

# **Ka-BAND AND X-BAND OBSERVATIONS OF THE SOLAR CORONA ACQUIRED DURING THE CASSINI 2001 SUPERIOR CONJUNCTION**

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## **1. ABSTRACT**

Simultaneous dual-frequency Ka-band (32 GHz) and X-band (8.4 GHz) carrier signal data have been acquired during the superior conjunction of the Cassini spacecraft June 2001, using the NASA Deep Space Network's facilities located in Goldstone, California. The solar elongation angle of the observations varied from  $\sim 4.1^\circ$  ( $\sim 16$  solar radii) to  $\sim 0.6^\circ$  ( $\sim 2.3$  solar radii). The observed coronal and solar effects on the signals include spectral broadening, amplitude scintillation, phase scintillation, and increased noise. The measurements were generally consistent with existing solar models, except during solar transient events when the signatures of the measurements were observed to increase significantly above the quiet background levels. This is the second solar conjunction of Cassini for which simultaneous X/Ka data were acquired. Both solar conjunctions, conducted in May 2000 and June 2001, occurred near the peak of the current 11-year solar cycle.

## **2. INTRODUCTION**

A solar conjunction of the Cassini spacecraft en route to Saturn occurred in June 2001 near the peak of Solar Cycle #23. Between June 2 and June 14, 2001, simultaneous X-band (8.4 GHz) and Ka-band (32 GHz) carrier signals transmitted by the spacecraft were received at antennas located in Goldstone, California. The sun-earth-probe (SEP) angle ranged from  $3.7^\circ$  on June 2 during ingress, to a minimum of  $0.6^\circ$  on June 7, to  $4.1^\circ$  on June 12 during egress. The Cassini spacecraft was at a distance of 6.9 au from the Earth. This is the second superior conjunction of the Cassini spacecraft for which simultaneous X-band and Ka-band signal data were acquired.

The first solar conjunction data acquisition period of the Cassini spacecraft occurred between May 8 and May 18, 2000, when Cassini was within  $3.2^\circ$  of the Sun as seen from Earth with the minimum SEP angle of  $0.56^\circ$  occurring on May 13. The measurements of amplitude scintillation, spectral broadening and phase scintillation were examined as a function of SEP angle and found to be consistent with accepted models [1]. However, large excursions of up to 20 dB on the Ka-band received signal SNR due to the spacecraft dead-band, complicated the analysis of the solar effects on the Cassini 2000 signal data. The received Ka-band signal strength data acquired during the Cassini June 2001 solar conjunction were very stable due to superior reaction wheel pointing used by the spacecraft, and thus the data were much easier to analyze. The Cassini 2000 and 2001 solar conjunctions coincided with the peak of Solar Cycle #23.

## **3. SPACECRAFT AND GROUND STATION CONFIGURATIONS**

The spacecraft configuration is described in detail in [1]. Most of the data were acquired in the one-way tracking mode using the internal Ultra-Stable Oscillator (USO) on-board the spacecraft as the signal reference. A few passes were conducted in a coherent tracking mode in which the spacecraft transponder was locked to an X-band uplink from an operational DSN station, and simultaneous X-band and Ka-band downlink signals were emitted by the spacecraft. The primary ground station used to receive the carrier signals was DSS-13, a 34-meter beam-waveguide (BWG) Research and Development antenna located at the NASA Goldstone Deep Space Tracking Complex near Barstow, California. A dichroic plate allowed for simultaneous reception of both X-band and Ka-band signals. The RF signals output from the low-noise amplifiers were down-converted to IFs near 300 MHz, and transported via optical fiber to a control room, where they were input into the receivers. In some cases, downlink signal data were also acquired from operational Deep Space Network (DSN) tracking stations.

The prime data for Cassini were open-loop carrier data recorded on Full Spectrum Recorders (FSRs). The FSR residing at DSS-13 was used to record the DSS-13 Ka-band carrier signal. The FSR residing at the Goldstone Signal Processing Center (SPC) was used to record the X-band carrier signal, which was transported from DSS-13 via optical fiber. The FSR configuration is described in detail elsewhere [1,2].

For most passes, the DSS-13 antenna used Ka-band monopulse tracking to actively point to the spacecraft with  $\sim 2$  millideg accuracy. For a few passes, pointing control was maintained using manually determined offsets to a blind pointing model.

