Analysis of Continuum Point Source Photometry Obtained During Test Time Oct. 28 & Nov. 10 1999

Richard Prestage

15th November 1999

Summary

This report describes some continuum point source photometry observations made with the 3mmhi receiver on 28th October and 10th November 1999. Observations were made on Jupiter, Saturn and 0239+108, a $\sim$0.3Jy point souce from Edelson (1987). The main results are as follows:

- Absolute calibration of the data produces values within $\sim$10% of expected, with a $\sim$13% difference between the two receiver channels, and a $\sim$5% change between the two observing runs. Relative calibration should be able to produce results rather better than this.
- There is a elevation-dependent gain variation in the data for all sources, at the level of $\sim$4% between zenith and two airmasses (this is hinted at in the User's Manual, but no details are given). The elevation dependence is due to an additional componenent in the (on-off) variation over and above that expected due to atmospheric attenuation, and does not appear in the (load-sky) calibration measurements. This dependence may vary with time.
- The measured rms noise levels were worse than theoretical by a factor of $\sim$2, but appeared stabled through-out the run. At least on timescales of 10-15 minutes, the S/N on a faint source increased as expected, and Allan variance measurements made on blank sky shown no sign of departure from $1/\tau$ behaviour.

Additional points to note:

- Channel 2 of the 3mmhi receiver had system noise temperatures consistently $\sim$30% higher than channel 1.
- Tuning the receiver to DSB mode proved difficult, and resulted in system noise temperatures apparently four times worse than SSB mode (although this may be a software error). These difficulties should be resolved if serious continuum observations are to be performed.
- the data processing performed by Condar appears correct, although there are minor errors in the User's Manual.
- the fluxes produced by the on-line pointing fits (at least for bright sources) are in good agreement with detailed photometry measurements, and so these might be useful for other purposes.

1 Introduction

This report describes the results of some continuum point source photometry observations made with the 3mmhi receiver on 28th October and 10th November 1999 (UT) during telescope test time. Apart from gaining familiarity with the 12m system, the aim of the observations was to test the continuum performance of the telescope. Two OTF maps of Orion were also made. Unfortunately, although these data can be displayed by the on-line system, and the headers can be read by Condar and AIPS, neither of these two packages can read the data. If these data can be salvaged, they will be reported on elsewhere.

Point source photometry was performed on Jupiter, Saturn and 0239+108. The planets provide a check on the absolute calibration, while 0239+108 (a 0.3Jy point source from Edelson (Astron. J. 94, 1150, 1987)) was chosen to test the performance of the telescope on comparatively faint program objects. Frequent sky tips were performed to determine the atmospheric attentuation. A number of sequences were also performed on blank sky to measure the NEFD without any fear of systematic effects (such as pointing variations).

Initial analysis of the 28th October data revealed an apparent elevation-dependent gain variation, although the lack of low-elevation planet measurements made the precise nature of this difficult to determine. Accordingly additional measurements of Jupiter and Saturn only, to low elevations, were repeated on 10th November.

The receiver was tuned to 95.0GHz USB. On 28th October, only SSB observations were performed. On 10th November, DSB tuning was attempted. However, in this mode the i.f. would get extremely noisy as total power was maximized. In addition, the resulting system temperatures were apparently four times SSB, as opposed to the two times expected. This may be a software error, since the measured flux on Jupiter was also twice as high as expected. Due to these uncertainties, DSB operation was abandoned, although they should be resolved if further continuum observations are to be performed.

2 Observing Conditions

Conditions were rather stable. The 225GHz tipper values were extremely constant at around 0.33 $\pm$ 0.01, and the RH varying smoothly between 35 - 40%. Wind was less than 10mph throughout. System temperatures ranged from $\sim$(150K,190K) near the zenith, to $\sim$(225K,275K) at 22 °elevation. RMS pointing offsets were small (<1" in az, < 2" in el). Saturn was extremely close to 0239+108 on the sky, so the relative pointing should have been extremely good. Observations were done with 5 second integration times, and between 3 and 60 repeats (60 to 1200 seconds total integration time).

3 Summary of calibration basics

This section is mainly for my own benefit, to clarify the processing steps performed at the 12m.

Define:

$\eta_l \equiv$ Telescope Efficiency ($= \eta_r \eta_{rss}$)
$\eta_{sky} \equiv$ Sky transmission ($\eta_{sky}(A) = exp(-\tau A)$)
$\eta_{fss} \equiv$ Forward spillover and scattering efficiency
$T_A^* \equiv$ corrected antenna temperature (corrected for atmospheric and telescope losses).

Assume single-sideband operation ($G_s = 1$, $G_i = 0$), or alternatively a continuum source in DSB operation with $g_i = g_s, gi + g_s = g$.

