Low-Frequency Gravitational Wave Searches Using Spacecraft Doppler Tracking

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JPL

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Low-Frequency Gravitational Wave Searches Using Spacecraft Doppler Tracking

- The Doppler Method
  - Signal transfer function
  - Noises and their transfer functions
- Experiments to date: some results from GLL/MO/MGS/Pioneer/ULS
- Cassini Experiment
  - Status
  - Expected sensitivity
- Can we do better than Cassini with earth-spacecraft Doppler tracking?

J. Anderson
B. Bertotti
F. Estabrook
R. Hellings
L. Iess
M. Tinto
H. Wahlquist

and many engineers and analysts from the JPL technical divisions, the Deep Space Network, and the flight projects

SOME JARGON

DSN	Deep Space Network, the NASA/JPL tracking system with antennas in California, Spain, and Australia
S-band	radio frequency ≈ 2.3 GHz (e.g., Galileo)
X-band	radio frequency ≈ 8.4 GHz (e.g., Mars Observer)
Ka-band	radio frequency ≈ 32 GHz (e.g., Cassini)
$y(t)$	time series of $\Delta f/f$
$S_y(f)$	power spectrum of $y(t)$
$S_\phi(f)$	power spectrum of phase

MORE JARGON

Allan variance

$\sigma_y(\tau)$, a measure of fractional frequency stability, $\Delta f/f$, as a function of integration time

$$\sigma_y^2(\tau) = \frac{1}{2}\left\langle \left|\bar{y}(t) - \bar{y}(t+\tau)\right|^2 \right\rangle$$

$$\bar{y}(t) = \frac{1}{\tau}\int_t^{t+\tau} y(t')\,dt'$$

$$\sigma_y^2(\tau) = 4\int_0^{\infty} S_y(f)\frac{\sin^4(\pi f\tau)}{(\pi f\tau)^2}\,df$$

$$S_y(f) = S\phi(f)\cdot f^2 f_0^{-2}$$

scintillation

variation of phase of radio signals due to refractive index variations by a medium (solar wind, ionosphere, troposphere) between the source and the receiver

JARGON (CONCLUDED)

clock	precision frequency standard
uplink	radio beam transmitted from the earth to a distant spacecraft
downlink	radio beam transmitted from a distant spacecraft to the earth
DSS	Deep Space Station. Followed by a number it designates antennas within the Deep Space Network, as in "DSS 25"

REPRESENTATIVE REFERENCES

Regarding the method:

Estabrook and Wahlquist, *GRG*, 6, 439 (1975)

Wahlquist *GRG*, 19, 1101 (1987)

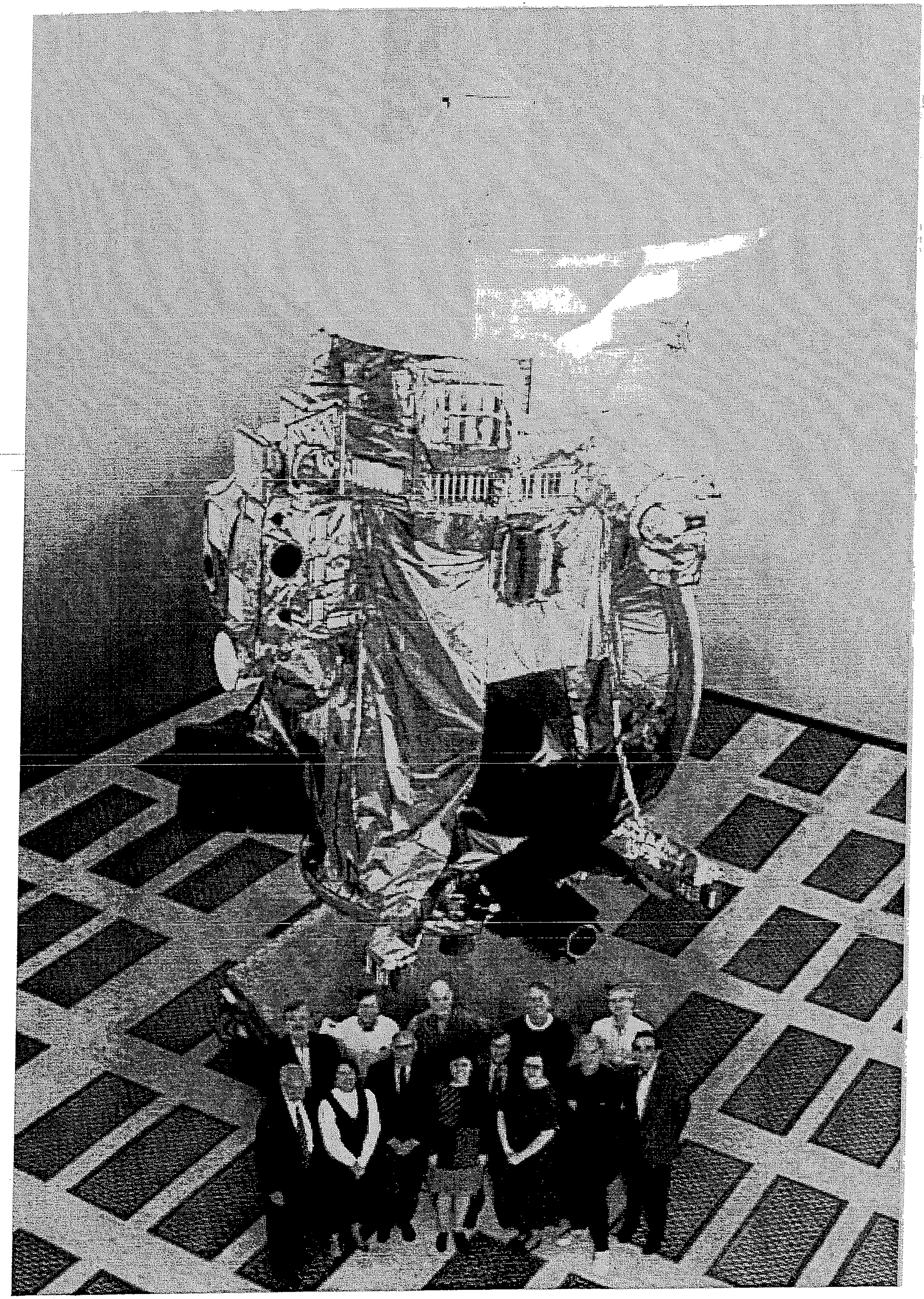
Tinto *Phys. Rev. D.* 53, 5354 (1996)

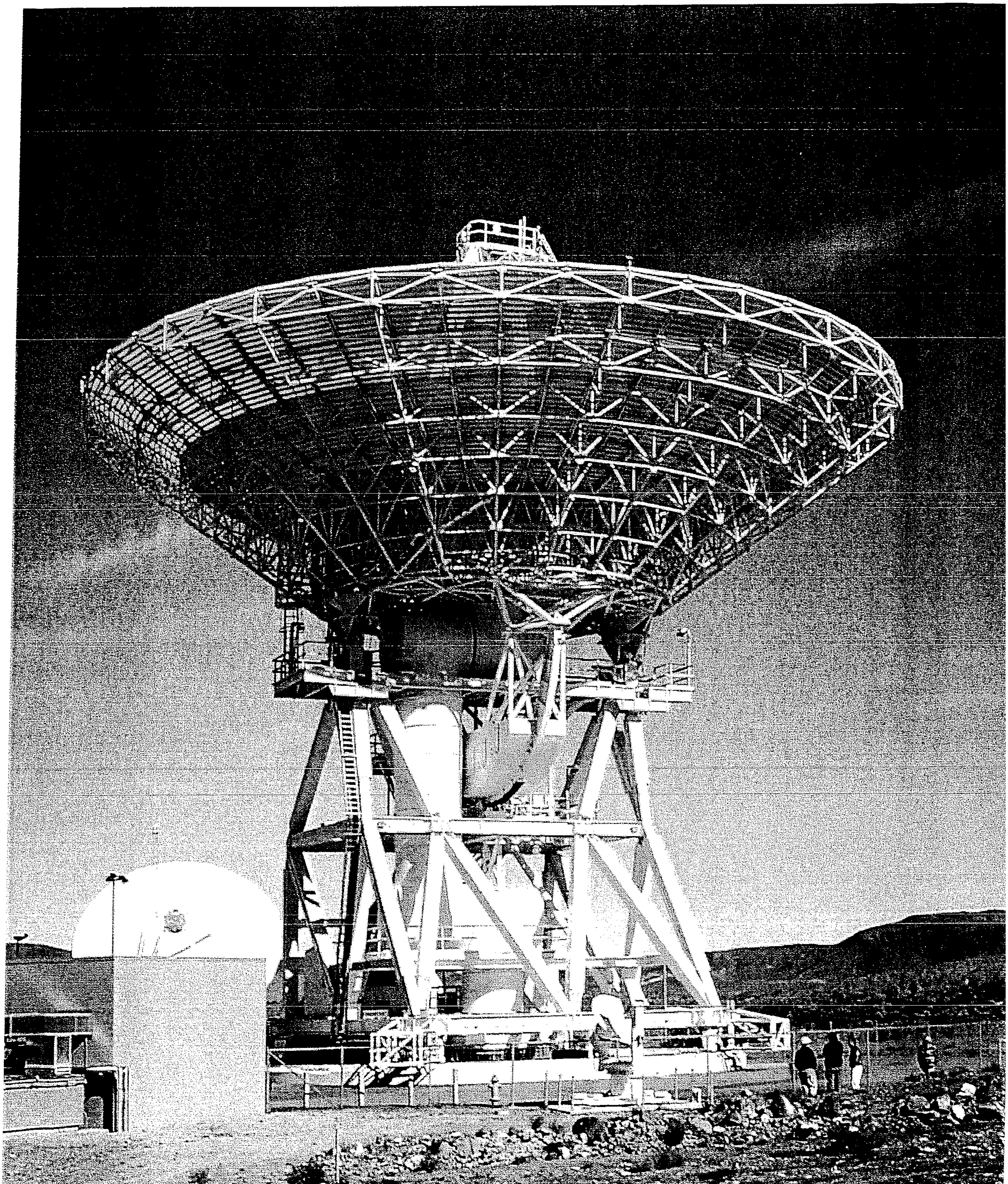
Regarding the noises:

Armstrong, Woo, and Estabrook *Ap. J.* 230, 570 (1979)

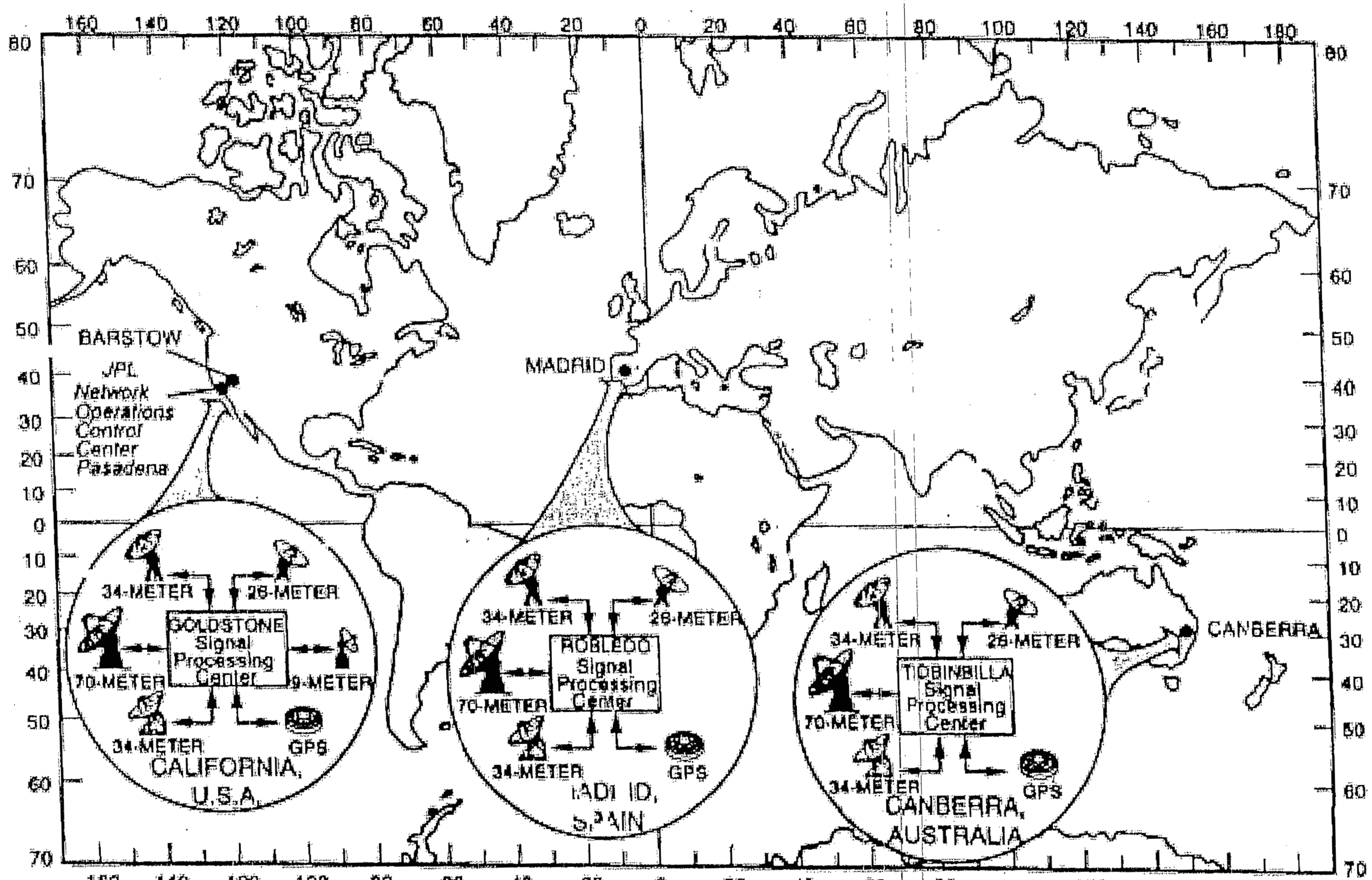
Armstrong *Radio Sci.* 33, 1727 (1998)

Iess et al. *CQG* 16, 1487 (1999)





THE DEEP SPACE NETWORK 1992 CONFIGURATION



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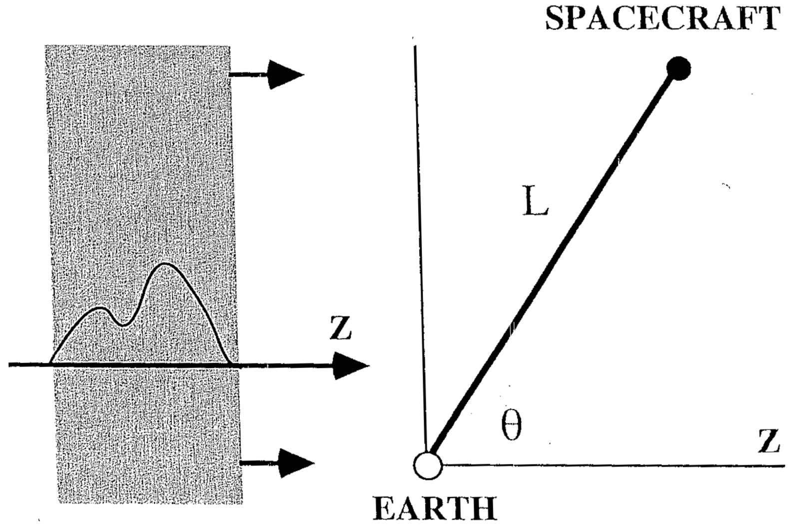
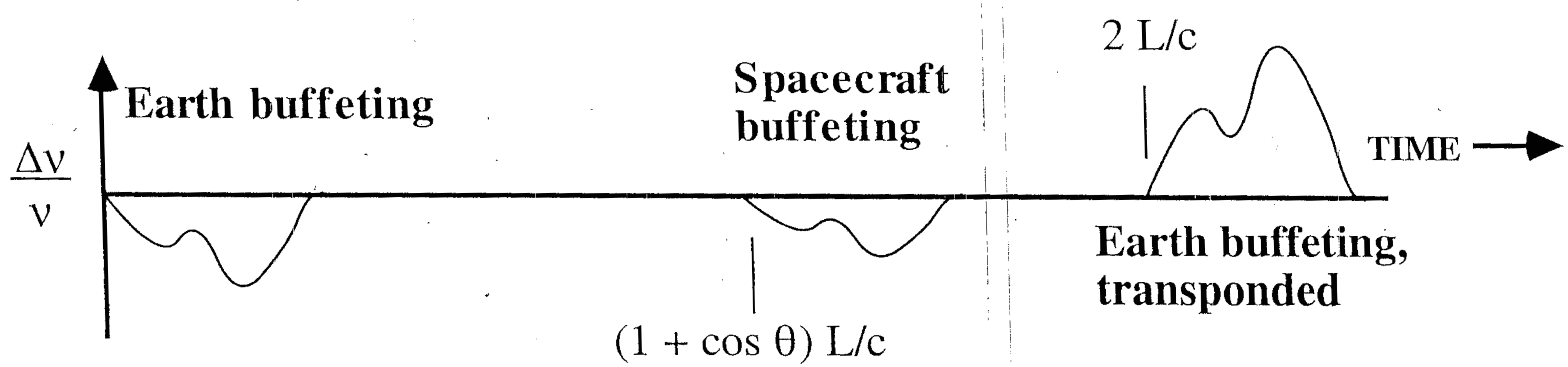
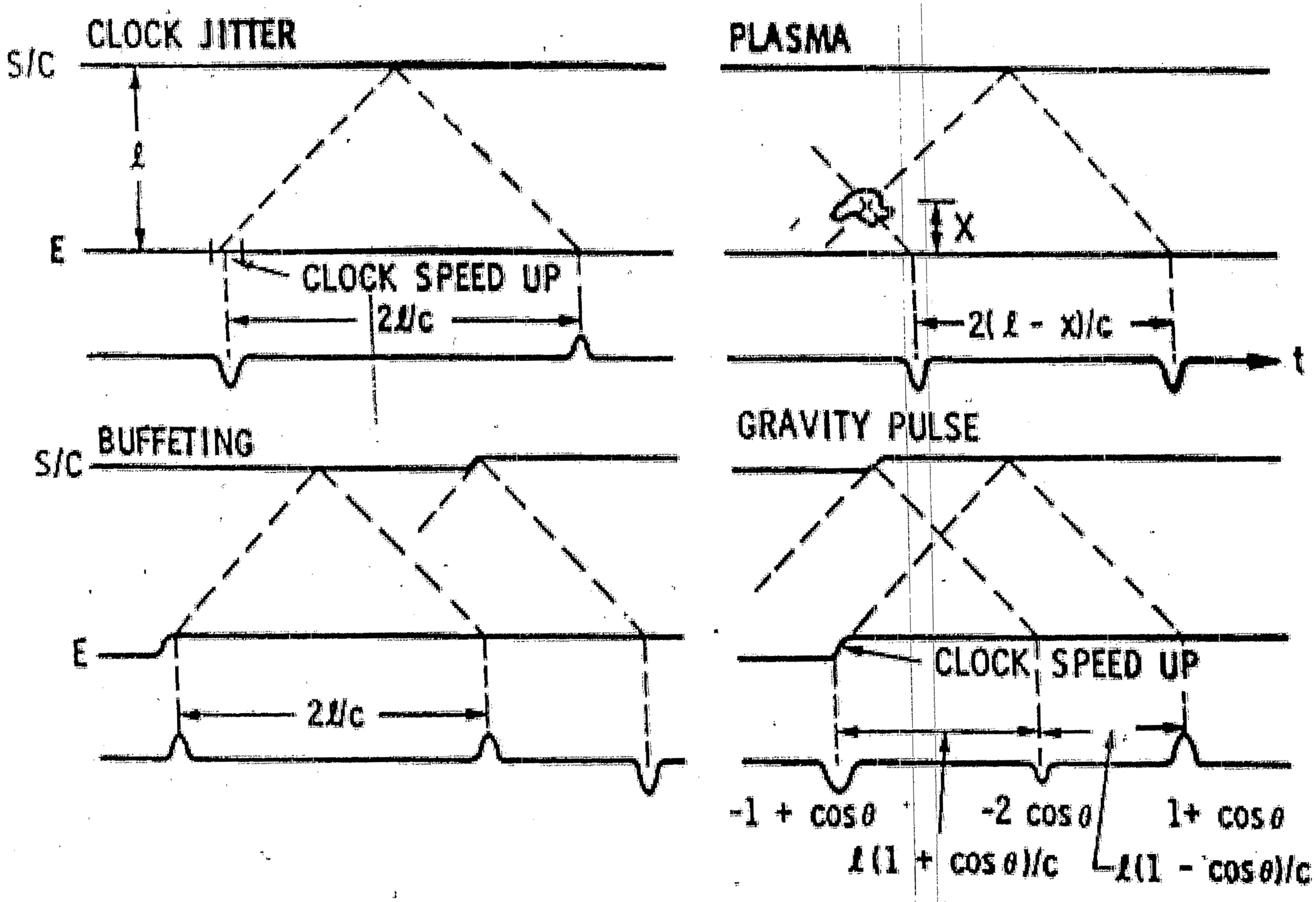
Response of Spacecraft Doppler Tracking to Gravitational Wave





Estabrook and Wahlquist, *Gen. Rel. Grav.* 6, 439 (1975)

DOPPLER SIGNALS CORRESPONDING TO DIFFERENT TYPES OF DISTURBANCE IN THE COMMUNICATION LINK



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Estimated Value of S/C's σ_Z^{GWE}

- **Results:**
  - 40 hours of data beginning 2001-DOY-152/T02:00:03.558 (sampling time is 4 s)
  - CAPS articulation motion was active over this time span (articulation frequency ≈ 0.0025 Hz)
  - Estimated value of σ_Z^{GWE} is ≈ 0.071 μm/sec. It is significantly better than the requirement (0.3 μm/sec)

- **Corresponding Allan deviation**

  $\approx 2.3\times10^{-16}$ < 10^{-15} (Requirement)

from: Won, Hanover, Belenky & Lee 10/18/01

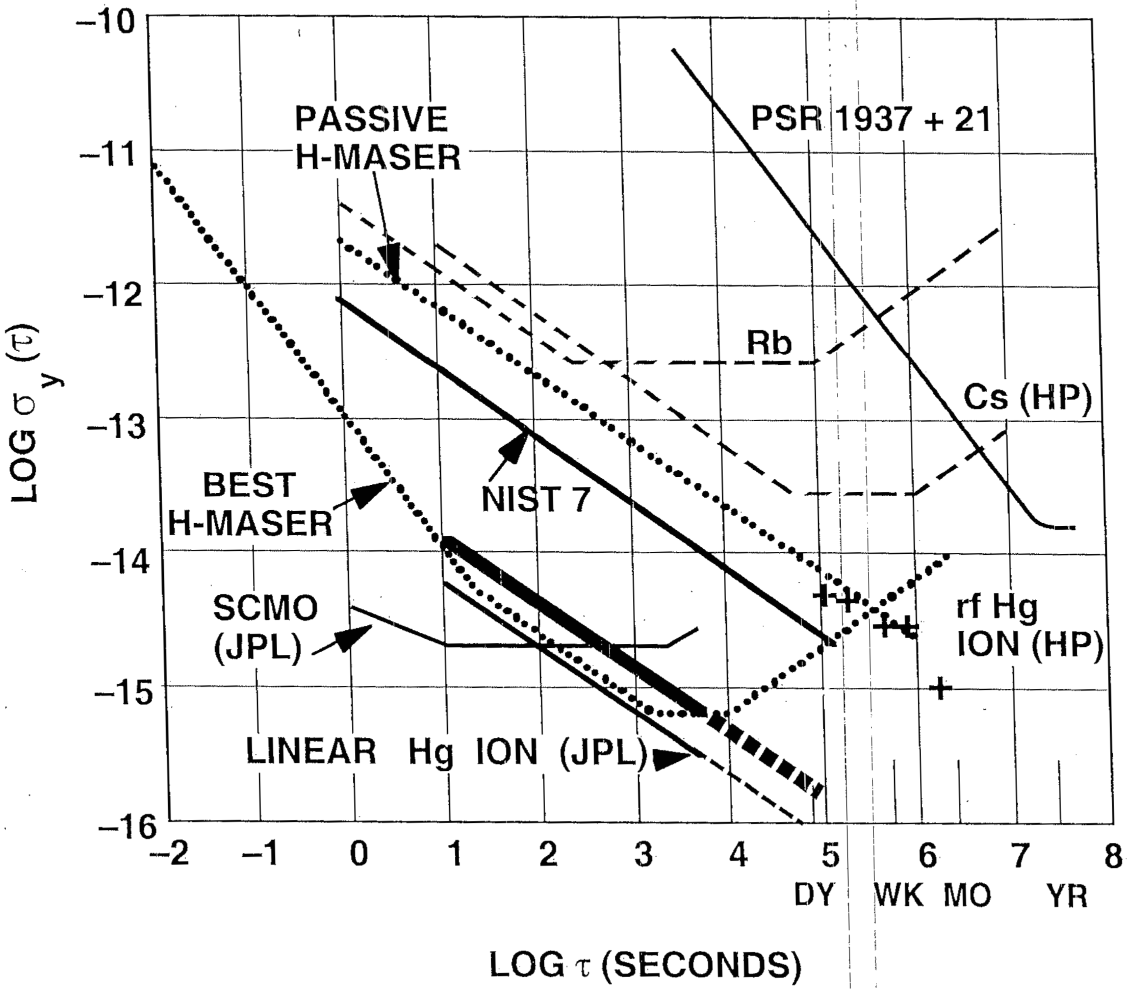
MAIN NOISES: FREQUENCY STANDARD STABILITY

- Spacecraft Doppler tracking is not interferometric; coherence is maintained through the frequency and timing system. Thus FTS is fundamental

- Transfer function in two-way Doppler: $\delta(t) - \delta(t - T_2)$

- Cassini era LITS/SCO has excellent stability on integration times 1–10,000 seconds (see Allan deviation plot, due to L. Maleki)