System noise operating temperature data were acquired at DSS-13 using a Total Power Radiometer. These data are used to quantify solar noise, refer receiver signal-to-noise measurements to received signal power, and characterize overall station performance, including detection thresholds. The Ka-band system operating noise temperature ( $T_{op}$ ) at zenith was  $\sim 76$ K during clear weather conditions. The X-band zenith  $T_{op}$  was typically  $\sim 45$ K.

#### 4. RESULTS

The data from the open-loop receivers were processed using a software phase-locked loop program to provide estimates of power (SNR), frequency and phase. The open-loop data samples were also processed using software tools to produce plots of spectral density and produce estimates of bandwidth broadening. Table 1 summarizes the processing results for the open-loop Ka-band data acquired using the FSR at DSS-13. Table 2 summarizes the processing results for the X-band open-loop data acquired using the FSR at the SPC. The SNR and its relative fluctuations (RMS of SNR variations divided by mean SNR) were taken over a representative quiescent  $\sim 30$ -minute period for each pass, in which solar events such as coronal mass ejections were not believed to be occurring in the signal path.

Spectral broadening of the received RF carrier signal occurs due to Doppler shifting or velocity-induced variations of the charged particle density irregularities. The broadened bandwidth,  $B$ , is defined as the bandwidth for which one-half of the signal power resides, and was computed by estimating power spectra on the recorded open-loop receiver samples [1,2]. The flight measured line-width of the Cassini USO in the absence of solar effects lies below 0.025 Hz based on examination of power spectral data at high SEP angles. The Cassini measurements are thus useful for measuring spectral broadening at small SEP angles. The estimates of  $B$  measured during periods of quiet background were in good agreement with models derived from earlier spacecraft measurements [3] (see Figure 1). One exception occurred on 2001/159 where the measurements were lower than the models. Estimates of frequency noise (Doppler) were reasonably consistent with expected values.

Figure 2 displays the observed spectral broadening of the carrier signals at the smallest SEP angle pass 2001/158. A possible significant event signature is evident during the first three hours of the pass, which reaches values as high as 2.6 Hz at Ka-band, and then decreases below 1 Hz for the remainder of the pass. The limited X-band data show a significantly increased bandwidth signature, which mostly lies above the model. The Ka-band carrier signal exhibits approximately one-eighth of the spectral broadening due to solar charged particles than the concurrent X-band carrier signal.

**Table 1**  
**Ka-band Open-Loop Data Processing Results**

Date	DOY	SEP (deg)	SNR (dB)			Relative SNR Fluctuations	B (Hz)
			Avg	- $\sigma$	+ $\sigma$		
June 2	153	3.7	25.3	-1.3	+1.0	-----	-----
June 3	154	3.0	29.4	-0.7	+0.6	0.04±0.03	-----
June 4	155	2.2	25.2	-0.6	+0.5	0.06±0.02	0.062±0.015
June 5	156	1.4	33.9	-1.1	+0.9	0.21±0.02	0.193±0.034
June 7	158	0.6-0.8	28.4	-9.3	+2.8	0.86±0.09	0.538±0.104
June 8	159	1.4	30.6	-0.9	+0.8	0.17±0.02	0.047±0.022
June 10	161	2.6	33.8	-0.4	+0.4	0.055±0.005	0.023±0.013
June 12	163	4.1	31.4	-0.3	+0.3	0.022±0.013	-----

**Table 2**  
**X-band Open-Loop Data Processing Results**

Date	DOY	SEP (deg)	SNR (dB)			Relative SNR Fluctuations	B (Hz)
			Avg	- $\sigma$	+ $\sigma$		
June 4	155	2.1	29.3	-3.3	+1.9	0.52±0.06	0.277±0.085
June 5	156	1.4	28.9	-7.4	+2.6	0.80±0.09	1.175±0.156
June 6	157	0.8	27.3	-7.0	+2.6	0.78±0.09	4.422±0.826
June 7	158	0.7	25.7	-8.1	+2.6	0.81±0.09	4.288±0.662
June 8	159	1.4	29.1	-2.9	+1.7	0.50±0.06	0.230±0.048
June 10	161	2.6	29.2	-1.2	+0.9	0.23±0.02	0.083±0.013
June 12	163	4.1	22.0	-0.6	+0.5	0.05±0.02	-----

