VLBA Electronics Memo No. 30

I.F. SIGNAL PROCESSING: PRELIMINARY SPECIFICATIONS

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1.0 INTRODUCTION

A block diagram of the VLBA station signal processing from the antenna to the digitizers is given in Figure 1. This configuration is now firmly established, and the design is not likely to change at the level of detail depicted in the figure. It remains, however, to specify the gains, signal levels, and their tolerances at various points in the signal path. That is the purpose of this document. Data to support some of the choices made are given in an Appendix.

In the following, references to the "I.F. band" mean the frequency range 0.5 to 1.0 GHz.

2.0 TOTAL POWER AND GAIN

2.1 Receivers: absolute power output. The power spectral density (PSD) delivered to the I.F. switch by the R.F. to I.F. converter shall be -65±1 dBm/MHz when the antenna temperature is equal to the value in Table I. This applies at a frequency corresponding to the center of any specified receiving band (for specified band limits, see VLBA Memo 354), and the PSD may be averaged over a bandwidth no larger than 1 MHz. Antenna temperature is defined for a signal plane at the output of the feed; the receiver temperature is also defined at this plane. It is expected that this will require a gain adjustment in each receiver, to be set manually when the receiver is installed. The adjustment may be made by setting the antenna temperature to a known value, not necessarily equal to the value in Table I, provided that the corresponding PSD required can be calculated and the actual value measured. Each receiver designer must specify a setup procedure which will result in this specification being met. If there is significant uncertainty in setting the antenna temperature, then this uncertainty must be included in the error budget.

TABLE I: STANDARD ANTENNA TEMPERATURES

(Zenith antenna temperature with dry air at sea level)

Band	Value	Band	Value	Band	Value
90 cm	74 K	50 cm	34 K	20 cm	18 K
13	20	6	15	3.7	21
2	18	1.3	27	0.7	35

