged S/C: $50-70M
  - Replace commercial S/C: $250-300M
  - Cost of major power blackout: $4-10B
  - Extreme storm (a la 1859): $1-2 Trillion

Impacts of Space Weather

- Industry-specific Space Weather Impacts
  - Electric power, spacecraft, aviation, and GPS-based positioning industries can be adversely affected by extreme space weather
  - January 2005: 26 United Airlines flights diverted to nonpolar or less-than-optimum polar routes during several days of disturbed space weather
  - October-November 2003: FAA's recently implemented GPS-based Wide Area Augmentation System disabled for 30 hours
  - January 1994: Outage of two Canadian telecommunications satellite. Recovery took 6 months and cost $50 million to $70 million.

Large Increase in Transpolar Airline Traffic

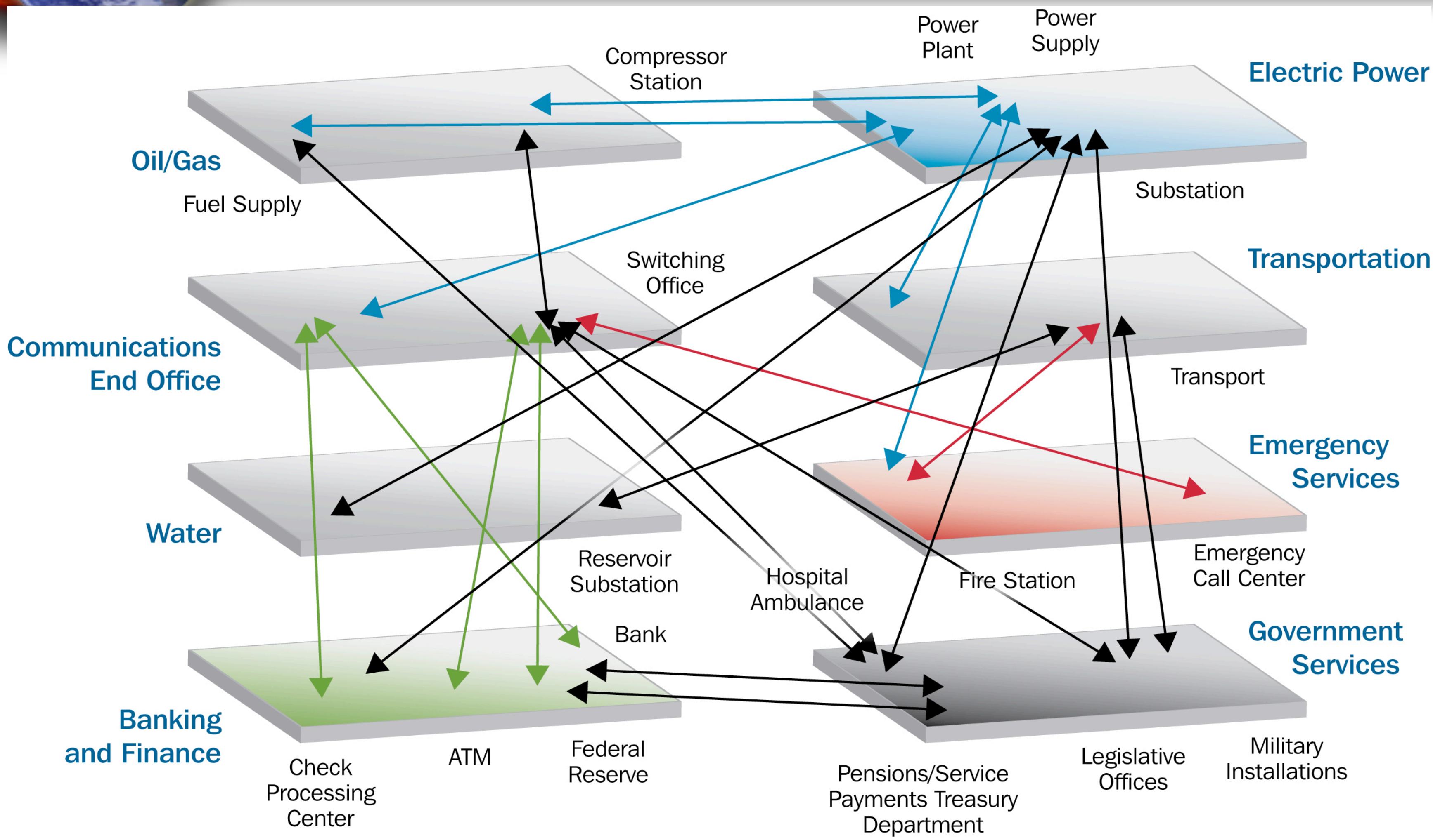


GPS Use Pervades Modern Society

FUGRO

Business Lines

The Interdependencies of Society