Examples of received signal strength are shown in Figure 3 for 36-second segments at X-band and Ka-band. This allows the nature of the fading and thermal noise signatures to be examined as a function of SEP angle. As the SEP angle decreases, the fading becomes more severe at both bands. However, the fading characteristics at Ka-band are significantly less severe than at X-band. At Ka-band, the fade depth only becomes severe (up to ~17 dB) for the case of SEP angle = 0.7° on 2001/158. At the start of the 2001/158 pass, at 15:00 UTC where the SEP angle was 0.6°, the Ka-band signal SNR was in or near saturation (scintillation index of  $m \cong 1$ ). Later, near the end of the 2001/158 pass, at 159/00:00 UTC, when the SEP angle increased to ~0.8°, the Ka-band signal SNR was in a state of weak scintillation ( $m \cong 0.5$ ) [4].

The X-band carrier signal fading is significantly larger than that of Ka-band at the same SEP angles. The X-band fading features for 2001/156 (SEP=1.3°) and 2001/159 (SEP=1.4°) are comparable to the Ka-band fading features on 2001/158 (SEP = 0.7°), in both fade depth and fade duration. The X-band data, for passes 2001/157 (SEP = 0.75°) and 2001/158 (SEP = 0.7°), which lie well within the X-band saturation regime, show many fades with significant depth (~25 dB) and very short durations (of a few milliseconds). Such effects present significant obstacles in achieving any reasonable spacecraft telemetry data return in this regime at X-band. The presence of fewer deep fades and longer fade durations in the Ka-

band data at this SEP angle, implies that a higher data return over that of X-band may be possible.

The measurements of relative fluctuation versus SEP angle were calculated from both open-loop and closed-loop receiver data and plotted for both X-band (Figure 4a) and Ka-band (Figure 4b). The predicted scintillation index models<sup>1</sup> (m versus SEP angle) are indicated by the solid curves on these figures. The X-band measurements, agree reasonably well with the model (Figure 4a), except at the smallest SEP angles, in the realm of strong scintillation. Here the X-band relative fluctuations lie below the scintillation model. This is likely due to filtering effects in signal processing. The Ka-band relative fluctuation measurements acquired agree reasonably well with the scintillation model predictions (Figure 4b). Note that multiple estimates from the open-loop receiver for pass 2001/158 are plotted on Figure 4b where the SEP angle ranged from 0.6° to 0.8°. The significantly smaller relative fluctuations at Ka-band relative to X-band predict that a telemetry link using Ka-band should perform better and be more resilient to fades than X-band at the very small SEP angles.

## 5. CONCLUSION

Dual-frequency Ka-band (32 GHz) and X-band (8.4 GHz) signals have been recorded during the superior solar conjunction of the Cassini spacecraft in June 2001. The measurements were generally consistent with solar models developed from theory and from earlier solar conjunction observations from other spacecraft. The Ka-band carrier link experiences significantly less degradation than the X-band carrier link at very small SEP angles. Such measurements are useful for evaluating telemetry links on future space missions using Ka-band, during close angular passages of a spacecraft's signal path through the Sun's corona.

