Solar Event Signatures Impressed Upon Spacecraft Radio Signals

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The SOHO/LASCO data used here are produced by a consortium of the Naval Research Laboratory (USA), Max-Planck-Institut fuer Aeronomie (Germany)), Laboratoire d'Astronomie (France), and the University of Birmingham (UK). SOHO is a project of international cooperation between ESA and NASA.

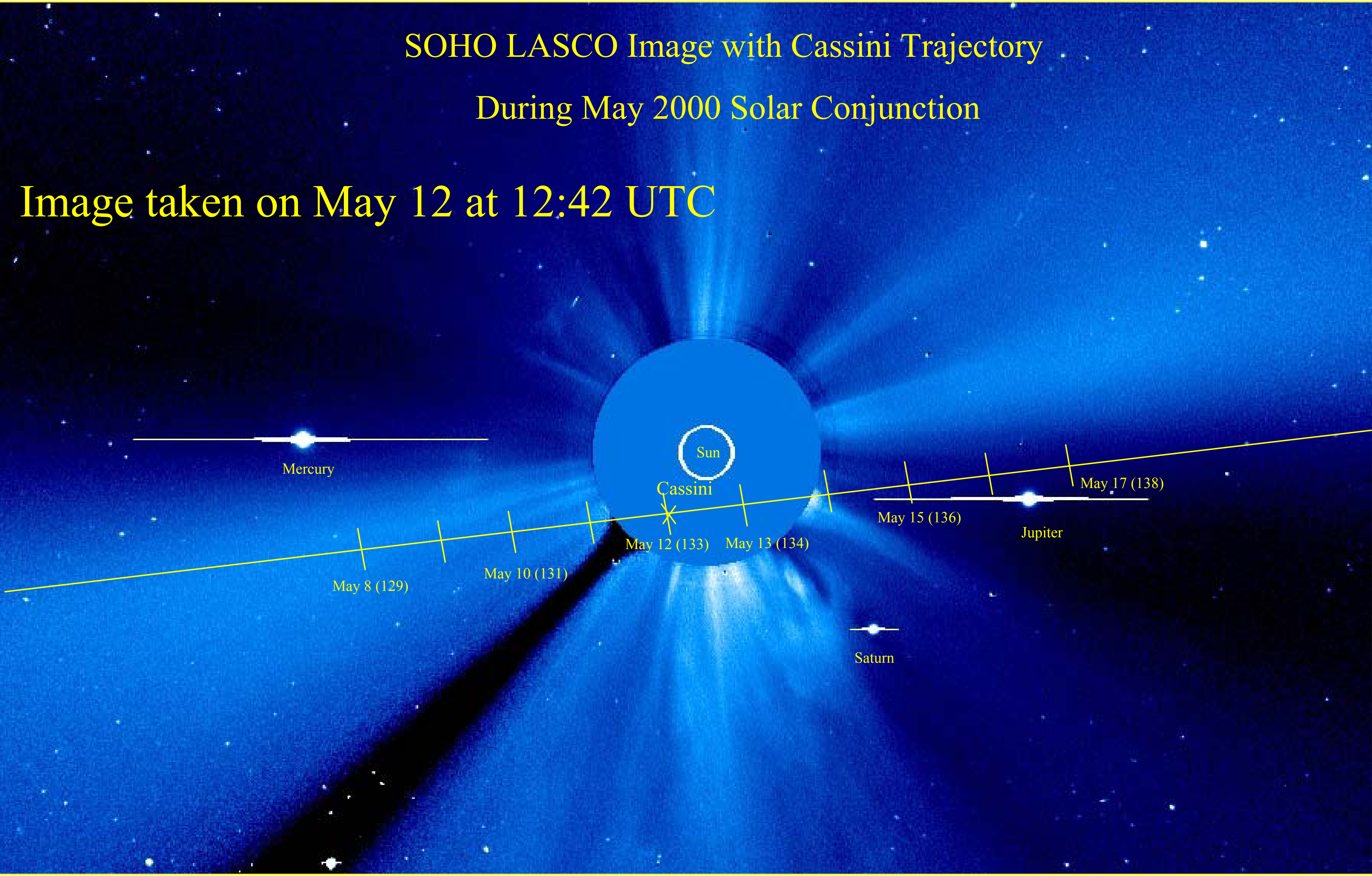
Background

- **This experiment was part of a telecommunications demonstration to evaluate the advantage of Ka-band (32 GHz) over X-band (8.4 GHz)**
- **An analysis of simultaneous Ka-band and X-band Mars Global Surveyor (MGS) data acquired from 1996 to 1998 demonstrated a 6 to 8 dB link advantage using a 34-m beam waveguide (BWG) ground antenna**
- **As part of the dual-frequency X/Ka link experiment, observations were made of several spacecraft during their solar conjunctions to study charged particle effects**
  - For spacecraft passages behind the Sun's corona, the signals will encounter significant degradation due to charged particle density variations and solar wind velocity variations
  - Ka-band signals will experience significantly less amplitude and phase scintillation than X-band signals
- **During the Cassini May 2000 and June 2001 solar conjunctions, X-band and Ka-band signal data were acquired for Sun-Earth Probe (SEP) angles between ~3° to ~0.6°**
  - These superior conjunction occurred near the peak of the current solar cycle
  - Observable quantities include
    - Amplitude Scintillation
    - Phase Scintillation
    - Spectral broadening

Solar Coronal Effects on Spacecraft Signals

- The magnitudes of phase scintillation and spectral broadening increase as the angle between spacecraft and Sun decreases as observed by the tracking station on Earth
- The magnitude of amplitude scintillation increases as the solar elongation angle decreases until it saturates
- For observations conducted during "quiescent" periods, these effects follow well-defined trends of established models as a function of SEP and radio frequency
- During periods of active solar events such as Coronal Mass Ejections (CMEs), the signatures of these effects on the received signals are observed to increase predominately above the "quiescent" background levels
- Several such events have been observed during the solar conjunctions of spacecraft during the peak of the current solar cycle
- Spectral broadening signatures, which rise above the quiescent background, appear to be associated with CMEs seen in white-light images and long duration events seen in X-ray data
- Amplitude and phase scintillation signatures, which rise above the quiet background, also appear to be correlated with such events