LINEAR ION TRAP STANDARD (LITS)
FRACTIONAL FREQUENCY STABILITY



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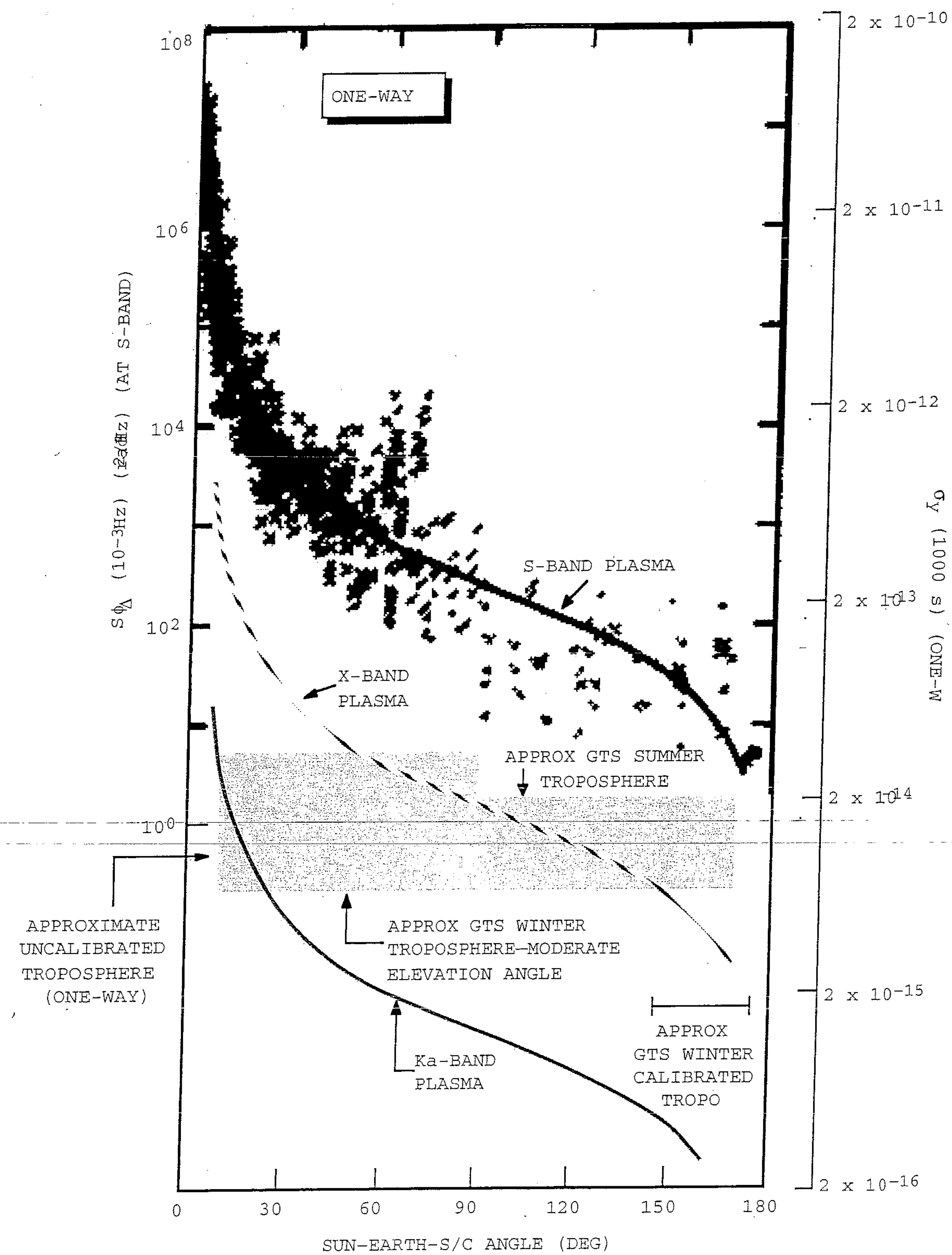
MAIN NOISES: PLASMA SCINTILLATION

- Dispersive, refractive index fluctuations proportional to λ^2
- Transfer function in two-way Doppler: $\delta(t) + \delta(t - T_2 + 2x/c)$
- Plasma scintillation is dominant noise in S-band observations (even at opposition), but a secondary noise source for Ka-band observations at opposition

INTERPLANETARY PHASE SCINTILLATION



MAIN NOISES: TROPOSPHERIC SCINTILLATION

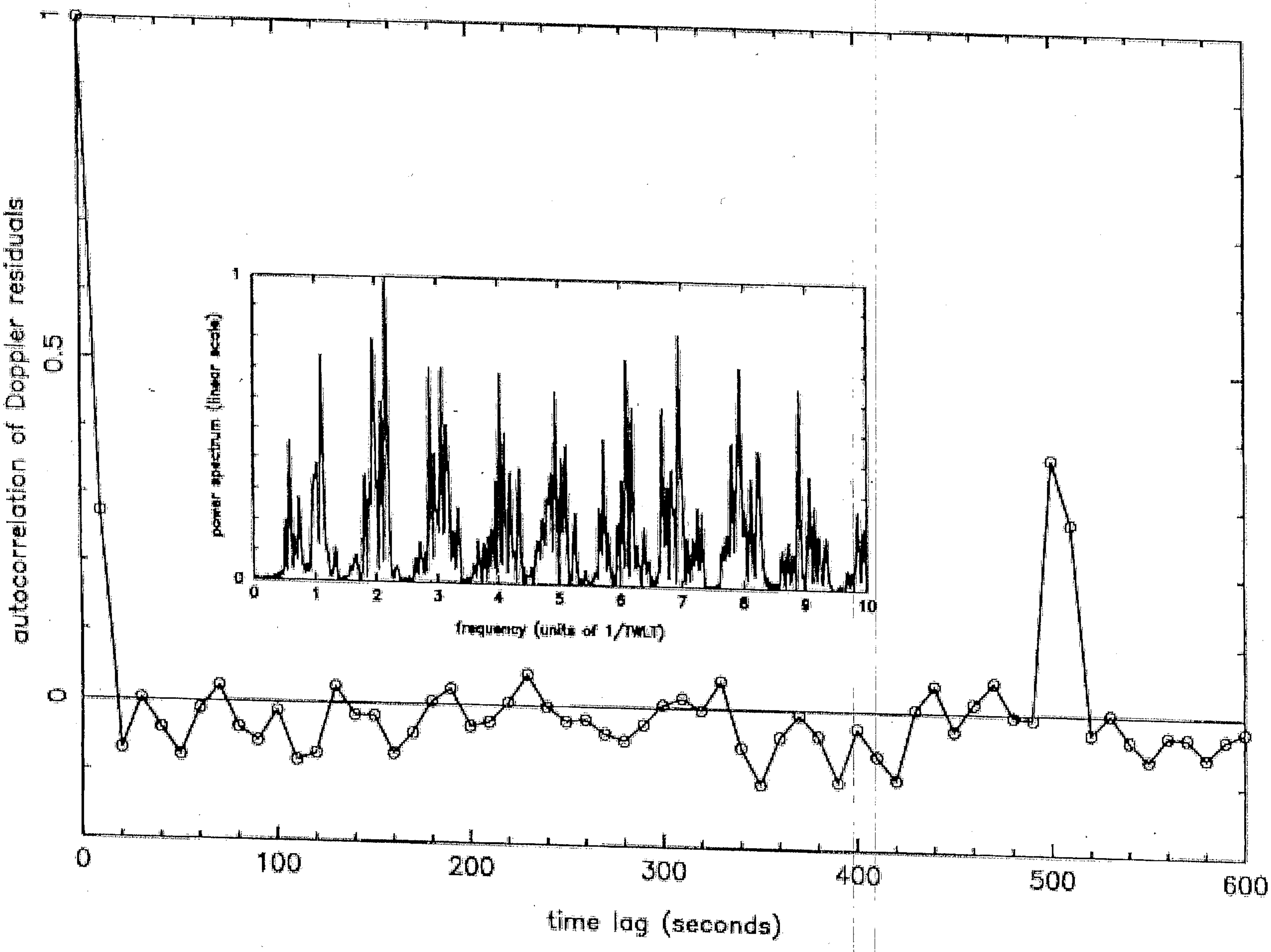
- Refractive index fluctuations at microwave frequencies are dominated by fluctuations of the water vapor along the LOS.

- Transfer function in two-way Doppler: $\delta(t) + \delta(t - T_2)$

- Independent measures of the effect available using WVRs (e.g., Keihm *TDA Prog. Rep.* 42-122, 1 (1995))

- Operational X-band data can be approximately decomposed into tropospheric and plasma scintillation; results consistent with Keihm's observations (Armstrong *Radio Sci.* 33, 1727 (1998))

- Cassini-era Advanced Media Calibrations System will calibrate and allow removal of ≈80% of the wet component; dry component + residual wet component will have transfer function $\delta(t) + \delta(t - T_2)$



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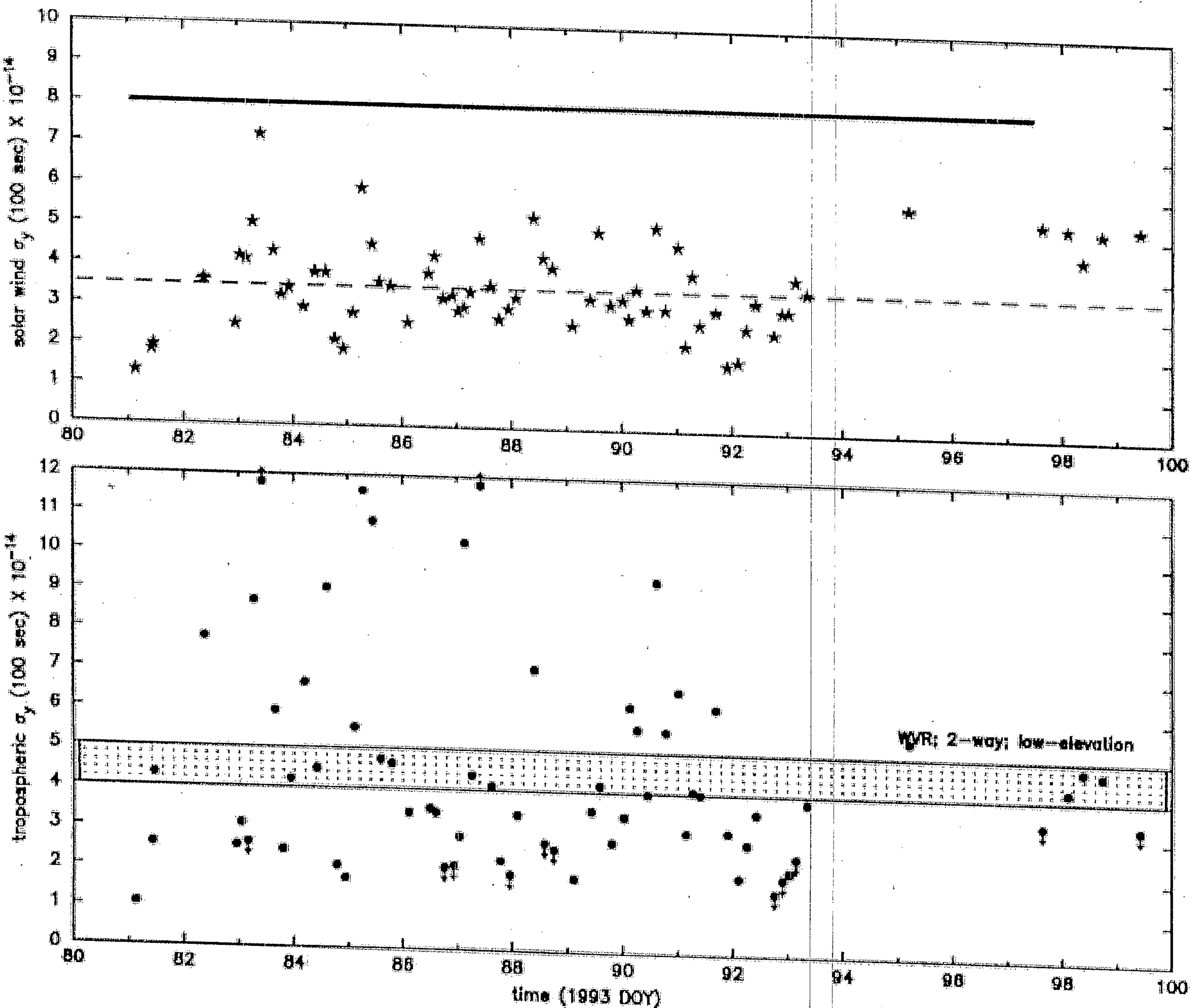
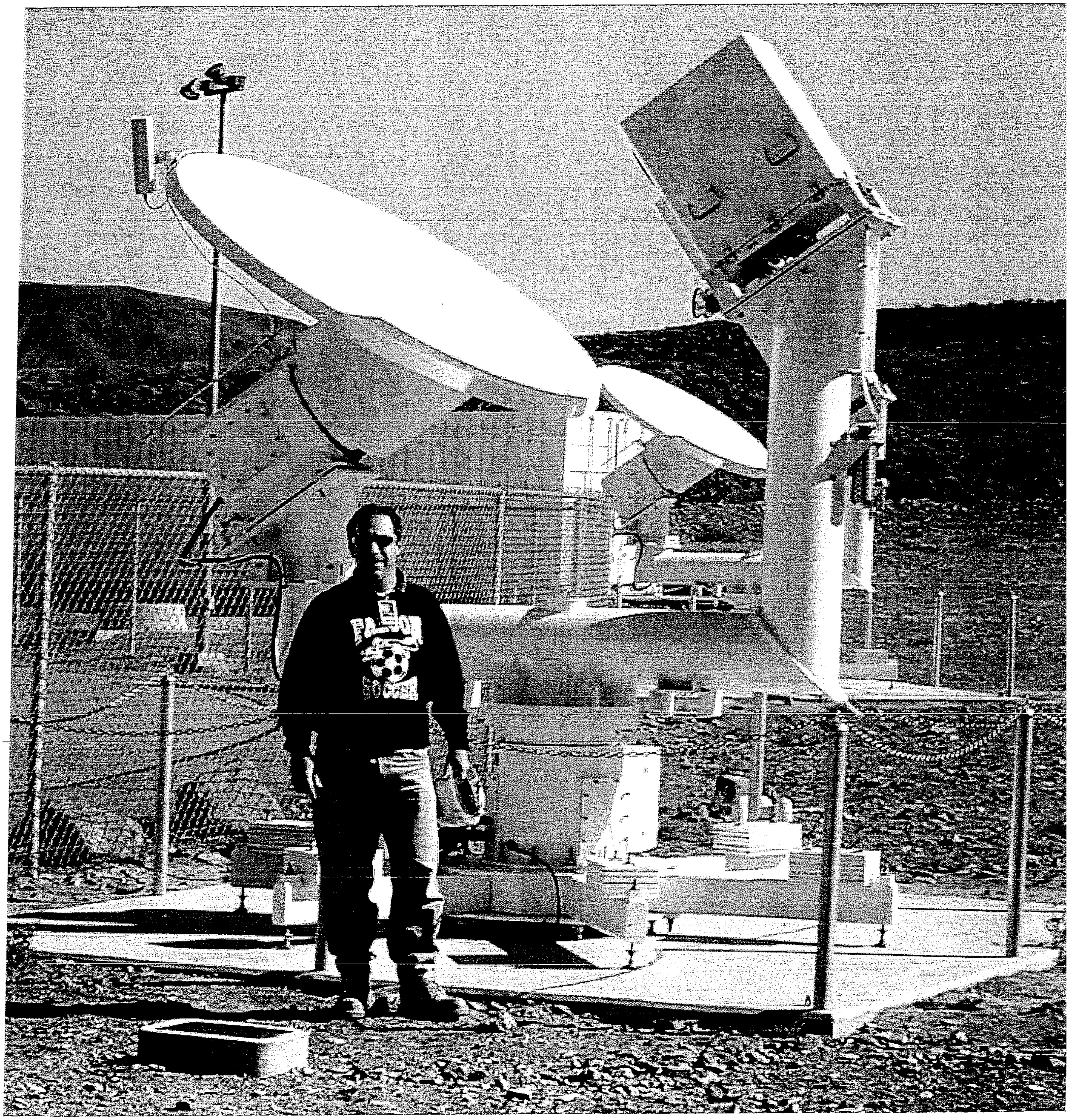
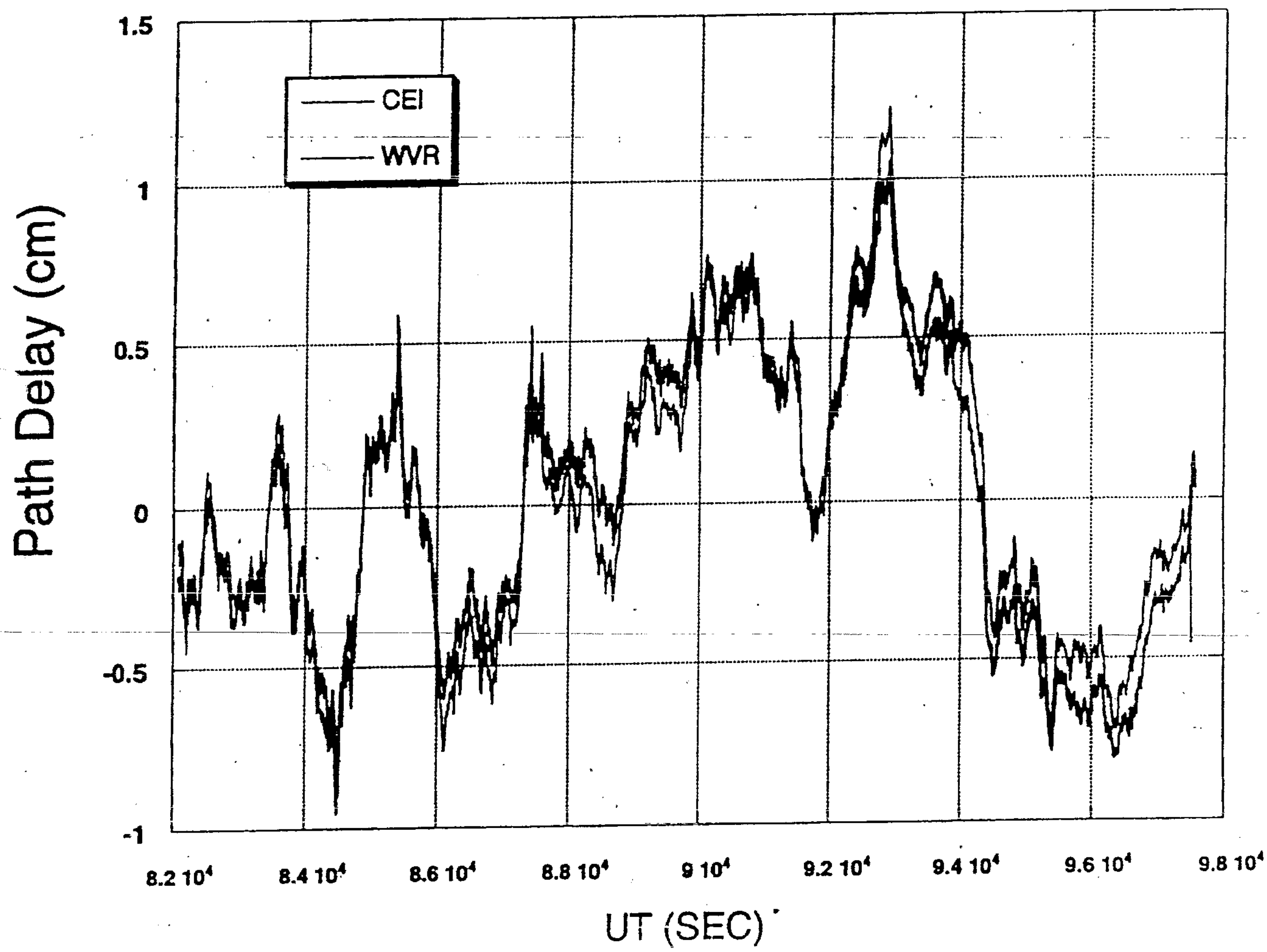
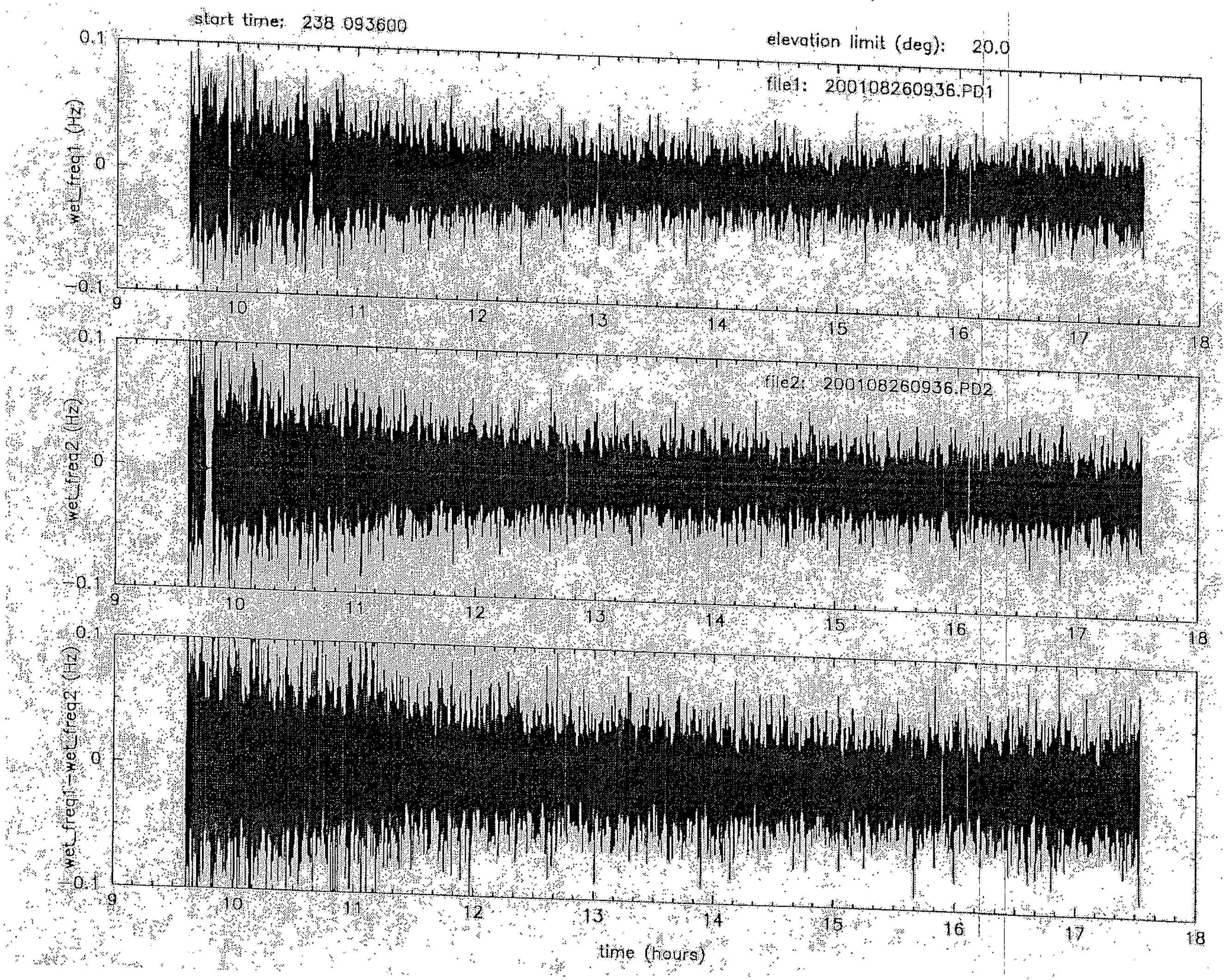

solar wind σ_y (100 sec) X 10^{-14}
tropospheric σ_y (100 sec) X 10^{-14}
WVR; 2-way; low-elevation
time (1993 DOY)