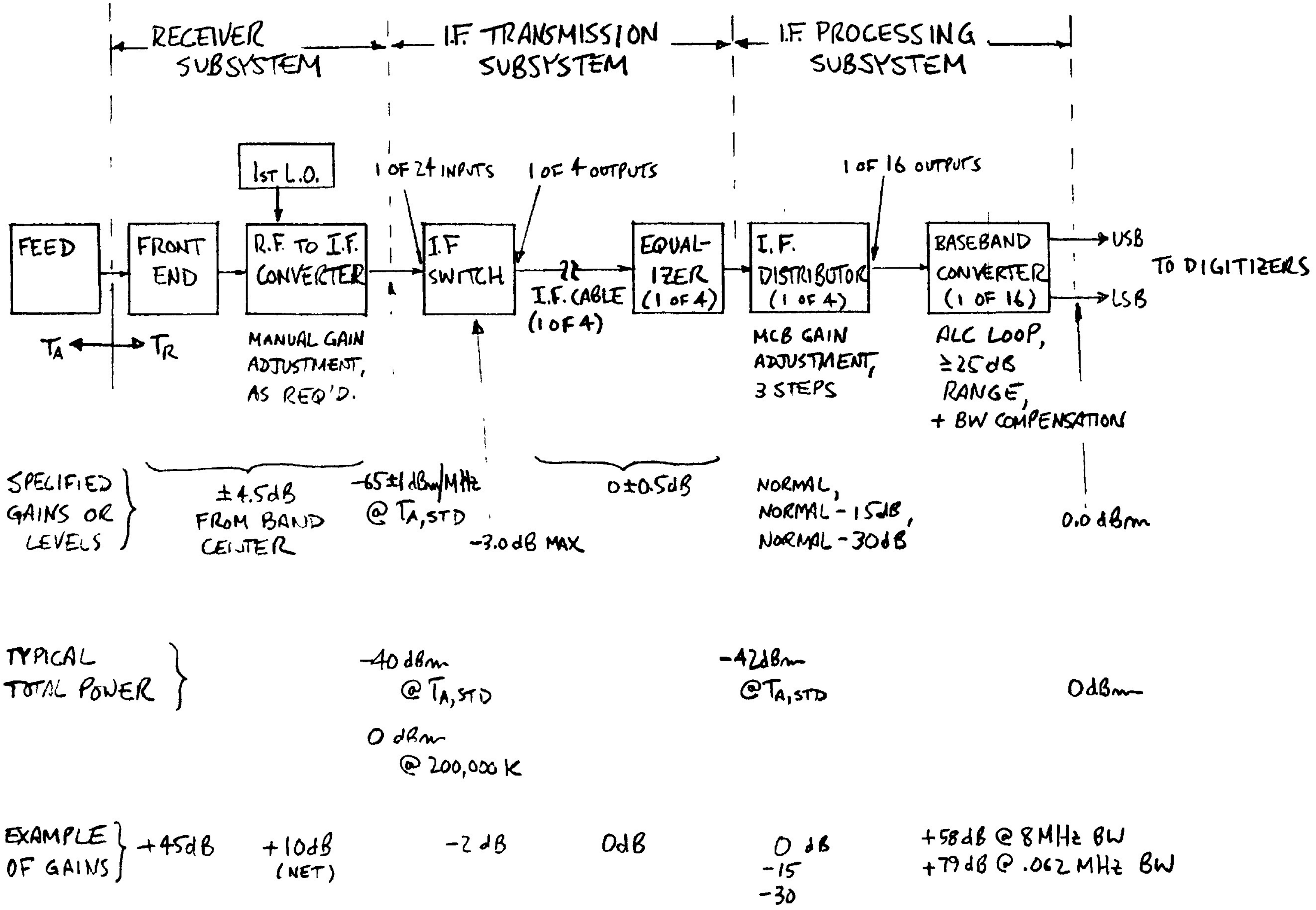

FIGURE 1: Block diagram with summary of gains and signal levels.

2.2 Receivers: flatness. The PSD delivered to the I.F. switch shall not vary more than ±4.5 dB from the band center value over the specified input band of any receiver. This applies to all allowed settings of the first L.O., and at any frequency in the I.F. band that corresponds to an input frequency in the specified band. (Each receiver designer may specify which L.O. settings are allowed, provided that sufficiently many are included to cover the band.)

2.3 I.F. Switch: loss. The loss through the I.F. switch, for any allowed signal path, shall be flat to 1.5 dB (peak to peak) over the I.F. band; shall be matched among all signal paths to 0.25 dB (maximum difference); and shall have an absolute value of less than 3.0 dB.

2.4 I.F. Cables: loss. The loss through each cable and its equalizer shall be 0.0 ± 0.5 dB from 0.5 to 1.0 GHz. (This cannot be specified in more detail at this time because the type of cable, cable routing, and total length have not yet been determined.) The cables at all stations shall be of the same type and of the same length to ±1.0 meter.

2.5 I.F. Distributor. The gain through this device shall have three values, settable through the Monitor/Control Bus (MCB): normal, -15 dB, and -30 dB. When the input PSD is -67 dBm/MHz, the normal setting shall result in a PSD into each baseband converter which is 5±2 dB above the minimum specified (see below). The other settings shall reduce the gain relative to normal by 15±1 and 30±1.5 dB, respectively.

2.6 Baseband Converter. At the minimum specified input PSD (selected by the designer), the gain shall be sufficient to provide 0.0 dBm output at any allowed bandwidth. An ALC loop shall be included to maintain this output power; it shall use a variable attenuator that is capable, at any allowed output bandwidth, of at least 25 dB attenuation beyond that required at the minimum input PSD.

3.0 DYNAMIC RANGE

3.1 Receivers. No more than 1% gain saturation shall occur in the signal delivered to the I.F. switch when the antenna temperature reaches 200,000 K on any band.