Solar Conjunction Spacecraft Trajectory



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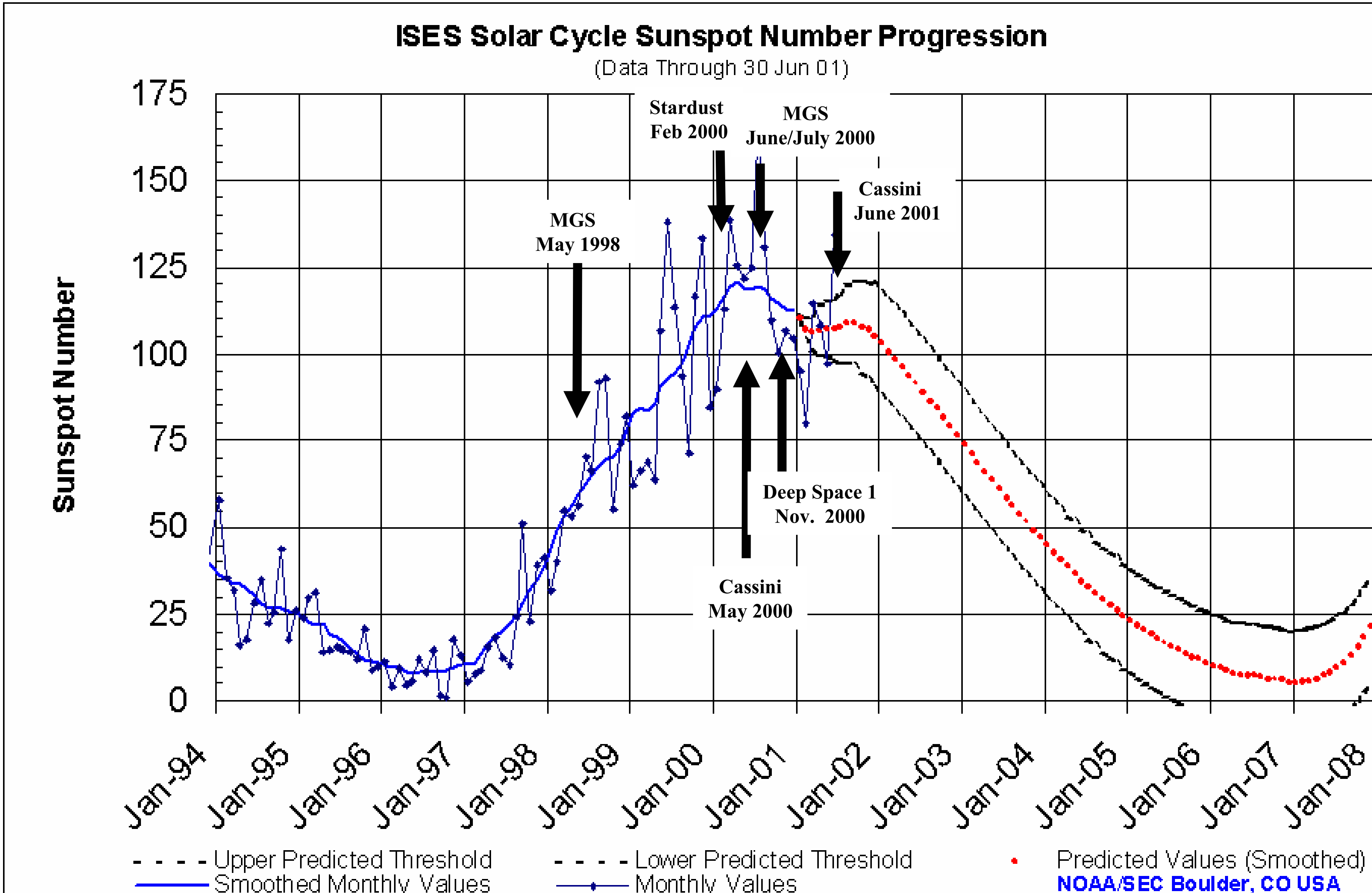
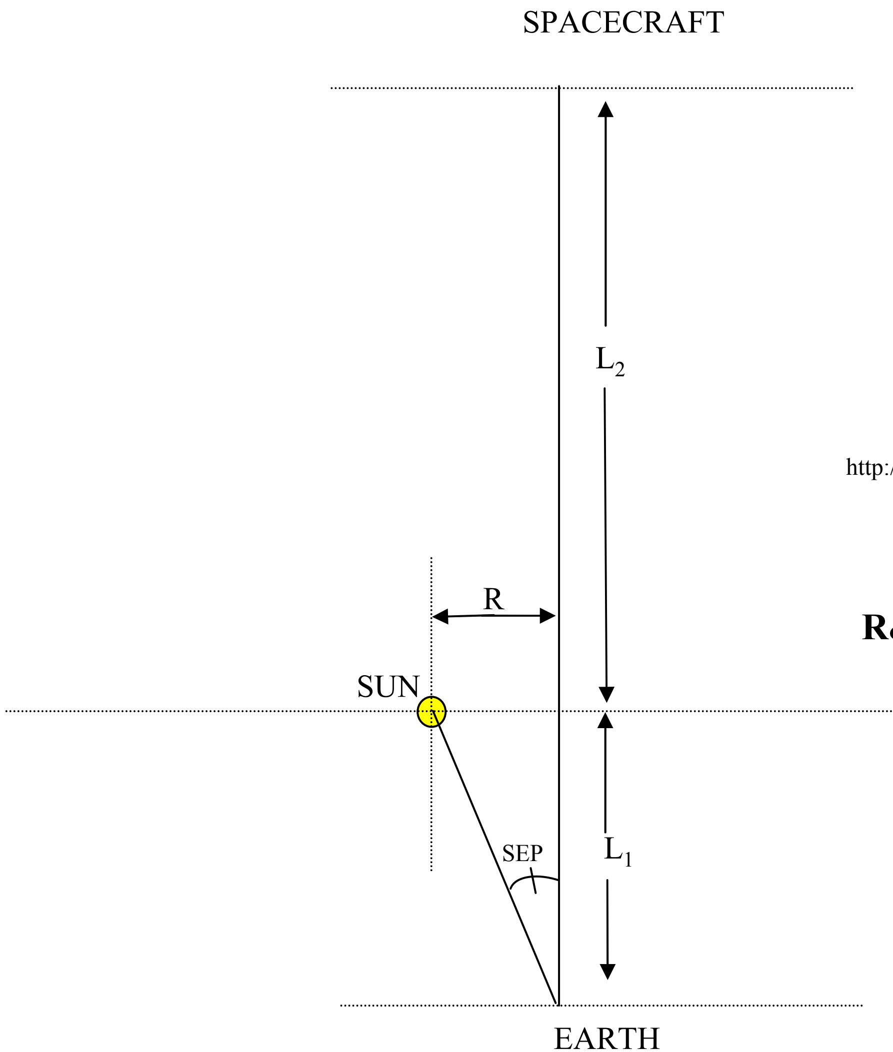
Sunspot Number versus Year and Spacecraft Solar Conjunctions



Plot created by U. S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), Space Environmental Center (web site at http://sec.noaa.gov).

Relevant Solar Conjunction Geometry



$L = L_1 + L_2$

Photo Credit:
http://www.jpl.nasa.gov/cassini/english/pic/cassini_slide_set.html

DSS-13:
R&D Beam Waveguide (BWG) Antenna
Located in Goldstone, California

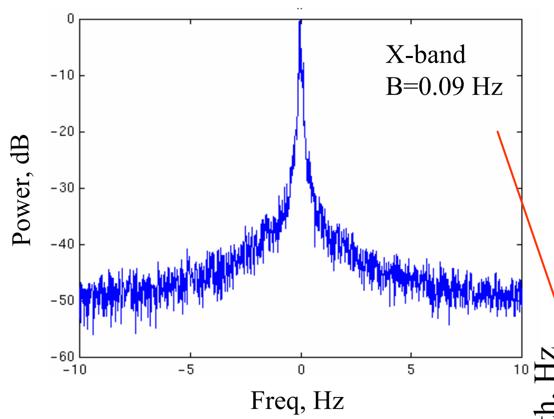
Solar Coronal Effects on Spacecraft Signals: Spectral Broadening

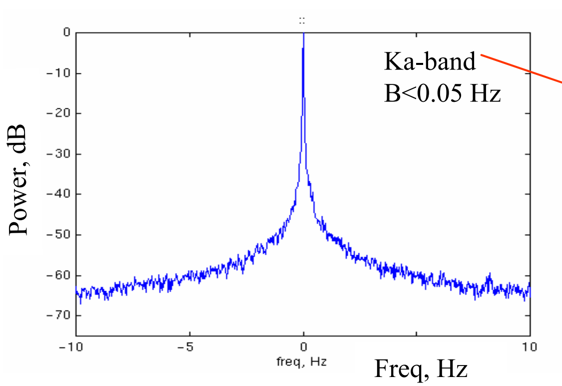
- **Spectral broadening is the observed increase in signal bandwidth due to Doppler shifts induced by the solar charged particles in the signal path**
- **Spectral broadening, B, is defined as the bandwidth for which half of the signal power resides and depends upon electron density fluctuations and solar wind velocity**
- **B does not saturate with decreasing SEP angle (unlike amplitude scintillation) and is thus a good indicator of solar transient activity for small SEP angles.**
- **Measurements of B are useful when they exceed the oscillator line-width**
- **The ratio of the Ka-band to X-band broadened bandwidths varies from 0.11 to 0.20**
- **During "quiet background" periods, the levels of B are consistent with model predictions**
- **During active solar events such as Coronal Mass Ejections (CMEs), the signatures of these effects are observed to increase predominately above the background levels.**
    - **Several such events were observed for solar conjunctions conducted during the peak of the current solar cycle. The durations of active periods ranged from 19% to 50% of a pass for $0.6° < SEP < 1.8°$**
    - **Spectral broadening signatures, which rise above the quiescent background, appear to be associated with CMEs seen in white-light images and long duration events seen in X-ray data**

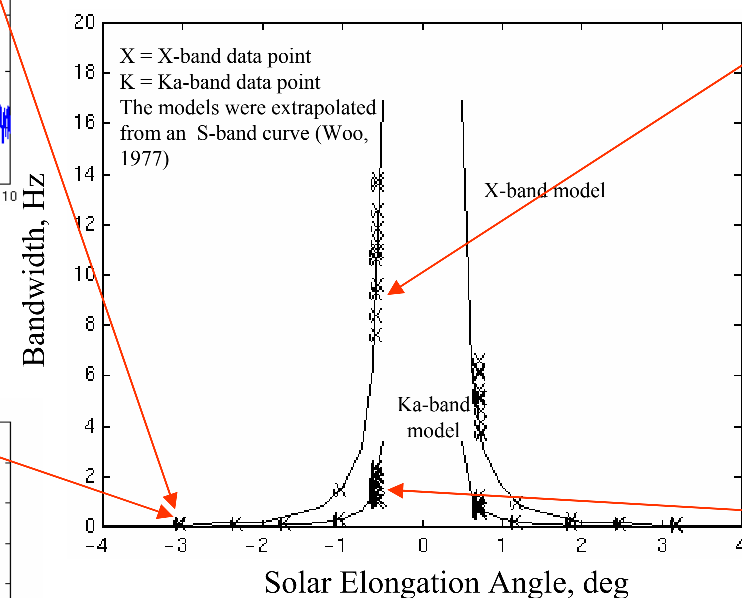
Power Spectra of Cassini Carrier Signals