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## 7. REFERENCES

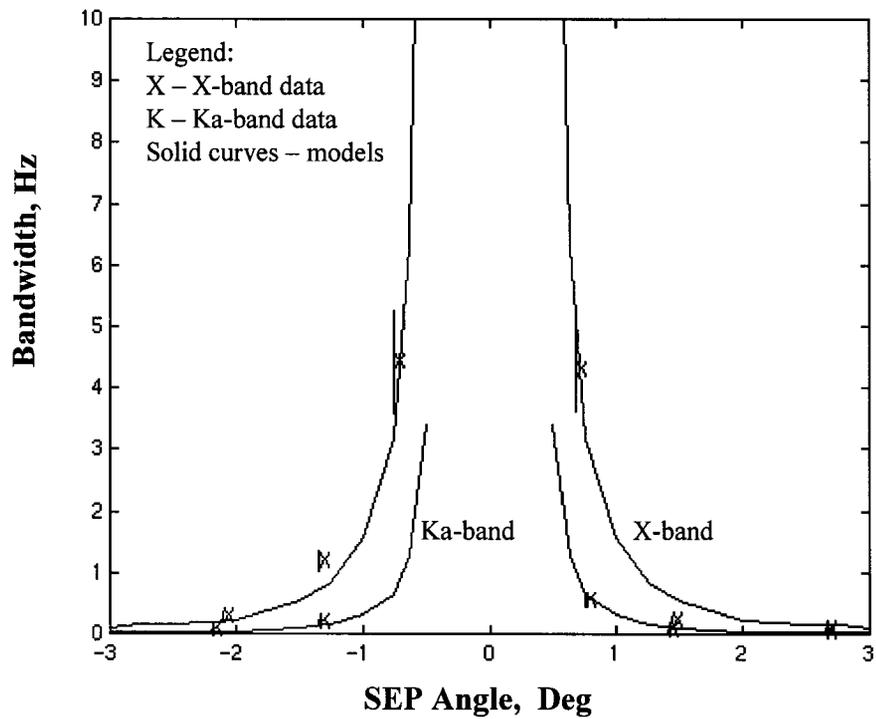
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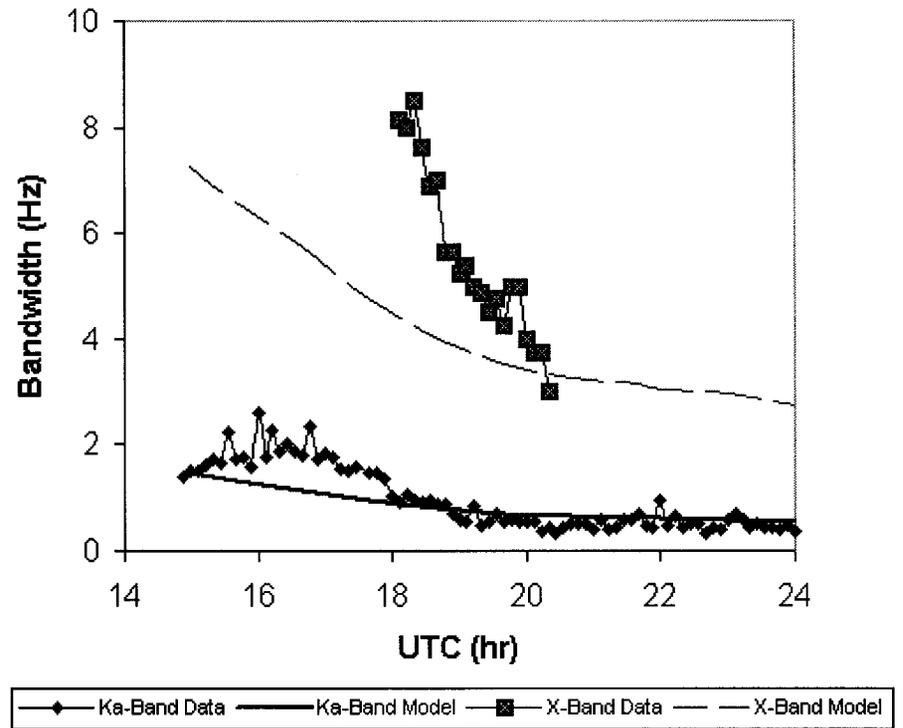
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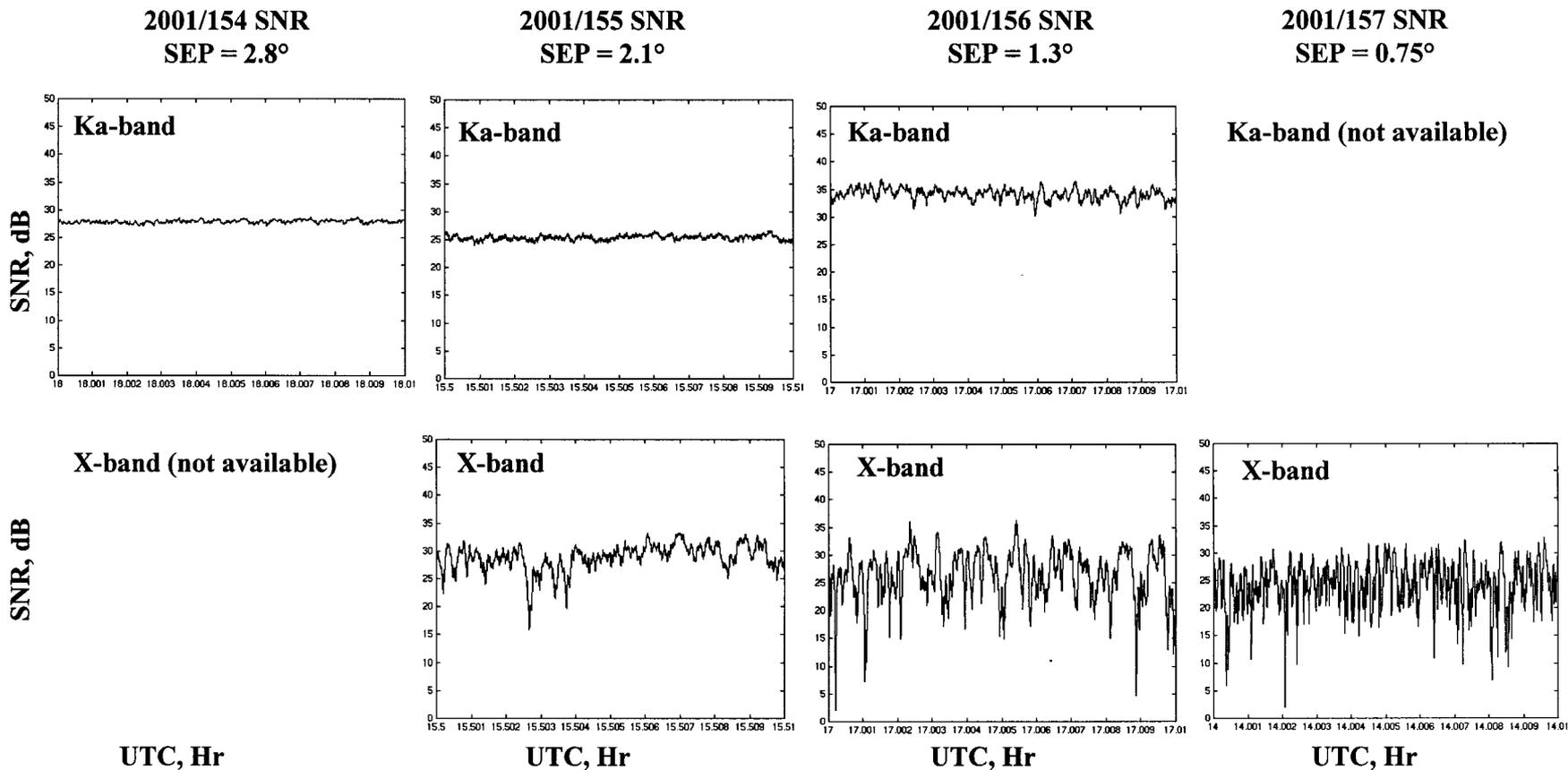
**Figure 1**  
Spectral Broadening Bandwidth