3.2 I.F. Switch, Cable, and Equalizer. The gain saturation of the cascade of these devices shall not exceed 1% for an input noise power of 0 dBm (-27 dBm/MHz over 500 MHz; worst case of T_A = 200,000 K). The noise temperature at the equalizer input shall not exceed 150,000 K when the noise temperature at the I.F. distributor input is 140,000 K, for any frequency in the I.F. band.

3.3 I.F. Distributor and Baseband Converter. At the normal gain setting and at any baseband bandwidth setting, the noise temperature of the distributor and converter combination shall be less than 140,000 K (-87 dBm/MHz) everywhere in the I.F. band, referred to the distributor input. Also at the normal gain setting, no more than 1% gain saturation shall occur for an input PSD of -47 dBm/MHz anywhere in the I.F. band, nor for a total input noise power of -20 dBm. (This gives a usable dynamic range of 20 dB.) The 1% saturation level shall be increased by at least 13 dB and 28 dB, respectively, when the -15 dB and -30 dB gain settings are selected.

4.0 PHASE VARIATIONS WITH SIGNAL LEVEL

4.1 I.F. Distributor and Baseband Converter. For any input frequency in the I.F. band, and for any allowed output bandwidth, the phase of the output signal shall not vary more than 4 degrees (peak to peak) as the gain of either the distributor or the converter is varied over its specified range (30 dB and 25 dB, respectively)

5.0 GAIN CALIBRATION

5.1 Switched noise sources. Each receiver shall be capable of increasing its noise temperature by adding noise in an amount sufficient to raise the PSD delivered to the I.F. switch by 10%±2% when the antenna temperature is equal to the value in Table I. This applies at any I.F. corresponding to the center of the specified input band; at other frequencies in the input band, the added noise referred to the output of the feed shall be flat to ±10% of its mid-band value. The added noise shall be settable to either on, off, or switched states via the MCB. In the switched state, it is controlled by the Station Timing Signal (a distributed square wave whose details are not yet determined, but which will probably have a frequency between 20 and 1000 Hz) and shall have a switching time of 1 microsec or less.

5.2 Synchronous Detectors. A portion of each baseband output signal shall be connected to a square law detector that has a time constant of 10 microsec or less. The detector output shall be integrated separately for the on and off states of the noise source, based on the Station Timing Signal. The integration times shall be selectable through the MCB, and the integration results shall be readable through the MCB. True integration (rather than running-mean or exponential averaging) shall be used.

5.3 Gain Setting Accountability. The setting of the attenuator used in the ALC loop shall be MCB readable. If the loop is digital, then the readout shall have the same resolution as the loop; otherwise it should resolve .0025 dB. All variable attenuators, whether or not in the ALC loop, shall be repeatable and stable to ±.004 dB (0.1%) at any setting within their required range and at any signal frequency.

6.0 STABILITY

6.1 Temperature Coefficients. It is desirable to obtain very high stability of complex gain and delay for periods of 24 hours or more over the range of environmental conditions expected in normal operation. A detailed budget has not been worked out, so only overall goals are stated here. The complex voltage gain of the signal processing electronics (not including the I.F. cables and not including any local oscillators) should be stable to 5% (power gain to 10%, phase to 2.8 deg); and the group delay should be stable to 30 psec. Of course, only a portion of this can be allocated to any one module. There are at least three levels of temperature control that can be expected, depending on location: ± 0.5 C can be expected for rack-mounted devices in the equipment room; ± 1.5 C for rack-mounted devices in the vertex room; ± 3 C for other ambient temperature devices in the vertex room. In order to obtain the best possible stability, designers are encouraged to use only the minimum required number of filter resonators and amplifier stages.

6.2 Cable Reflections. The I.F. switch output that drives the I.F. cable and the cable equalizer input shall each have a return loss of 20 dB or more (VSWR < 1.02) over the I.F. band.