Cassini 2000 Solar Conjunction Spectral Broadening

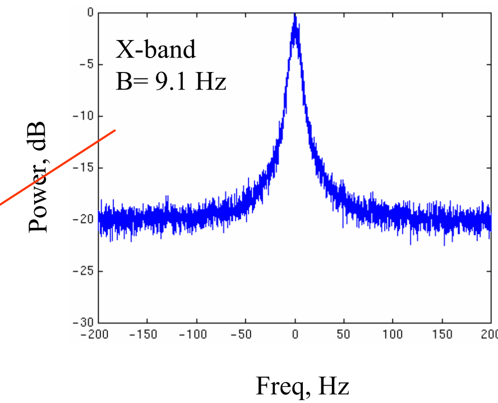
Power Spectra Pass 2000/129 SEP = 3.1°



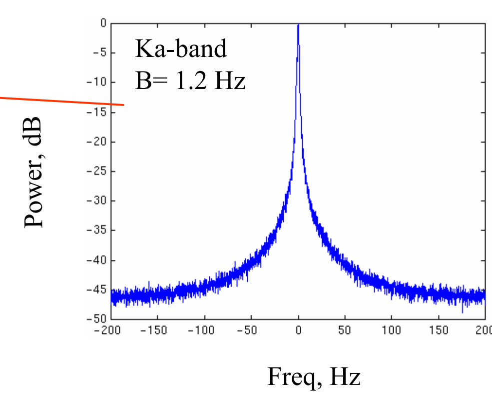




Power Spectra Pass 2000/133 SEP = 0.6°

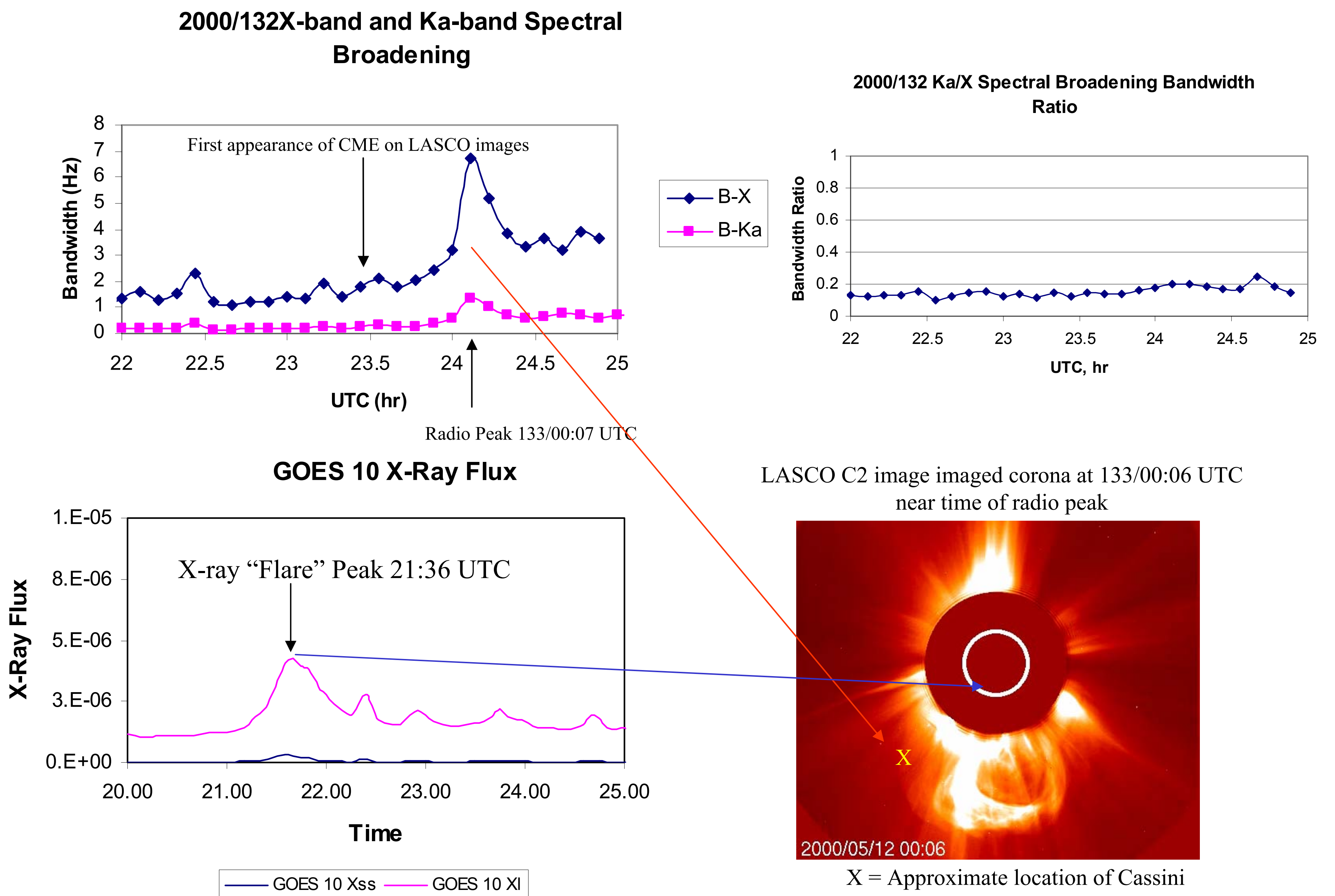


Note change in frequency scale



Ref: Morabito et. al. IEEE Trans. On Ant & Prop. 2003 (in press)

Cassini 2000/132 May 11, SEP = 1.1°



X = Approximate location of Cassini

National Oceanic and Atmospheric Administration

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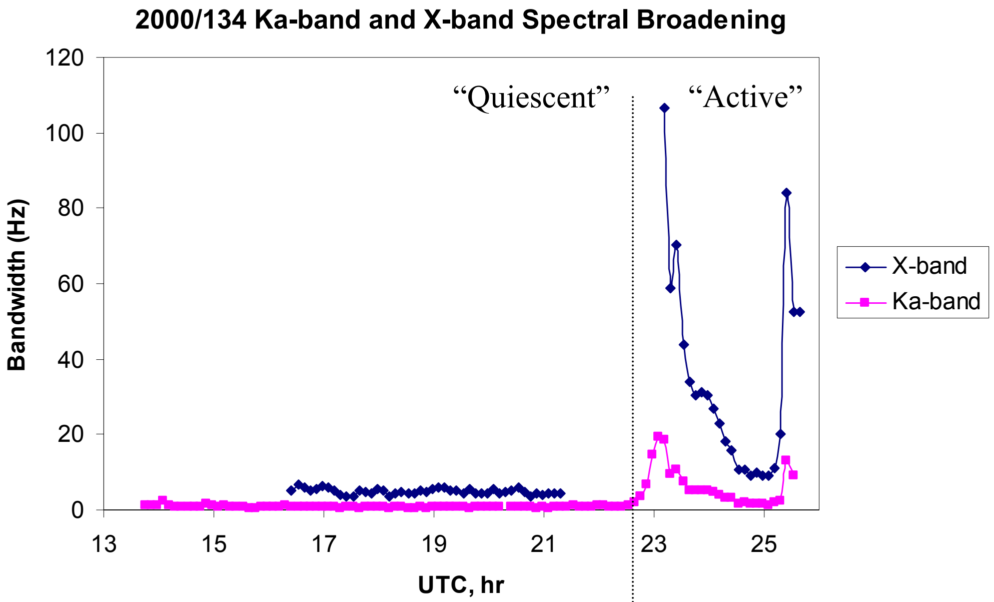
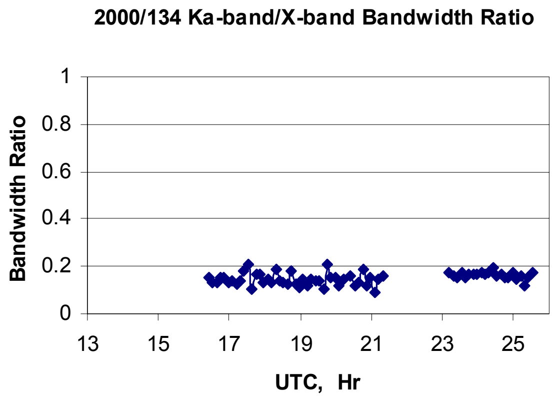
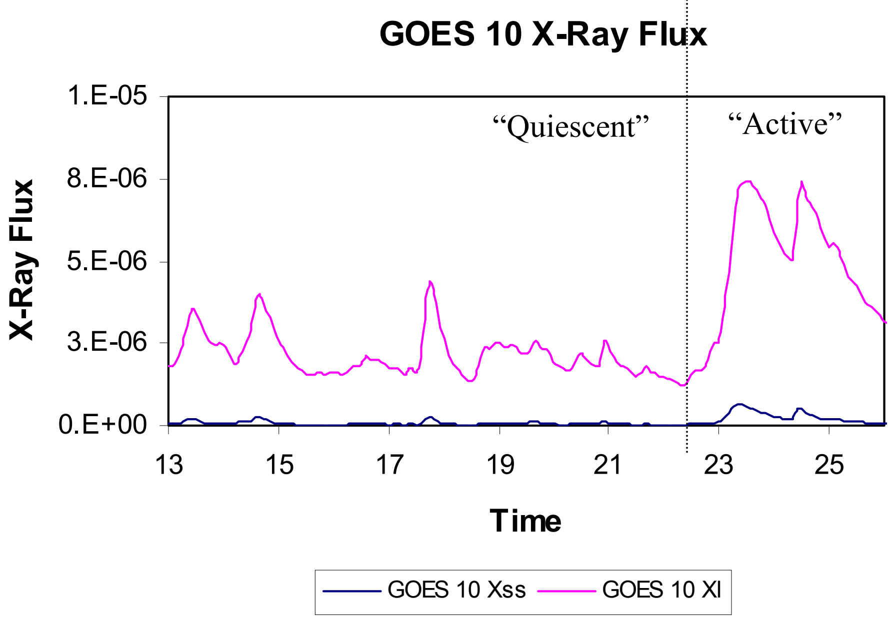
Cassini 2000/134 May 13, SEP = 0.6°