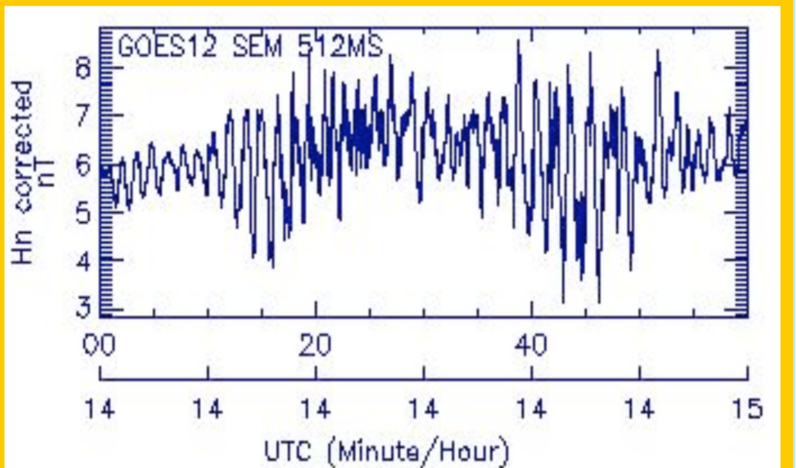
Impacts of Space Weather

Collateral Impacts of Space Weather

- "Electric power is modern society's cornerstone technology, the technology on which virtually all other infrastructures and services depend"
- "Collateral effects of longer-term outage would likely include, for example, disruption of the transportation, communication, banking, and finance systems, and government services; the breakdown of the distribution of potable water owing to pump failure; and the loss of perishable foods and medications because of lack of refrigeration."
- "…it is difficult to understand, much less predict, the consequences of future LF/HC events. Sustaining preparedness and planning for such events in future years is equally difficult."

Solar Cycle Variation of Geosynchronous Plasma Mass Density Derived from the Frequency of Standing Alfven Waves

GOES – 12, March 31, 2008
14 – 15 UT (11-12 Local Time)