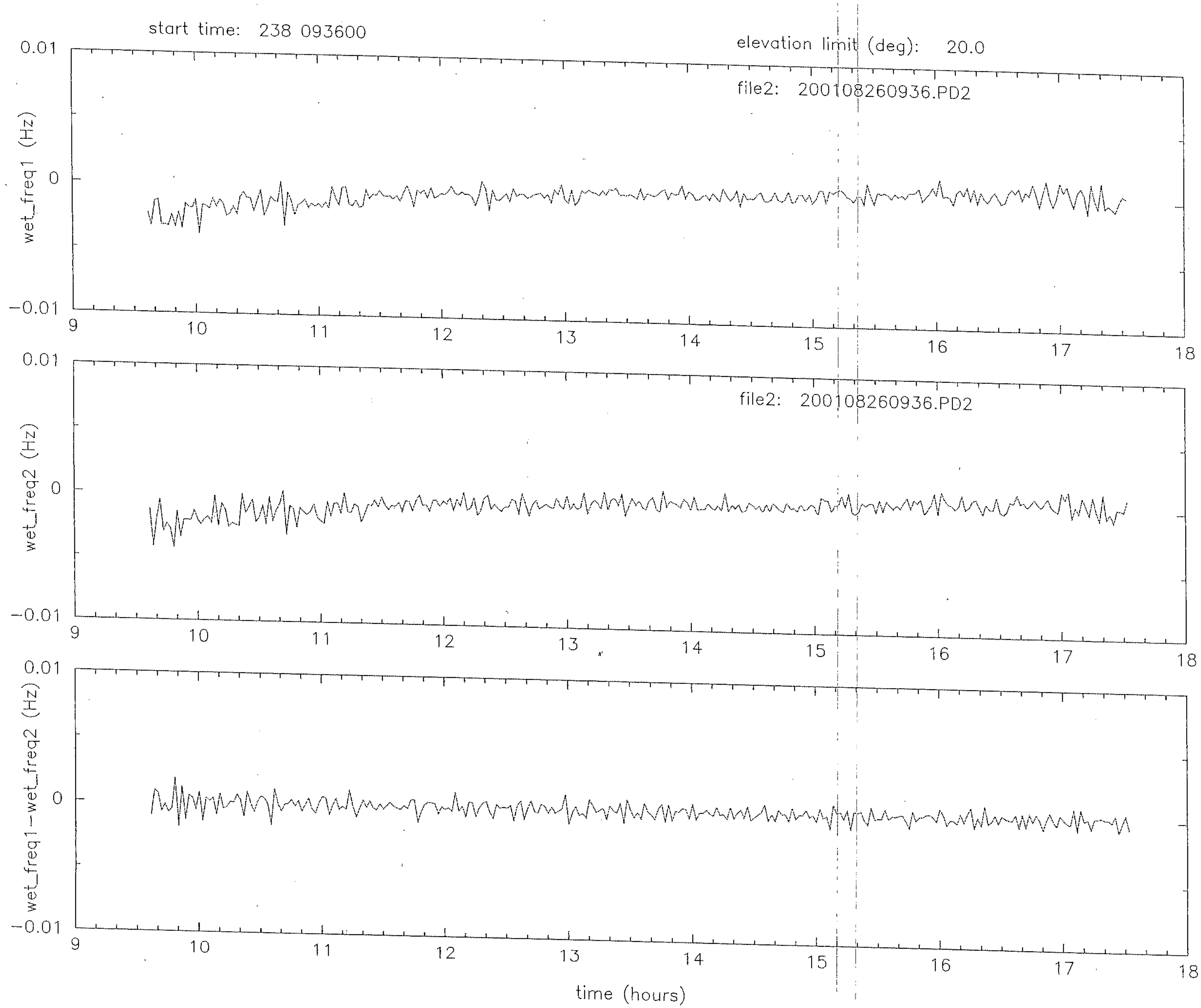


WVR-CEI Comparison
DOY 138, 2000

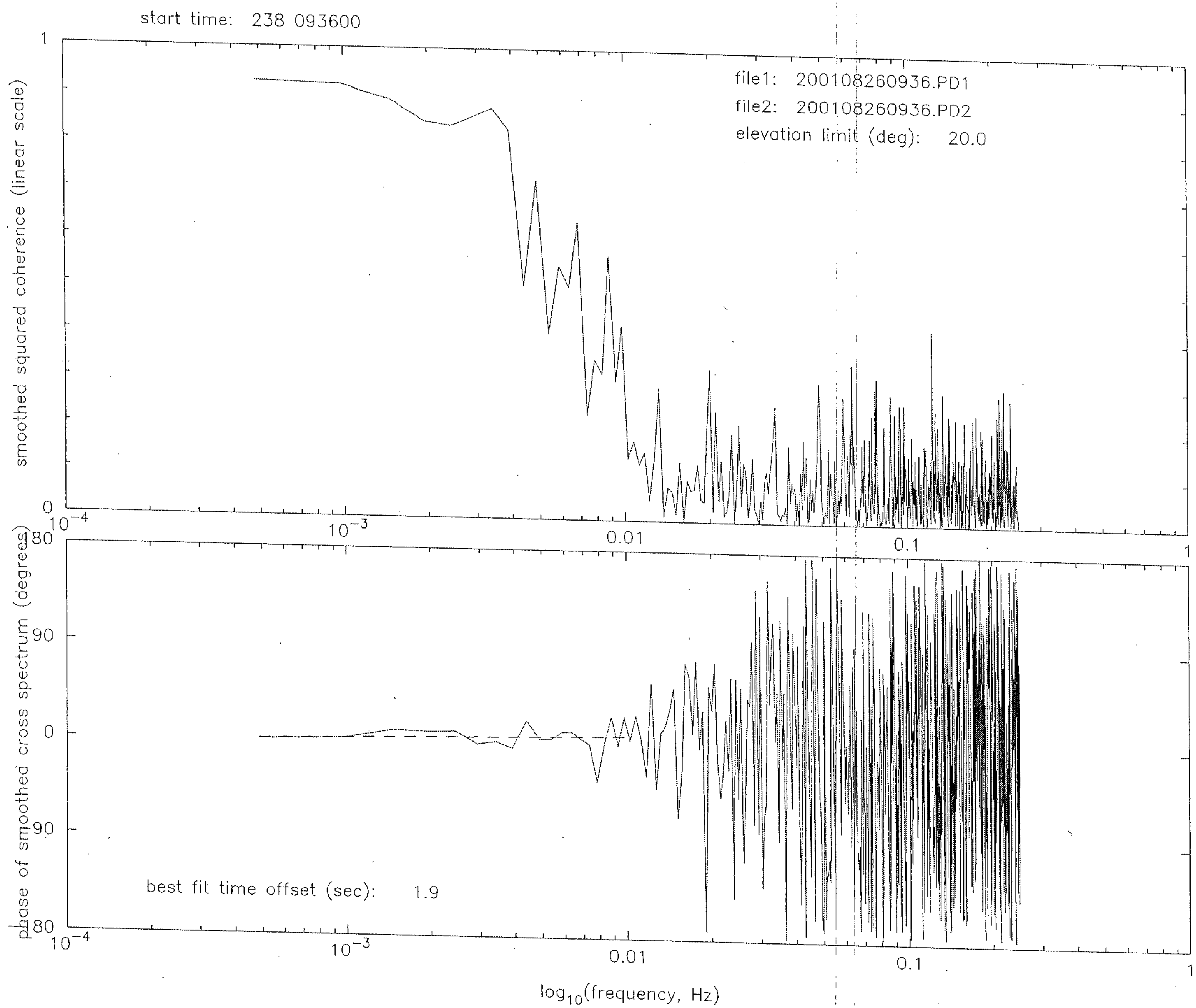




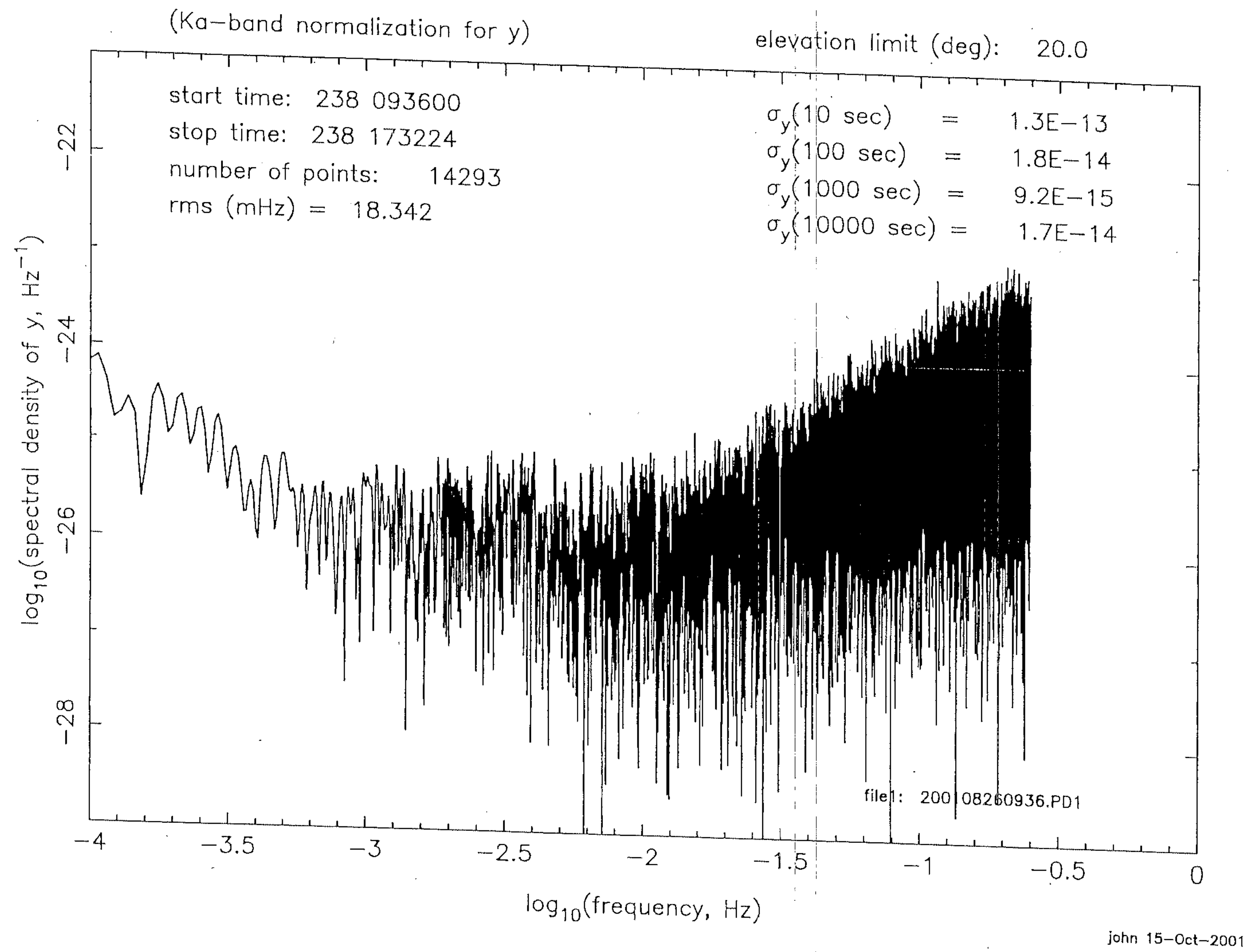
start time: 238 093600
elevation limit (deg): 20.0
file1: 200108260936.PD1
wet_freq1 (Hz)
file2: 200108260936.PD2
wet_freq2 (Hz)
wet_freq1-wet_freq2 (Hz)
time (hours)



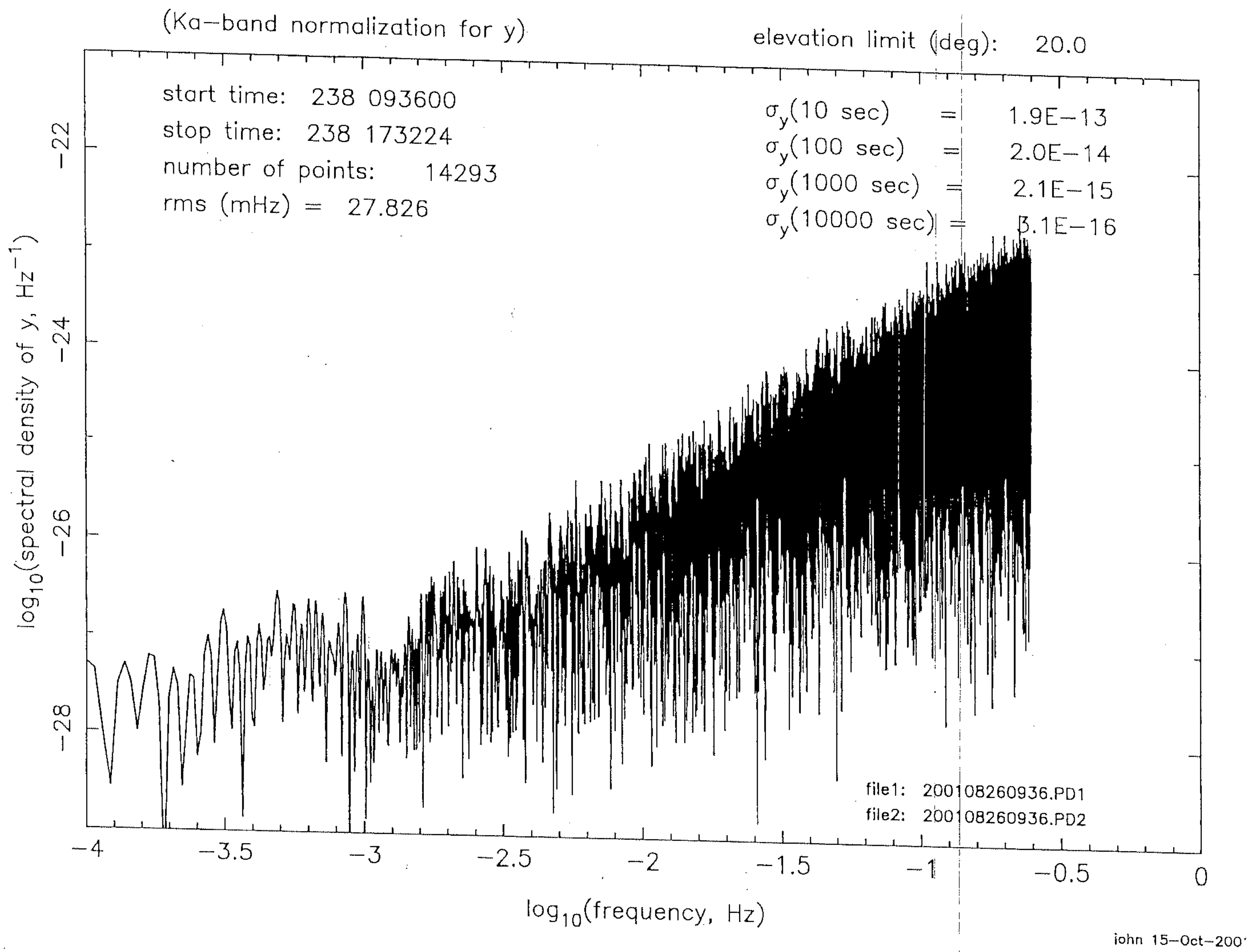
john 15−Oct−2001 05:49



john 15-Oct-2001 05:49



(Ka−band normalization for y)
elevation limit (deg): 20.0
start time: 238 093600
stop time: 238 173224
number of points: 14293
rms (mHz) = 18.342
σy(10 sec) = 1.3E−13
σy(100 sec) = 1.8E−14
σy(1000 sec) = 9.2E−15
σy(10000 sec) = 1.7E−14
log10(spectral density of y, Hz−1)
−22
−24
−26
−28
file1: 200108260936.PD1
−4
−3.5
−3
−2.5
−2
−1.5
−1
−0.5
0
log10(frequency, Hz)
john 15−Oct−2001


(Ka–band normalization for y)
elevation limit (deg): 20.0
start time: 238 093600
stop time: 238 173224
number of points: 14293
rms (mHz) = 27.826
σy(10 sec) = 1.9E–13
σy(100 sec) = 2.0E–14
σy(1000 sec) = 2.1E–15
σy(10000 sec) = 3.1E–16
log10(spectral density of y, Hz–1)
–22
–24
–26
–28
–4
–3.5
–3
–2.5
–2
–1.5
–1
–0.5
0
log10(frequency, Hz)
file1: 200108260936.PD1
file2: 200108260936.PD2
john 15–Oct–200

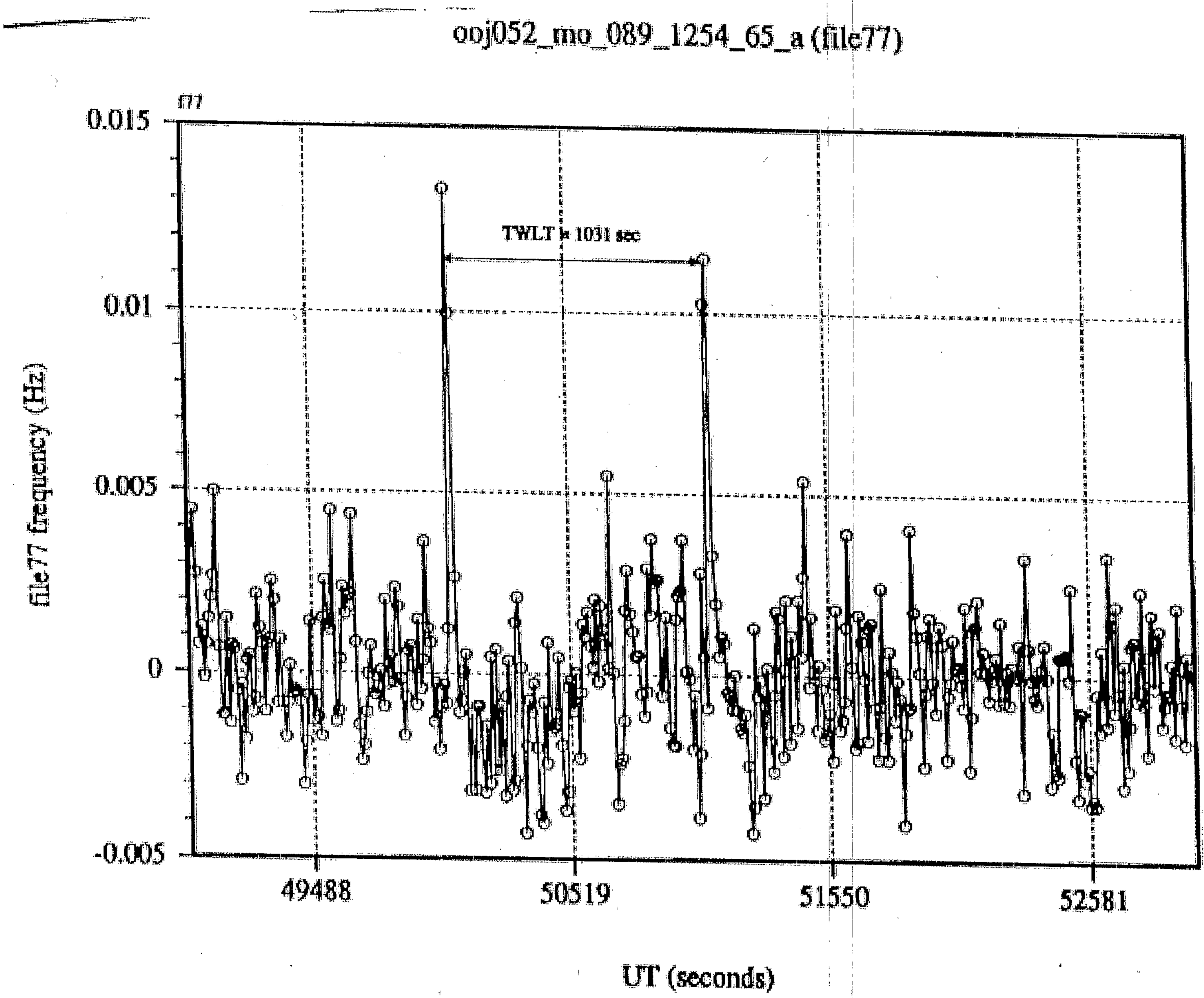
MAIN NOISES: ANTENNA MECHANICAL STABILITY

- Differential measurements (under controlled conditions) indicate $\sigma_y(1000\text{sec}) \approx 1 \times 10^{-15}$ (Otoshi and Franco, *TDA Prog. Report 42-10*, 151 (1992))

- Transfer function in two-way Doppler is $\delta(t) + \delta(t - T_2)$

- Measurements at X-band under operational conditions are confused with tropospheric scintillation and produce only poor limits ($< 1 \times 10^{-14}$ at τ = 1000 sec) (Armstrong *Radio Sci.* 33, 1727 (1998))

- Infrequent large events—almost certainly antenna mechanical—are observed, however (see example)


ooj052_mo_089_1254_65_a (file77)
f77
0.015
0.01
0.005
0
-0.005
TWLT = 1031 sec
file77 frequency (Hz)
49488
50519
51550
52581
UT (seconds)

MODEL OF THE DOPPLER TIME SERIES

$y(t) = \Delta f(t)/f_0$ = gravity waves

+ propagation noise + antenna mechanical noise
+ clock noise + thermal noise
+ systematic effects

$$= g(t) * \{[(\mu - 1)/2]\delta(t) - \mu\delta[t - (1+\mu)L/c] + [(1+\mu)/2]\delta(t - 2L/c)\}$$

$$+ \text{propagation}(t) * \{\delta(t) + \delta(t - 2L/c)\}$$

$$+ \text{antenna mechanical}(t) * \{\delta(t) + \delta(t - 2L/c)\}$$

$$+ \text{frequency standard}(t) * \{\delta(t) + \delta(t - 2L/c)\}$$

$$+ \text{thermal}(t)$$

$$+ \text{systematic effects}$$

where: $g(t) = (1 - \mu^2)^{-1}\{n \cdot [h_+(t)e_t + h_x(t)e_x] \cdot n\}$

L = earth-s/c distance

$\mu = k \cdot n$

$*$ = convolution

SUMMARY OF SIGNALS AND NOISE

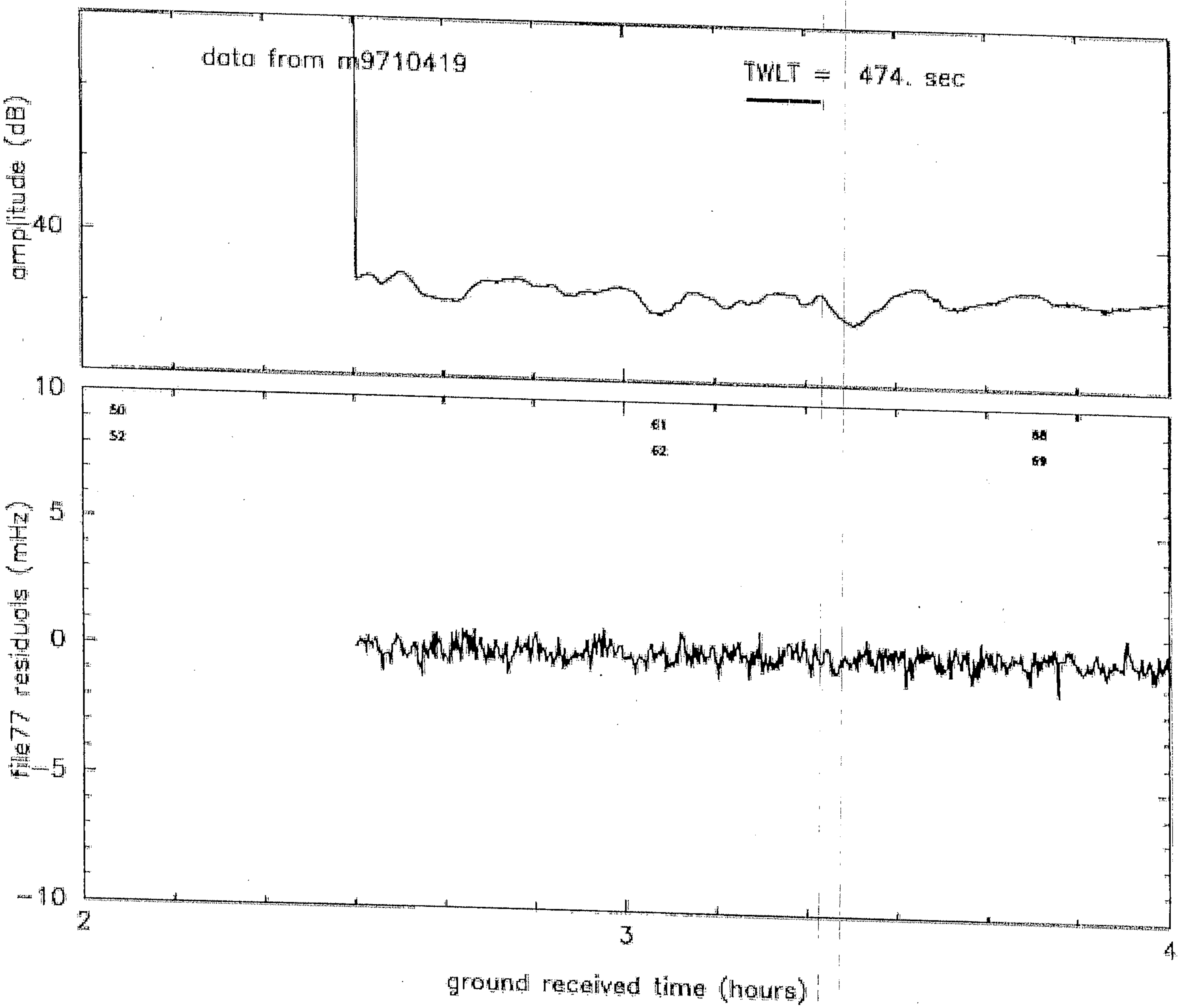
- Signals: "three-pulse" response in the Doppler of the GW excitation
  - Depends on direction to source and s/c two-way light time
  - Not shift-invariant if direction or distance depend on time-of-observation
  - Bandpass: low-frequency signals attenuated due to pulse cancellation; high frequencies cut off by thermal and clock noise. Typical wave duration for best sensitivity depends on T_2 but ~10-10,000 seconds
  - Unlike LISA and other detectors: antenna size/wavelength ~1 to 100
- Noise sources: various "2-pulse" transfer functions for clock instability, propagation noise (solar wind, ionosphere, troposphere), thermal noise
  - Noise nonstationarity
  - Systematic errors

HOW TO DO A DOPPLER TRACKING EXPERIMENT

- Need two separated test masses—the earth and a spacecraft in cruise as operationally quiet as possible (need to be far from perturbing masses and need to minimize unmodeled motion of the spacecraft)
- Spacecraft should be as close to anti-solar direction as practical (minimize charged particle scintillation due to solar wind)
- Spacecraft-earth separation should be large (maximize band of Fourier frequencies to which the experiment is sensitive)
- Highly-stable Doppler system to measure relative velocity of the earth and spacecraft (excellent frequency standard; careful signal distribution, etc.)
- Ground system and spacecraft telemetry (correct for or veto data based on known systematics of the apparatus)
- Good weather and media calibration data

OBSERVATIONS TO DATE

1980	Voyager	Hellings et al. (1981) (few passes; bursts)
1981	Pioneer 10	Anderson et al. (1984) (3 passes, long T_2; no GW from Geminga)
1983	Pioneer 11	Armstrong, Estabrook, Wahlquist (1987) (broadband search for periodic waves)
1988	Pioneer 10	Anderson et al. (1993) (10 days; chirps and coalescing binaries)
1992	Ulysses	Bertotti et al. (1995) (1 month; sinusoids and chirps)
1993	MO/GLL/ULS	jGWE collaboration (19 days; X-band on MO; only LF coincidence experiment)
1994-5	Galileo	Estabrook et al. (40 days; long T_2)
1997	Mars Global Surveyor	Armstrong et al. (3 weeks; X-band)



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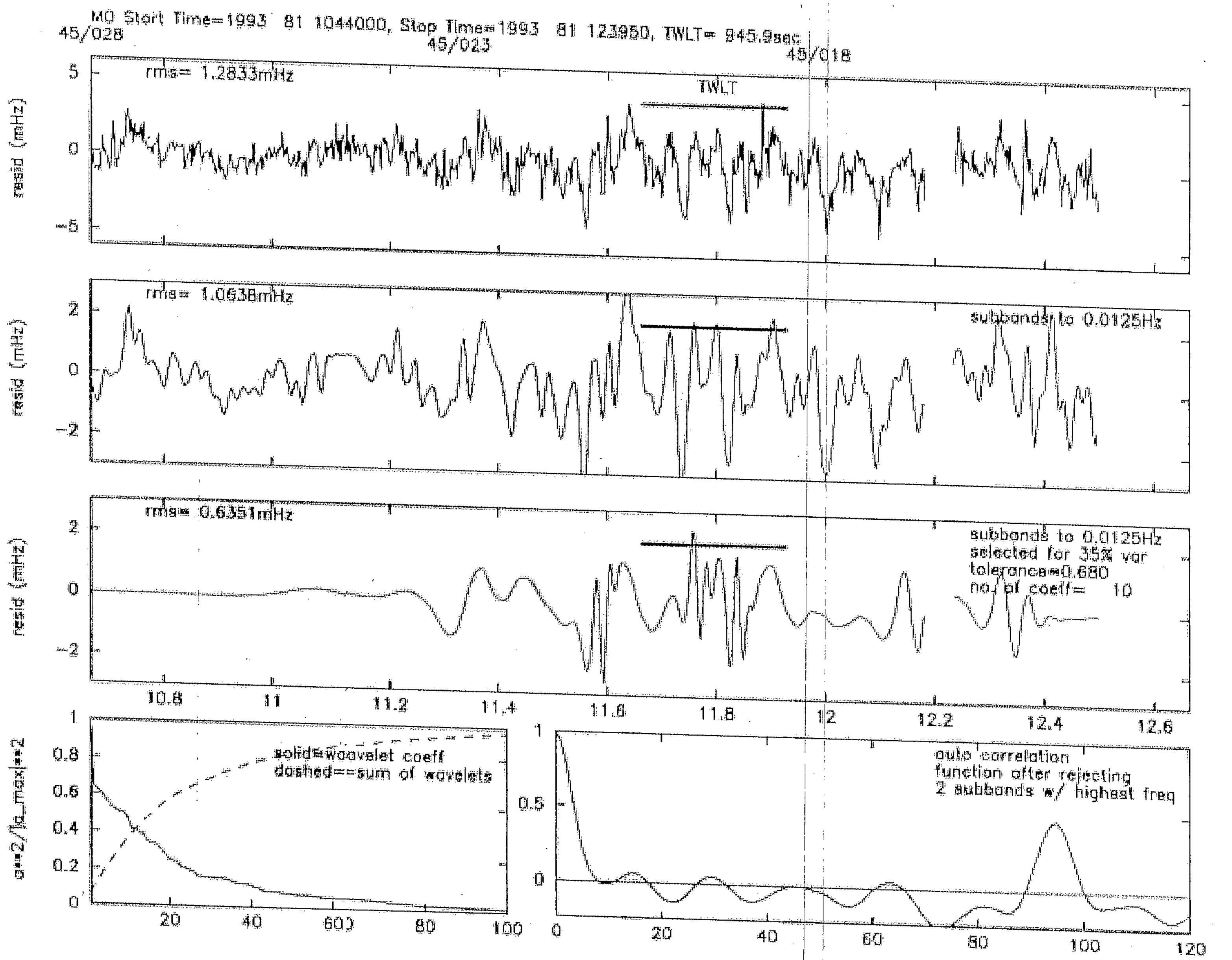

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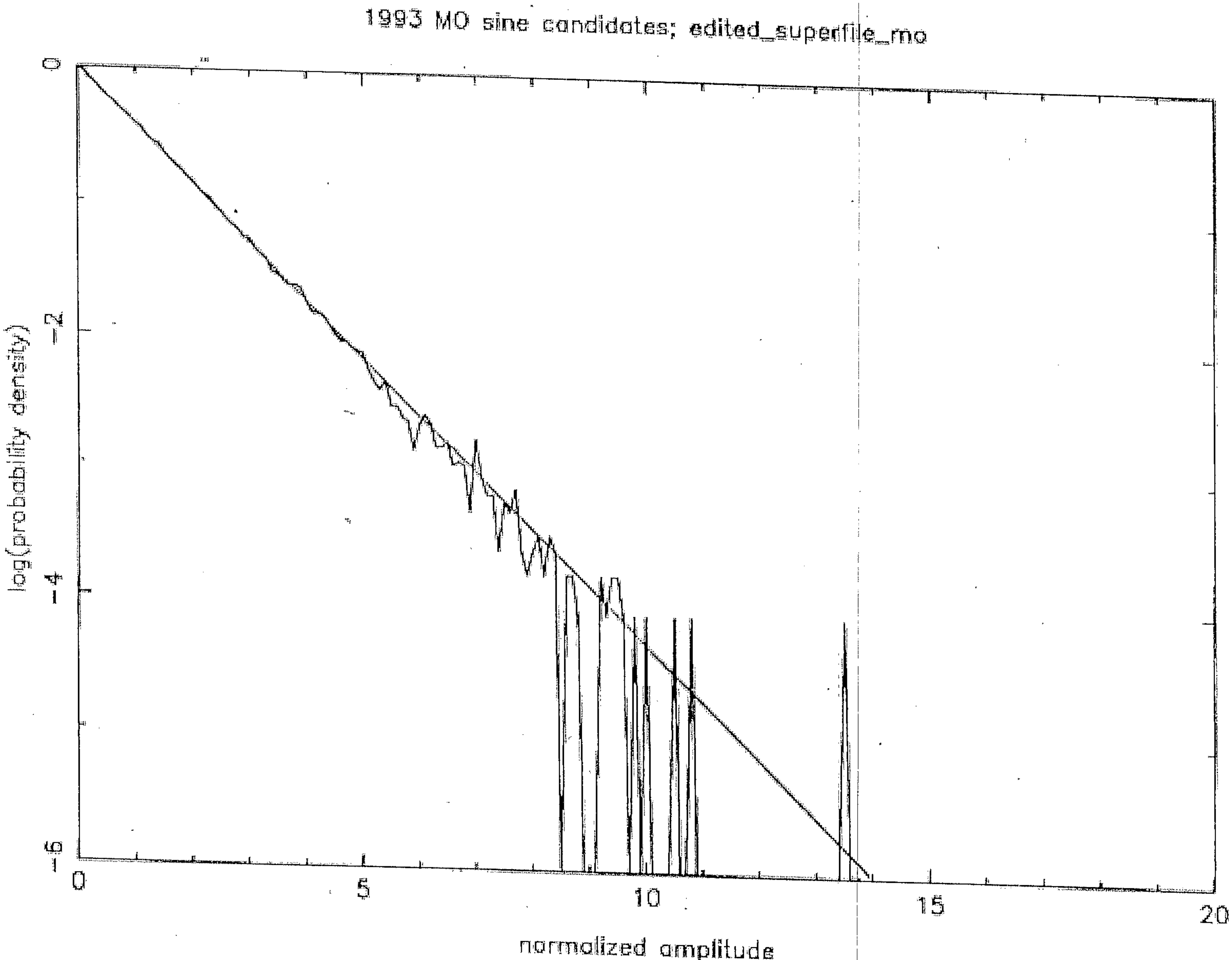