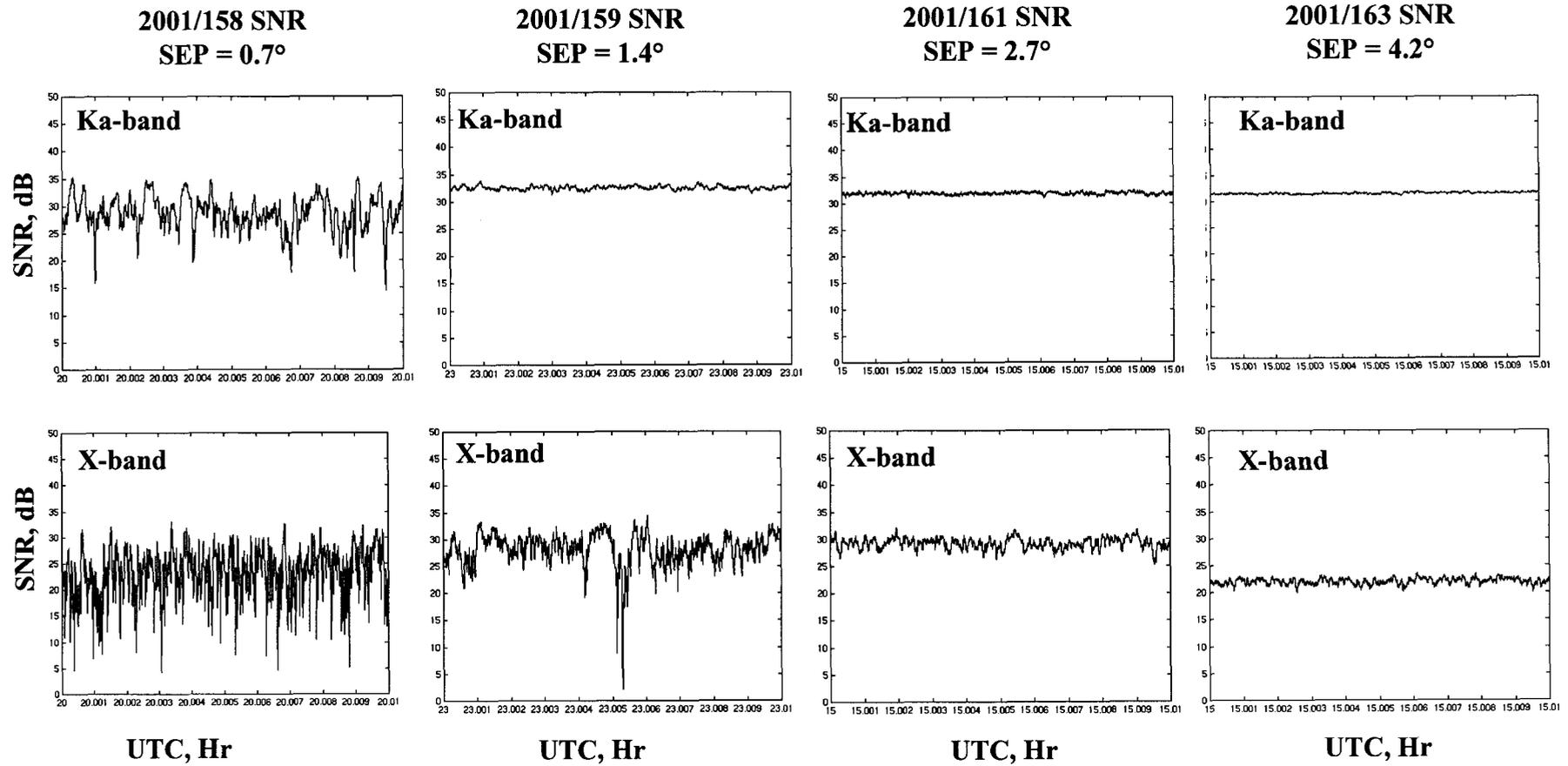
**Figure 2**  
2001/158 X-band and Ka-band Spectral Broadening