The antenna temperatures on- and off-source are given by:

$$T_A^{on} = T_A^{sky} + T_{rec} + \eta_l \eta_{sky} T_{source} \tag{1}$$
$$T_A^{off} = T_A^{sky} + T_{rec} \tag{2}$$

So that

$$T_{source} \equiv T_A^* = \frac{T_A^{on} - T_A^{off}}{\eta_l \eta_{sky}} \tag{3}$$

The measured quantities (Voltages) are V_{on}, V_{off}, and V_{load}:

$$\begin{aligned} V_{on} &= g(T_{rec} + T_A^{sky} + \eta_l \eta_{sky} T_{source}) \\ V_{sky} &= g(T_{rec} + T_A^{sky}) \\ V_{load} &= g(T_{rec} + T_{load}) \end{aligned} \tag{4}$$

Then:

$$g = \frac{(V_{load} - V_{sky})}{(T_{load} - T_A^{sky})} \tag{5}$$

$$\begin{aligned} T_A^{on} - T_A^{off} &= \frac{(V_{on} - V_{sky})}{g} \\ &= (V_{on} - V_{sky}) \frac{(T_{load} - T_A^{sky})}{(V_{load} - V_{sky})} \end{aligned} \tag{6}$$

Define a calibration temperature T_C by:

$$T_C = \frac{(T_{load} - T_A^{sky})}{\eta_l \eta_{sky}} \tag{7}$$

then from (4) and (6)

$$T_A^* = \frac{(V_{on} - V_{sky})}{(V_{load} - V_{sky})} \times T_C \tag{8}$$

Define T_{sys} by:

$$T_{sys} = \frac{(T_A^{sky} + T_{rec})}{\eta_l \eta_{sky}} \tag{9}$$

then

$$T_{sys} = \frac{V_{sky}}{(V_{load} - V_{sky})} \times T_C \tag{10}$$

Temperatures can be put onto the T_R^* scale (corrected for forward spillover and scattering) as is standard at the 12m by dividing T_C by η_{fss}.

The 12m makes the assumption that T_C can be set to 400K (for the T_R^* temperature scale - this corresponds to 272K for the T_A^* scale) for SSB operation independent of elevation and atmospheric transmission. Given the assumptions made for chopperwheel calibration ($J_{amb} = J_{spill} = J_{atm}$) then the term ($V_{load} - V_{sky}$) should vary as exp($\tau$ A), which then corrects for the increasing atmospheric attenuation of the source signal.

4 Calibration Implementation

T_C is stored in the Condar header location pointed to TCAL. At the start of every scan, the DBE performs a vane calibration. The quantity T_{sys} as defined above is calculated from V_{load}, V_{sky} and T_C and stored in the header location pointed at by STSYS. The quantity $1/(V_{load} - V_{sky}) \times T_C$ is also calculated and stored in the header location pointed to by RTSYS.

For continuum observations, FREQRES is used to indicate the type of calibration, with the value of 2 being used to indicate vane calibration.

The SWITCHED [1] command in Condar takes the four phases of each sample (ON or OFF) and converts them to a temperature on the T_R^* scale via:

$$ON\ (OFF) = (\Phi_1 - \Phi_4 + \Phi_3 - \Phi_2)/2 \times RTSYS \tag{11}$$

This leaves a series of OFF-ON-ON-OFF measurements in the data array. Note that each ON and OFF should consist of a sky-subracted source signal, here ON and OFF simply refer to whether the source is in the chopper signal or reference beam.

The TEMPS command forms the average (with appropriate signs) of the four OFF-ON-ON-OFF measurements for each repeat. The AVG command forms the mean and rms error in the mean of all the repeats in a sequence. the AVG command also converts the mean and error into flux densities, using the equation:

$$S_\nu = \frac{2kT_R^*}{\eta_A A_p} \eta_l \eta_{fss} \tag{12}$$

using values $\eta_A = 0.47$, $\eta_l = 0.94$, $\eta_{fss} = 0.68$ gives the conversion factor 33.21.

After this, temperatures should be on the T_r^* calibration scale, and flux densities should be corrected for all losses, including atmospheric attenuation. The manual suggests that another correction factor of exp(τA) is required; this appears to be a misprint and this correction is not in fact applied by the software.

[1] routines for performing SWITCHED and other commands described here are located in caub.f in /source/conline/condar

5 RMS sensitivities

The expected rms sensitivity is given by

$$T_{rms} = \frac{2T_{sys}}{\sqrt{\Delta\nu t}} \tag{13}$$

This gives a value of 4mK for a 10s sample, assuming 600MHz bandwidth and 150K system temperature. Other values, together with the equivalent flux density, are given for a range of integration times and system temperatures below:

Int Time	Tsys=150		Tsys= 200		Tsys=250	
	T (mK)	S (mJy)	T (mK)	S (mJy)	T (mK)	S (mJy)
60	1.581	52.51	2.108	70.00	2.635	87.52
120	1.118	37.13	1.491	49.51	1.863	61.88
300	0.707	23.48	0.943	31.31	1.179	39.14
900	0.408	13.56	0.544	18.08	0.680	22.60
1200	0.354	11.74	0.471	15.66	0.589	19.57

Note: these are a factor of $\sim$three better than quoted in the User's Manual - I am not sure why this is the case. Note also that Jupiter is sufficiently bright that it significantly affects the system temperature when it is in the beam.

6 Planetary Fluxes

These were derived using the summit planets program, with the following results:

Source	Freq	FWHM	SD	G.D.	Temp	Flux	Tr*
Jupiter	96.5	66	95.2	3.97	172	1716 Jy	51.67 K
				4.01	172	1687 Jy	50.80 K
Saturn	96.5	66	78.2	8.22	149	271 Jy	8.16 K
0239+108	96.5	66	-	-	-	344 mJy	10.36 mK

The second Jupiter values is appropriate for 10th November.

7 Sky Tips

Frequent sky tips were performed through-out the night, although in fact as evidenced by the 225 GHz tipper values, the transmission was extremely stable. The results of the on-line fits to the sky tips were stored in the data-file; off-line fits performed using Condar gave the same results, and are shown below:

Scan	UT	tau(1)	tau(2)
4	7:26	0.0872	0.0871
12	8:33	0.0842	0.0837
18	9:21	0.0839	0.0834
24	10:06	0.0847	0.0845
107	11:30	0.0831	0.0819
118	13:34	0.0778	0.0772

Ignoring the last value (which was taken around sunrise, and well after all but the blank-sky observations), these are well approximated by a single mean value of 0.0844.