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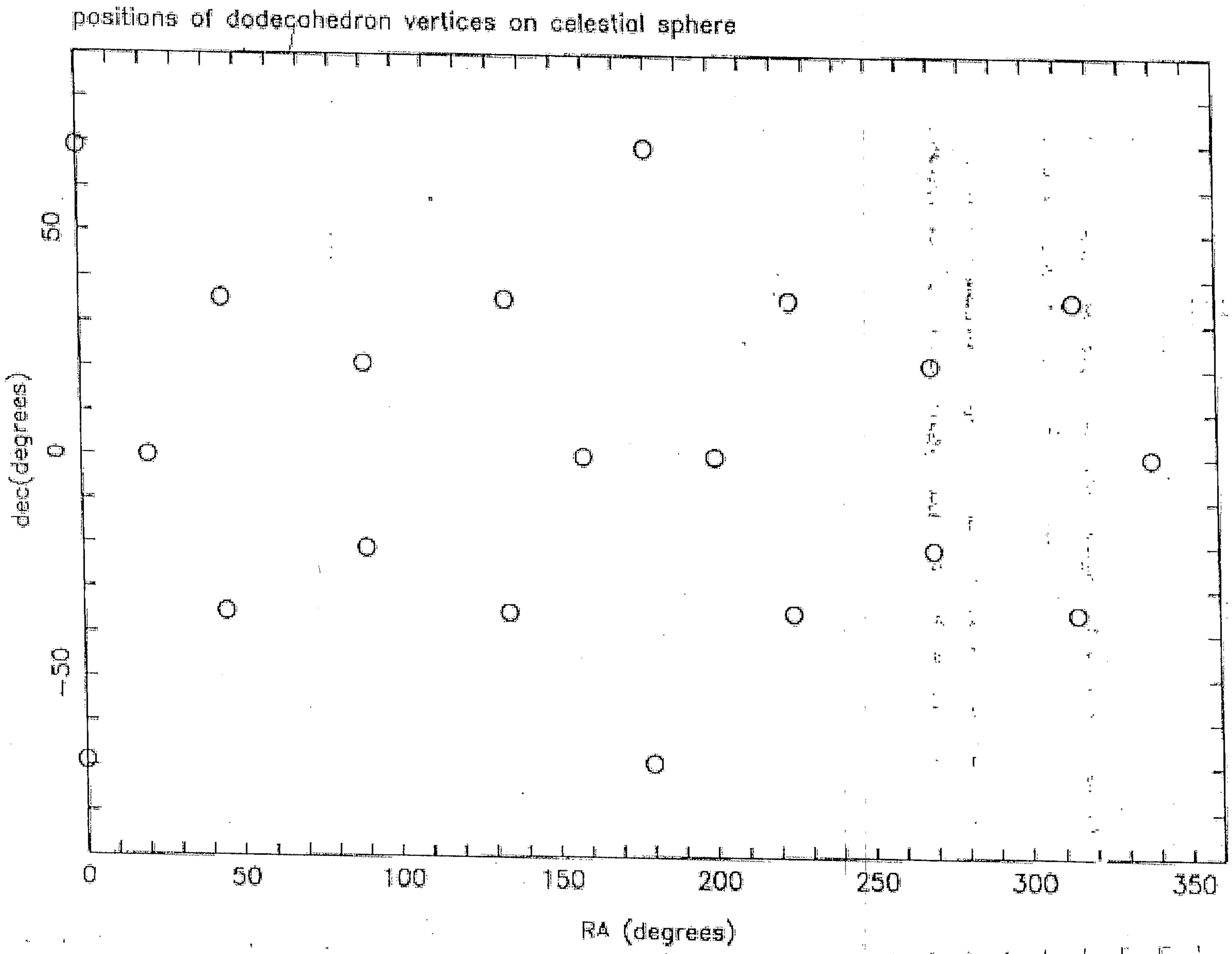

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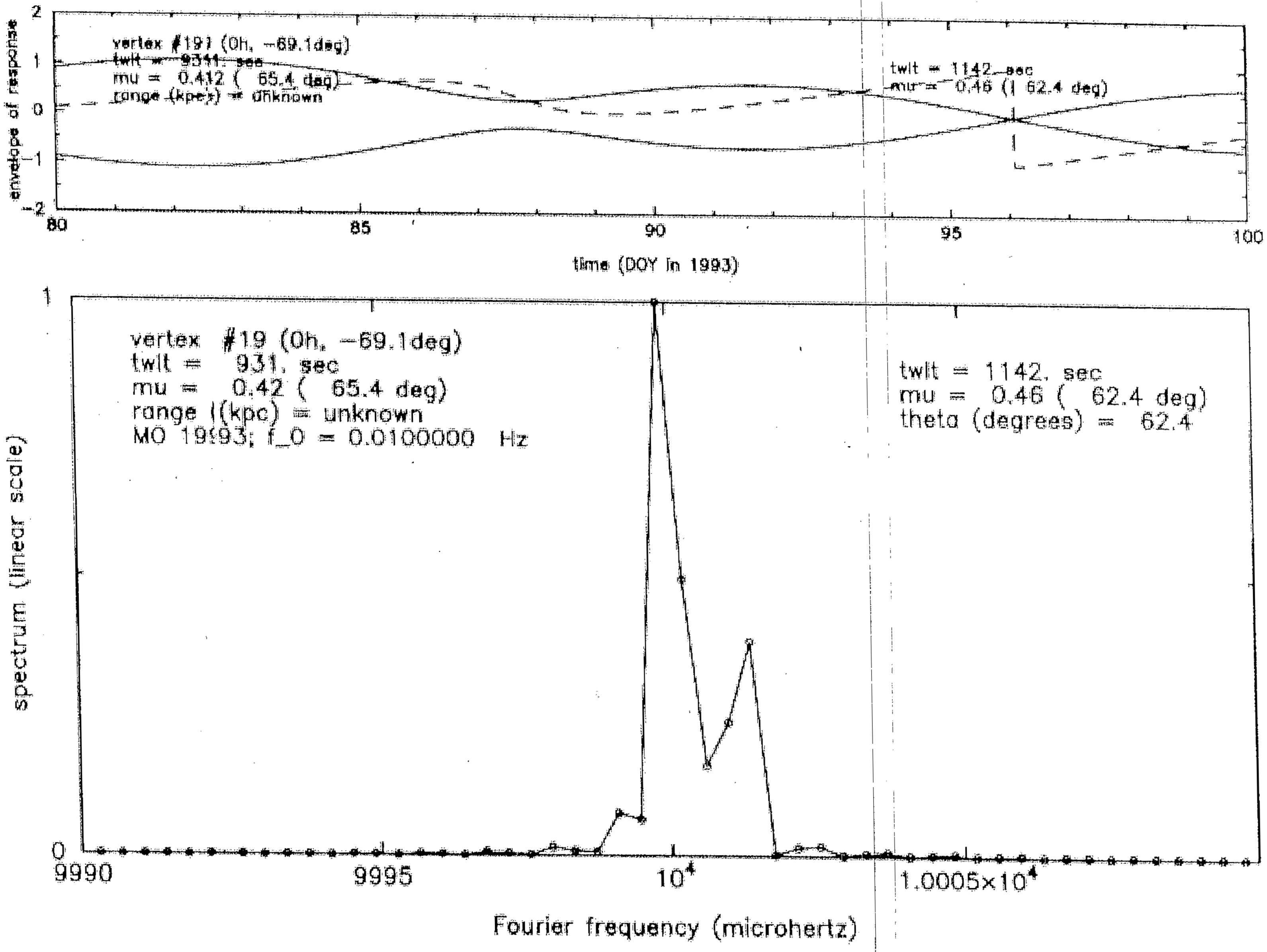

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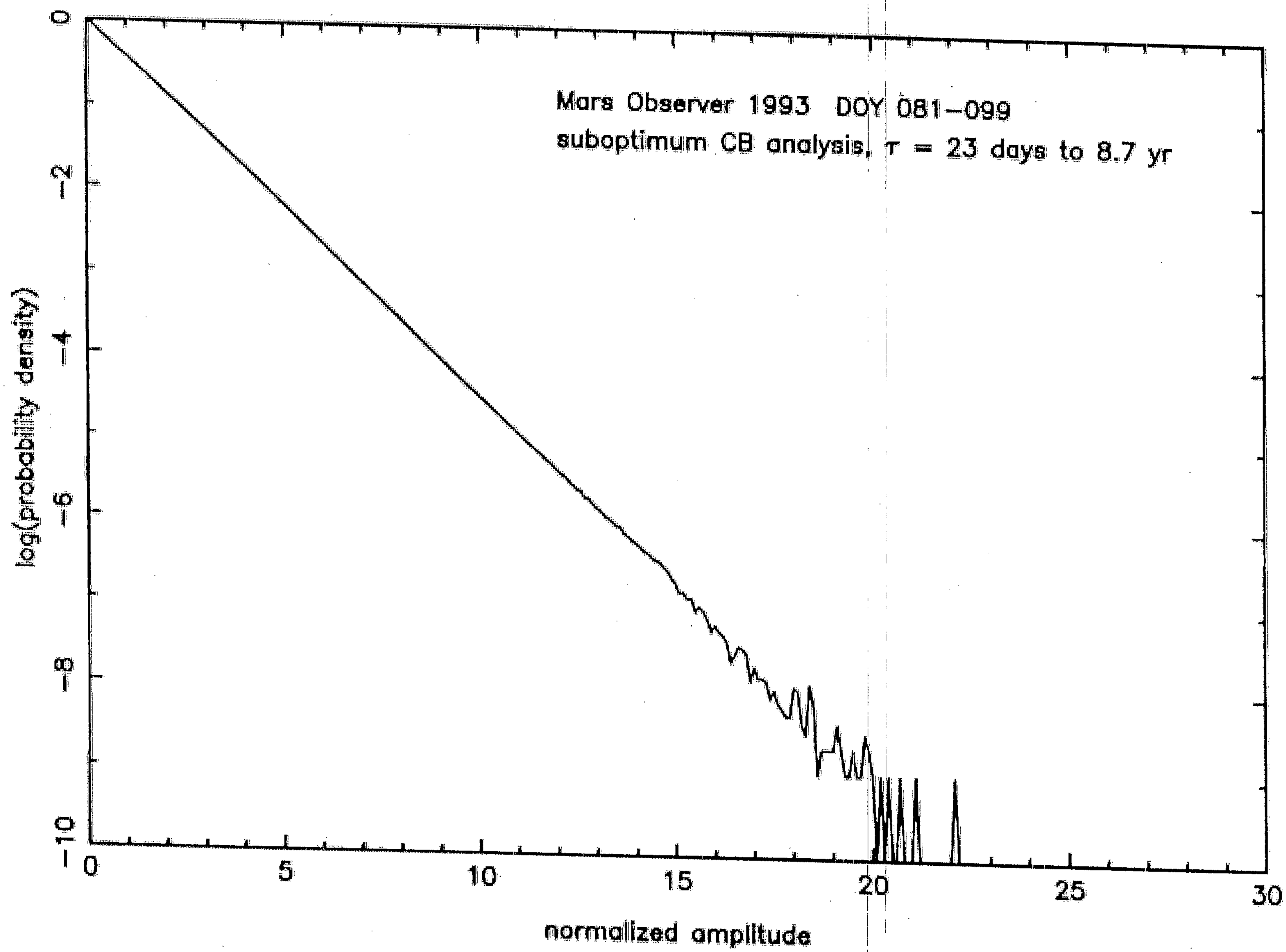

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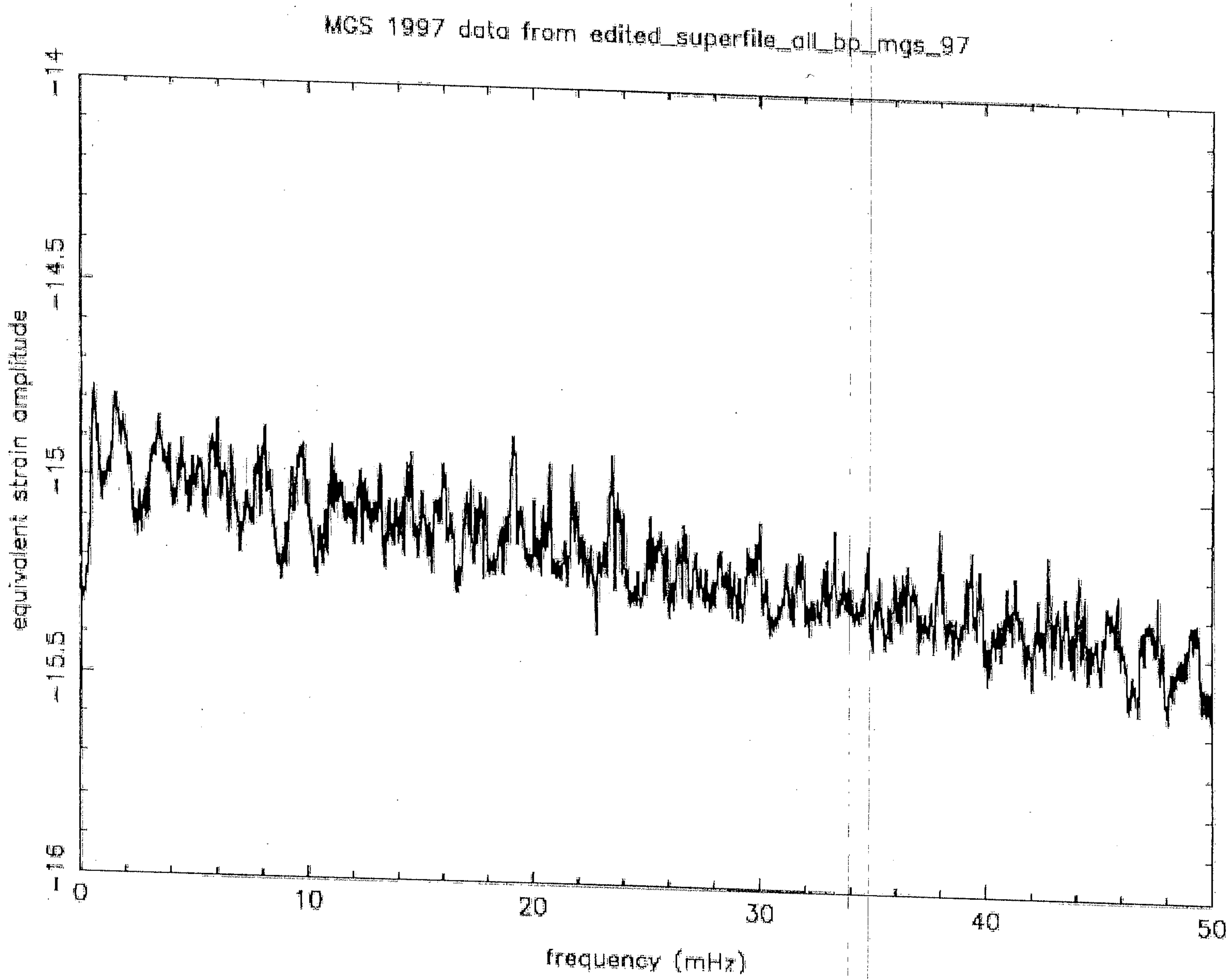

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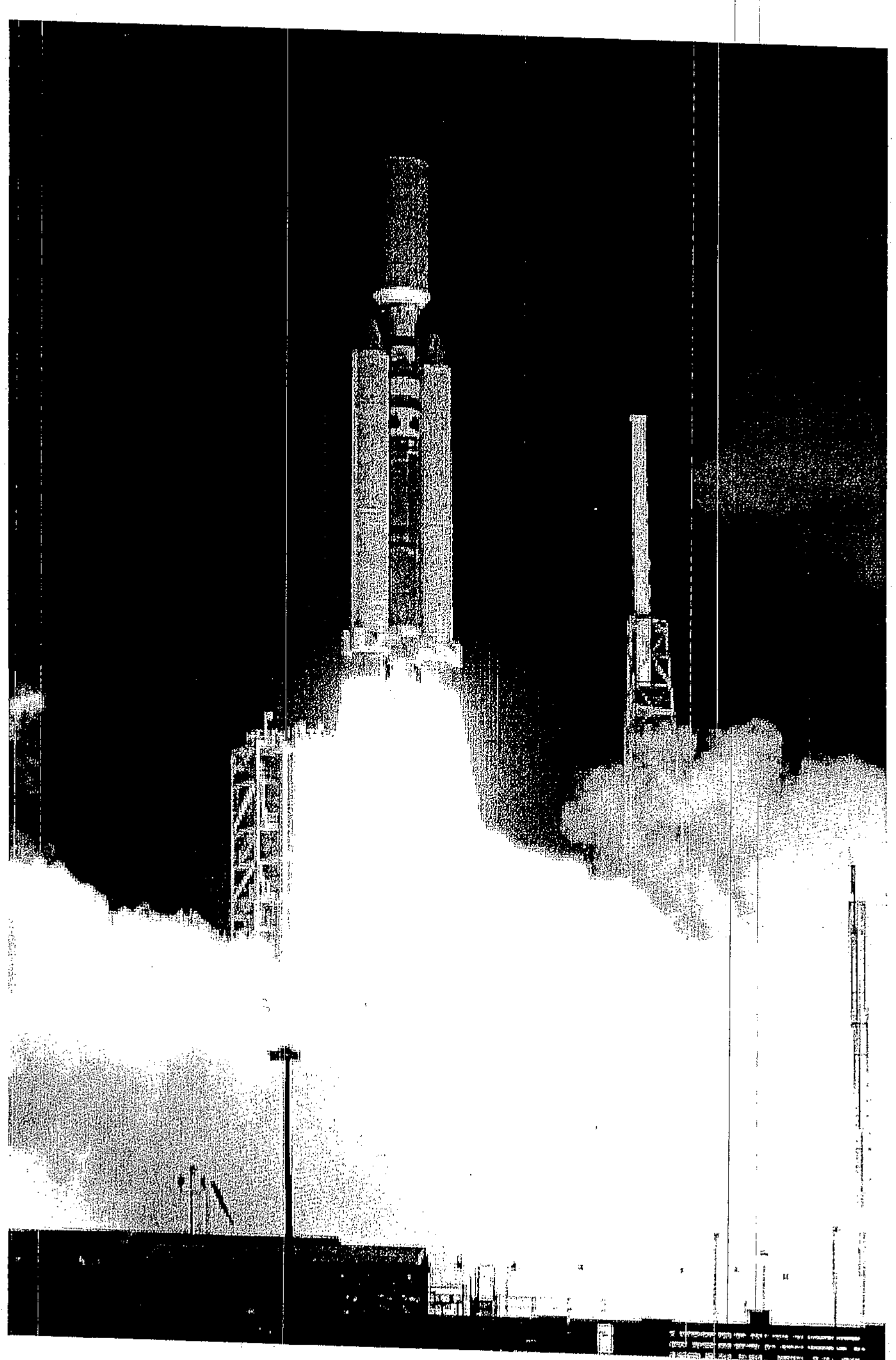

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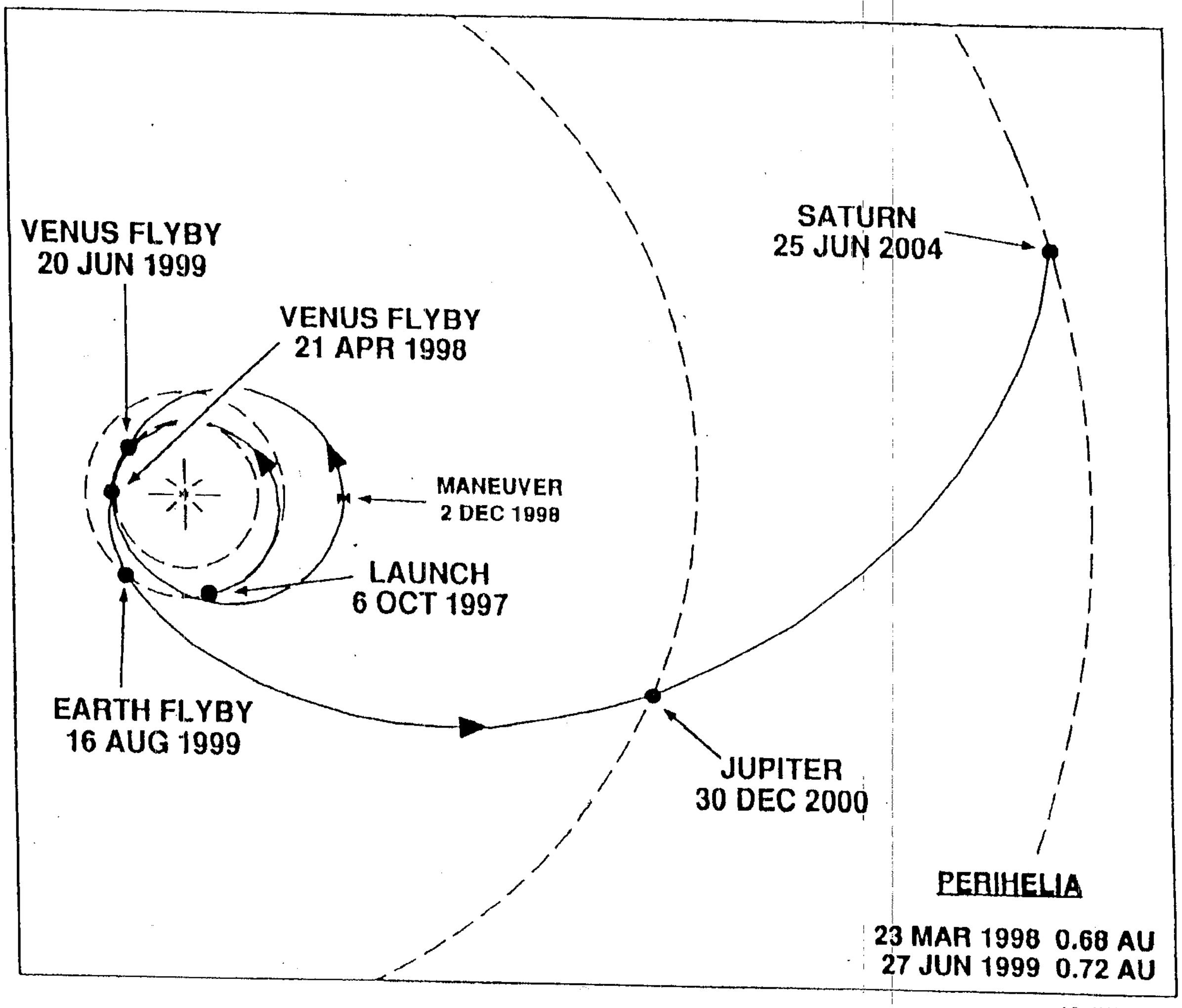
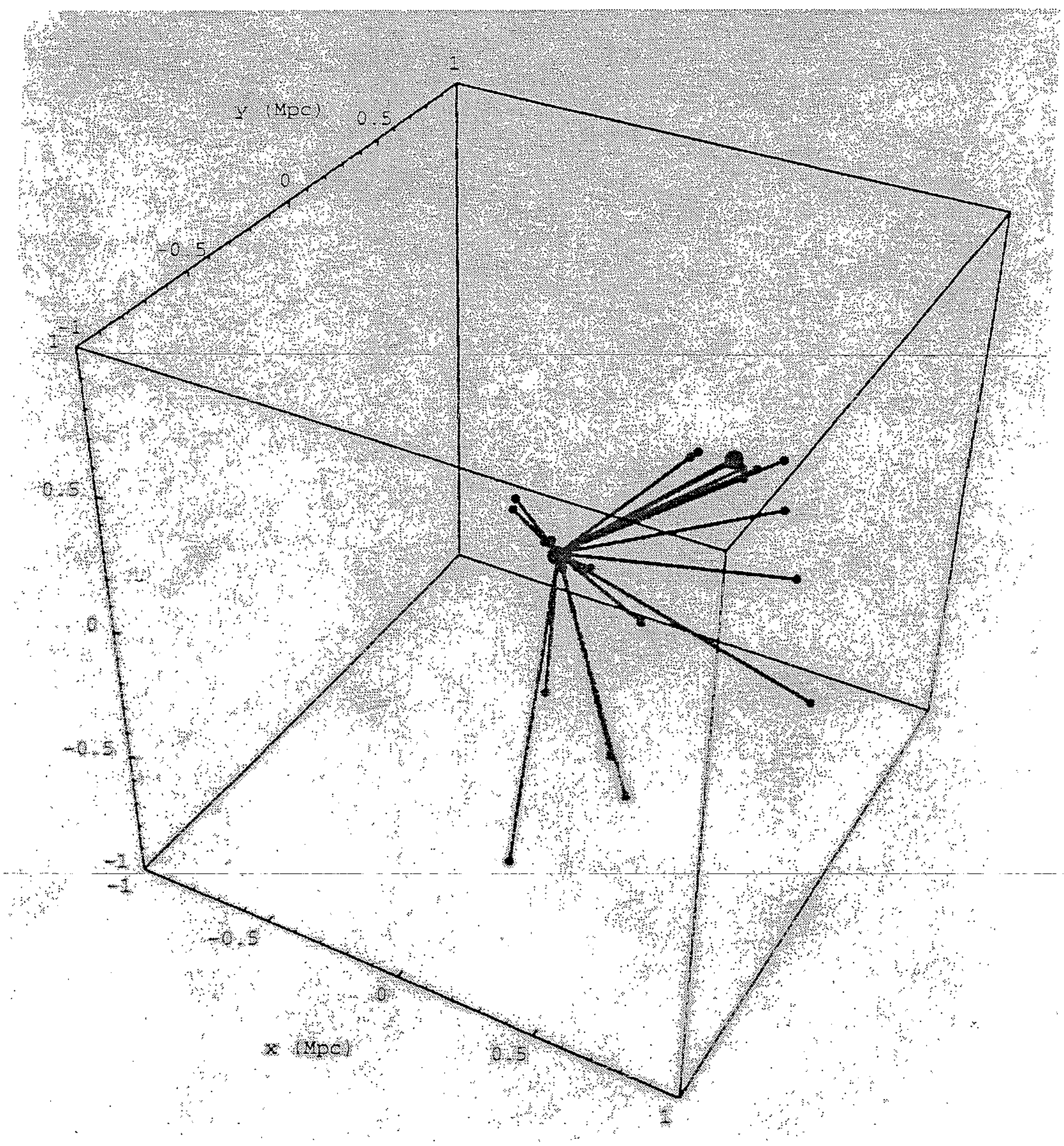
CASSINI OCT 1997 VVEJGA
INTERPLANETARY TRAJECTORY