APPENDIX: CALCULATIONS AND EXPLANATIONS

DISCUSSION

At a system temperature $T_S = T_A + T_R$ of 50 K (= -122 dBm/MHz) and an output bandwidth of 1 MHz, a net gain of 122 dB is needed. The range of system temperatures which must be accomodated (not counting solar observations) extends from about 30 K to 500 K, or about 12 dB. The sum of the tolerances on the gains of the numerous components making up the 122 dB probably exceeds 20 dB. Finally, the output bandwidth range extends form .062 to 8 MHz, and since the output power must be kept constant this adds 21 dB to the range of gain required. The total gain range, about 53 dB, can obviously not be accomodated without some adjustment. Furthermore, to achieve a reasonable dynamic range, not all of the gain adjustment can be put in one place. After some study, we have chosen to provide gain adjustments in three places, each with a different kind of control: a manual adjustment in each receiver; a computer-controlled coarse adjustment just after the I.F. cable; and an ALC loop at baseband.

Although considerable freedom in the distribution of gain is left to the subsystem designers, the scheme specified here does try to place as much gain as possible in the equipment room rather than the vertex room. This is because the former should have a much better controlled environment, since it doesn't need to move. We presently plan to bring I.F. signals to the baseband converters at 500 MHz bandwidth, even though not all of this bandwidth can be used. If it becomes necessary to install I.F. filters which limit this bandwidth (e.g., for interference protection), then these must be placed (a) ahead of as much gain as possible, and (b) in the most stable environment possible. This design allows such filters to be placed in the equipment room.

Another consideration is the need to accomodate solar observations. Computer-controlled gain reduction must be accomplished early enough so that no device saturates with reasonable antenna temperatures for solar observations (it is very difficult to accomodate the strongest possible bursts). Yet, to allow transfer of calibrations from weak sources to the Sun (or other strong sources), the change in complex gain (including phase) should be accurately known. This implies attenuators at I.F. (not R.F.), and with only a small number of well-calibrated attenuation values. It also limits the total R.F. gain, unless rather high power amplifiers are used.

The dynamic range required in the baseband converter could be reduced if more and finer steps were included in the I.F. gain, and if the latter were part of an ALC loop. But since the most stable, repeatable, and low-phase shift attenuators can be built at baseband, it is preferable to keep the I.F. gain fixed as much as possible. The 20 dB dynamic range specified here is sufficient to accomodate the largest range of total power variation expected from any one receiver (including about 9 dB from T_A vs. elevation and weather, and 9 dB from T_R and receiver gain vs. frequency).

The gain accountability specification is intended to support gain calibration schemes which do not rely on detection of the injected noise signal. In many cases, the latter is subject to very low accuracy.

The cable reflections specification is intended to limit the deviations of the transmission function from linear phase vs. frequency behaviour. The L.O. system will monitor the electrical lengths of the cables at 500 MHz; accurate corrections for cable length variations will be possible across the I.F. band if linear phase can be assumed. The specification limits deviations caused by end-reflections to about 0.6 deg; in practice, this should cause the effects of connectors and cable non-uniformity to dominate.

CALCULATIONS

A. Evaluation of variations in T_R and T_A.

In Table A-1 are presented data on the range of receiver temperatures and antenna temperatures expected on each band. The receiver data is based on recent estimates by S. Weinreb (private communication); the typical and minimum values are for the center of each band, and the maximum is over the specified frequency range. The antenna data is mostly based on calculations by P. Napier (VLBA Project Book 840501, Section 5), with additions for wet atmospheric conditions (2 cm precipitable water vapor) and an elevation angle of 10 deg.

B. Choice of standard receiver output PSD.

To arrive at the specified value of -65 dBm/MHz, we start with the maximum antenna temperature to be accomodated at <1% gain compression, namely 200,000 K (for solar observations, justified below). We assume that this must not correspond to too high a power level at the I.F. converter output; choosing 0 dBm in 500 MHz bandwidth, or -27 dBm/MHz, will probably require amplifiers with a specified CW 1 dB compression point of +10 to +15 dBm, and this seems reasonable. The minimum system temperature at the standard antenna temperature is expected to be about 28 K (this occurs for the 20 cm band; see Table A-1), which is 38.5 dB lower than 200,000 K, giving -65.5 dBm/MHz at the converter output. For bands where the minimum standard system temperature is higher, less compression will occur at T_A = 200,000 K.

