EVLA Memo 70
Desiderata for Solar Observing with the EVLA

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Abstract

Radio telescopes are generally designed for high performance on cold sky. When pointed at the sun, the total power will rise from cold sky values by a factor between 100 and 1 million, depending on the band and level of solar activity present at the time. Much of the most physically interesting activity is not only very powerful, but very brief, implying rapid changes in input power. This memo summarizes the range and time scales of input power changes caused by the sun to a 25-meter telescope, and describes the desired instrumental capabilities to enable solar observing on the EVLA.

1 Introduction

The sun is a bright, very large, and highly variable object at radio wavelengths. This variability covers an enormous range both in flux density and in time scale. The combination of high input power and rapid time variability present significant challenges to any radio astronomical telescope optimized for observations of cold sky.

Effective solar observing with the EVLA will require careful planning. The following is an attempt to describe the maximum range of solar activity, and is meant as a planning guide. We would like to ensure the EVLA will be a useful tool for investigations of the wide range of solar phenomena. However, as will be noted below, accommodating the most powerful and rare solar flares for all of the EVLA's frequency bands will likely exceed the available budget, thus requiring a careful prioritization. These issues are discussed at the end of this memo.

2 Solar Radio Emission Characteristics

In this section we briefly discuss the characteristics of solar radio emission.

2.1 The Quiet Sun

At radio wavelengths shorter than $\sim$ 10 cm, the quiet sun appears much like it does at optical wavelengths – a relatively uniform disk of diameter $\sim$30 arcminutes, with a brightness temperature increasing from 6000 K at $\lambda < 1$ cm to $\sim$70000 K at 10 cm wavelength. At longer wavelengths, the quiet sun becomes brighter due to the increasing contribution of the solar corona, somewhat larger, and can be modestly limb-brightened. At 327 MHz, for example, the quiet sun is about 40 arcminutes in diameter, with a disk-center brightness of $\sim$400,000 K.

Table 1 shows the effect of the quiet sun on the EVLA receivers. The first two columns show the band names and frequency span, the third column gives the total flux density in SFUs[1] emitted by

[1] 1 SFU = 10^4 Jy = $10^{-22}\mathrm{watt\,m^{-2}\,Hz^{-1}}$

the quiet sun, with the mean brightness temperature given in column 4. Column 5 shows the effective antenna temperature, evaluated via:

$$T_A = \frac{A_e}{\lambda^2} \iint T_b(\theta, \phi) P_n(\theta, \phi) d\Omega \tag{1}$$

where A_e is the effective antenna collecting area, T_b is the solar brightness distribution, and P_n is the normalized antenna gain. At the lower frequencies, (the UHF, L, and S bands) where the sun is smaller than the main beam, the integral has been evaluated using the known variation of the VLA's primary power pattern. At higher frequencies, where the sun is larger than the primary beam, we have simply assumed a main-beam efficiency of 75%. The power from the sun provided to the front end amplifier, $kT_a\Delta\nu$, is given in column 7, and the ratio of this power to that from cold sky is given in column 6. An observation of the quiet Sun yields an increment in the input power to the first amplifier that is a factor of ~100 to ~2000 times that of the cold sky.

The Effect of the Quiet Sun						
Band	Freq.	S_{QS}	T_b	T_a	T_{sys}/T_{cold}	P_{in}
	GHz	SFU	1000 K	1000 K	dB	dBm
UHF1	0.24 - 0.41	10	500	15	25	-75
UHF2	0.41 - 0.70	18	300	20	27	-71
UHF3	0.70 - 1.20	35	200	30	30	-67
L	1 - 2	50	100	40	33	-63
S	2 - 4	130	70	40	32	-60
C	4 - 8	225	30	20	28	-60
X	8 - 12	420	20	15	26	-61
U	12 - 18	500	10	7.5	23	-62
K	18 - 26	1000	9	6.8	21	-60
A	26 - 40	1400	6	4.5	19	-61
Q	40 - 50	2500	6	4.5	18	-62

Table 1: The expected effect on the receivers from observing the quiet sun with the EVLA antennas. Column 1: Common band name. Col. 2: Frequency span. Col 3: Quiet sun spectral flux density, in SFU. Col. 4: Mean brightness temperature, assuming solar disk of 0.224 sq. deg. Col. 5: Contributed antenna temperature for an EVLA antenna. Col. 6: Ratio of system temperature while pointed on the quiet sun to that for cold sky. Col. 7: Power input to the first LNA, in decibel milliwatts.