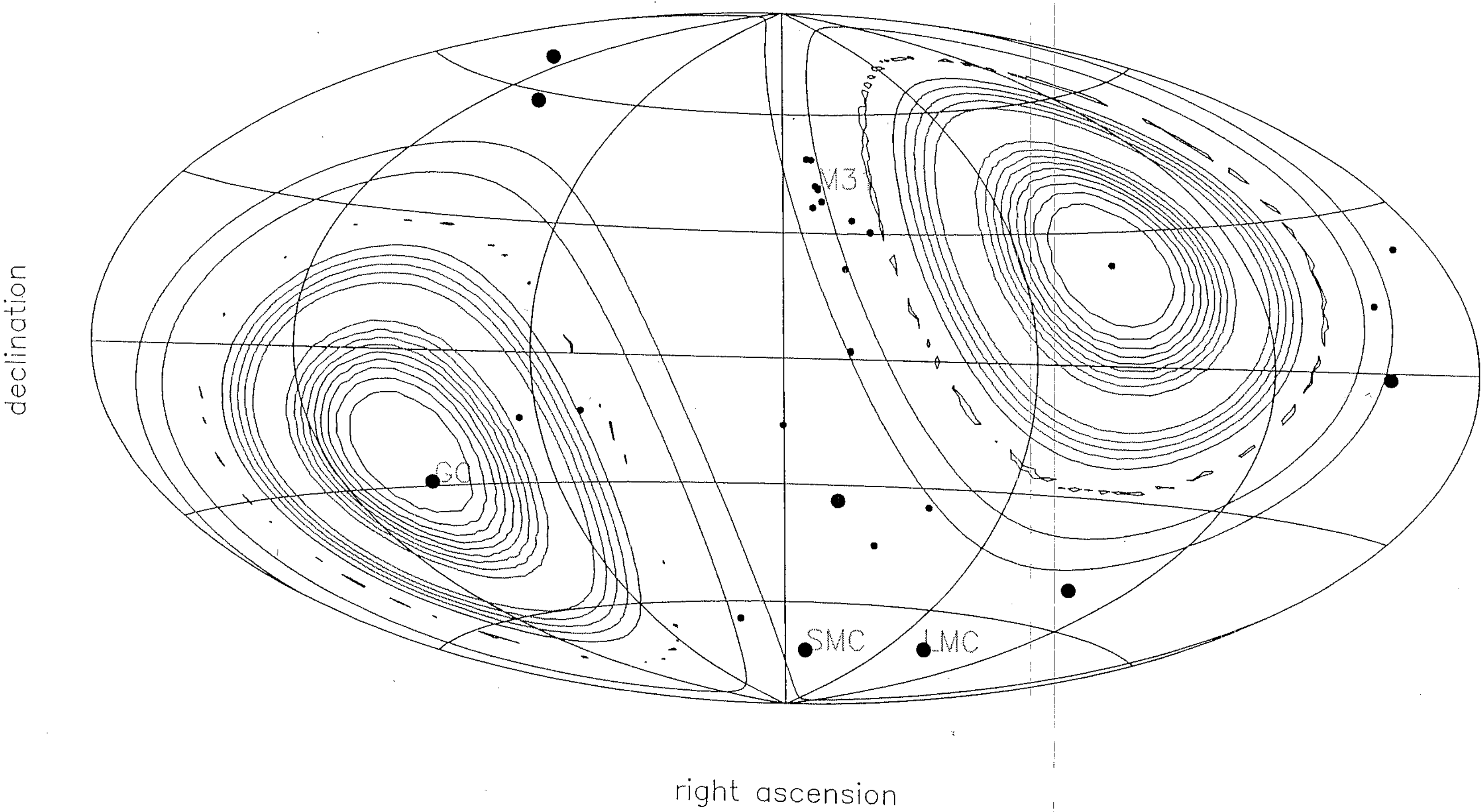


13 JUL 1992

The Local Group

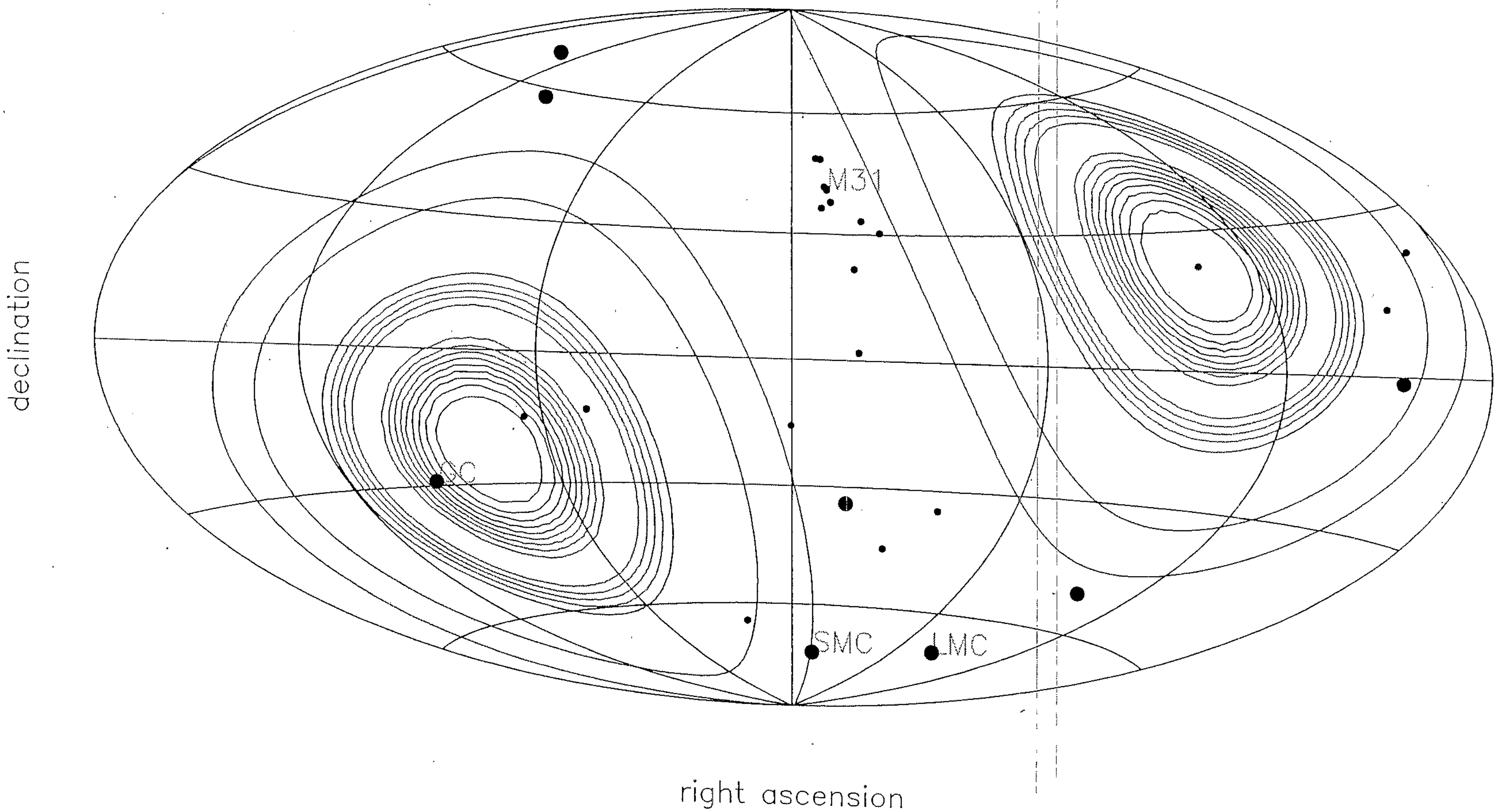


relative energy response for Cassini 2001 December 16
circular–pol: sin(2 π (0.001 Hz) t)*exp(–t/1000 sec)

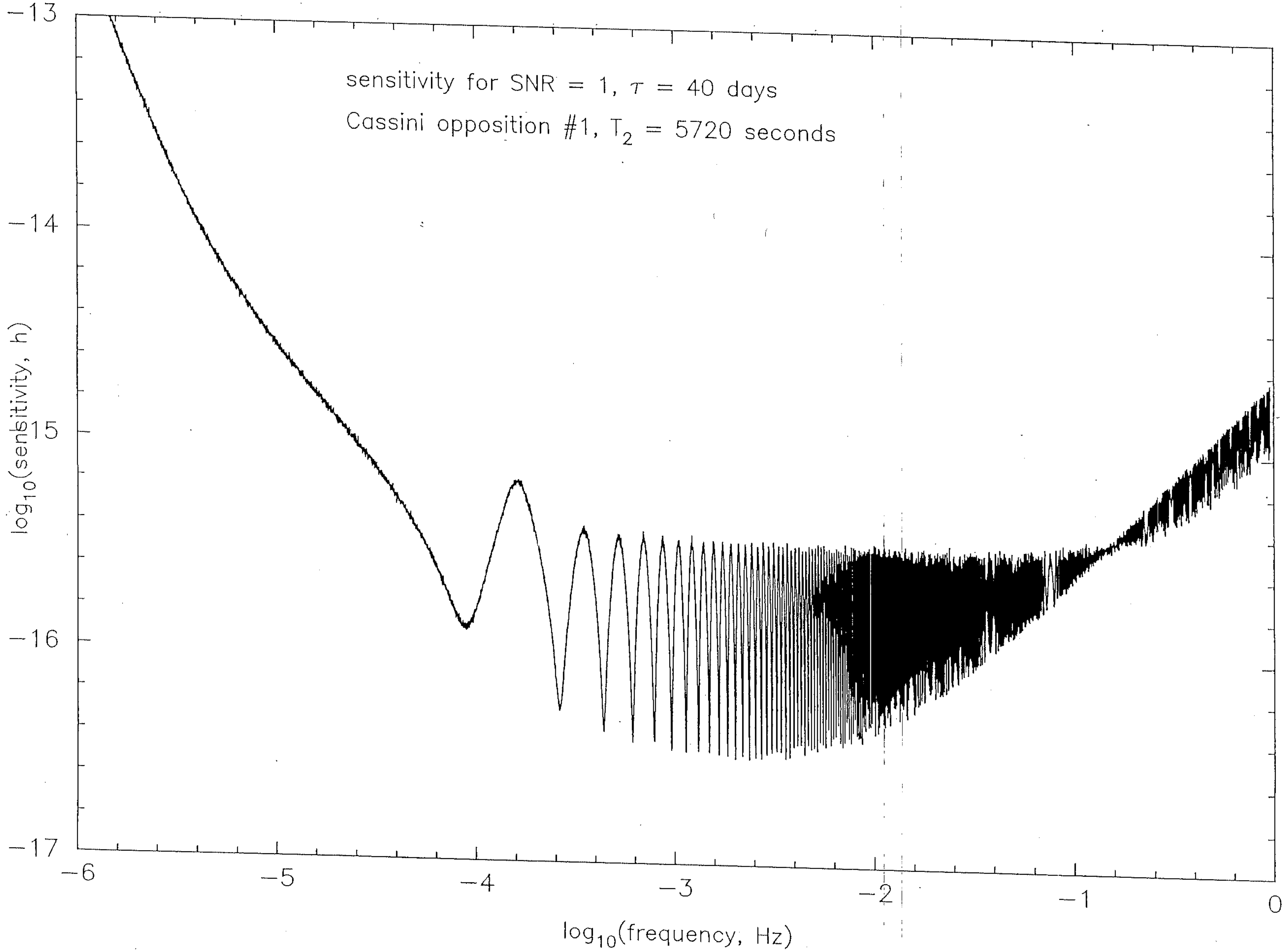


hammer–aitoff equal–area projection (center of plot is RA = 0, dec = 0)

relative energy response for Cassini 2004 January 4
circular–pol: sin(2 π (0.001 Hz) t)*exp(–t/1000 sec)



hammer–aitoff equal–area projection (center of plot is RA = 0, dec = 0)



sensitivity for SNR = 1, τ = 40 days
Cassini opposition #1, T_2 = 5720 seconds
−13
−14
−15
−16
−17
$\log_{10}$(sensitivity, h)
−6
−5
−4
−3
−2
−1
0
$\log_{10}$(frequency, Hz)

Backgrounds

$$\Omega = \frac{\rho}{\rho_c}$$

$$\rho_c = \frac{3H_o^2}{8\pi G} \approx 1 \times 10^{-29} \text{ grams/cm}^3, \text{ if } H_o = 80 \text{ km/sec/Mpc}$$

$$\rho = \left(\frac{243}{208}\right)\pi^3 \frac{f_c^4}{G} \int df \frac{Sy(f)}{\left(4\pi^2 f^2\right)}$$

$$= \left(\frac{243}{208}\right)\frac{f_c^3 S_y(f_c)}{(4G)}$$

Expected Cassini spectrum for S_y implies $\Omega \lesssim 10^{-2}$ for $f_c \approx 10^{-4}$ Hz

Topics

- Short review of the GWE (what we are doing; why we are doing it; signal and noise transfer functions; new instrumentation, etc.)
- Quick-look data: noise statistics
- Some interesting things in the quick-look data
    - Propagation noise/media cal data
    - Antenna mechanical noise (things that go bump in the night...) examples
    - FTS noise examples
    - Spacecraft noise
    - Lunar occultation
- Discussion

Cassini GWE

- 40 days around the clock tracking of Cassini, searching for gravitational waves in the "low-frequency" (~0.0001-0.01 Hz) band
- New equipment at Goldstone and elsewhere
    - Ka-band up- and down-link, Advanced Media Calibration [AMC] units, new radio science receivers, new FTS, aberration correction, monopulse pointing, more)
    - Supports several Cassini RS investigations (GWE, SCE, ring occultations, atmosphere occultations, precision Doppler during Tour)
- GWE is first beneficiary of this work—main utility for GWE:
    - Ka-band (~32 GHz) reduces plasma scintillation noise to negligible levels
    - AMCs: measure/calibrate tropospheric scintillation

Cassini GWE (cont.)

- Two-way Ka-band supported on the spacecraft (by hardware supplied by Italian Space Agency--the "KaT") and on the ground (by the DSS25 Cassini radio science upgrade supplied by NASA)

- Discussion of error budget and sensitivity at:

  http://www.its.caltech.edu/~cajagwr/pdf/Armstrong.pdf

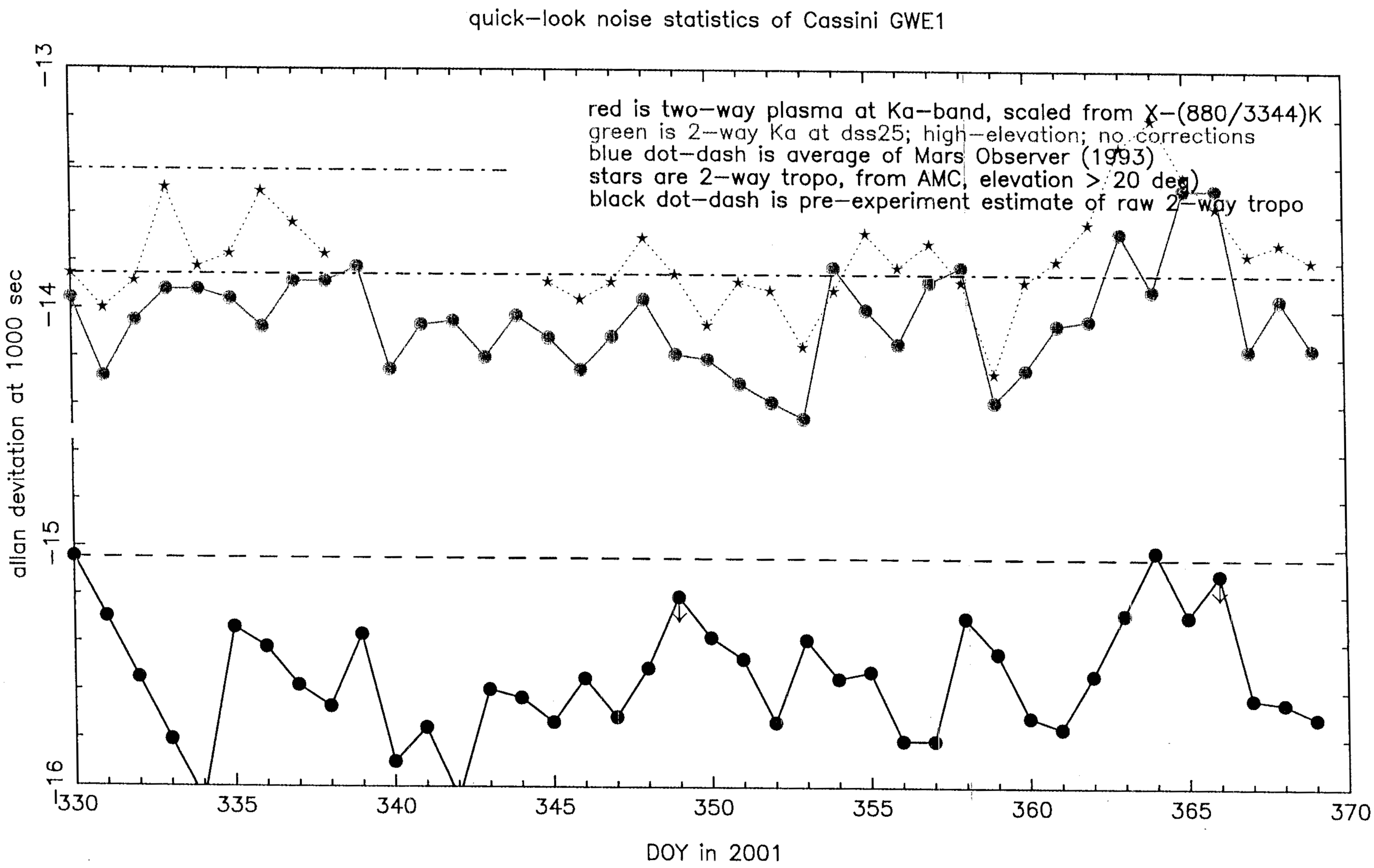
- Discussion of Doppler tracking in context of overall GW astronomy strategy:

  http://www.its.caltech.edu/~cajagwr/scripts/participating_projects.html

- Pre-experiment sensitivity goal, after all corrections, $\sigma_y(1000 \text{ sec}) \approx 3 \times 10^{-15}$

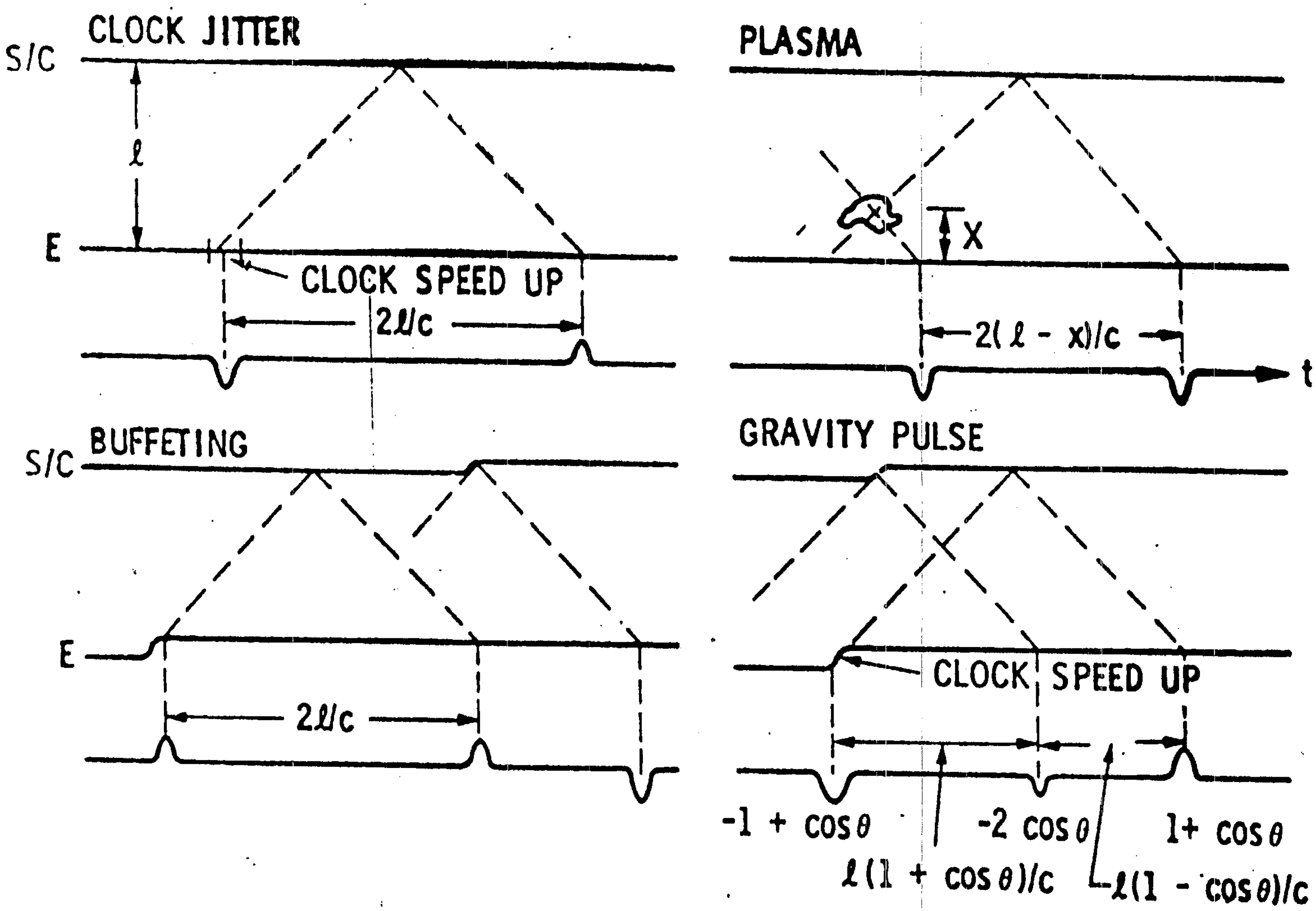
Quick-Look Analysis

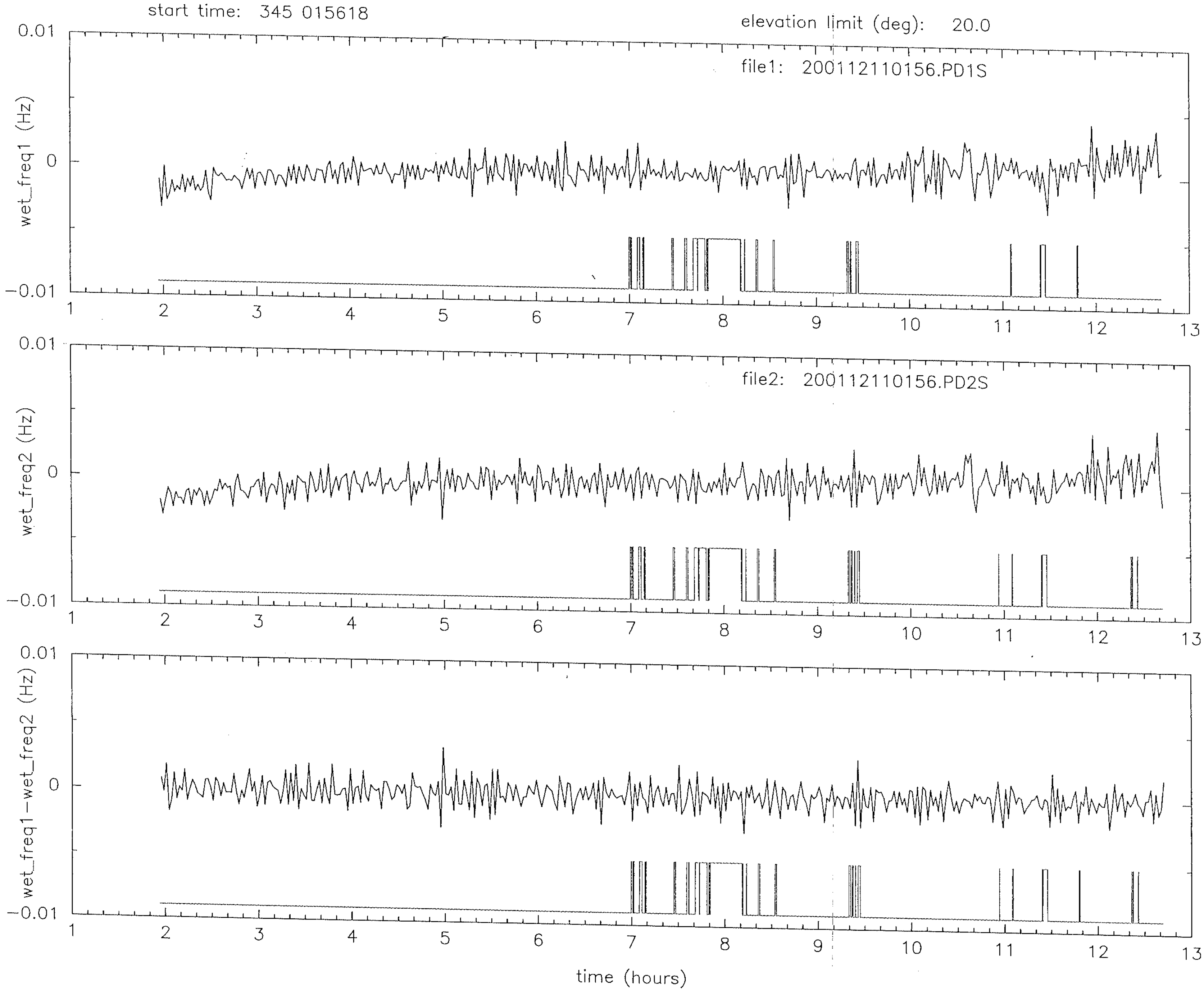
- Quick-look data were two hours/day at DSS 25, selected to be near meridian transit
  - High elevation minimizes many problems: antenna mechanical systematic effects due to M1 mirror sag, minimum tropospheric noise, dry component approximately linear and thus absorbed in 4-paramter orbit fit, etc.)
  - PLL of open-loop data to estimate signal amplitude and frequency, solve for average velocity, average acceleration, and sine/cosine of earth rotation Doppler to remove an approximate orbit --> "residuals"
  - Simultaneous X and Ka1 allows simple estimate of plasma scintillation level—time series/spectra taken also
  - Convert AMC tropospheric delays to fractional frequency deviations—produce spectra of these to see what the troposphere is doing