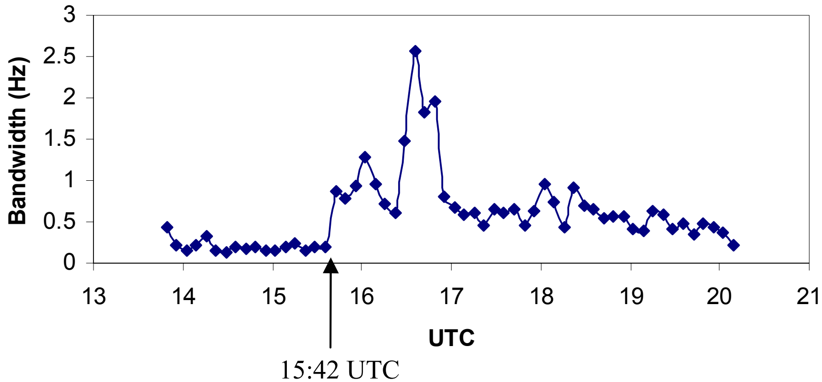
National Oceanic and Atmospheric Administration

Radio event and X-ray event occur almost simultaneously for this observation.

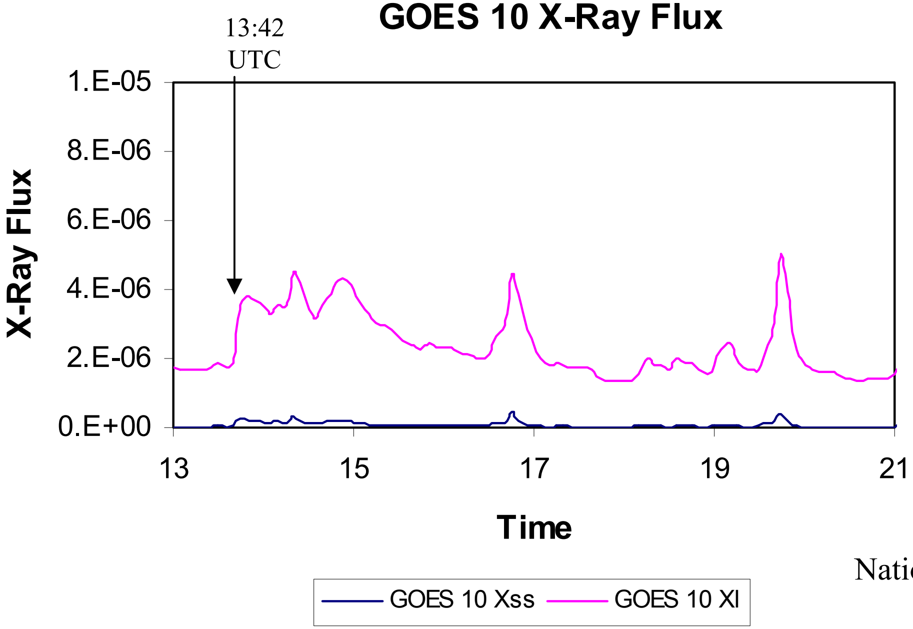
Radio events are typically correlated with long duration X-ray events.