Some solar or solar-related observing will be done with the antennas pointed at the limb, or a little further out. In this case, the increase in system temperature may be only a fraction of these values, and it may change as the object being tracked (which might be a background source) approaches, or recedes from, the Sun.

2.2 Active Solar Regions

In reality, the sun is a strongly variable source – and it is the physics of the variability which is one of the topics of primary scientific interest. When active solar regions lie within the antenna beam, the system temperature can increase by factors of a few to about ten over 'quiet sun' levels. Table 2 shows the effect of an active region, plus the solar disk, on an EVLA antenna. Column 2 gives the active region spectral flux density, column 3 the antenna temperature contributed by this region, plus that of the mean solar disk[2] The remaining two columns give the ratio of system temperatures when observing an active region to that for cold sky, and the power input to the first LNA.

[2]Assuming the active region is small compared to the primary beam, the antenna temperature is given by $T_a = 1775\epsilon S_{SFU}$, where ϵ is the antenna efficiency.

The Effect of an Active Region				
Band	S_{AR}	T_a	T_{sys}/T_{cold}	P_{in}
GHz	SFU	1000K	dB	dBm
0.24 - 0.41	35	30	28	-69
0.41 - 0.70	50	50	31	
0.70 - 1.20	75	90	34	
1-2	100	100	37	-57
2-4	150	160	38	-53
4-8	80	85	35	-52
8-12	70	62	34	-54
12-18	50	44	31	-54
18-26	40	32	28	-53
26-40	30	20	27	-53
40-50	30	16	24	-55

Table 2: The expected effect on the EVLA receivers of observing the active sun with the EVLA antennas. Column 2 gives the flux in SFUs of an active region, column 3 the total antenna temperature due to the solar disk and the active region, column 4 the factor by which the system temperature is raised above cold sky values, and column 5 the power input to the first LNA for an EVLA antenna.

2.3 Solar Flares

Solar flares present the most challenging technical problem, and are the subject of considerable scientific interest. Flares commonly occur in the range of 10 to a few hundred SFUs at frequencies > 1 GHz. These will increase the system temperature over quiet Sun values by factors of more than 10, to perhaps 100. Although rare, extreme flare events top out at 10^4 to 10^5 SFUs – thus multiplying the system temperature (over quiet sun values) by factors as large as 10^6 at the Cassegrain bands, and by 10^7 at the lower prime focus bands. The (inverse) frequency of occurrence of solar flares during the solar maximum period is shown in Figure 1 as a function of frequency. We note that the rate is relatively constant for frequencies > 1 GHz, and that the power of these flares increases dramatically at longer wavelengths.

The effect of solar flares of various strengths and frequencies is shown in Table 3. Here we have used Figure 1 to calculate the strengths of flares with a probability of occuring within a 12-hour period (during solar maximum) of 1%, 5%, and 25%.

Time scales for flux variations vary considerably. During the impulsive phase of a flare the flux density can change by 1 - 2 SFU/sec; more extreme cases can double the system temperature in ~ 1 sec. More typically, large flux variations occur during the course of tens of seconds to minutes.

At lower frequencies (below 4 GHz), coherent emission phenomena generate bright ($T_b \sim 10^{15}$ K!), narrow band (1% of the front-end bandwidth, 10 MHz), and rapidly time varying (10 msec) emission. Because these phenomena are small both in frequency bandwidth and in angular size, the added power is not extreme when 'diluted' by the 2:1 BWR front end signals. A single 1000 SFU spike may increase the broad-band system temperature by a few 10s of percent in 20 msec. Many such bursts can occur at different frequencies at the same time – the net effect could be to multiply the system temperature by a factor up to 10 on timescales of ~ 1 sec. This phenomenon will set the dynamic response requirements.

3 Amplifiers and Compression

Observations of the sun will drive the EVLA's amplifiers to power levels beyond their designed range. The general situation is shown in Fig 2.