8 Results

The Condar SWITCHED and AVG commands were used on each ON-OFF sequence, to produce the following results:

JUPITER

Scan	UT	Airm	int	T	Trms	S	T	Trms	S	Ts1	Ts2
			(s)	(K)	(mK)	(Jy)	(K)	(mK)	(Jy)	(K)	(K)
6	7:49	1.109	120	50.67	23	1682.2	57.19	24	1898.6	180	224
11	8:30	1.173	60	50.28	56	1669.2	56.49	74	1875.6	181	225
17	9:18	1.311	60	49.91	65	1657.0	55.89	119	1855.5	187	232
105	11:25	2.498	60	47.30	186	1570.4	52.95	289	1757.9	248	298

SATURN

Scan	UT	Airm	int	T	Trms	S	T	Trms	S	Ts1	Ts2
			(s)	(K)	(mK)	(Jy)	(K)	(mK)	(Jy)	(K)	(K)
9	8:24	1.062	60	7.894	7	262.0	9.01	5	299.1	154	195
15	9:13	1.113	60	7.936	15	263.4	9.01	9	299.3	157	198
106	11:27	1.635	60	7.585	15	251.8	8.67	3	287.9	183	227
109	11:52	1.856	60	7.356	8	244.2	8.46	14	281.0	192	237

0239+108

Scan	UT	Airm	int	T	Trms	S	T	Trms	S	Ts1	Ts2
			(s)	(mK)	(mK)	(mJy)	(mK)	(mK)	(mJy)	(K)	(K)
7	7:55	1.072	1200	10.87	0.88	360.8	14.10	0.60	467.9	152	192
13	8:43	1.102	1200	11.75	0.98	390.1	14.60	0.60	484.6	153	193
19	9:30	1.182	300	10.93	1.86	362.7	11.91	0.94	395.4	156	196
20	9:38	1.199	300	10.74	1.66	356.5	14.06	1.72	466.8	157	198

21	9:45	1.218	300	12.39	1.82	411.1	12.82	0.94	425.4	158	199
22	9:52	1.239	300	13.02	1.79	432.1	13.27	1.53	440.6	159	200
110	11:54	2.069	300	12.01	2.93	398.5	10.49	1.55	348.3	202	246
111	12:01	2.173	300	13.27	2.87	440.4	10.76	1.57	357.1	205	251
112	12:08	2.289	300	8.99	2.82	298.4	13.18	1.61	437.4	211	257
113	12:15	2.421	300	6.40	2.01	212.4	11.03	1.94	366.3	217	263

BLANK SKY

Scan	UT	Airm	int (s)	T (mK)	Trms (mK)	S (mJy)	T (mK)	Trms (mK)	S (mJy)	Ts1 (K)	Ts2 (K)
114	12:25	1.155	900	-0.04	1.21	-1.4	-0.49	0.80	-16.3	154	195
115	12:42	1.155	900	1.02	0.95	33.9	-0.50	0.84	-16.8	154	195
116	12:59	1.155	900	1.85	0.77	61.6	0.32	0.75	10.6	155	195
117	13:17	1.155	900	-0.57	0.96	-19.1	0.14	0.82	4.9	155	195

9 Discussion

9.1 Absolute Calibration

Both Jupiter and Saturn show clear evidence for an elevation-dependent gain variation. Further discussion of this is postponed until Section 10.

Taking the highest elevation points for Jupiter and Saturn, and the mean of the six high-elevation points for 0239+108, and including data from 10th November, we get the following results:

		Jupiter		Saturn		0239+108	
		Ch1	Ch2	Ch1	Ch2	Ch1	Ch2
predicted	(Oct)	1716	1716	271	271	344	344
	(Nov)	1687	1687	271	271	344	344
Observred	(Oct)	1682	1899	262	299	380	461
	(Nov)	1578	1752	256	290	-	-

The channel 2 values are consistently ∼13% higher than channel 1 for Jupiter and Saturn, with the channel 1 values slightly lower than expected, and the channel 2 values somewhat higher.

The November Jupiter values are 7% lower than the October values, while the Saturn results are 3% lower.

For 0239+108, the channel 2 values are 20% higher than channel 1, while the channel 1 value is itself 10% higher than expected (although the predicted values are based on 1987 measurements).

9.2 Noise Performance

The rms errors for Jupiter and Saturn are likely to be due to systematic effects, and do not reflect the underlying performance of the system.

The results for 0239+108 and blank sky observations are quite consistent; the observed rms noise performance is approximately 2.5 times that predicted for channel 1, and 1.4 times that predicted for channel 2. These results appear to be independent of integration time and system temperature.

Note that the fact that channel 2 comes considerably closer to the theoretical noise performance means that this channel is still more sensitive for continuum observations, despite the increased system noise temperature.

Figures 1 & 2 show the cumulative mean, rms error in the mean, and signal to noise for the first six scans (one hour of integration time) of 0239+108 for channels 1 and 2 respectively. These all behave as expected.