Spectral Broadening for 2000/135 (May 14) Egress 1.1° SEP

2000/135 Ka-band Spectral Broadening

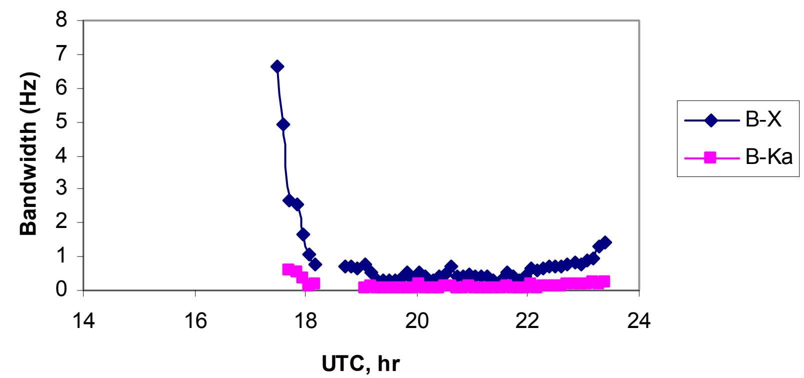


GOES 10 X-Ray Flux

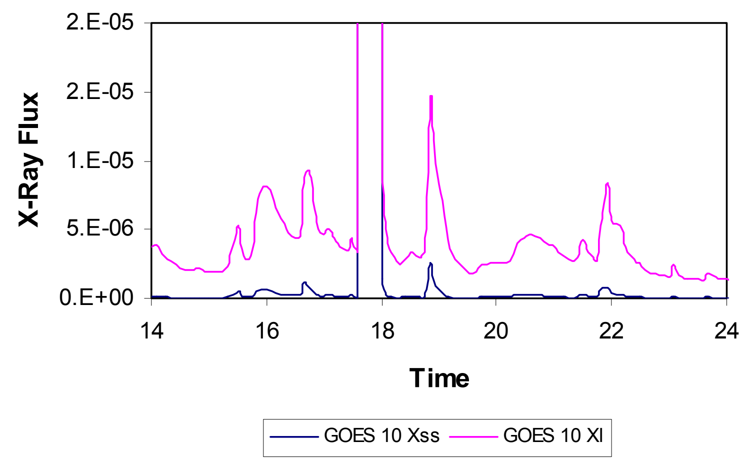


Spectral Broadening For 2000/136 (May 15) Egress 1.8° SEP

2000/136 Spectral Broadening Ka-band/X-band



GOES 10 X-Ray Flux

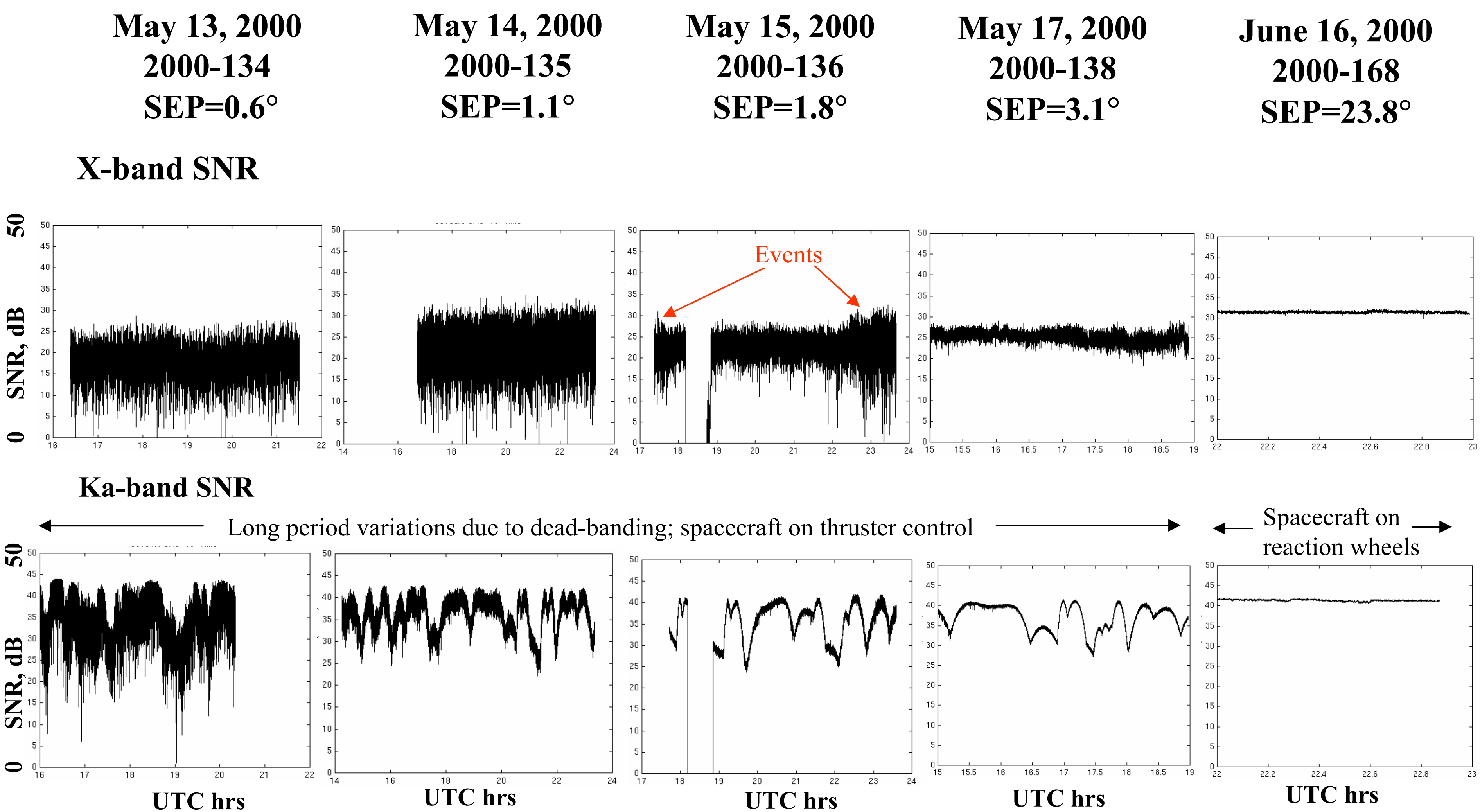


National Oceanic and Atmospheric Administration

Solar Coronal Effects on Spacecraft Signals: Amplitude Scintillation

- Amplitude Scintillation characterizes the charged particle density fluctuations for small scale sizes less than a Fresnel Zone Size
- The amplitude scintillation parameter, m, is defined as the RMS of intensity divided by the mean intensity and it characterizes the relative signal strength fluctuations
- m depends on the electron density fluctuations
- m increases with decreasing SEP angle up to some point where it saturates (m=1)
- Scintillation effects are greater for larger wavelength signals. The model predicts that the ratio of the Ka-band to X-band scintillation indices will be about 0.12 to 0.15 (assuming weak scintillation)
- During "quiet background" periods, the levels of scintillation index are consistent with model predictions
- During active solar events, the scintillation index has been observed to increase above the background level (when in weak scintillation)

Signal Strength versus Solar Elongation Angle



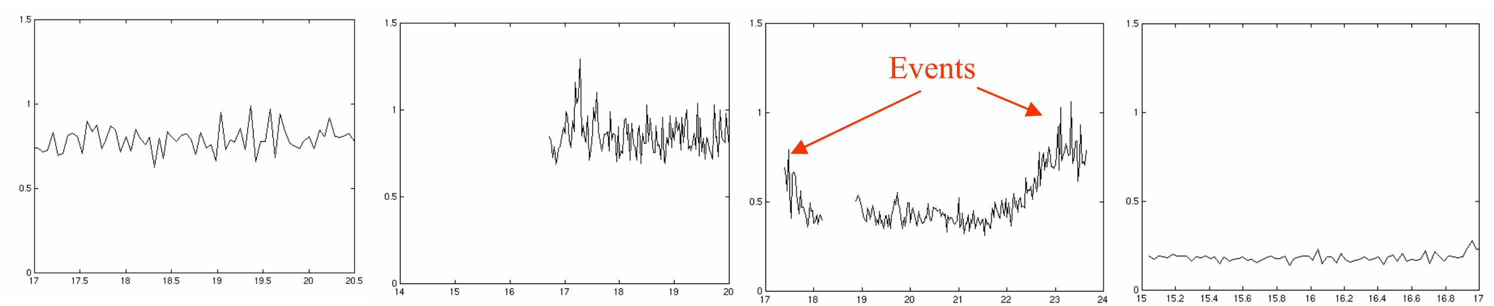
Ref: Morabito et. al. IEEE Trans. On Ant & Prop. 2003 (in press)

Relative Signal Fluctuations versus Solar Elongation Angle – Cassini 2000 Solar Conjunction

May 13, 2000	May 14, 2000	May 15, 2000	May 17, 2000
2000-134	2000-135	2000-136	2000-138
SEP=0.6°	SEP=1.1°	SEP=1.8°	SEP=3.1°