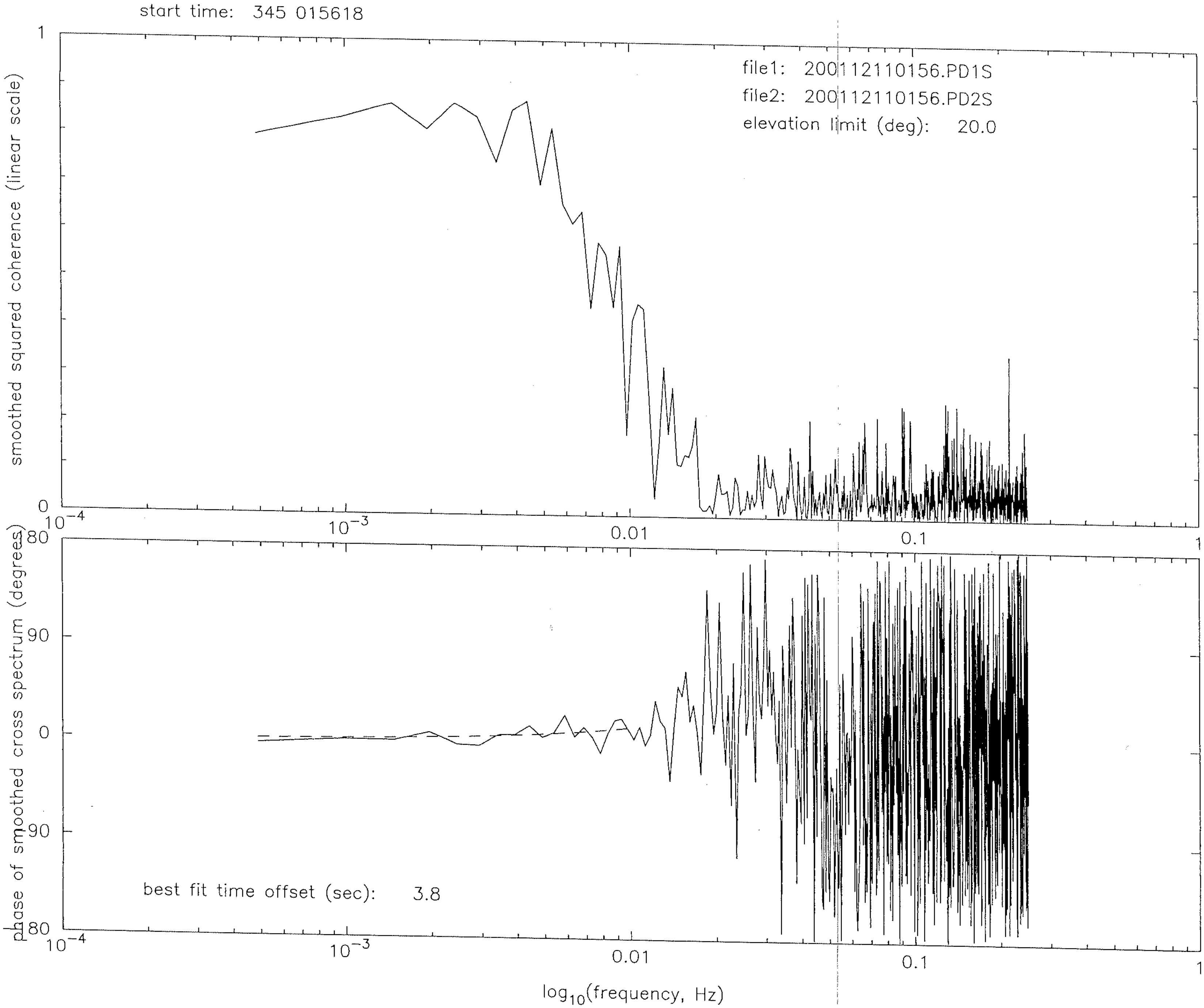
quick–look noise statistics of Cassini GWE1
red is two–way plasma at Ka–band, scaled from X–(880/3344)K
green is 2–way Ka at dss25; high–elevation; no corrections
blue dot–dash is average of Mars Observer (1993)
stars are 2–way tropo, from AMC, elevation > 20 deg)
black dot–dash is pre–experiment estimate of raw 2–way tropo
allan devitation at 1000 sec
–13
–14
–15
–16
330
335
340
345
350
355
360
365
370
DOY in 2001

Doppler Signals Corresponding To Different Disturbances in the Radio Link

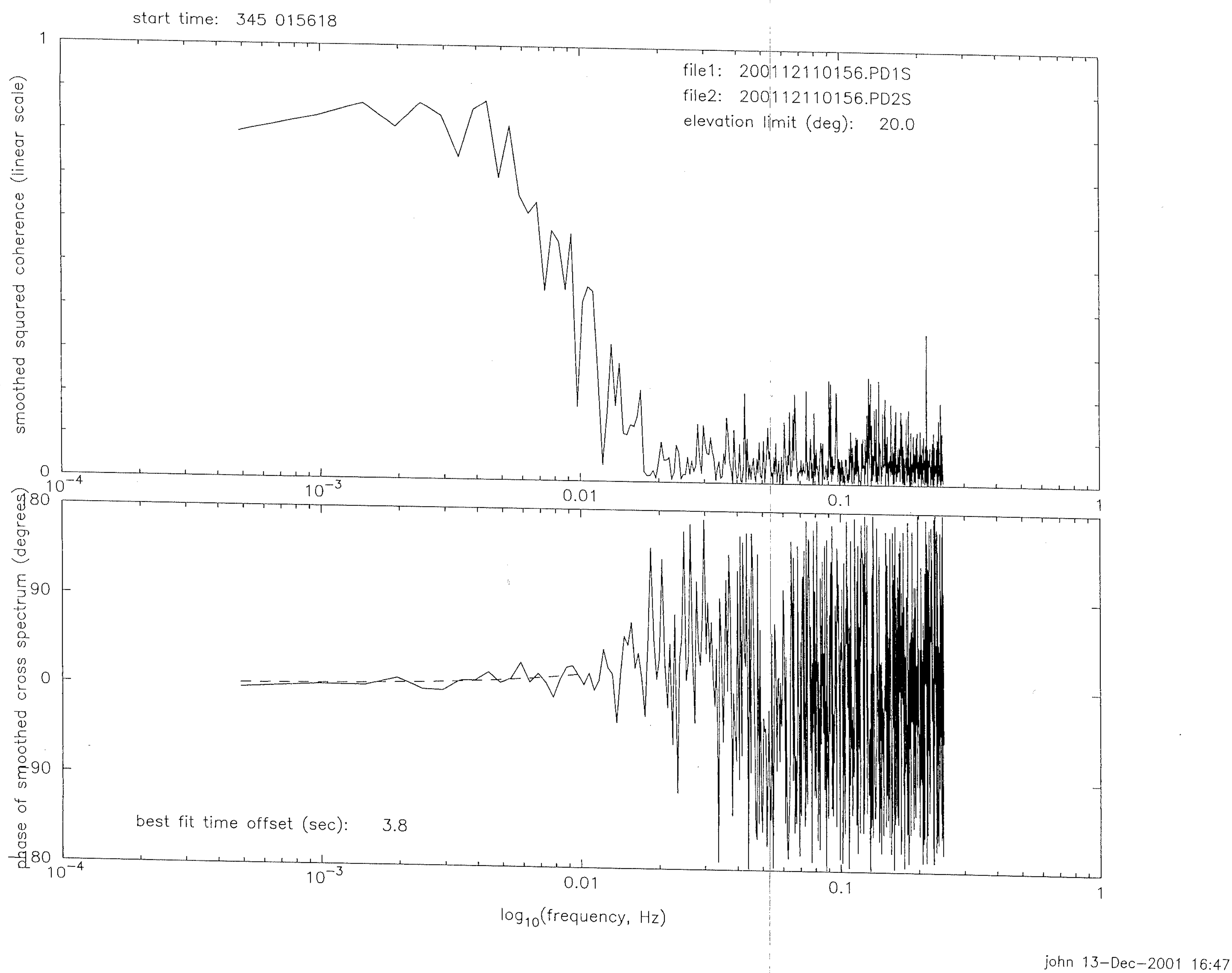


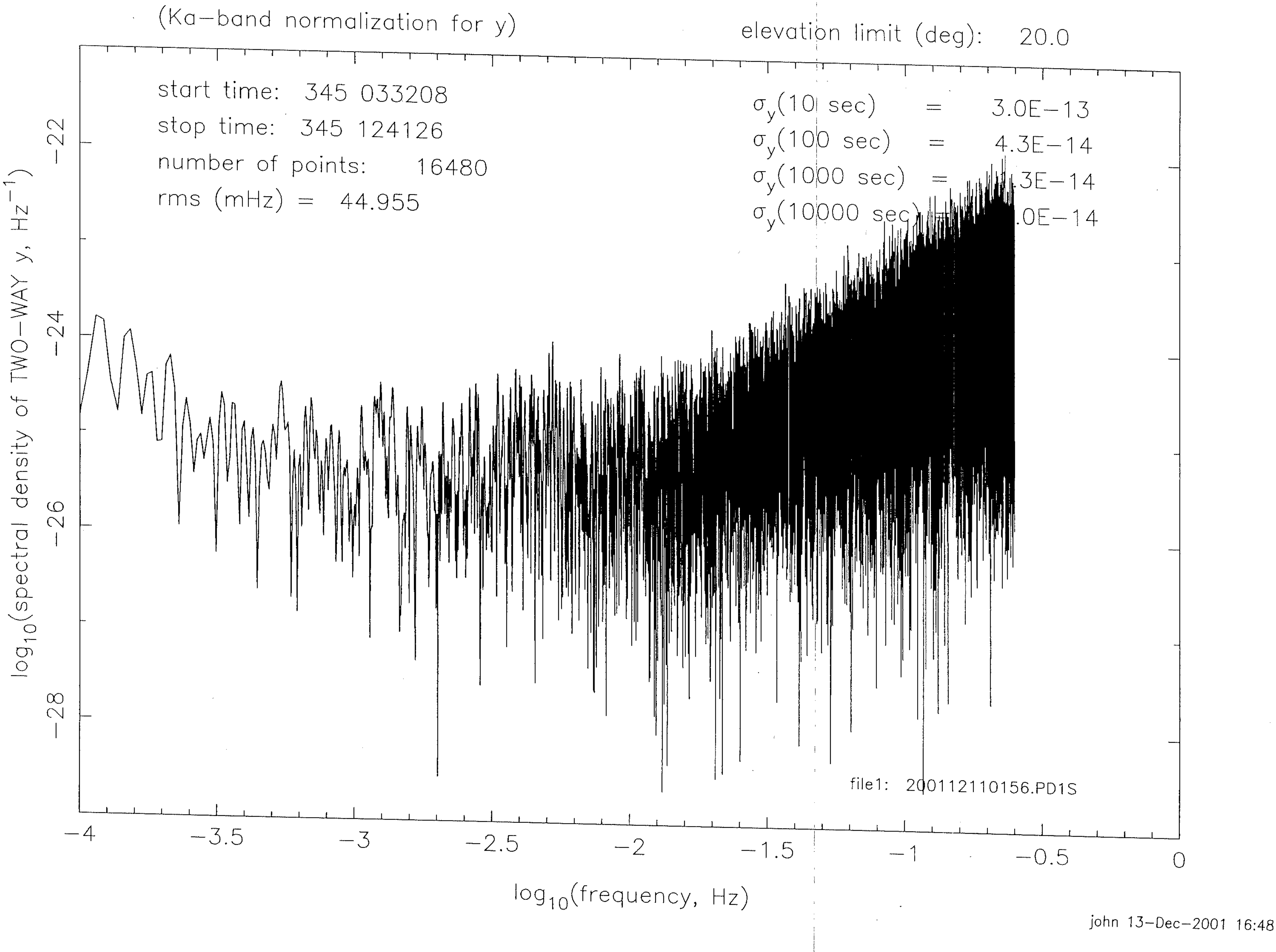


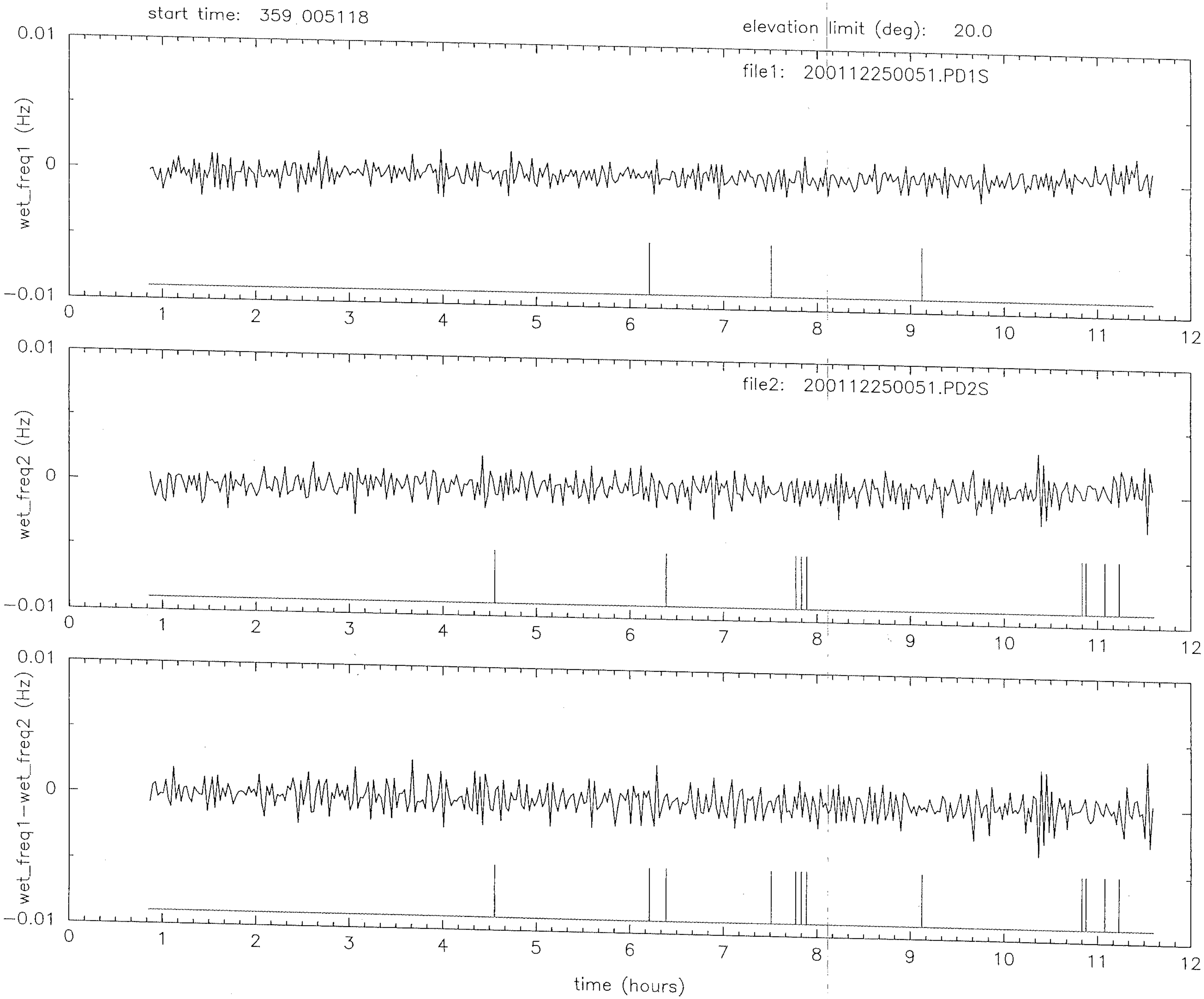
john 13-Dec-2001 16:47



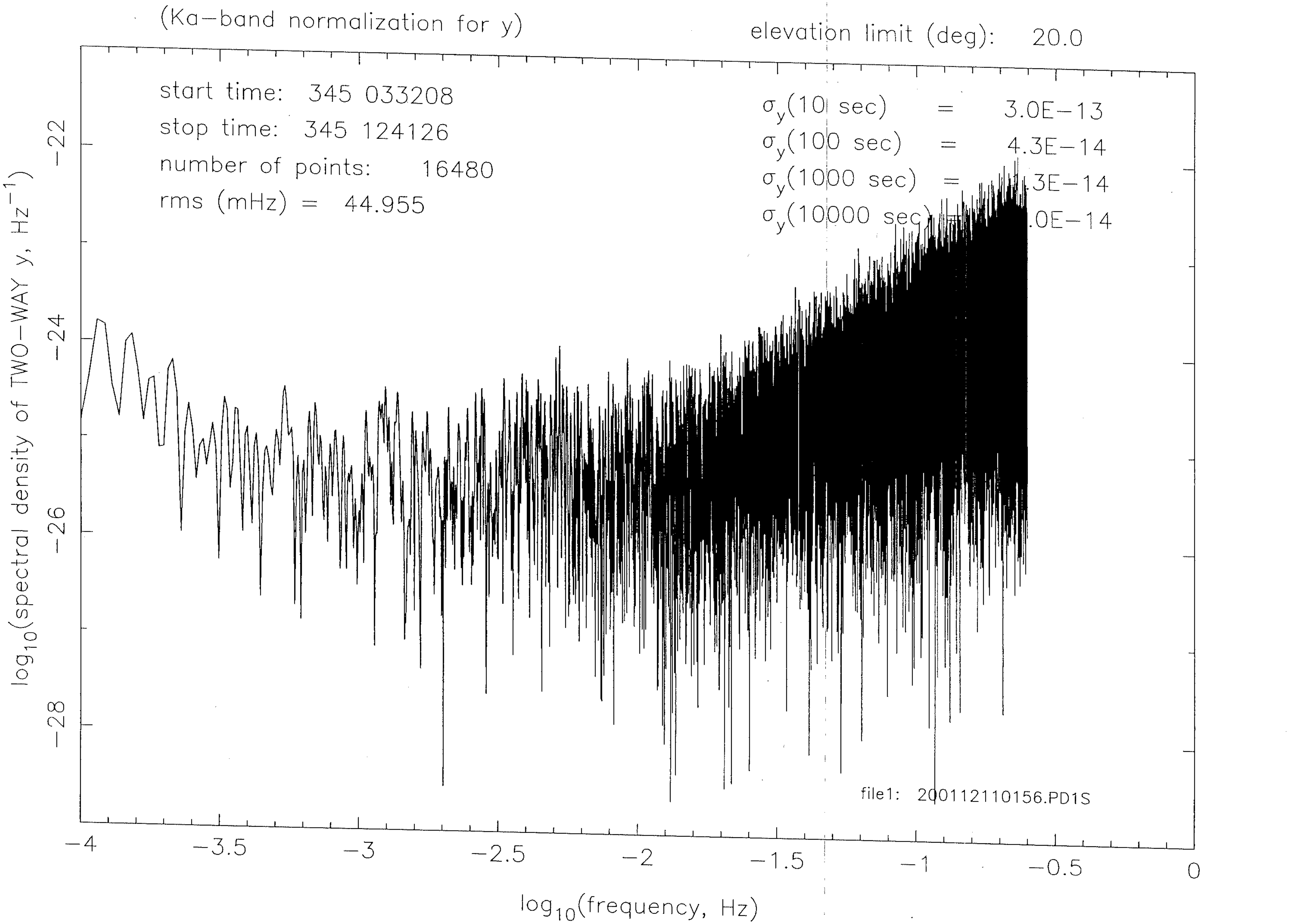
john 13-Dec-2001 16:47


start time: 345 015618
file1: 200112110156.PD1S
file2: 200112110156.PD2S
elevation limit (deg): 20.0
smoothed squared coherence (linear scale)
1
0
10^-4
10^-3
0.01
0.1
1
phase of smoothed cross spectrum (degrees)
180
90
0
-90
-180
best fit time offset (sec): 3.8
log10(frequency, Hz)
john 13-Dec-2001 16:47

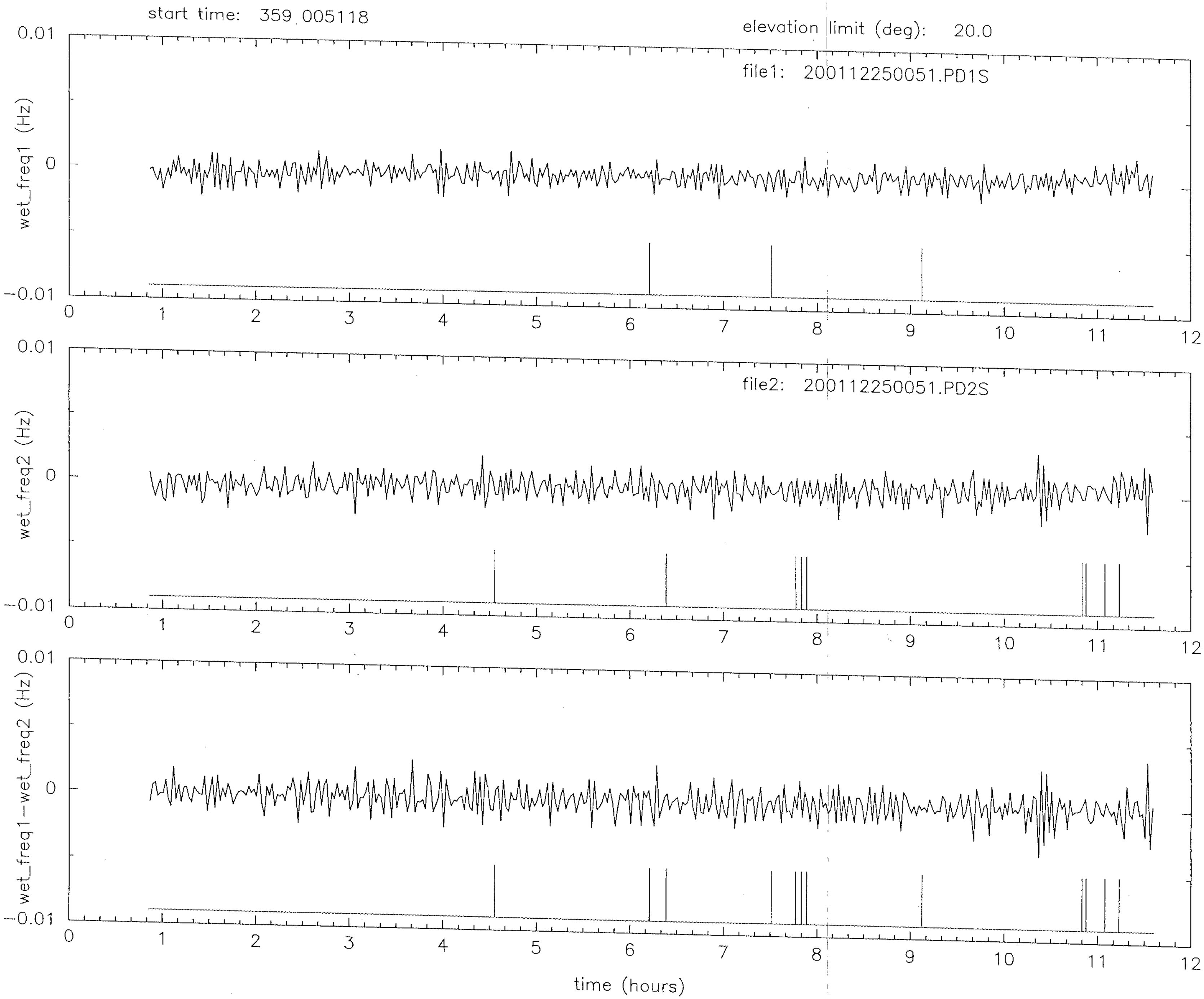

(Ka−band normalization for y)
elevation limit (deg): 20.0
start time: 345 033208
stop time: 345 124126
number of points: 16480
rms (mHz) = 44.955
σy(10 sec) = 3.0E−13
σy(100 sec) = 4.3E−14
σy(1000 sec) = .3E−14
σy(10000 sec) = .0E−14
file1: 200112110156.PD1S
log10(spectral density of TWO−WAY y, Hz−1)
log10(frequency, Hz)
−22
−24
−26
−28
−4
−3.5
−3
−2.5
−2
−1.5
−1
−0.5
0
john 13−Dec−2001 16:48