Figures 3 & 4 show Allan variance plots for the four blank sky measurements for channels 1 and 2 respectively. The Allan variance is defined by:

$$\sigma_y^2(\tau) = \langle 1/2(\overline{y}_{k-1} - \overline{y}_k)^2 \rangle \tag{14}$$

Where $\overline{y}$ is the average signal in sampling time τ. Values of $\sigma_y^2(\tau)$ for increasing values of τ were generated by simply averaging consecutive samples together.

For a noise power spectrum which contains drift, flicker noise and white noise, the Allan variance is expected to vary as:

$$\sigma_y^2(\tau) = C_1\tau^q + C_2 + C_3\tau^{-1} \tag{15}$$

One hour of data was generated simply by concatenating the four sky noise observations together. Although the limited total observation time means that the results get noisy after around ten minutes (60 samples), there is no sign of a departure from the white noise behaviour out the maximum twenty minutes for which values can be generated.

10 Elevation-Dependent Gain

As noted in Section 9, both the Jupiter and Saturn data obtained on 28 October showed evidence for an elevation dependence of the measured antenna temperatures. Preliminary analysis suggested that for both sources, Vload - Vsky varied with airmass as expected, but Von-Voff dropped off more rapidly than expected. However, while the low elevation Saturn point suggested this extra drop-off was an additional factor of exp(τ A) (suggesting a possible bug in the calibration software) the single low-elevation Jupiter point did not fit this relation.

To investigate further, a number of additional measurements of Saturn and Jupiter over a range of airmass were obtained on 10th November. The values of (Von-Voff) were taken as the averages of the raw data, while (Vload - Vsky) was obtained from TCAL / RTSYS. Plots of these values are shown in Figures 5 & 6.

Attempts were made to obtain sky-tips throughout the night. A number of these either failed or were rendered suspect due to problems with the apex translation stage during the tip. However, the following results were obtained:

scan	tau ch1	tau ch2
144	0.0552	0.0594
145	0.0589	0.0626
168	0.0564	0.0607
207	0.0590	0.0636

There is some indication that the opacity may have increased slightly with time, and this is corroborated by the Saturn plots. However, assuming a fixed slope in the log(v1-v2) versus airmass relation, the following values were obtained:

	Von-Vsky	Von-Voff
Saturn ch1	-0.0608	-0.0960
Saturn ch2	-0.0643	-0.1185
Jupiter ch1	-0.0417	-0.0700
Jupiter ch2	-0.0532	-0.0885

The slope for Von-Vsky appears reasonably consistent with the measured opacity. The Von-Voff slopes are considerably steeper than this, although not as steep as 2τ, as had been expected earlier.

This additional term in (Von-Voff) translates directly into a variation in the measured antenna temperature as a function of elevation. The average change in gain going from zenith to two airmasses is 5% for Saturn and 3% for Jupiter (but note that the value for the Saturn data obtained on 28th October is considerably worse than this).

A Figures

Figure 1. Cumulative mean, rms error in the mean, and S/N for 0239+108 Channel 1, generated by concatenating observations 7,13,19,20,21,22. Each sample consists of a 10 second (ON-OFF), giving one hour of data total.

Figure 2. Same as figure 1, but for channel 2.

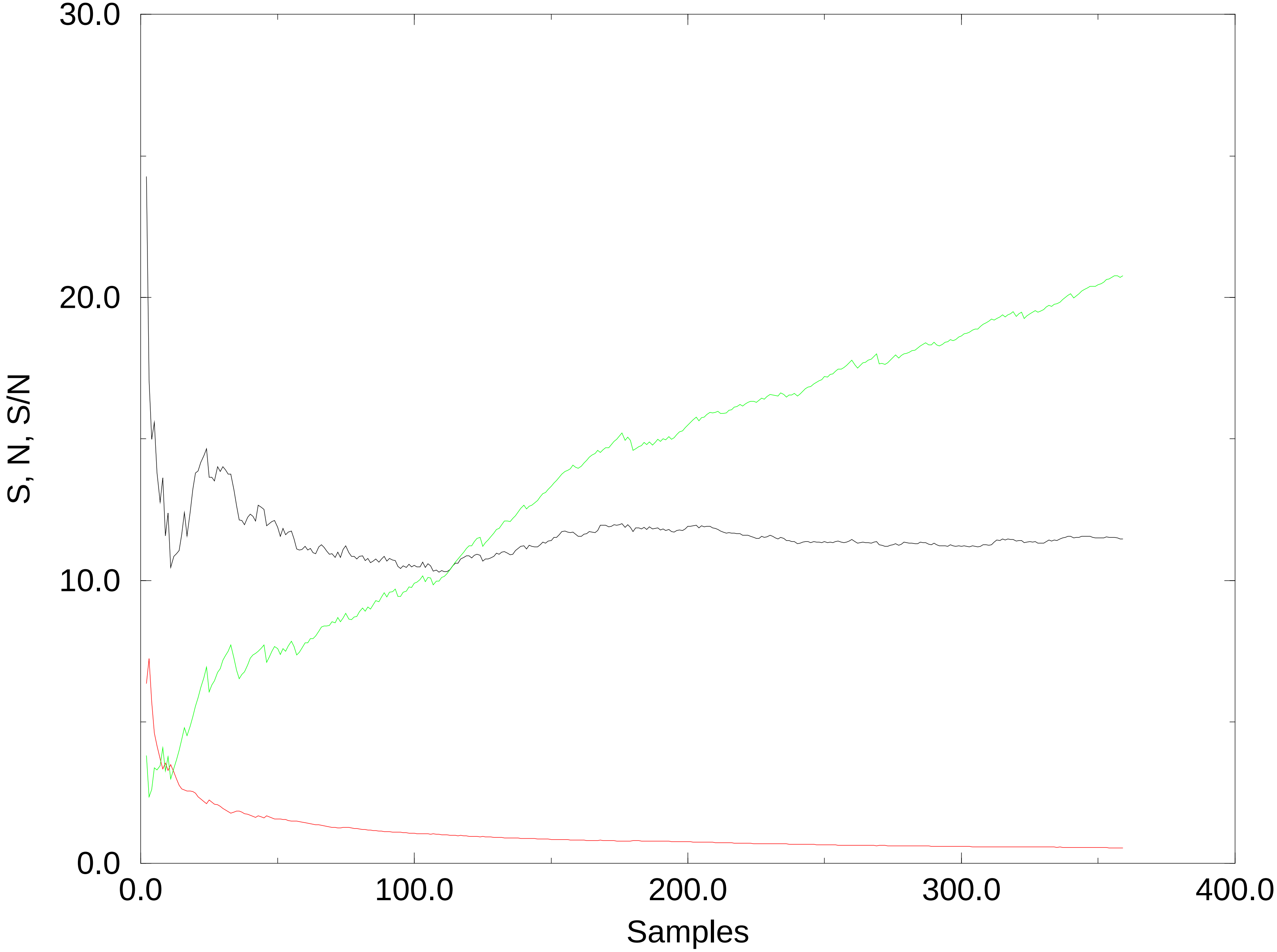
Figure 3. Allan variance for blank sky channel 1, formed by concatenating observations 114,115,116,117. This produced one hour of data total; Allan variances out to 20 minutes were generated by averaging successively larger sections of the raw data together.