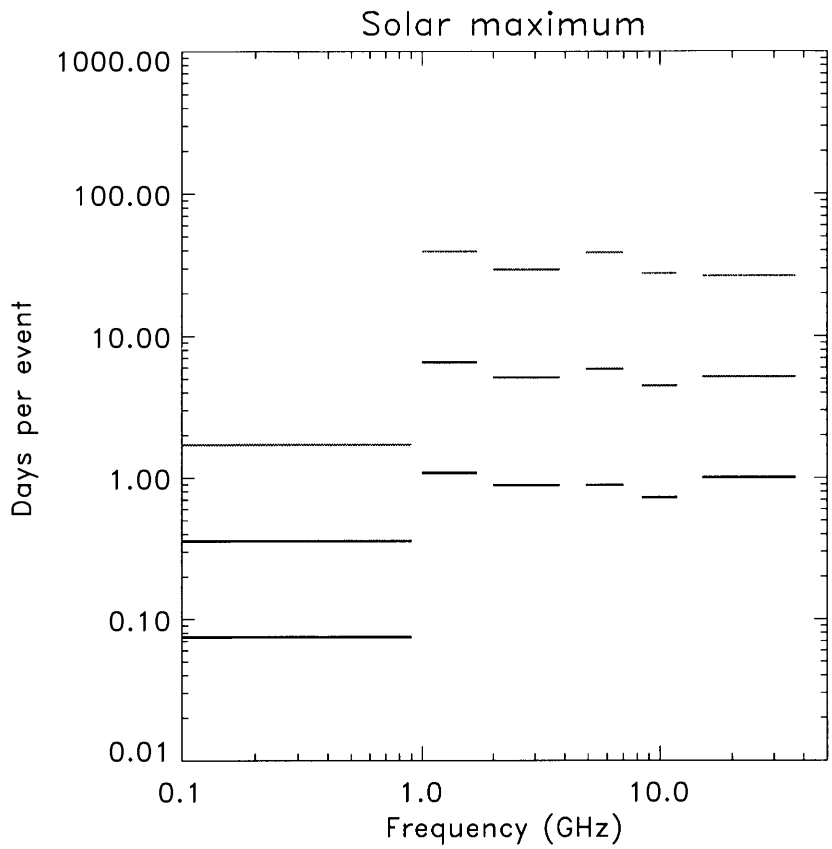

Figure 1: The mean time separation of solar flares, by power, for the active sun, color-coded by flare power. The yellow distribution is for flares of 10^5 SFU (10^9 Jy,), red for 10^4 SFU, purple for 1000 SFU, and black for 100 SFU. The intervals shown for the 0.1 – 1 GHz bin are appropriate for the low frequency end. We have interpolated between these values and those for 1 – 2 GHz for the UHF bands shown in the table.

The figure shows that in general, input powers exceeding $\sim$ 36 dB above cold sky will result in significant gain compression. Hence, for observations of the rarer, and more powerful, active phenomena, the standard EVLA receiver systems will not be useable, and a different receiver design will be needed.

4 EVLA System Desiderata

The overall goal is to enable accurate interferometry of these powerful and rapidly varying phenomena. Ideally, this requires:

- Retaining adequate system linearity throughout a power input range extending from cold sky values to as high as 60 dB above these values.
- The ability to monitor the system temperature change with an accuracy of 5%, during the course of active phenomena.
- These accuracies are desired on the following timescales:
  - 10 dB change in power input in 1 sec.
  - 30 dB change in 1 min.

The Effect of Solar Flares									
	1%			5%			25%		
Band	S_{FL}	DR	P_{in}	S_{FL}	DR	P_{in}	S_{FL}	DR	P_{in}
GHz	SFU	dB	dBm	SFU	dB	dBm	SFU	dB	dBm
0.24 - 0.41	1×10^6	71	-28	1×10^5	61	-38	1×10^4	51	-48
0.41 - 0.70	2×10^5	64	-33	1×10^4	52	-46	2×10^3	45	-53
0.70 - 1.20	4×10^4	58	-37	4×10^3	48	-47	5×10^2	42	-55
1-2	2×10^4	58	-36	2×10^3	48	-46	2×10^2	38	-56
2-4	2×10^4	58	-33	2×10^3	48	-43	2×10^2	38	-53
4-8	2×10^4	58	-30	2×10^3	48	-40	2×10^2	38	-50
8-12	2×10^4	58	-30	2×10^3	48	-40	2×10^2	38	-50
12-18	2×10^4	57	-28	2×10^3	47	-38	2×10^2	37	-48
18-26	2×10^4	54	-27	2×10^3	44	-37	2×10^2	34	-47
26-40	2×10^4	54	-26	2×10^3	44	-36	2×10^2	34	-46
40-50	2×10^4	51	-29	2×10^3	41	-39	2×10^2	31	-49

Table 3: The expected effect on the EVLA receivers of observing solar flares with the EVLA antennas. Listed are the flux densities (in SFU), power increments (from cold sky), and the power delivered to the first amplifier, due to a flare with a probability of 1%, 5% and 25% of occuring within a 12-hour period during solar maximum. Even the relatively commonplace flares will contribute more power than the entire thermal solar disk.