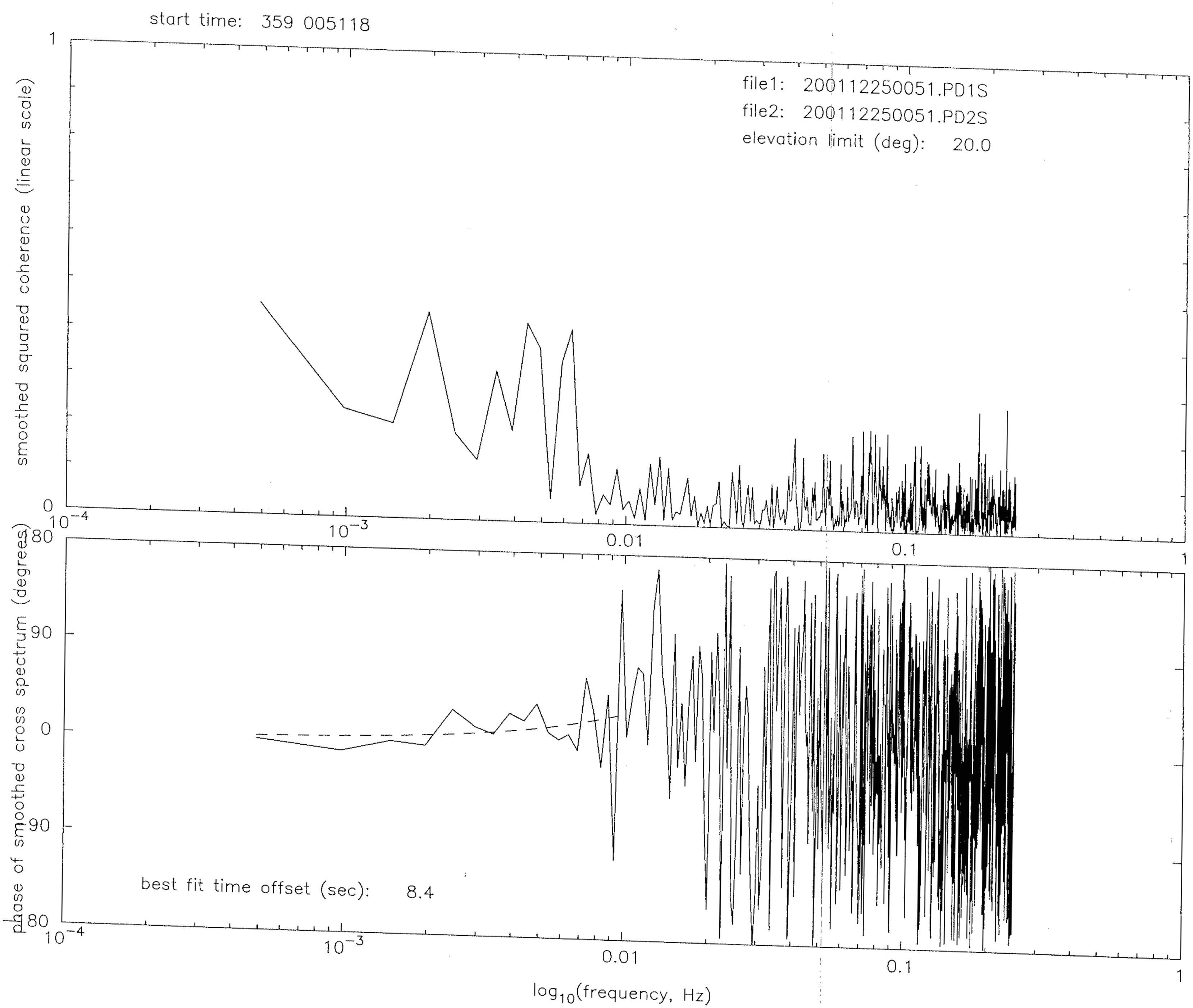
john 26-Dec-2001 10:12



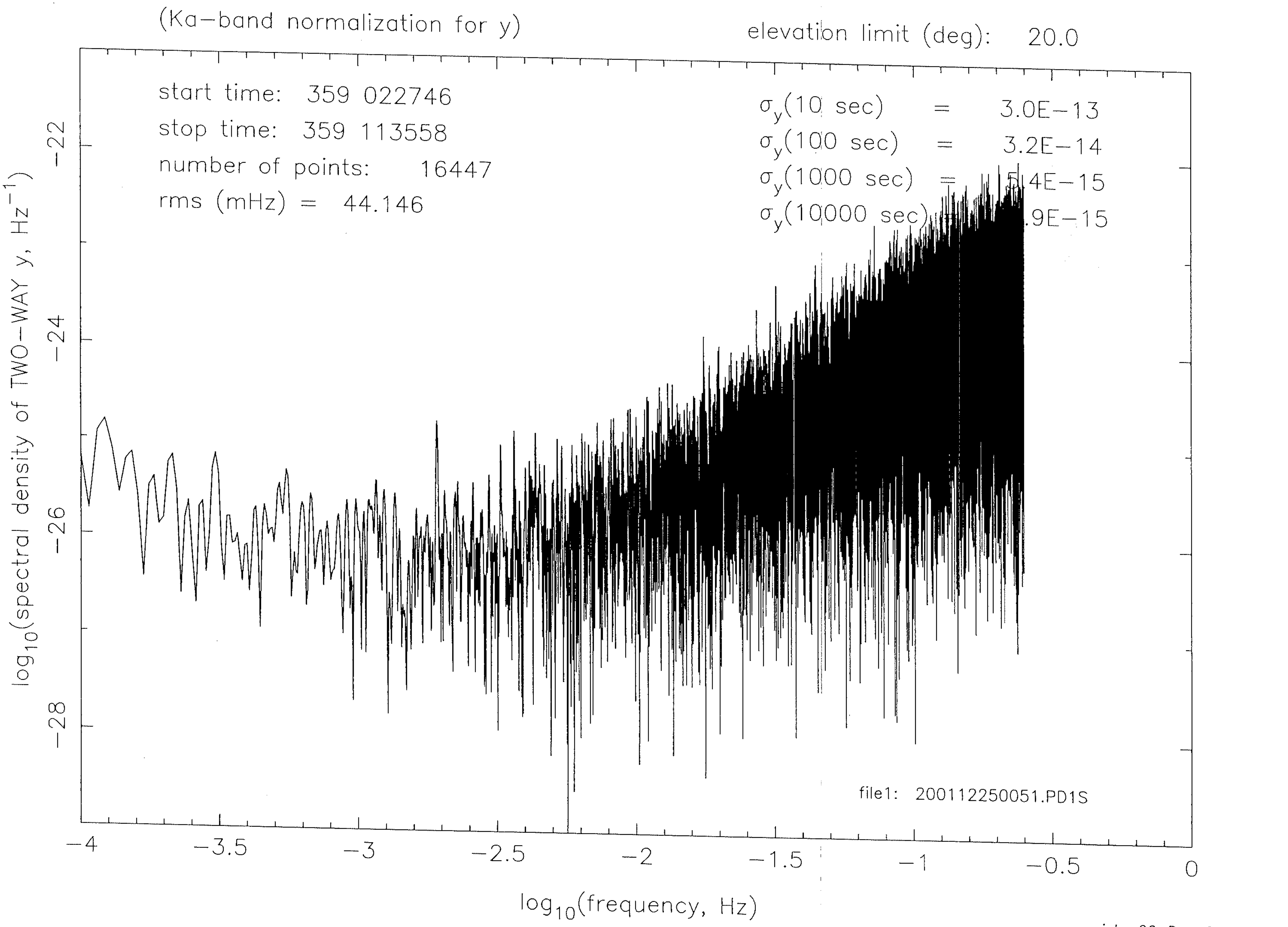
john 13−Dec−2001 16:48



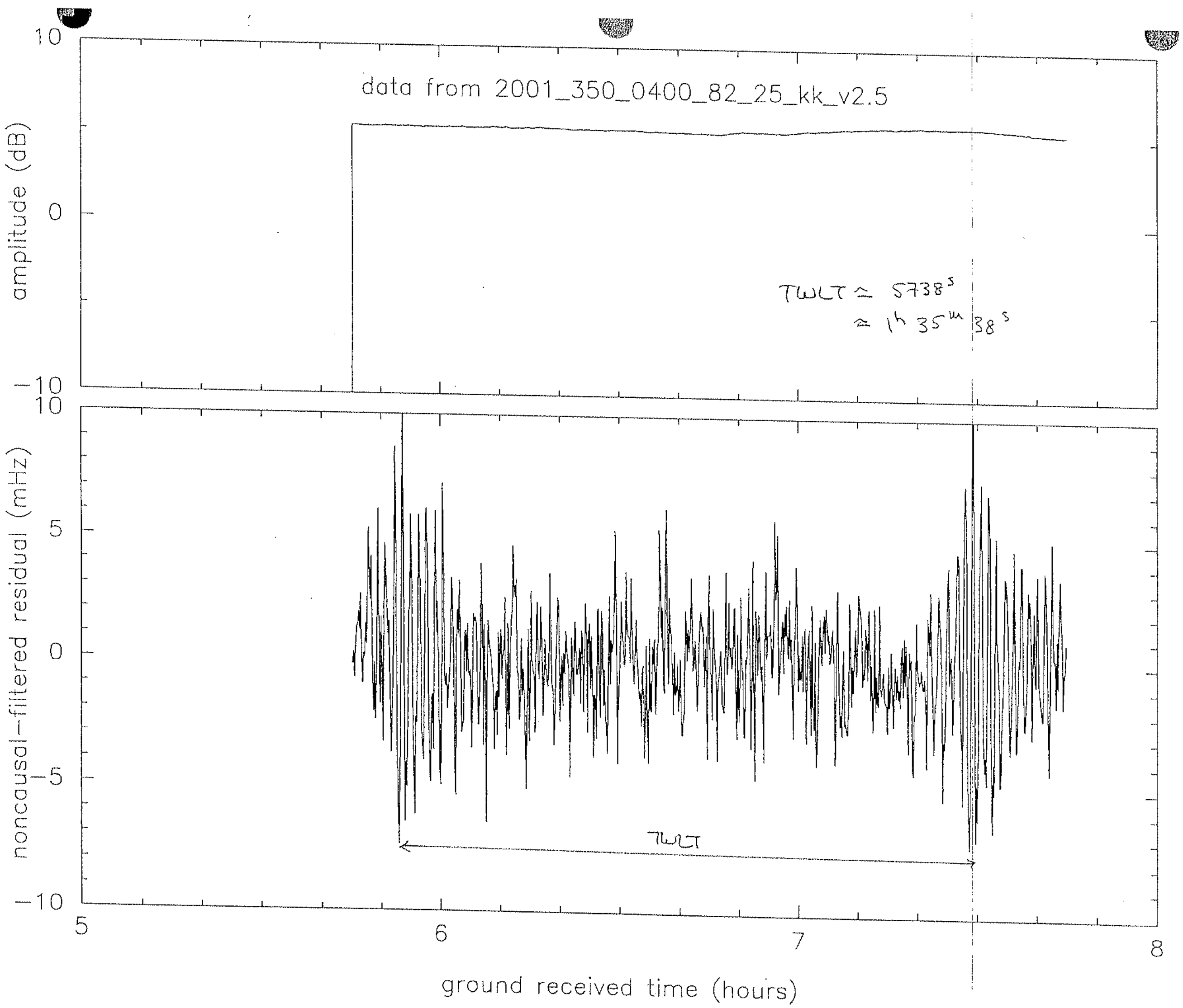
john 26-Dec-2001 10:12



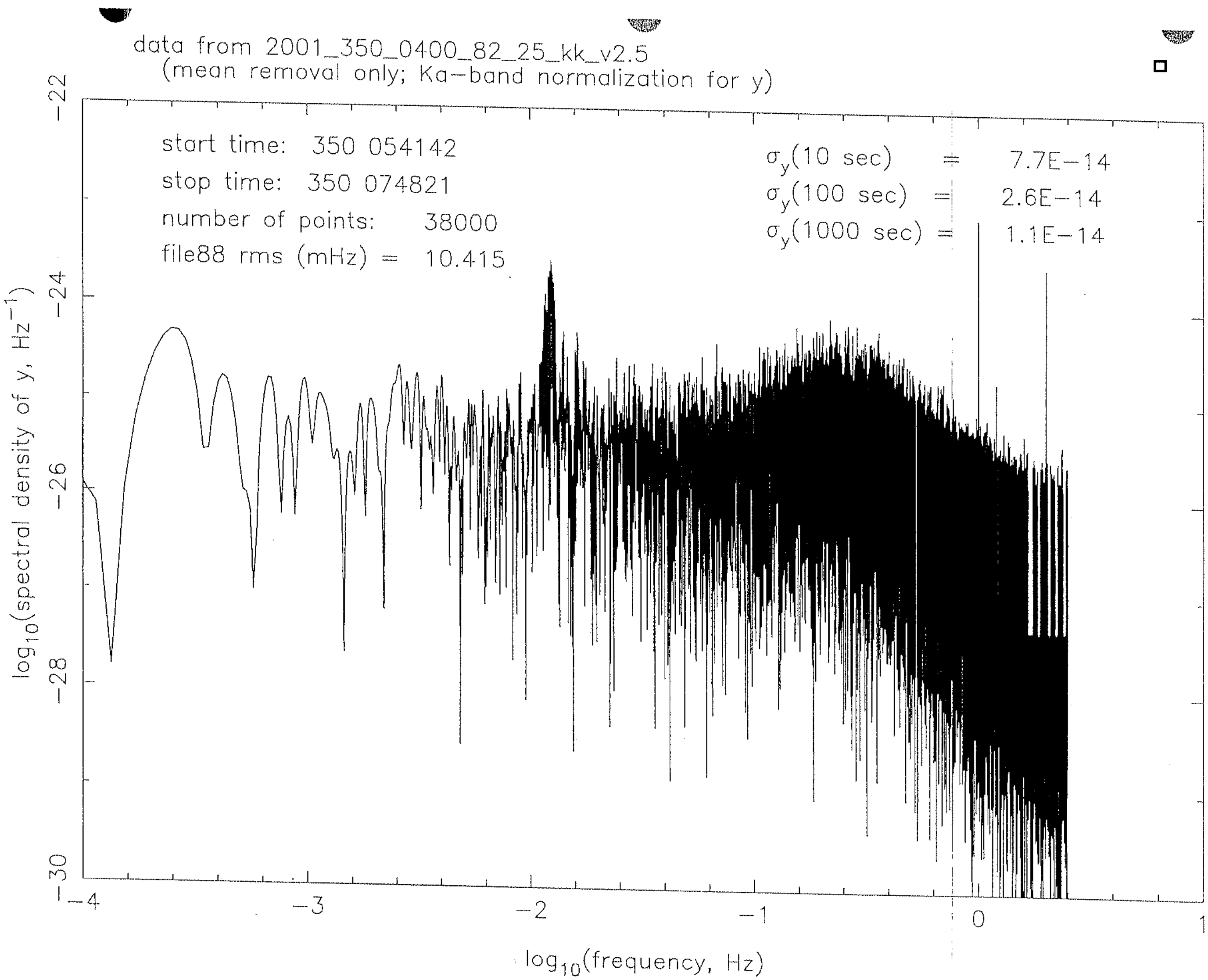
john 26-Dec-2001 10:12



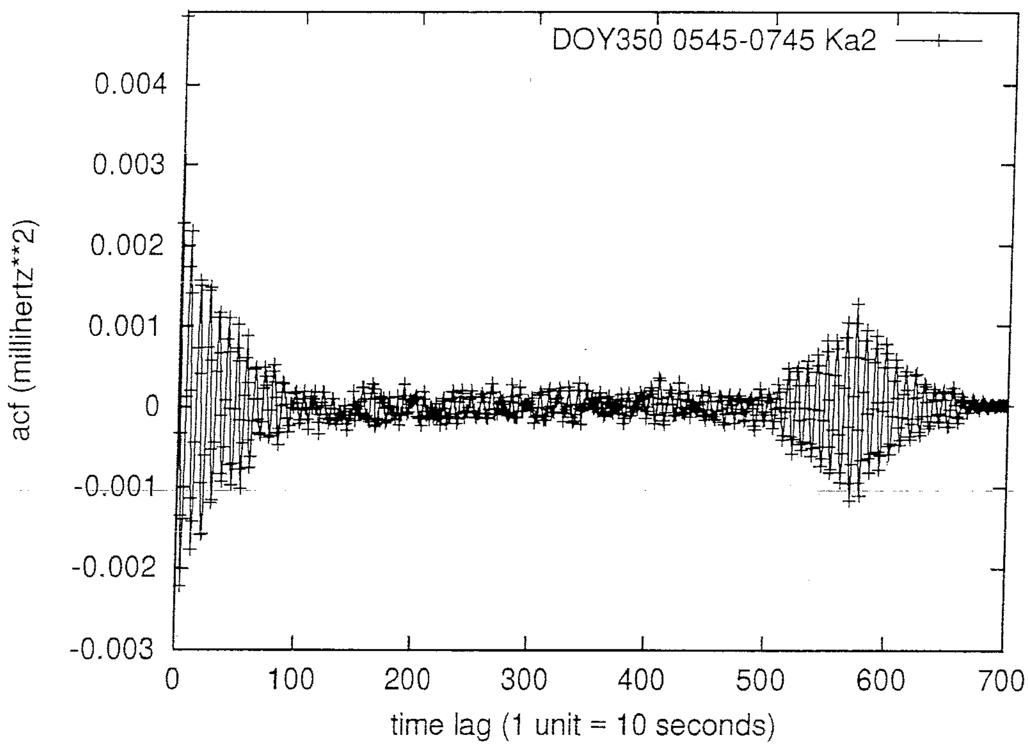
(Ka-band normalization for y)
elevation limit (deg): 20.0
start time: 359 022746
stop time: 359 113558
number of points: 16447
rms (mHz) = 44.146
σy(10 sec) = 3.0E-13
σy(100 sec) = 3.2E-14
σy(1000 sec) = 5.4E-15
σy(10000 sec) = .9E-15
-22
-24
-26
-28
log10(spectral density of TWO-WAY y, Hz-1)
-4
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
0
log10(frequency, Hz)
file1: 200112250051.PD1S
john 26-Dec-2001 10:12

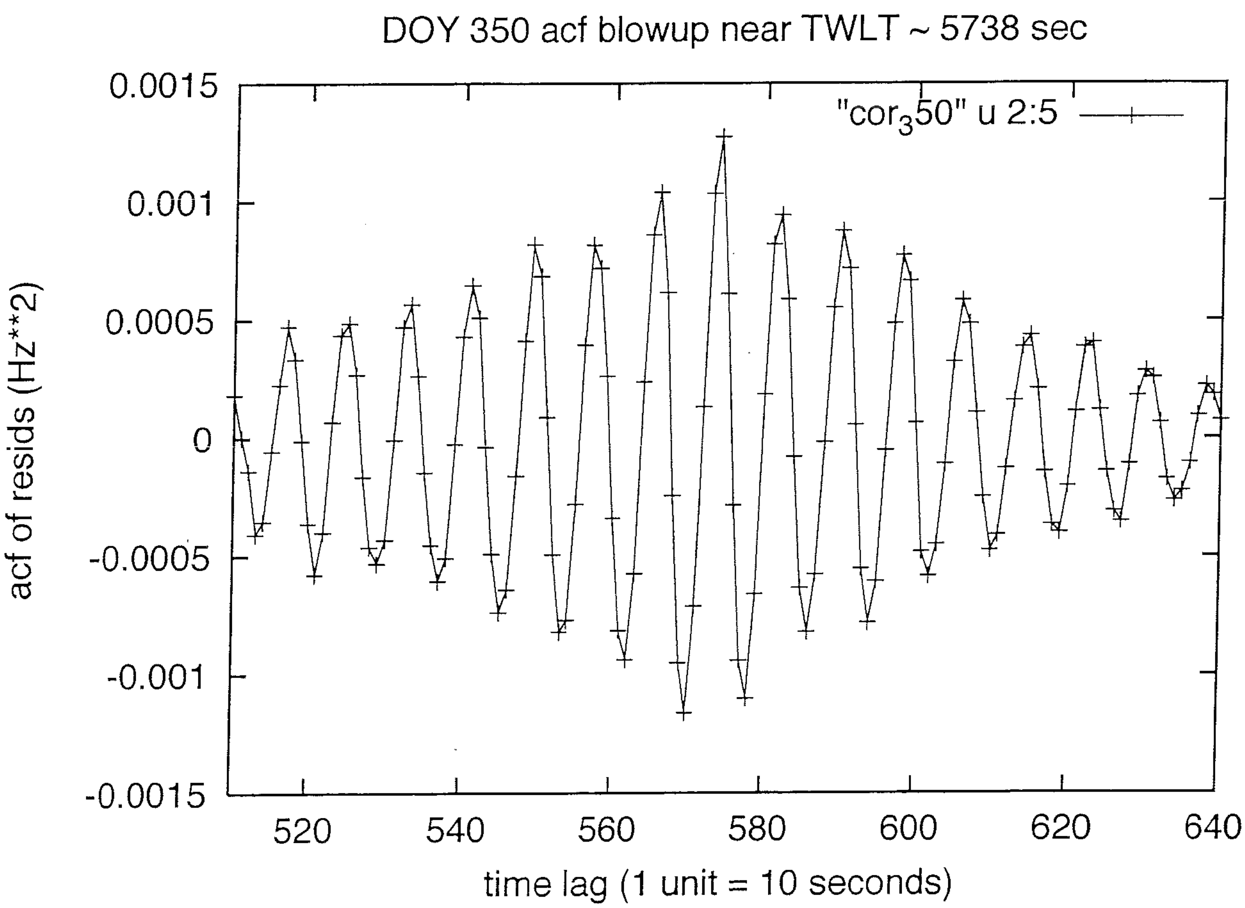


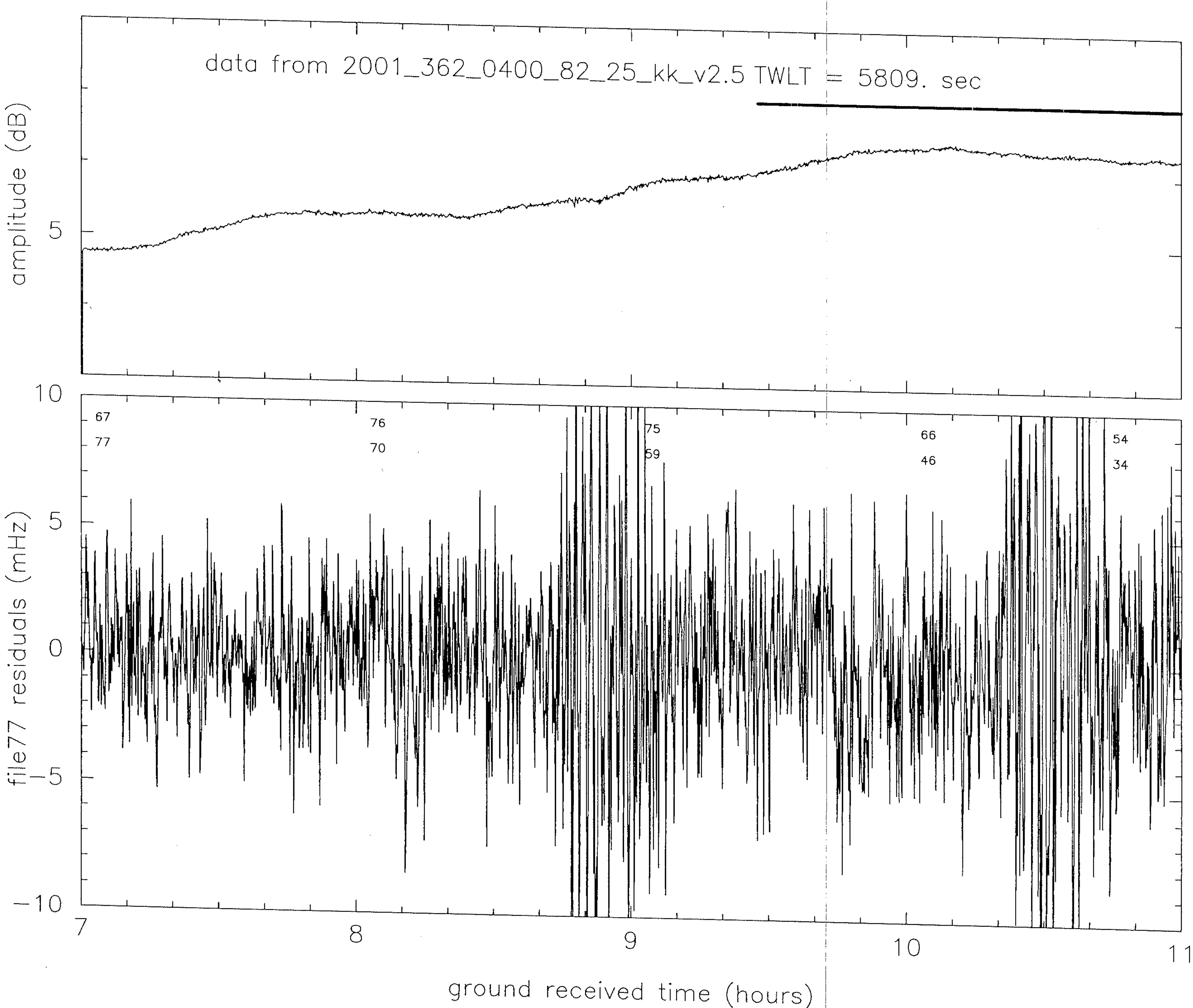
data from 2001_350_0400_82_25_kk_v2.5
amplitude (dB)
noncausal-filtered residual (mHz)
ground received time (hours)
TWLT ≃ 5738s
≃ 1h 35m 38s
TWLT
10
0
−10
10
5
0
−5
−10
5
6
7
8



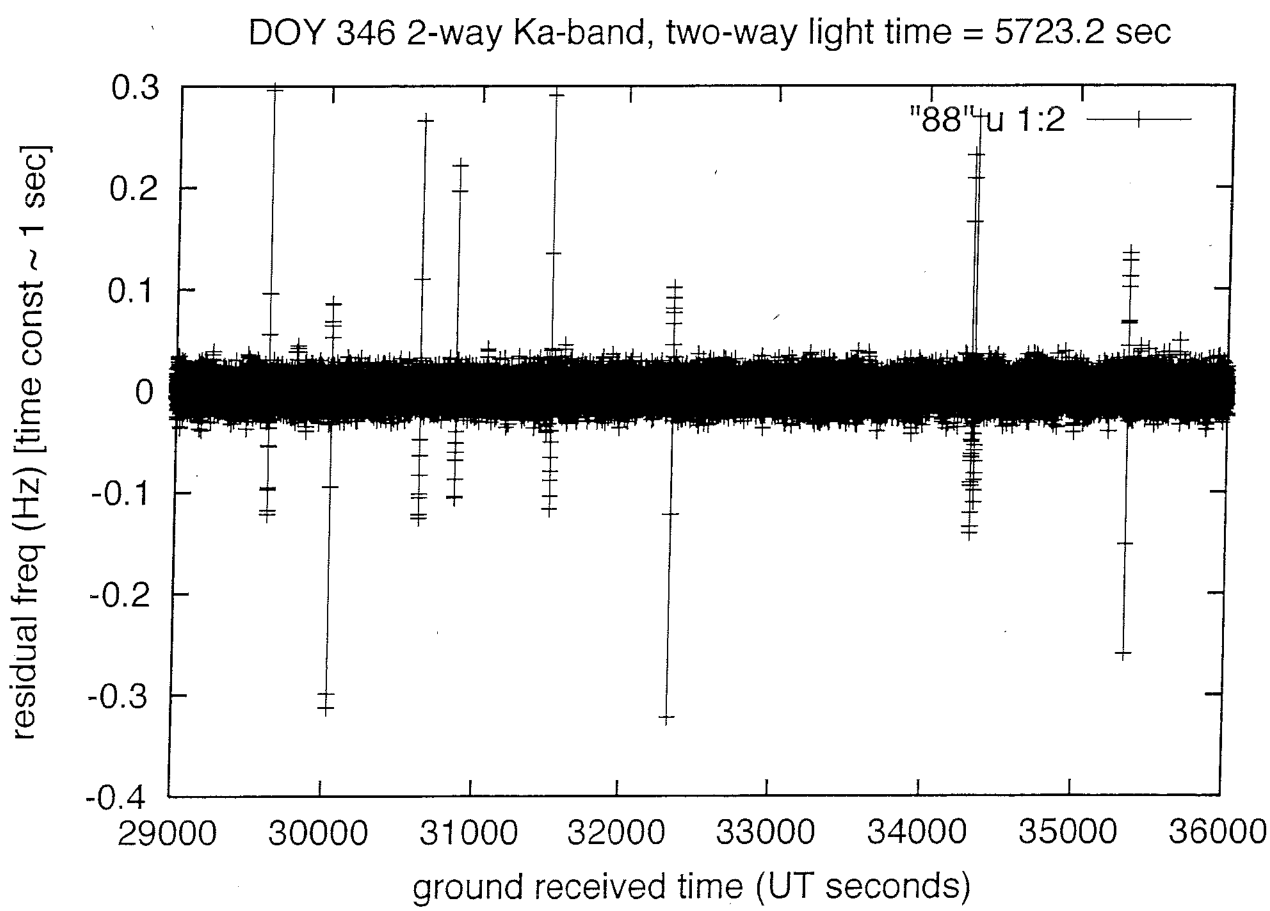
data from 2001_350_0400_82_25_kk_v2.5
(mean removal only; Ka-band normalization for y)
start time: 350 054142
stop time: 350 074821
number of points: 38000
file88 rms (mHz) = 10.415
σy(10 sec) = 7.7E-14
σy(100 sec) = 2.6E-14
σy(1000 sec) = 1.1E-14
-22
-24
-26
-28
-30
log10(spectral density of y, Hz-1)
-4
-3
-2
-1
0
1
log10(frequency, Hz)


DOY350 0545-0745 Ka2
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
acf (millihertz**2)
0
100
200
300
400
500
600
700
time lag (1 unit = 10 seconds)

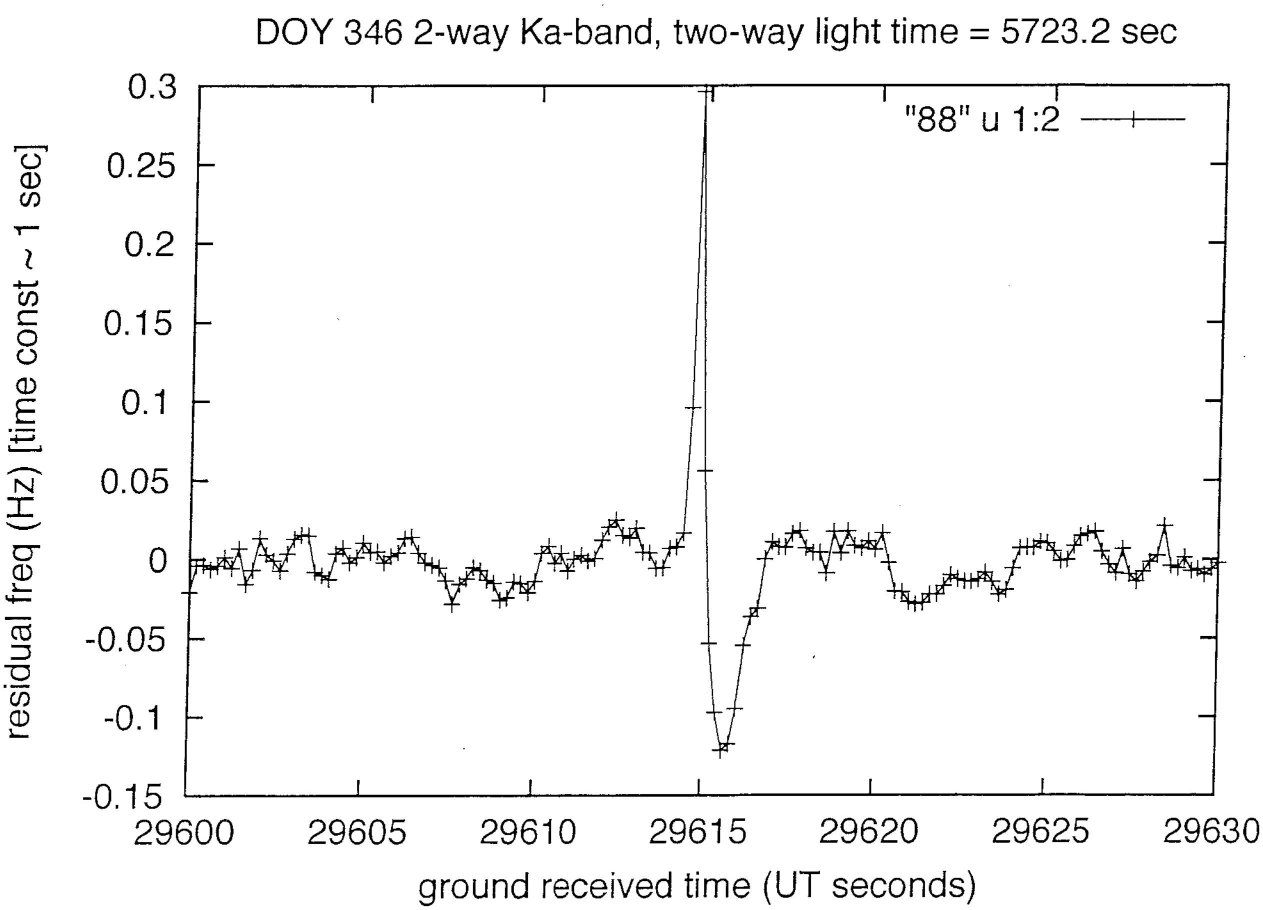

DOY 350 acf blowup near TWLT ~ 5738 sec
"cor350" u 2:5
acf of resids (Hz**2)
time lag (1 unit = 10 seconds)
0.0015
0.001
0.0005
0
-0.0005
-0.001
-0.0015
520
540
560
580
600
620
640