Figure 4. Same as figure 3, but for channel 2.

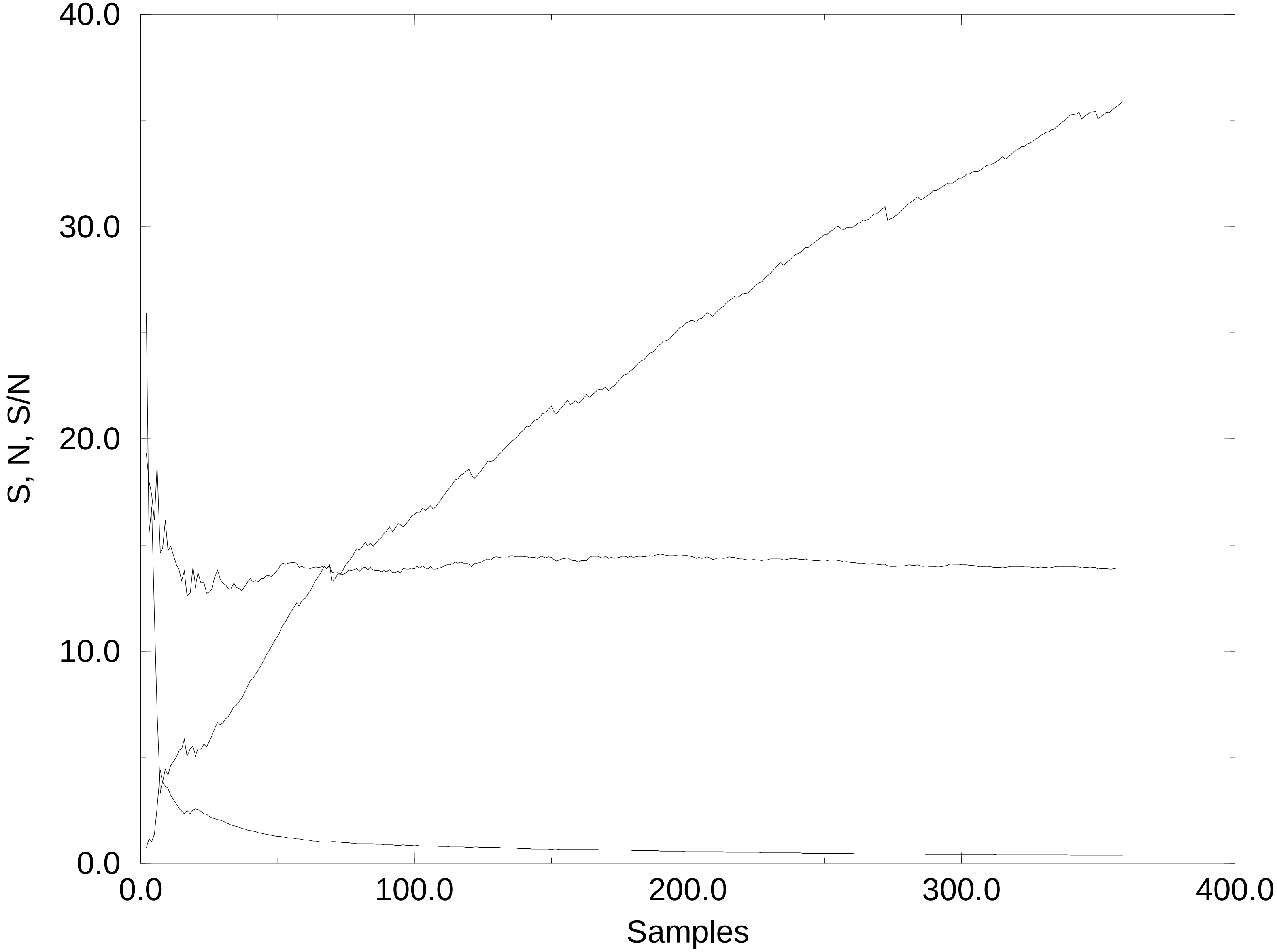
Figure 5. Log of (Von-Voff) (top data points) and (Vload - Vsky) (bottom data points) for Saturn for channel 1 (upward triangles) and channel 2 (downward triangles). The data have had an arbitrary zero-point removed.