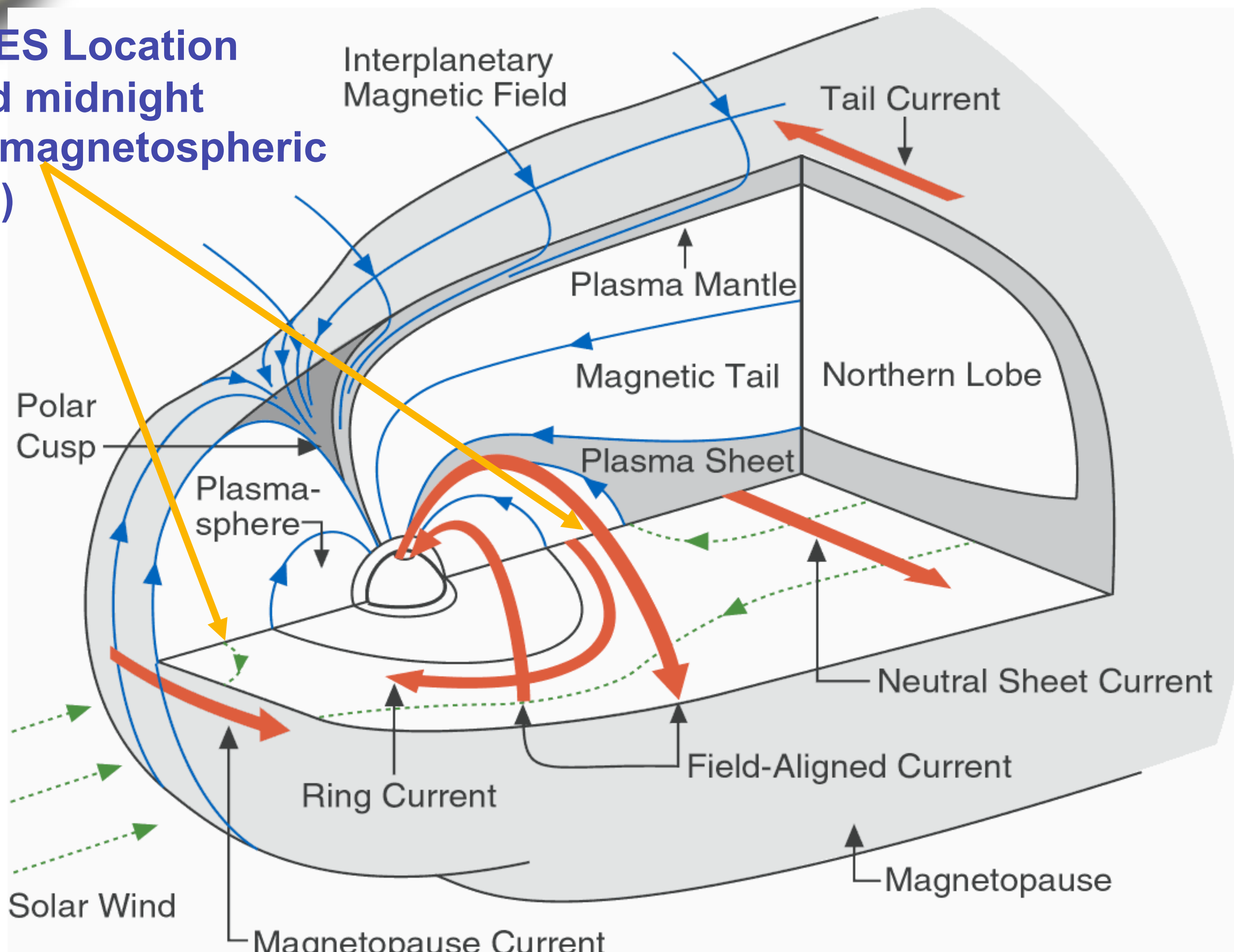
Azimuthal Magnetic Field
~ 100 s waves

Takahashi, Denton, and Singer, accepted JGR, 2010

- Ultra-low frequency (ULF) waves with periods from a few seconds to about 10 minutes are observed in Earth's magnetosphere and by ground-based magnetometers
- An example of these oscillations is shown from the GOES spacecraft in geosynchronous orbit
- These waves are generated both by interactions with the solar wind as well as by internal magnetospheric processes
- While these waves can be used to describe space weather conditions…
- A new result demonstrates that a long-time series of these data provide information about long-term changes in magnetospheric mass density and solar UV/EUV emissions

SOLAR WIND – INDUCED ELECTRIC CURRENTS FLOWING IN THE MAGNETOSPHERE

Typical GOES Location at noon and midnight (relative to magnetospheric boundaries)