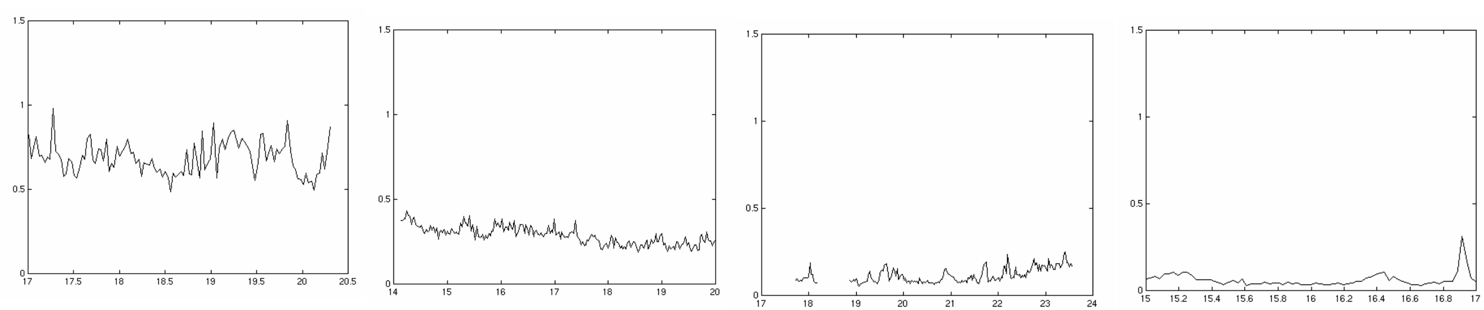
X-band Relative Fluctuations

Relative Fluctuation



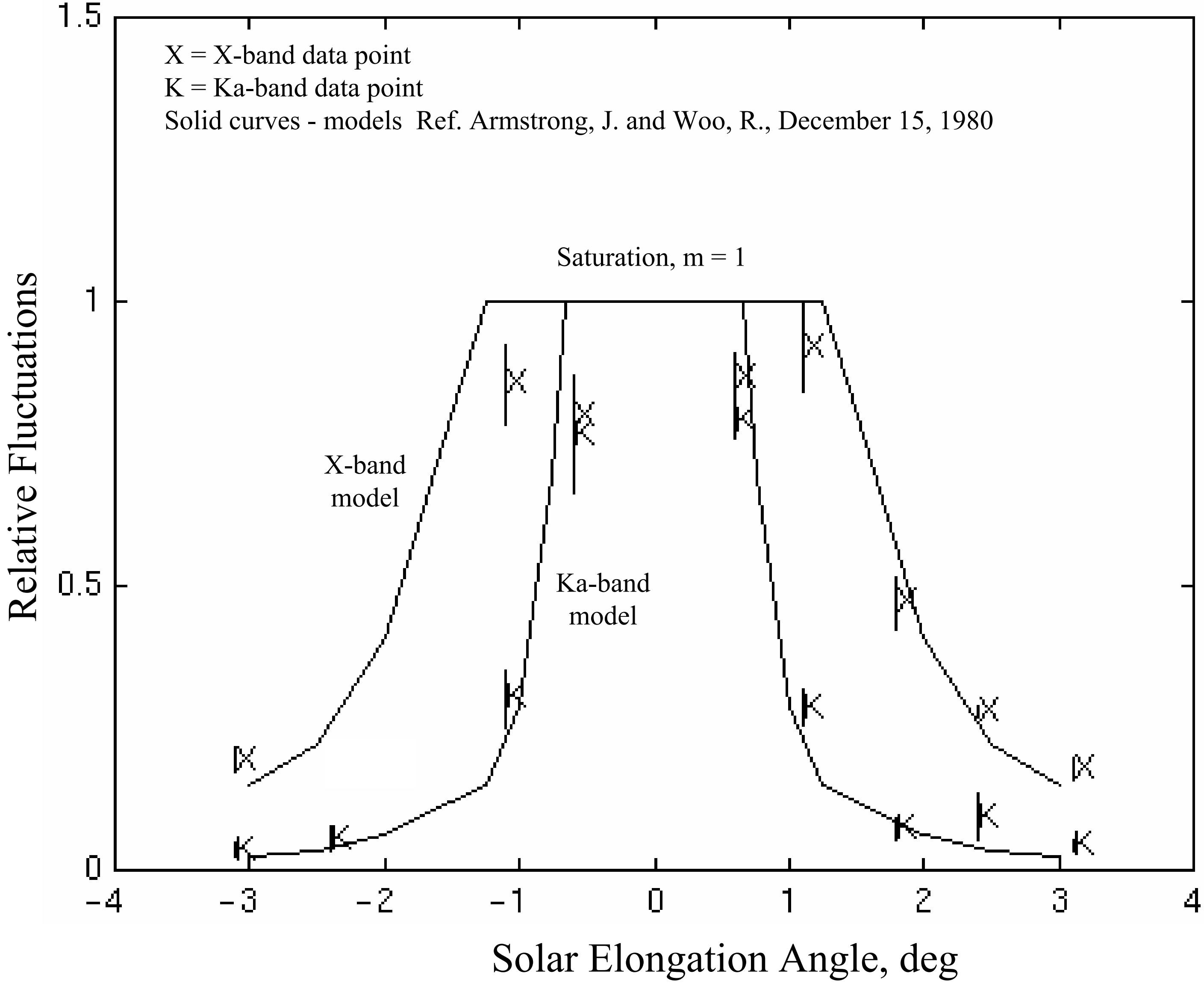
Ka-band Relative Fluctuations

Relative Fluctuation



UTC hrs UTC hrs UTC hrs UTC hrs

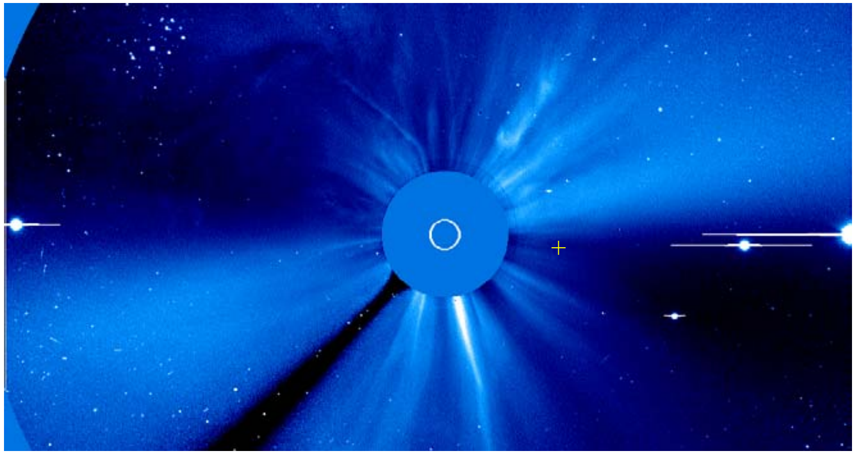
Cassini 2000 Solar Conjunction
Relative Signal Power Fluctuations (rms/mean)



Ref: Morabito et. al. IEEE Trans. On Ant & Prop. 2003 (in press)

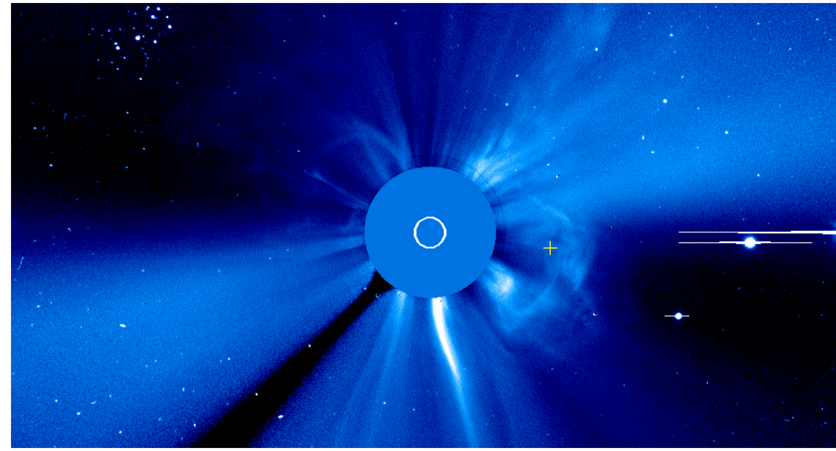
Cassini 2000/136 (May 15)
SEP = 1.8°

Before Event
LASCO C3 Image 12:42 UTC



http://sohowww.nascom.nasa.gov/data/summary/gif/20000515/slas_c3wlc_fd_20000515_1242.gif

Event Captured
LASCO C3 Image 17:42 UTC



http://sohowww.nascom.nasa.gov/data/summary/gif/20000515/slas_c3wlc_fd_20000515_1742.gif

Solar event observed in Cassini 2000/136 data at ~17:30 UTC was captured in a LASCO image taken at 17:42 UTC (the approximate location of the Cassini spacecraft is indicated by the "+")

This event is characterized by both intensity and frequency fluctuations.

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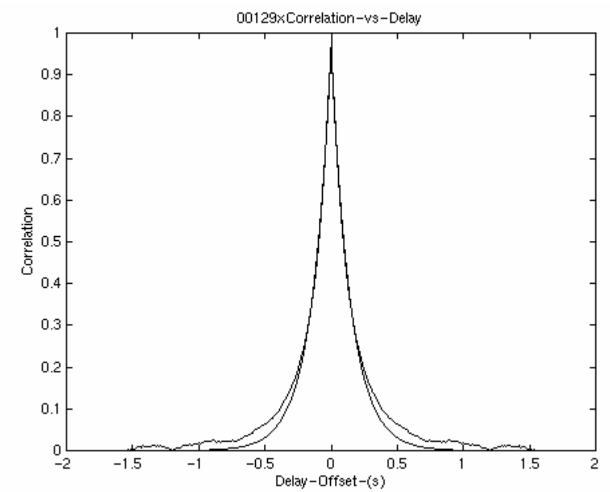
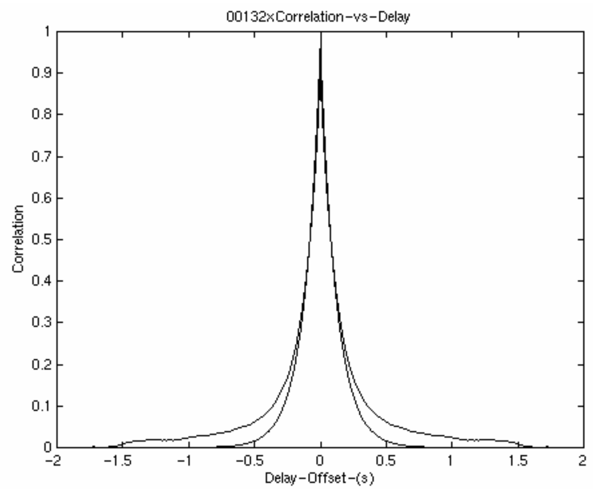
Examples of X-band Auto-Correlation Functions and Amplitude Histograms

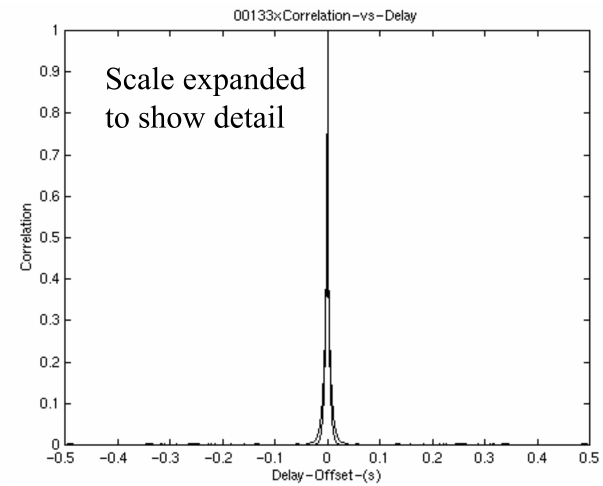
2000/129 X-band
18:15 - 19:00 UTC
SEP = 3.1°
lag size = 10 ms
τ = 100 ms

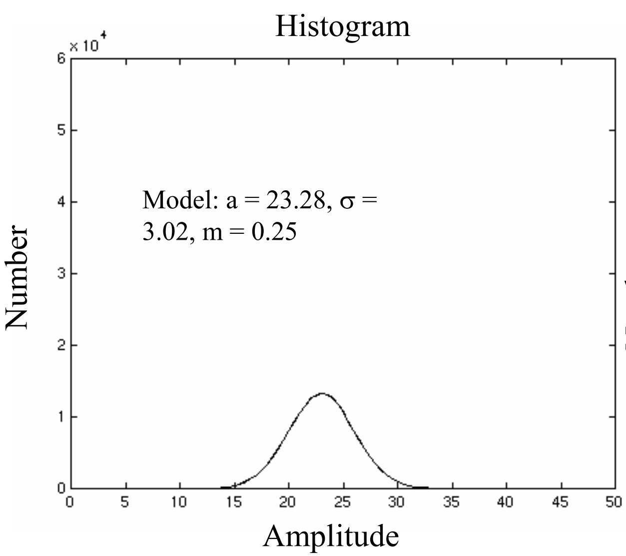
2000/132 X-band
22:30 - 24:00 UTC
SEP = 1.1°
lag size = 10 ms
τ = 84 ms