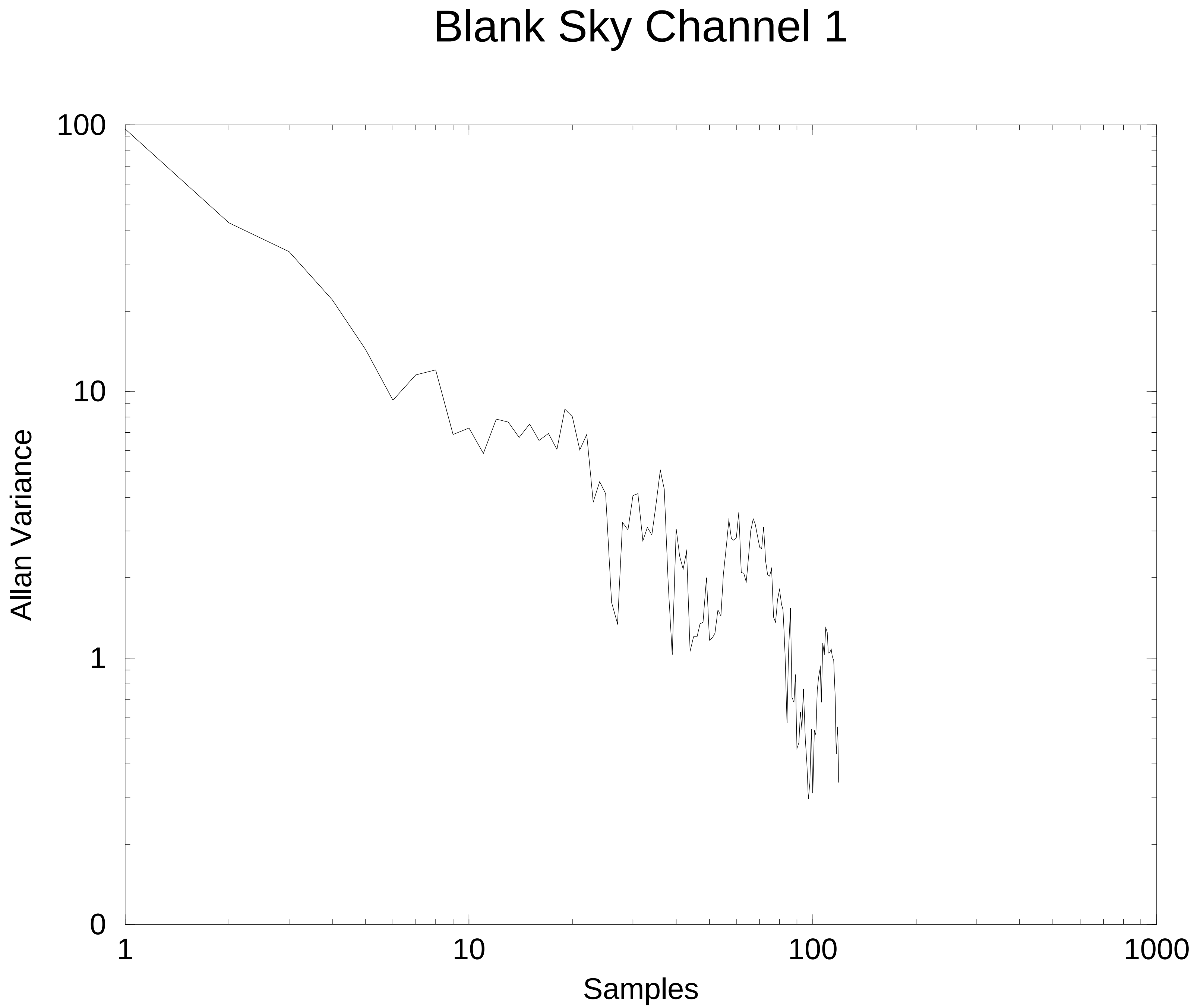
Figure 6. Same as figure 5, but for Jupiter.