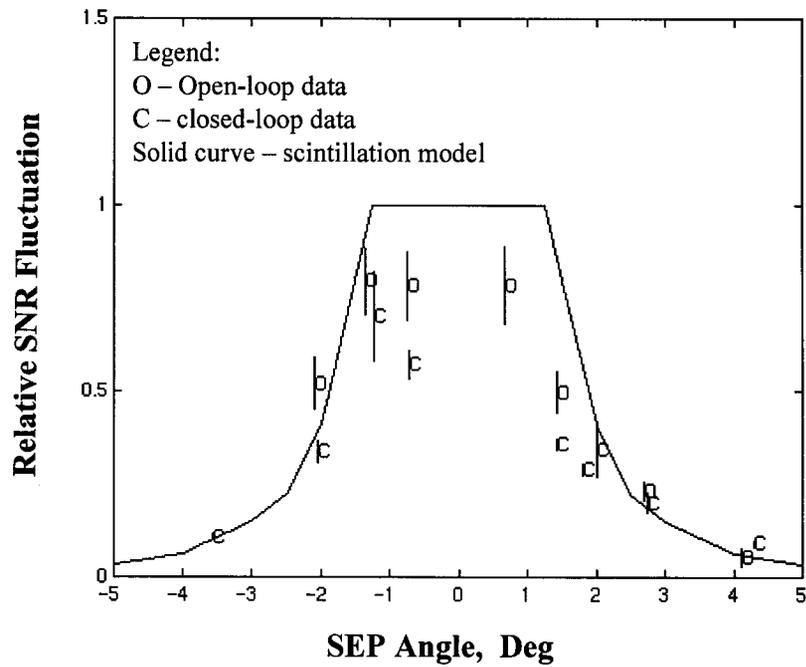
**Figure 3**  
**Examples of short period time-scale fluctuations**  
**At Ka-band and X-band due to solar charged particles**



**Figure 3 (continued)**  
**Examples of short period time-scale fluctuations**  
**At Ka-band and X-band due to solar charged particles**



**Figure 4a**  
**X-Band Relative Power Fluctuations**  
**and Scintillation Model**



**Figure 4b**  
**Ka-Band Relative Power Fluctuations**  
**and Scintillation Model**