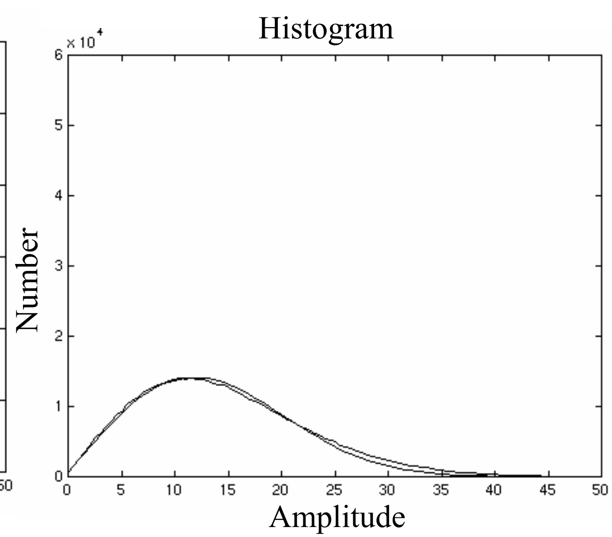
2000/133 X-band
16:30 - 18:00 UTC
SEP = 0.6°
lag size = 2.5 ms
τ = 2.5 ms

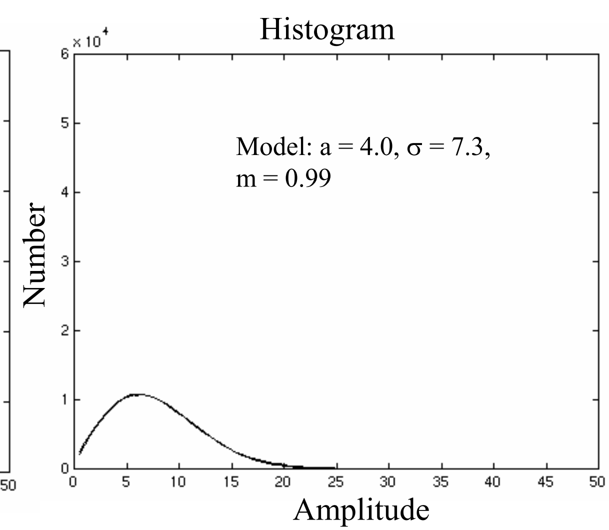








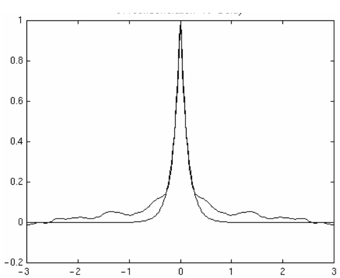




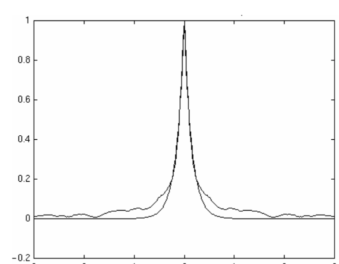
Ka-band Amplitude Scintillation
Auto-correlation functions and model fits

- Model predicts Ka-band transition at saturation, mean(SNR)=rms(SNR), occurs at SEP~0.62°
- Histograms of Ka-band amplitude samples acquired during Cassini 2001 solar conjunction show the change from Rician to "Gaussian-like" distribution as the transition region is crossed
- Model of form $R(\tau) = \exp(-\tau \ln(2)/\tau_{HPHW})$ fit to Amplitude Auto-correlation Function
- Fits to ACF show fluctuation time scales of τ_{HPHW} = 100 ms increasing to 180 ms as transition region from strong to weak scintillation is crossed
- Ka-band spectral broadening bandwidth varies from 1.9 Hz during strong scintillation to down to 0.6 Hz near end of pass.
- Concurrent X-band data is in strong scintillation realm during this period

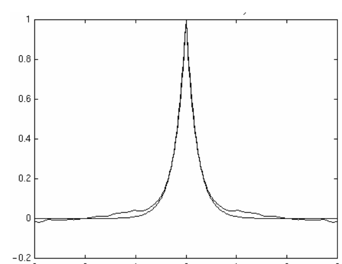
15:30 UTC
SEP = 0.60°
τ_{HPHW} = 100 ms
B = 1.8±0.2 Hz



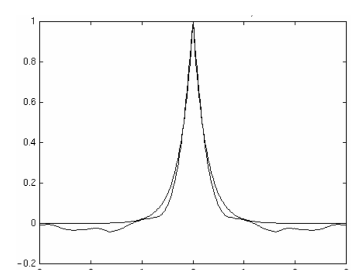
16:30 UTC
SEP = 0.63°
τ_{HPHW} = 105 ms
B= 1.9 ±0.2 Hz