 Introduction to Space Physics, ed. by Kivelson and Russell

Magnetospheric Normal Modes: Standing Alfven Waves

$$1/f = T \sim \int ds/v_a \sim \int \sqrt{\rho}\, ds/B$$

Poloidal mode	Toroidal mode
E_azimuthal	E_radial
B_radial	B_azimuthal

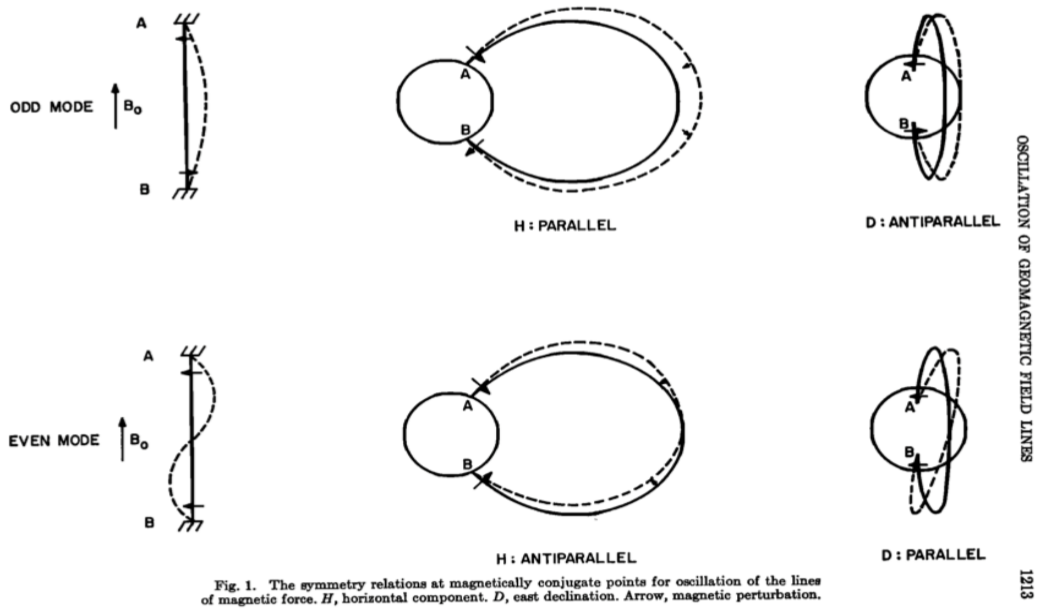


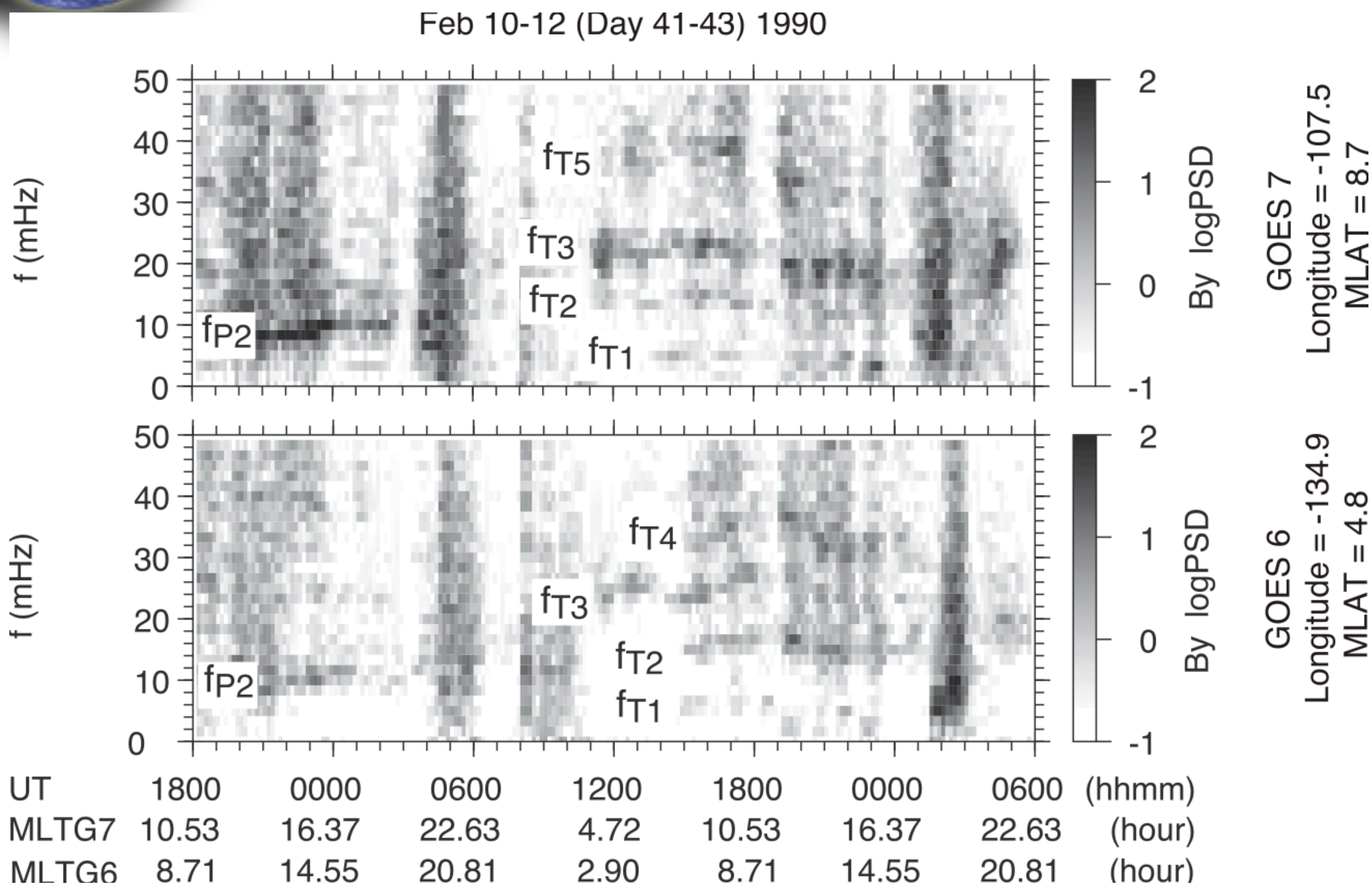
Fig. 1. The symmetry relations at magnetically conjugate points for oscillation of the lines of magnetic force. *H*, horizontal component. *D*, east declination. Arrow, magnetic perturbation.