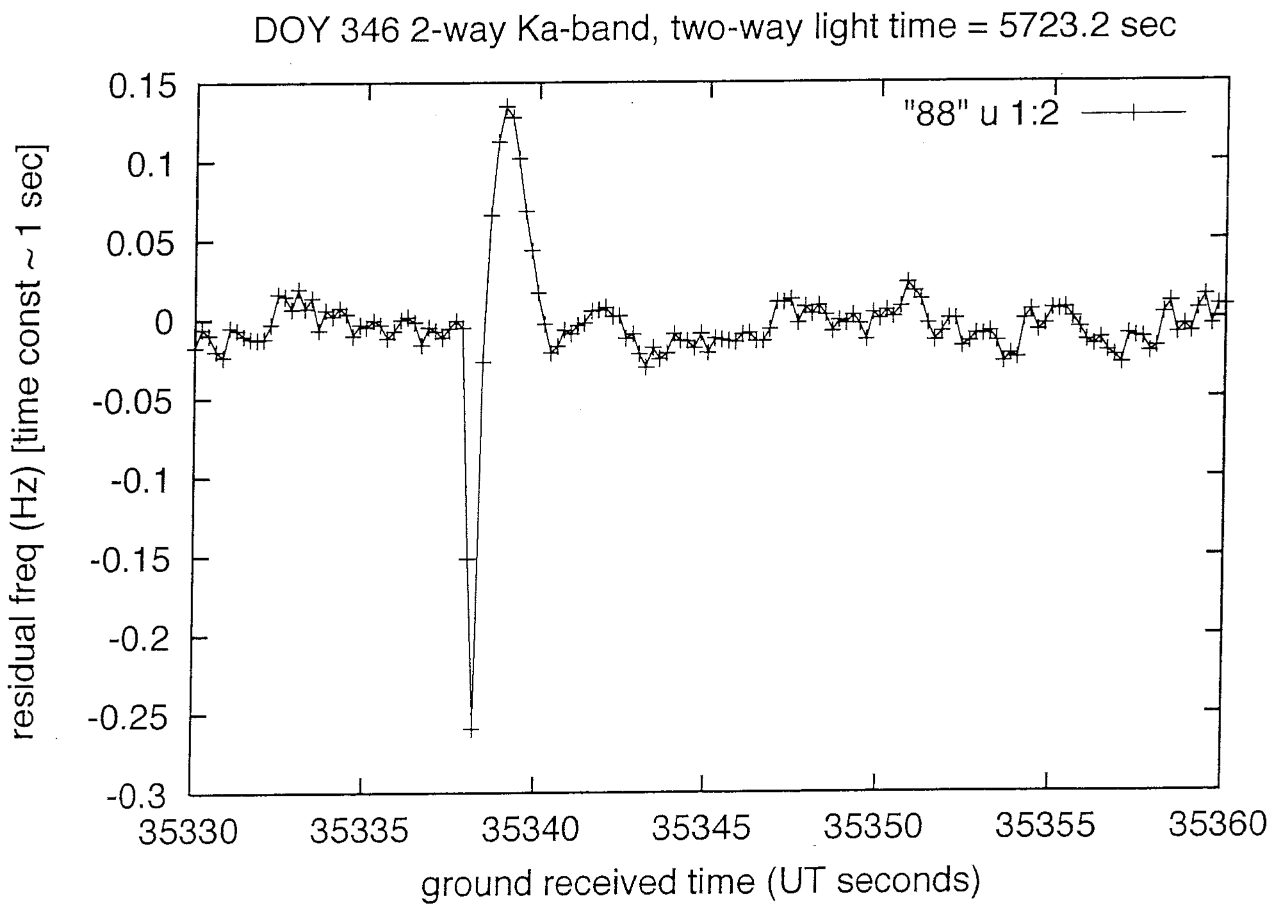
data from 2001_362_0400_82_25_kk_v2.5 TWLT = 5809. sec
amplitude (dB)
5
10
67
77
76
70
75
59
66
46
54
34
file77 residuals (mHz)
10
5
0
−5
−10
7
8
9
10
11
ground received time (hours)



DOY 346 2-way Ka-band, two-way light time = 5723.2 sec
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
"88" u 1:2
29000
30000
31000
32000
33000
34000
35000
36000
residual freq (Hz) [time const ~ 1 sec]
ground received time (UT seconds)



DOY 346 2-way Ka-band, two-way light time = 5723.2 sec
"88" u 1:2
residual freq (Hz) [time const ~ 1 sec]
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
29600
29605
29610
29615
29620
29625
29630
ground received time (UT seconds)


DOY 346 2-way Ka-band, two-way light time = 5723.2 sec
"88" u 1:2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
35330
35335
35340
35345
35350
35355
35360
residual freq (Hz) [time const ~ 1 sec]
ground received time (UT seconds)

Estimated Value of S/C's σ_Z^{GWE}

- **Results:**
  - 40 hours of data beginning 2001-DOY-152/T02:00:03.558 (sampling time is 4 s)
  - CAPS articulation motion was active over this time span (articulation frequency ≈ 0.0025 Hz)
  - Estimated value of σ_Z^{GWE} is ≈ 0.071 μm/sec. It is significantly better than the requirement (0.3 μm/sec)

- **Corresponding Allan deviation**

  $\approx 2.3\times10^{-16} \quad < 10^{-15}$ (Requirement)

from: Won, Hanover, Belenky & Lee 10/18/01

DOY 363 Lunar Occultation

DOY 363 was notable for (a) very bad weather, (b) a precursor to the most noisy plasma day seen to date (possibly associated with a coronal mass ejection—see below) and (c) a lunar occultation of the Cassini signal.

W.r.t. the weather: this is the only day I have seen so far where the AMC data quality warning flags are set for the **whole** pass.

W.r.t. the plasma: this was the day before the worst plasma noise day to date (see first plot—the last red dot is the DOY 364; the ka-band plasma is still very low compared with other noises!). It is probable that this enhanced plasma is just a statistical attribute of the corotating solar wind (since the plasma noise was smoothly rising anyway, perhaps due to rotation of a noisy solar wind sector onto the line of sight, for the last several days). But Elias alertly found this information on the web (Dec 28 is DOY 362):

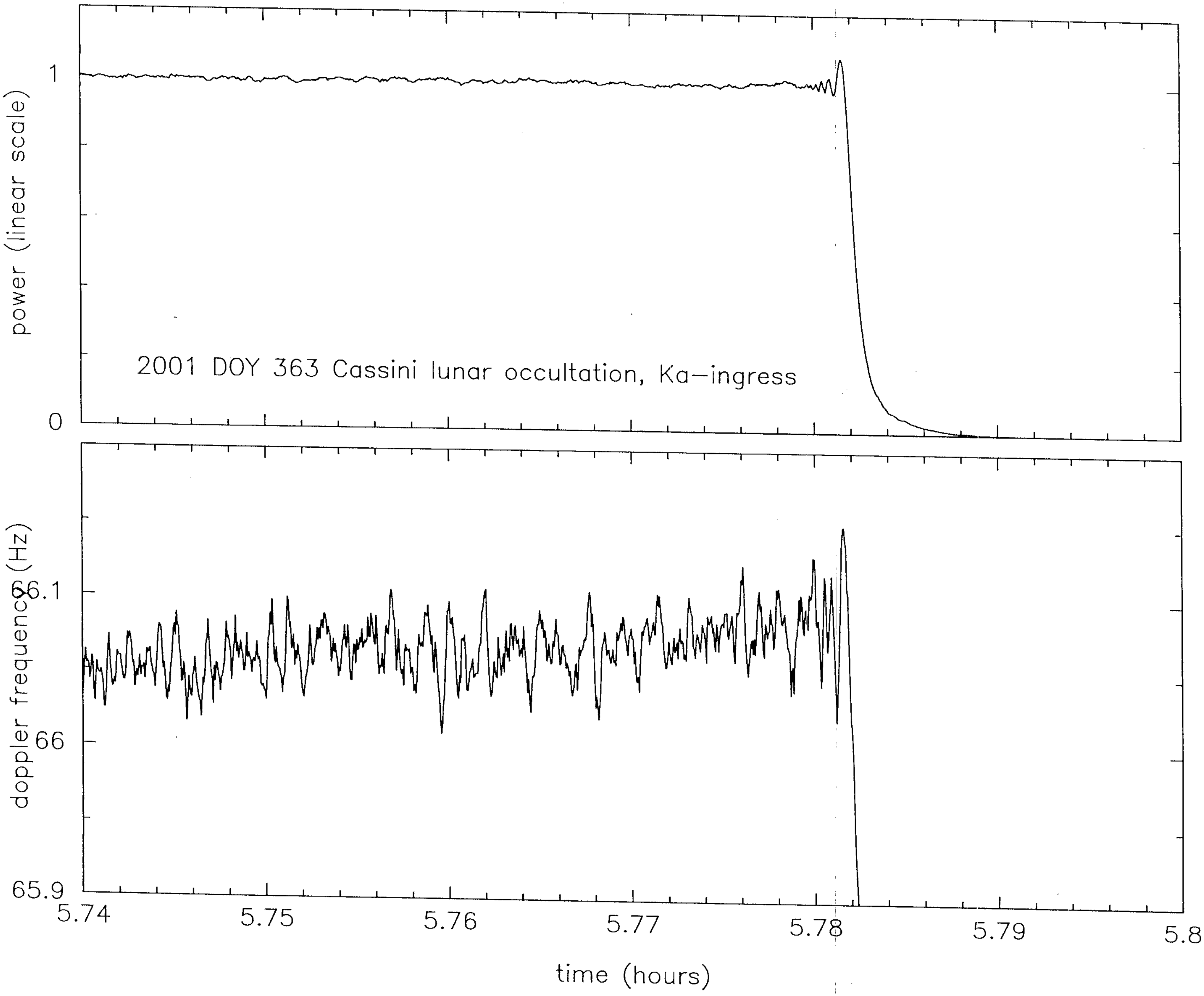
"Space Weather News for Dec. 26, 2001
http://www.spaceweather.com

GEOMAGNETIC STORM WARNING: An explosion on the Sun today triggered a solar proton storm around our planet and hurled a bright coronal mass ejection (CME) into space. Although the fast-moving (~1100 km/s) CME was not squarely Earth-directed, it could deliver a glancing blow to Earth's magnetosphere as early as Dec. 28th Universal Time -- that is, Thursday night for North Americans, Friday morning for Europeans. NOAA forecasters estimate a 10% chance of severe geomagnetic storms at middle latitudes when the expanding cloud sweeps past Earth. Sky watchers along the northern tier of US states (and similar latitudes) should be alert for auroras during the nights ahead."

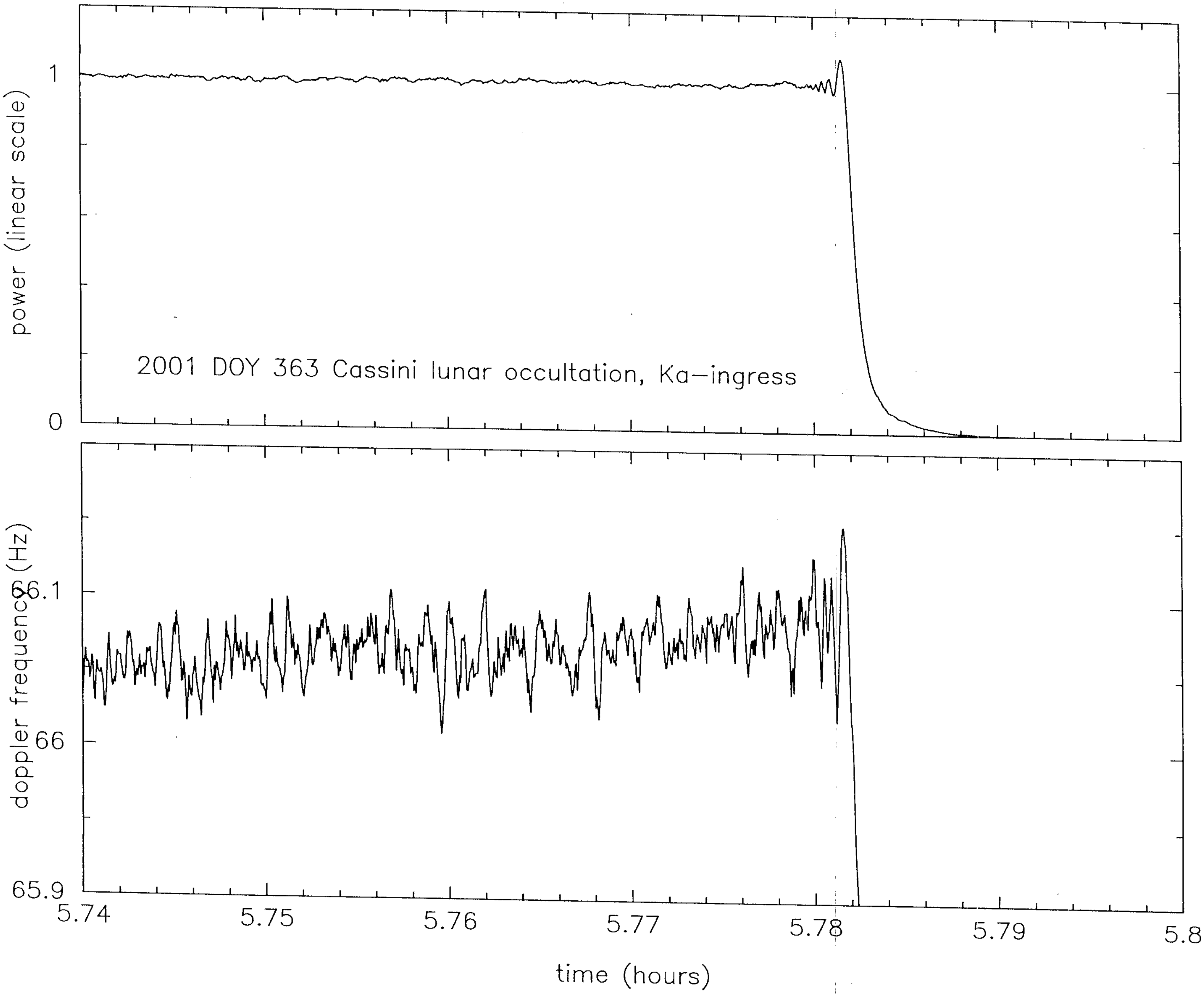
[If the CME was directed to the trailing side of the Earth in its orbit, I would expect it to influence the Cassini line-of-sight 1-3 days **after** it hit the earth, i.e., roughly consistent with larger plasma noise on DOY 364. But I don't know if the CME was actually directed to the trailing side and in any case maybe this is a coincidence.]

W.r.t. lunar occultation: For fun (and because it comes out almost for free in the quick-look analysis) I plotted the power versus time for the entry occultation. I show here the Ka-band ingress occultation. Time constants for amplitude estimation are about 1 second in these plots. The Fresnel structure is clearly evident (also evident in the X-band power and frequency/phase, not shown here because of the poorer SNR on that link.)

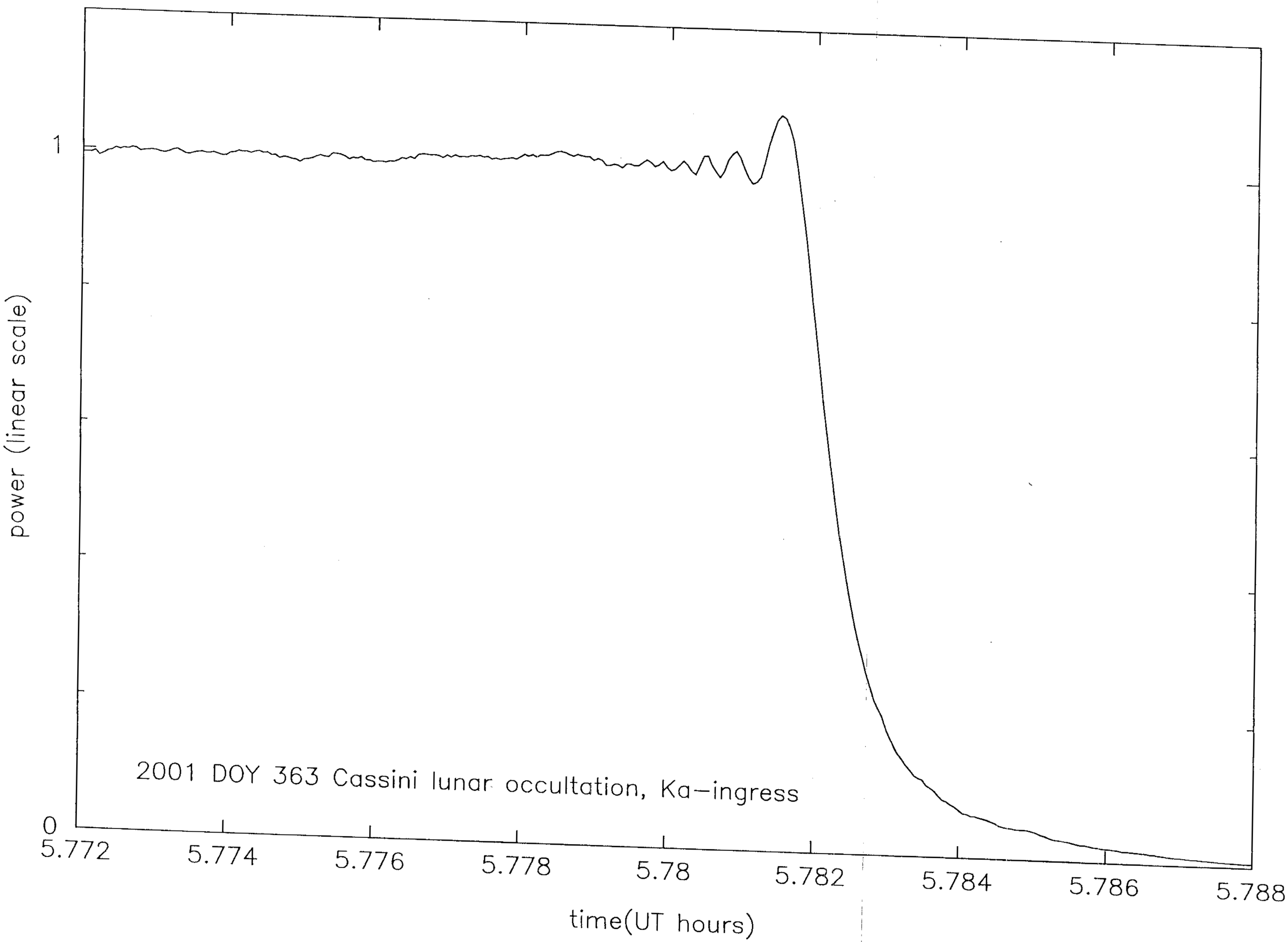
Two plots follow, an "overview" plot and a zoom in on the time around the actual occultation.



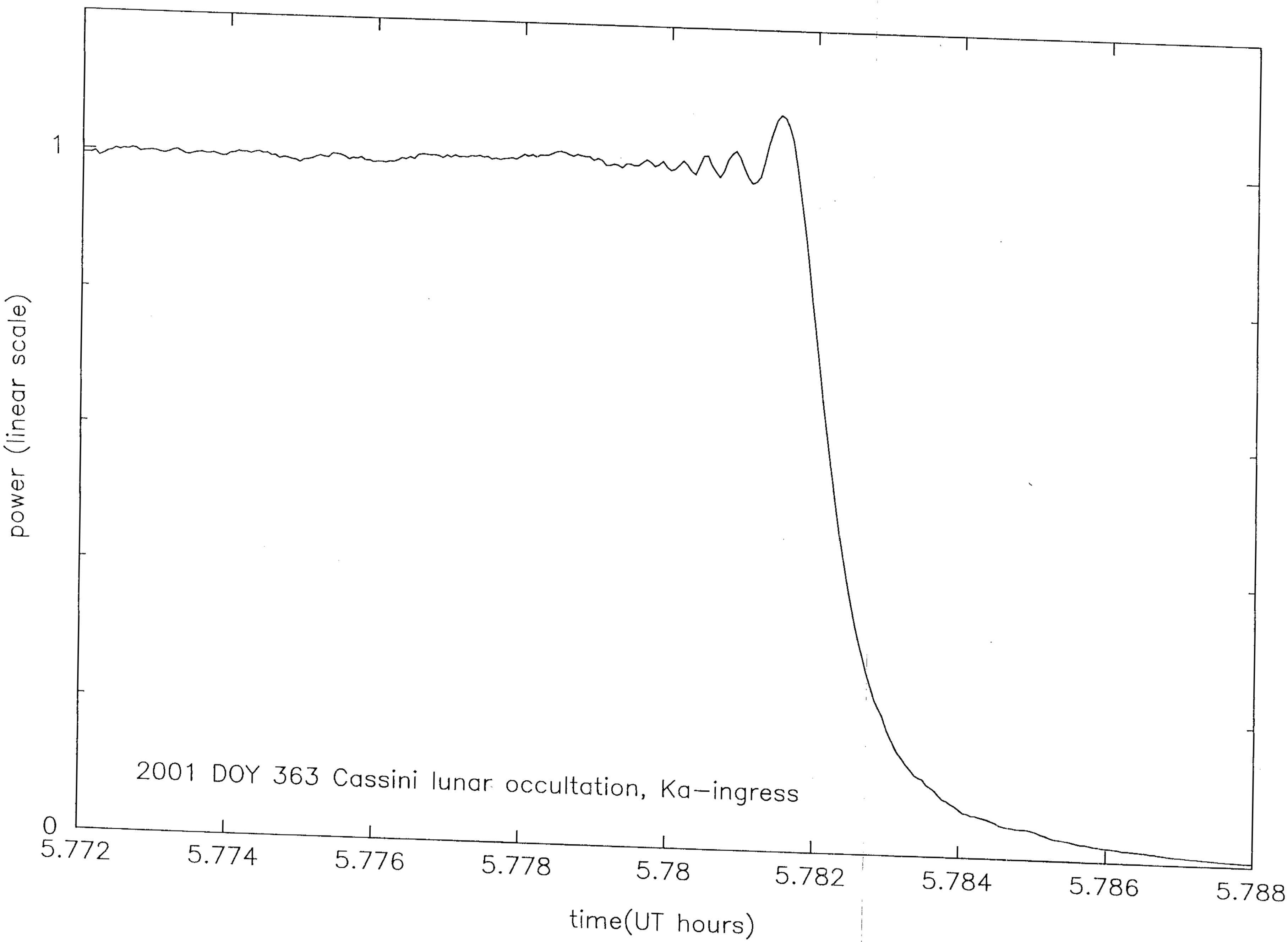
2001 DOY 363 Cassini lunar occultation, Ka–ingress
power (linear scale)
1
0
doppler frequency (Hz)
66.1
66
65.9
5.74
5.75
5.76
5.77
5.78
5.79
5.8
time (hours)



2001 DOY 363 Cassini lunar occultation, Ka−ingress
power (linear scale)
1
0
doppler frequency (Hz)
66.1
66
65.9
5.74
5.75
5.76
5.77
5.78
5.79
5.8
time (hours)



1
0
power (linear scale)
2001 DOY 363 Cassini lunar occultation, Ka-ingress
5.772
5.774
5.776
5.778
5.78
5.782
5.784
5.786
5.788
time(UT hours)



1
0
power (linear scale)
2001 DOY 363 Cassini lunar occultation, Ka-ingress
5.772
5.774
5.776
5.778
5.78
5.782
5.784
5.786
5.788
time(UT hours)

Discussion

- Ka-band up/down, as it had to, knocked the plasma scintillation noise out of the error budget
  - X – (880/3344)K independently estimates the downlink plasma
  - Two-way Ka-band plasma consistent with pre-experiment expectation
- 2-way Ka-band (uncorrected, selected for high elevation angles) limited by nondispersive process (e.g. some combination of troposphere, antenna mechanical, FTS, KaT instability, s/c motion noise,...)
  - Level is consistent with independent estimate of the troposphere, therefore should be able to correct for this to about the target sensitivity level
  - Potential problem: significant fraction of AMC data flagged—liquid water in AMC beam may degrade AMC correction of the data

Discussion (continued)

- KaT
  - After very difficult experience through most of 2001 the KaT worked for GWE1 (see Randy's presentation for operational issues)
  - When in the locked state, the stability seems fine (at least as good as 5E-15 at 1000 seconds and probably << 5E-15)
- AMCs discussed earlier
  - Still learning best way to use these data
  - Weather (e.g. liquid water in the beam) degrades calibration some of the time
- RSRs worked well (useful real-time diagnostics, in addition to primary function—see Randy's presentation)

Discussion (concluded)

- Antenna mechanical
  - Have clear examples of "events"—Bad news: affect ~1% of the data; Good news: "wrong" correlation structure and thus won't affect GW search [will look for lower-level *random* process after systematics taken out]
- Systematics (largely elevation angle dependent)
  - General antenna sag (dominated by M1 mirror sag?) will have to be modeled to correct low-elevation data to sub-10^{-14} level
  - Dry troposphere more subtle than is generally acknowledged (at better than 10^{-14} level)
- Removal of the average orbit and other systematics w/o introducing artifacts in the Fourier band of interest may be tricky

The Story So Far...

- Quick-look noise statistics are consistent with pre-experiment noise budget
- Data quality as we expected

Can We Do Better than Cassini?

Problems Are	Possible Fixes
• tropospheric scintillation	• better calibrations and/or Estabrook/Hellings idea
• plasma scintillation	• higher radio frequency and/or Cassini-style multi-frequency links
• antenna mechanical noise	• look in nulls of transfer function (?)
• frequency standard noise	• 30X better clocks are "straightforward"
• spacecraft position noise	• very careful design (?)

Conclusion: *Maybe* 10-fold improvement—to ~3 x 10^{-18} for periodic sources at selected Fourier frequencies—is possible using spacecraft Doppler tracking from an Earth-based station. <u>However the cost to achieve this would be very high</u>.

Concluding Ideas

- Doppler tracking of Cassini can be used as a broadband gravity wave detector
  - Apparatus is large compared with GW wavelength; thus detector properly described in terms of three pulses GW response
  - Low-frequency band edge is ≈1/(two-way-light-time) set by pulse-overlap
  - High-frequency band edge is ~10^{-1} to 10^{-2} Hz, set by combination of downlink SNR, FTS, ability to calibrate troposphere
  - Not an interferometer: coherence maintained by excellent frequency standard on the ground
- Main noise sources
  - FTS stability
  - Plasma scintillation (dominates S-band; secondary at Ka-band)
  - Tropospheric scintillation (nondispersive)
  - Antenna mechanical stability

Concluding Ideas (continued)

- Signals and noises enter with different transfer functions—a *very* useful discriminator

- Cassini experiment will be ≈10-fold more sensitive than previous observations

  - Ka-band lowers plasma noise at opposition to below troposphere noise

  - Sophisticated tropospheric scintillation calibration

  - Sensitivity:

    - $\approx 3 \times 10^{-15}$ for bursts (i.e., $\sigma_y(\tau \approx 1000$ sec))

    - $\Omega \lesssim 10^{-2}$ for backgrounds ($f_c \approx 10^{-4}$ Hz)

    - $\approx 3 \times 10^{-17}$ for periodic waves (at selected Fourier frequencies); $\approx 1.5 \times 10^{-16}$ averaged over the band