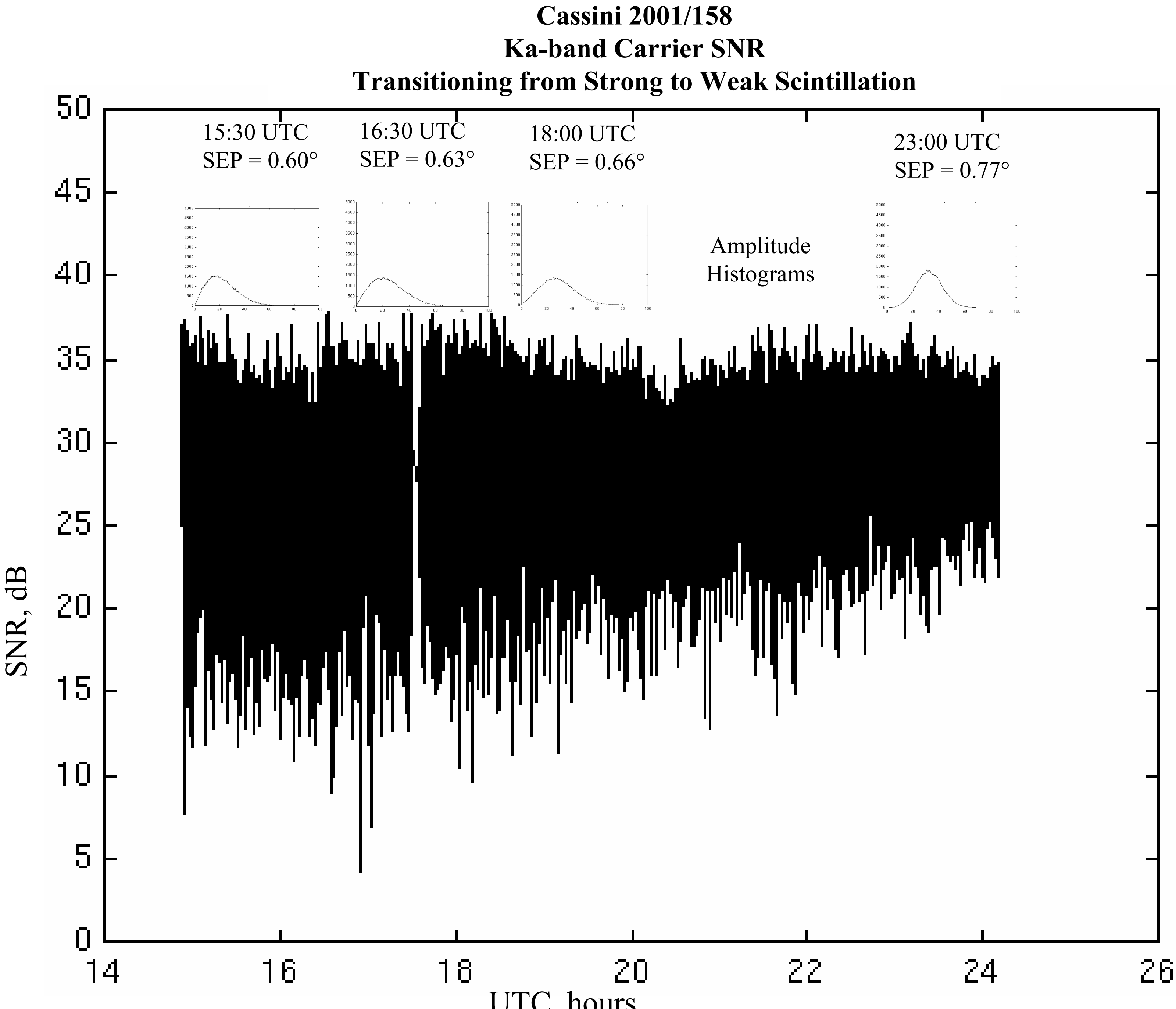


18:00 UTC
SEP = 0.66°
τ_{HPHW} = 150 ms
B = 0.98±0.06 Hz



23:00 UTC
SEP = 0.77°
τ_{HPHW} = 180 ms
B = 0.6±0.1 Hz

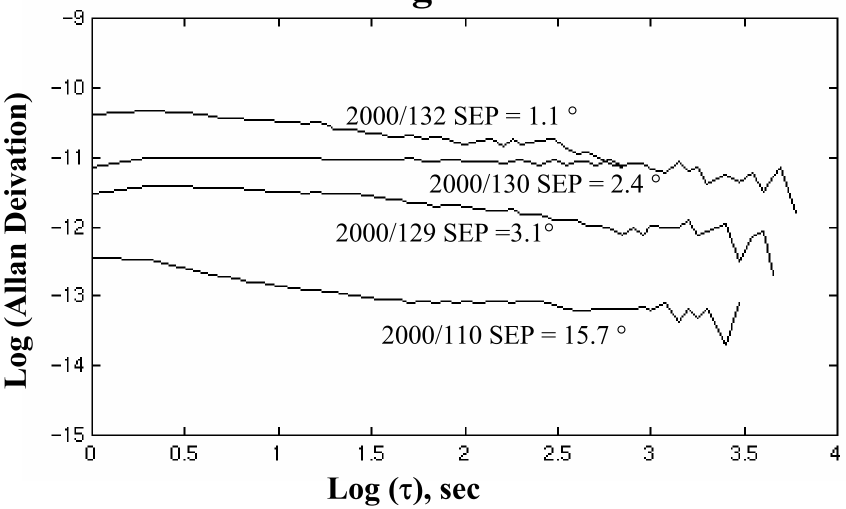




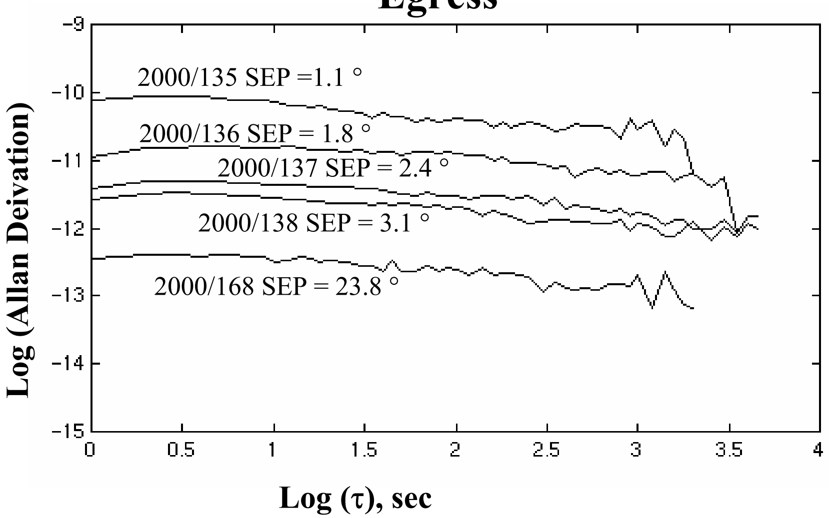
Cassini 2001/158
Ka-band Carrier SNR
Transitioning from Strong to Weak Scintillation
15:30 UTC
SEP = 0.60°
16:30 UTC
SEP = 0.63°
18:00 UTC
SEP = 0.66°
23:00 UTC
SEP = 0.77°
Amplitude
Histograms
SNR, dB
UTC, hours
0
5
10
15
20
25
30
35
40
45
50
14
16
18
20
22
24
26

Solar Coronal Effects on Spacecraft Signals: Phase Scintillation

Allan deviation of X/Ka Difference Frequency Ingress



Allan deviation of X/Ka Difference Frequency Egress

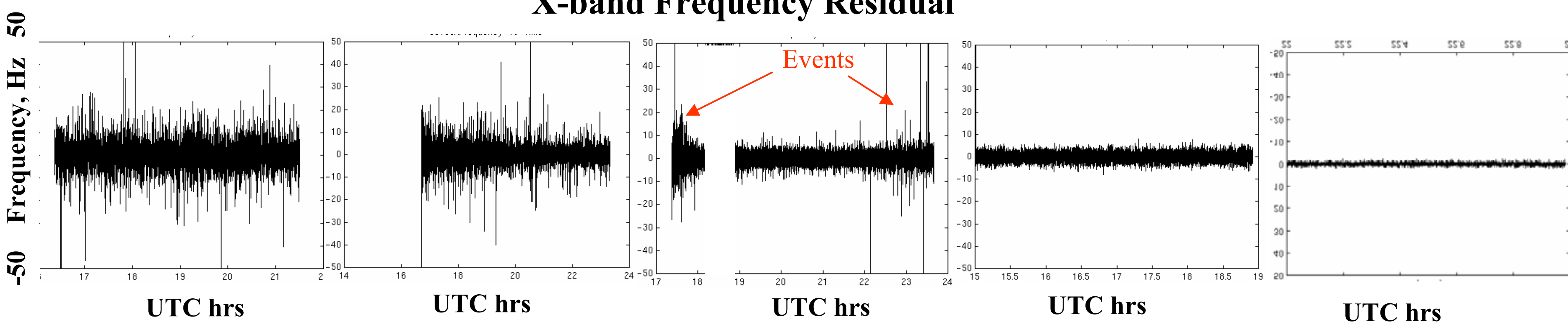


- **Phase Scintillation provides information on the full range of scale sizes**
- **Phase fluctuations do not saturate (as does intensity scintillation)**
- **One measure is Doppler noise or scatter on frequency residuals. Another measure is Allan deviation on frequency residuals**
- **Phase scintillation depends on electron density fluctuations and solar wind velocity**
- **Scintillation effects are greater for larger wavelength signals**
- **Scintillation increases with decreasing SEP angle**
- **During "quiet background" periods, the levels of scintillation index are consistent with model predictions**
- **During active solar events such as Coronal Mass Ejections (CMEs), phase scintillation has been observed to increase above the background levels**

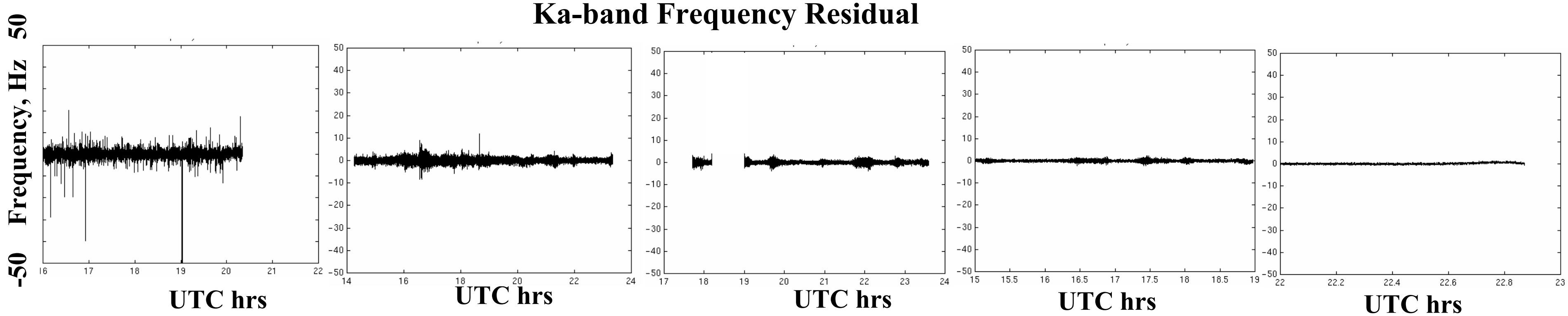
Frequency Residuals versus Solar Elongation Angle

May 13, 2000 2000-134 SEP=0.6°	May 14, 2000 2000-135 SEP=1.1°	May 15, 2000 2000-136 SEP=1.8°	May 17, 2000 2000-138 SEP=3.1°	June 16, 2000 2000-168 SEP=23.8°

X-band Frequency Residual



Ka-band Frequency Residual



Conclusions

- The Cassini Solar Conjunctions in May 2000 and June 2001 resulted in a collection of simultaneous Ka-band and X-band carrier data used to characterize solar charged particle effects on signal propagation through the solar corona
- The measured effects of solar charged particles during “quiescent” periods on the carrier signals were consistent with predictions based on models derived from theory and previous solar conjunction data
- Several transient events were observed in which the measured solar effects were increased above their “quiescent” values

The research described in this presentation was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.