Fundamental harmonic ($n = 1$)

Second harmonic ($n = 2$)

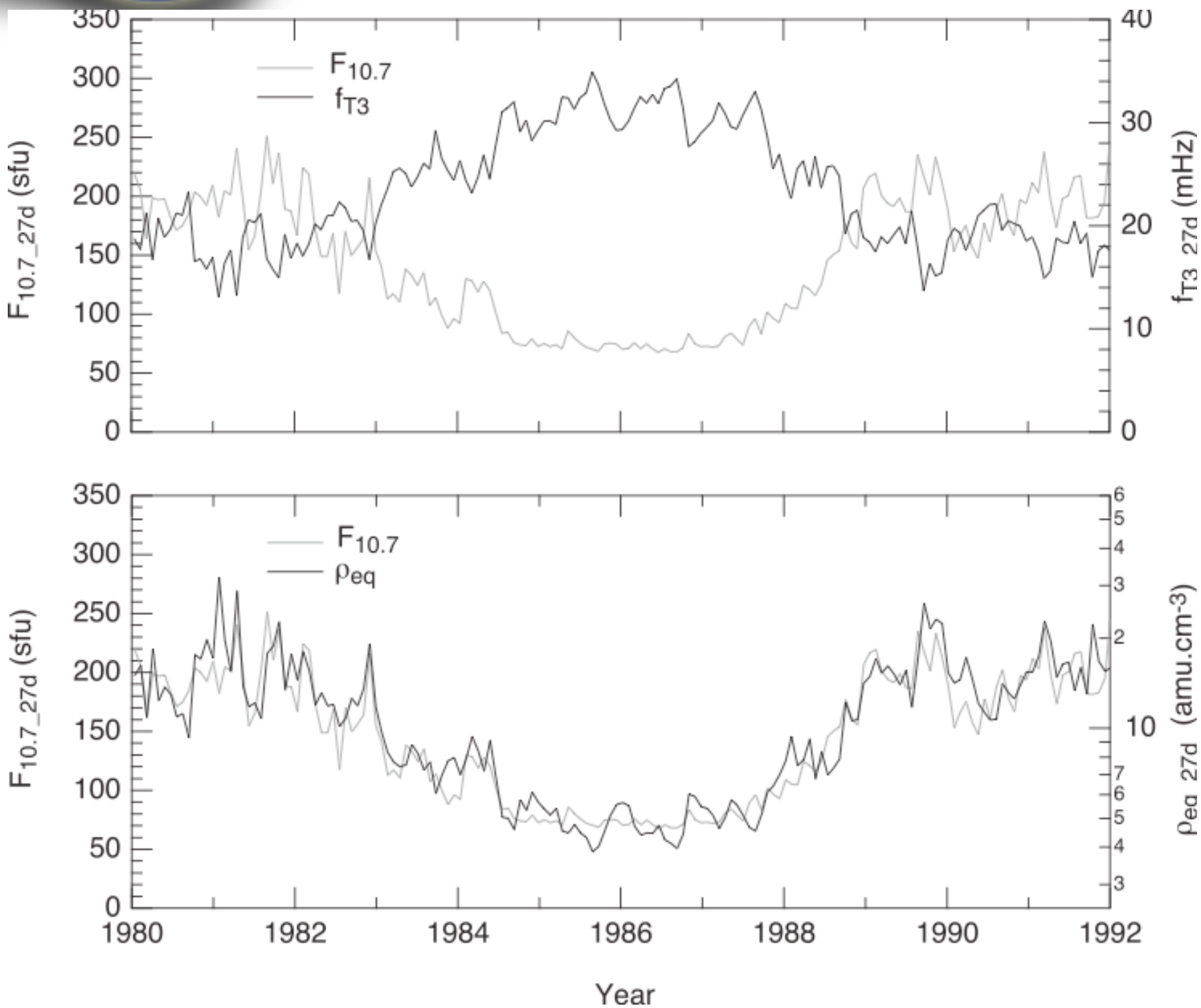
Sugiura and Wilson [1964]