0239+108 Channel 1

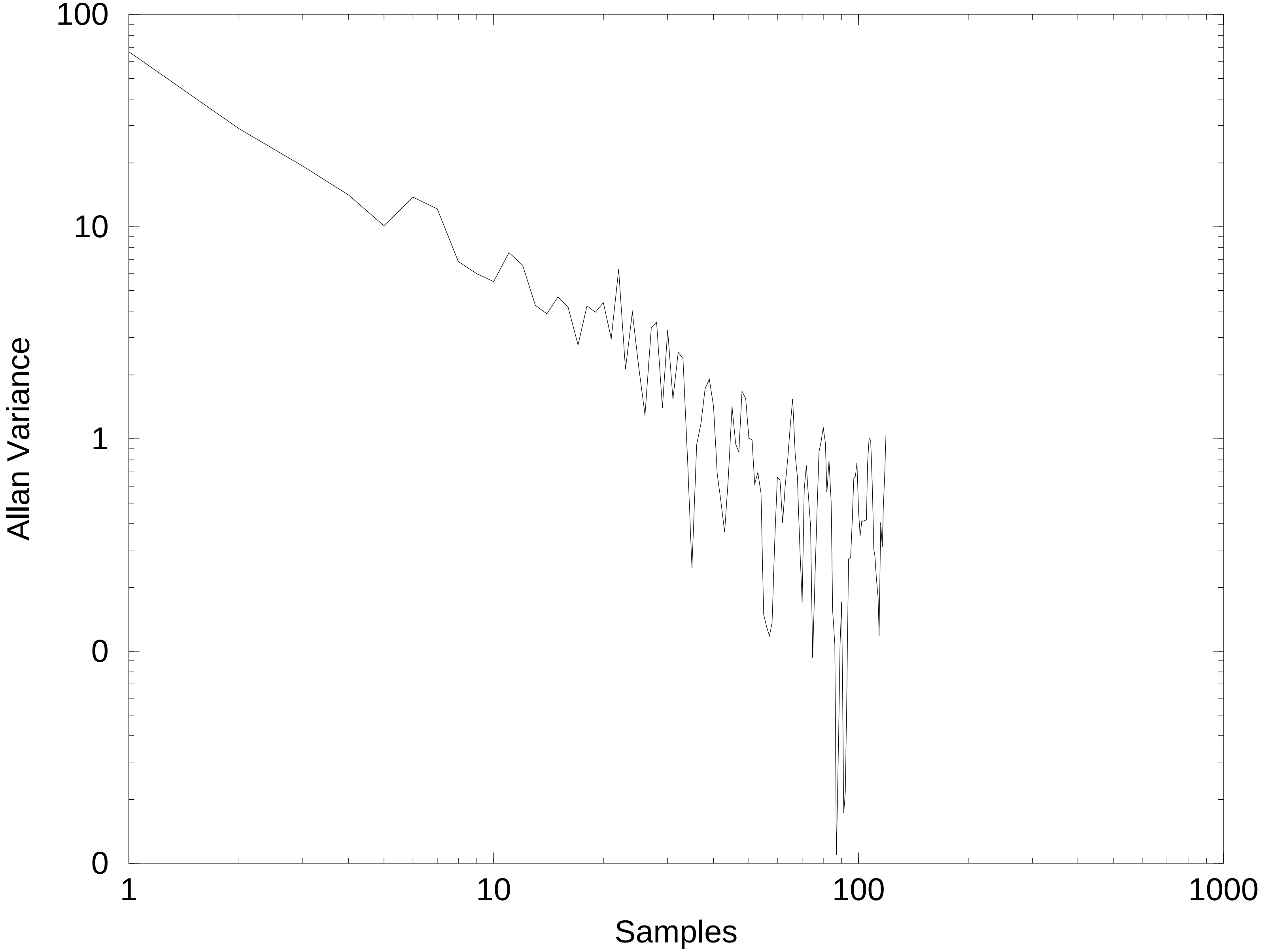


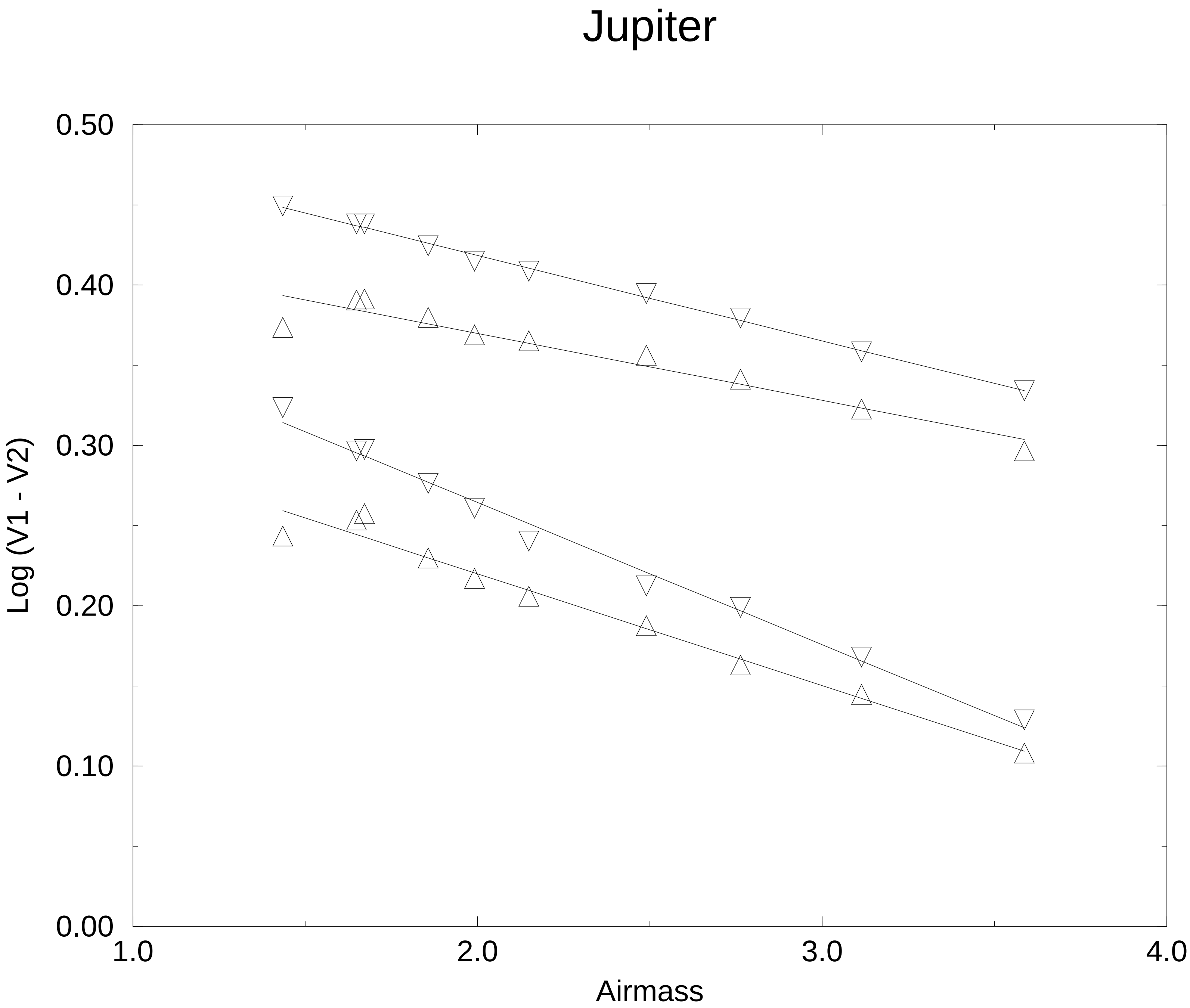
0239+108 Channel 2

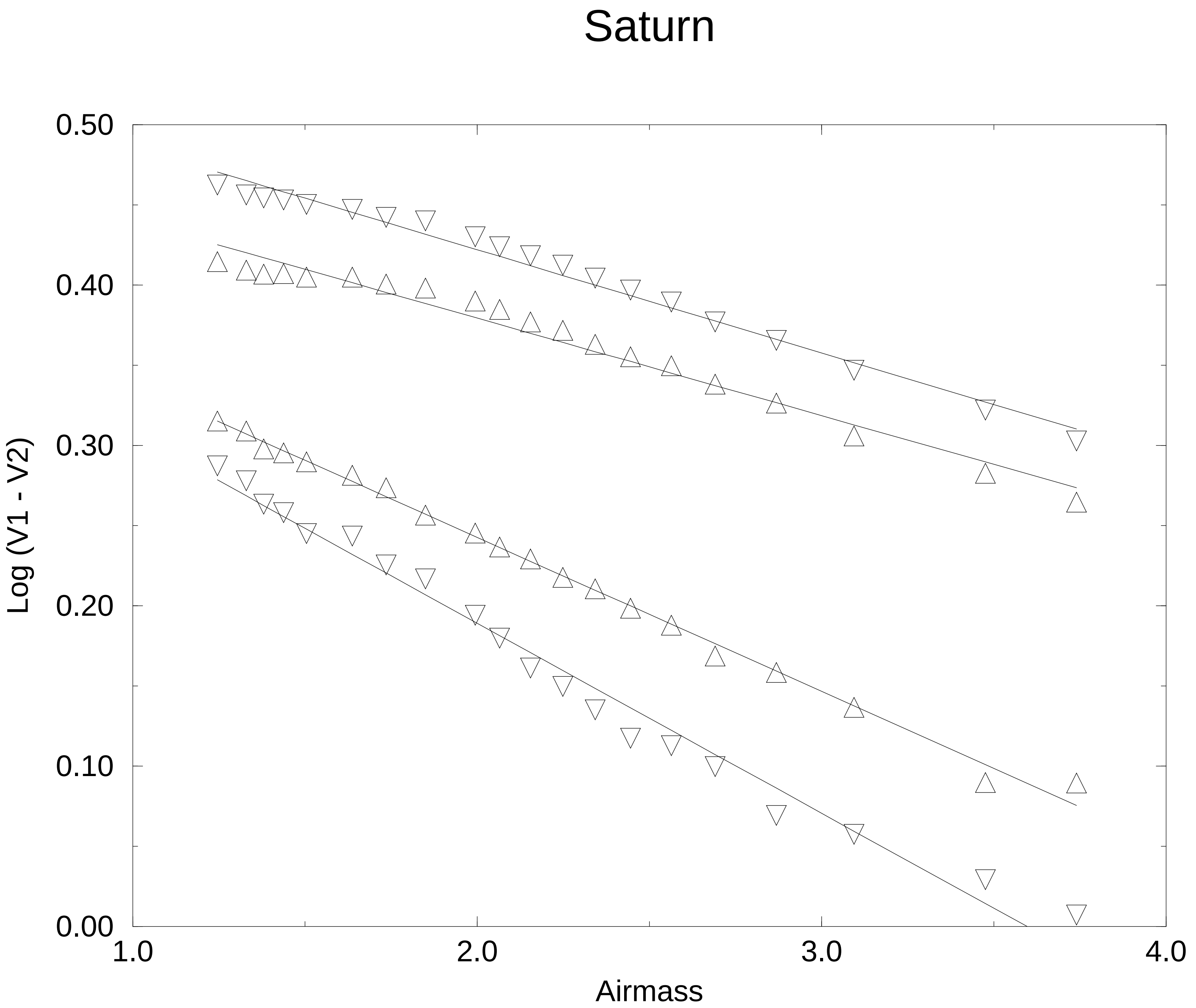



Blank Sky Channel 1
Allan Variance
Samples
100
10
1
0
1
10
100
1000

Blank Sky Channel 2




Jupiter
0.50
0.40
0.30
0.20
0.10
0.00
Log (V1 - V2)
1.0
2.0
3.0
4.0
Airmass


Saturn
0.50
0.40
0.30
0.20
0.10
0.00
Log (V1 - V2)
1.0
2.0
3.0
4.0
Airmass