These capabilities would be useful at all bands.

A key question – yet unanswered – is what defines 'adequate linearity'. This is a difficult issue, as the effect on imaging when observing with the amplifiers at, say, 1% compression is unknown, although general arguments indicate that imaging performance may still be sufficient. Realistic tests will be required to answer this question. Another, provisionally answered, is what defines adequate accuracy in monitoring the system temperature and gain. It is suggested here that 5% is adequate over the timescales and power ranges listed above.

In practice, limitations will be imposed on EVLA observations of solar phenomena; in some cases, severe limitations. We note that the EVLA LNAs have a gain of 40 dB. Moreover, their 1 dB compression point, which represents a 25% departure from linearity, occurs at approximately -4 dBm (output power) – a level which will prevent useful EVLA observations of the most powerful 25% of all flares. The most powerful flares will drive the EVLA amplifiers 20 dB or more above their 1% compression points. Without a modified receiver system, solar observers will be restricted to observing flares of a few $\times 100$ sfu or less for frequencies of ~ 4 GHz and above.

The increasing departure from linearity as flux levels increase is also problematic. Flux calibration could depart significantly from the desired level of accuracy (unless each LNA goes into compression gracefully and predictably, in which case the gain can perhaps be cross-calibrated against another instrument on an antenna by antenna, and band by band, basis). An open issue surrounding gain compression is whether the increasing presence of intermodulation products across the RF band introduces significant phase closure errors downstream.

A final limitation is budgetary. Present plans call for support of the 1- 2 GHz band and one other for solar observing. It is possible that one or two more bands will be supported out of contingency. The support of addit ional bands will likely require additional resources. The solar community must therefore prioritize which bands must be supported by the EVLA project.

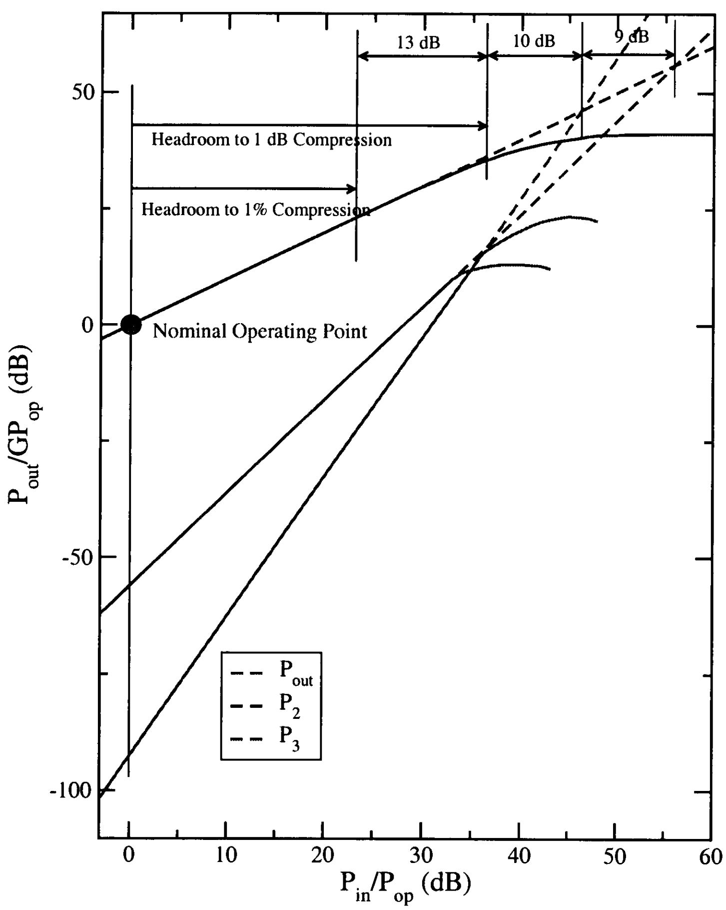

Figure 2: The blue line shows the relationship between the input and output power for a typical EVLA amplifier. Both axes are normalized by their 'cold sky' values. The roll-off in output power is due to gain compression, which effectively transfers power from the desired output to higher harmonics and intermodulations between input power frequencies. The powers in the 2nd and 3rd order intermodulation products are shown by the red and green lines.It is generally assumed that 1 dB compression marks the end of the useable amplifier range – for a typical EVLA receiver, this occurs about 36 dB above the nominal 'cold sky' operating point. Hence, only low-power, commonplace flares can be observed with the high-sensitivity EVLA receiver setups.