GOES-6 and -7 Dynamic Spectra
(Toroidal Waves)



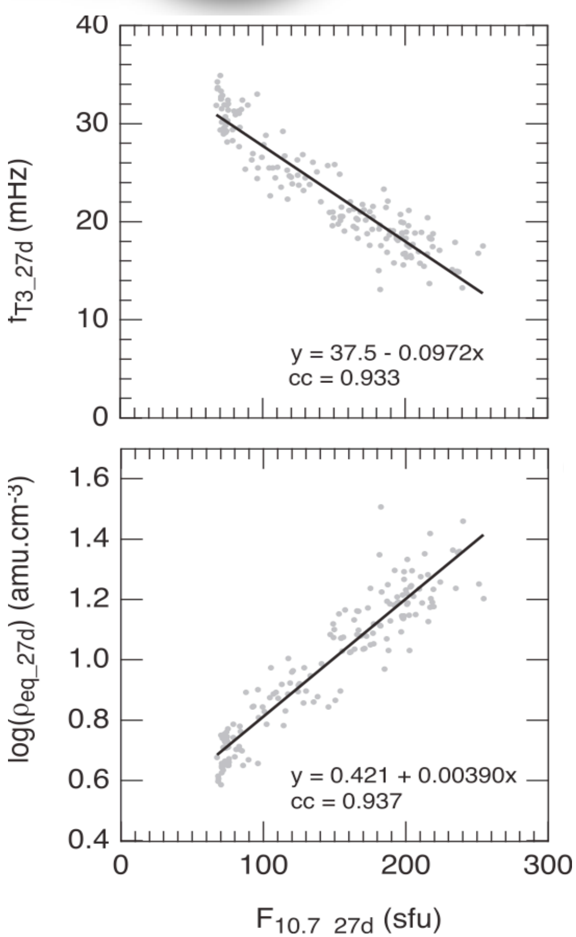
Takahashi, K., R. E. Denton, and H. J. Singer, *J. Geophys. Res., doi:10.1029/2009JA015243, in press.*

F10.7 vs. Toroidal Wave Frequency and Mass Density at Geosynchronous Orbit over a Solar Cycle



- F10.7: 10.7 cm solar radio flux in solar flux units of 10^{-22} $Wm^{-2}Hz^{-1}$ from Penticton British Columbia, Canada used as a proxy for solar output in the UV bands
- f_{T3}: third harmonic toroidal magnetic wave

F10.7 Correlation with 27-day Means of Frequency and Mass Density



- These results demonstrate:
  - Solar UV/EUV (based on F10.7 proxy) increase (decrease), causes an increase (decrease) in ionospheric density and/or scale height along field lines threading the outer magnetosphere and consequent increase (decrease) in the plasmatrough mass density resulting in a decrease (increase) in plasma wave frequency.
  - Over a solar cycle the toroidal wave frequency changes by a factor of 2 and the density by a factor of 4. Therefore, during solar minimum Alfven waves in this region propagate twice as fast. This in turn affects radiation belt wave/particle interactions and other magnetosphere processes that can have societal impacts.
- Example of global-change and solar-terrestrial environment
- Importance of long-term space weather observations for understanding space climate

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