TABLE A-1: SYSTEM TEMPERATURE DATA

Band	T_R			T_A							T_{s1} [4]	T_{s2} [4]	T_{s2}/T_{s1}	Gain
λ, cm	Typ [1]	Min [1]	Max [2]	Intrinsic	Atmosphere Dry		Wet [3]		Galactic Bkgnd (MAX)	Cosmic Bkgnd	$T_{R,min} + T_{A,std}$	$T_{R,min} + T_{A,max}$	dB	K/Jy
					90°	10°	90°	10°						
90	65	52	80	24	2	12	2	12	350	3	126	441	5.4	.063
50	75	50	90	24	2	12	2	12	70	3	84	159	2.8	.09
20	12	10	15	12	2	12	2	12	6	3	28	147	7.2	.13
13	16	13	20	14[5]	2	12	2	12	-	3	33	42		.13
6	25	20	45	9	2	12	3	17	-	3	35	49		.13
3.6	35	28	60	14[5]	3	17	4	23	-	3	49	68		.13
2	45	36	75	9	3	17	5	29	-	3	54	77		.12
1.3	40	32	80	11	7	40	40[6]	230	-	3	59	276	6.7	.11
0.7	30	20	60	12	20	115	30	173	-	3	55	208	5.8	.063
0.35	60	40	100	13	20	115	80	461	-	3	65	517	9.0	.007

NOTES:
[1] At band center.
[2] Over full band.
[3] "Wet" means 20 mm of precipitable water vapor.
[4] $T_{A,std}$ from Table I; $T_{A,max}$ = intrinsic + wet atmosphere @ 10° + galaxy(max) + 3 K.
[5] With dichroic optics.
[6] Worst case, on H_2O line.

C. Solar observations.

Table A-2 gives the antenna temperature expected from the quiet sun and from a 100 sfu (1E6 Jy) active region for each band, and the ratios of each to the minimum standard system temperatures. The largest quiet sun ratio is about 30 dB, which is the reason that the -30 dB gain step was specified for the I.F. distributor. Active regions can easily lead to higher antenna temperatures, some of which can be accomodated using the 20 dB or so of ALC attenuator range at baseband. At least a few hundred sfu can be accomodated on any band, but compression may start to occur in the receivers above 150 sfu (T_A = 200,000 K on many bands). We cannot gaurantee that very strong active regions (a few thousand sfu) will be observable without significant compression; but it is hard to specify the details of the compression, so no precise limit can be put on the usable antenna temperature.

TABLE A-2: SOLAR OBSERVING DATA

Band	T_{s1} [1]	T_A(QS) [2]	R(QS) [3]	T_A(100 sfu)	R(100 sfu) [3]
90 cm	126 K	80,000 K	28 dB	63,000 K	27 dB
50	84	40,000	27	90,000	30
20	28	30,000	30	130,000	36
13	33	30,000	30	130,000	36
6	35	20,000	28	130,000	35
3.6	49	10,000	23	130,000	34
2	54	8,000	22	120,000	34
1.3	59	6,000	20	110,000	33
0.7	55	6,000	20	63,000	31

[1] See Table A-1.

[2] Quiet sun antenna temperature; ref. Kruger, 1979, Intro to Solar Radio Astronomy and Radio Physics. Boston: D. Reidel.

[3] Ratio to T_{s1}.

The switched noise injection specified for gain calibration will be too weak to be useful when observing the sun. No high-level noise injection has been specified because no fixed level would yield accurate gain measurements in the face of the highly variable nature of solar emission. Instead, we will rely on the specified accountability of the attenator settings and on their *a priori* calibration.