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To: UVLBI Group
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Subject: Receiver for CSO

1] Introduction

In order to make a cryogenic sapphire oscillator (CSO) useful for VLBI we need to derive a 10 MHz signal from the CSO with optimum stability and minimum drift relative to the national frequency standard broadcast by the GPS. The CSO outputs a frequency around 11 GHz which has superb short and medium term stability but degrades on time scales longer than about 10^3 seconds. In addition to the long term instability the CSO may change frequency significantly when it is warmed up and cooled down again.

2] CSO Receiver block diagram

The block diagram of the receiver is shown in figure 1. A high quality 10 MHz crystal oscillator is phase locked to the CSO. This crystal provides very low phase noise at frequencies more than 30 Hz from the carrier as follows:

 10^2 Hz -155 dBc/Hz 10^3 Hz -165 dBc/Hz 10^4 Hz -165 dBc/Hz

The phase lock is implemented by synthesizing an 11 GHz signal from the 10 MHz which is mixed with the CSO to form an I.F. frequency in the 60-70 MHz range and phase detected using a direct digital synthesizer (DDS). The phase detector is then filtered using an analog loop filter, whose circuit is shown in figure 2. This loop filter has a loop bandwidth of 30 Hz and a damping constant of 0.7 based on a phase detector sensitivity of 0.1 volts/radian at 11 GHz and a crystal oscillator tuning sensitivity of 0.4 Hz/volt at 10 MHz or 440 Hz/volt at 11 GHz. The DDS also provides a quadrature output which when phase detected provides an indication of lock and a measure of detector sensitivity and signal level.

The DDS has a frequency resolution of 1 micro Hz which allows a very fine adjustment of the frequency so that a software loop can be used to bring the 10 MHz derived from the CSO into alignment with GPS on a time scales longer than about 10^5 seconds. This is accomplished by comparing the CSO 10 MHz with 10 MHz from a Trimble Thunderbolt GPS disciplined oscillator.

The parameters of the "GPS phase lock loop" are under software control. The phase between the CSO and GS is derived from a quadrature phase detector from which an unambiguous phase is derived using the C "atan2" function. The GPS Loop makes the

CSU track GPS on a long time scale by changing the DDS. A change of one in the least most significant digit of the DDS corresponds to a change of one part in the 10^{16} in the 10 MHz output.

3] Performance of the receiver

The receiver was tested with the GPS loop turned off using the block diagram shown in figure 3. The phase noise performance was

Freq. offset at 10 MHz	Luff dBc/Hz	E8257D-UNX
1 Hz	-120	-130
10 Hz	-130	-142
10^2 Hz	-145	-145
10^3 Hz	-150	-150

		Allan std. dev.		
tau (s)	Luff syn	E8257D-UNX	Modified Luff	TSC 5115A
10^{-2}	10^{-11}		8×10^{-12}	3×10^{-12}
10^{-1}	10^{-12}	8×10^{-13}	1×10^{-12}	3×10^{-13}
10^0	10^{-13}	8×10^{-14}	1×10^{-13}	4×10^{-14}
10^1	1.5×10^{-14}	1×10^{-14}	1.5×10^{-14}	6×10^{-15}
10^2	3×10^{-15}	1×10^{-15}	1.5×10^{-15}	6×10^{-16}
10^3	1×10^{-15}	3×10^{-16}	3.0×10^{-16}	1×10^{-16}
10^4	7×10^{-16}		1×10^{-16}	

The CSO receiver performance is limited by the Luff research SLSM3 11 GHz synthesizer. The SLSM3 uses an Analog Devices ADF4106 PLL digital synthesizer which locks an oscillator which covers 11 to 12 GHz to a 10 MHz reference. The oscillator is digitally divided by 2 prior to entering the ADF4106 whose upper frequency limit is 6 GHz. Unfortunately the performance of the ADF4106 is degraded by conditioning of the 10 MHz by low speed electronics. In 2008 we suggested improvements and some simple improvements were made to reduce the sensitivity of this interface so that the temperature coefficient of delay was reduced to about -30 ps/degC. Measurements of the serial number 548 gave a temperature coefficient of -19 ± 3 ps/degC. This temperature sensitivity limits the performance. For example if the ambient temperature changes by 1 degC in 500 seconds the temperature coefficient of -19 ps/degC limits performance to about 4×10^{-14} . The Agilent E8257D is also temperature sensitive but has a lower coefficient (about 10 ps/degC – yet to be accurately determined) along with a long thermal time constant. SLSM3 serial number 564 was modified to put the a.c. coupled 10 MHz directly to the ADF4106 as recommended by Analog Devices.

This modification reduced the temperature coefficient to -6 ± 2 ps/degC. Further improvement to about -2 ± 1 ps/degC was achieved by adding a high speed comparator AD8611 but this requires a separate module and has not yet been implemented. The table of receiver performance gives the Allan standard deviation using the unmodified Luff, substitution of an Agilent E8257D for the Luff, the modified Luff and the limits imposed by the TSC 5115A measurement system.

4]. Estimated coherence loss for VLBI at 345 GHz

Table 2 shows the estimated coherence loss using the relation between Allan variance and coherence given in equation 12 of Rogers and Moran (1981). The loss in the Haystack CSO receiver prototype is significant and further development is needed to improve the performance.

Rogers & Moran (1981). Coherence limits for Very-Long-Baseline Interferometry, *IEEE Transaction on Instrumentation and Measurement*, **IM-30**, No. 4, pp. 383-286.

	A	B	C	D
Coherent Integration (sec)	H-masers	H-masers +Atmos	CSO receivers	CSO
1	0.996	0.996	0.994	1.000
3	0.986	0.986	0.979	1.000
10	0.967	0.967	0.958	1.000
30	0.940	0.936	0.942	0.984
100	0.879	0.849	0.919	0.809
300	0.775	0.649	0.904	0.508
1000	0.568	0.400	0.800	0.294

Estimates of coherence loss at 345 GHz

- A State of the art H-masers at each site
- B H-masers with 50 micron rms atmosphere at each site
- C Loss due to Haystack CSO receivers at each site
- D Loss due to CSO at each site based on 4×10^{-15} and 1×10^{-14} at 10^3 and 10^4 seconds respectively and better than 1×10^{-15} at shorter time scales

Conditioning the CSO using GPS should improve the CSO on very long time scales ($\sim 10^5$ or longer) which will reduce the uncertainty in the location of the fringes thereby reducing the need for a wide fringe search.

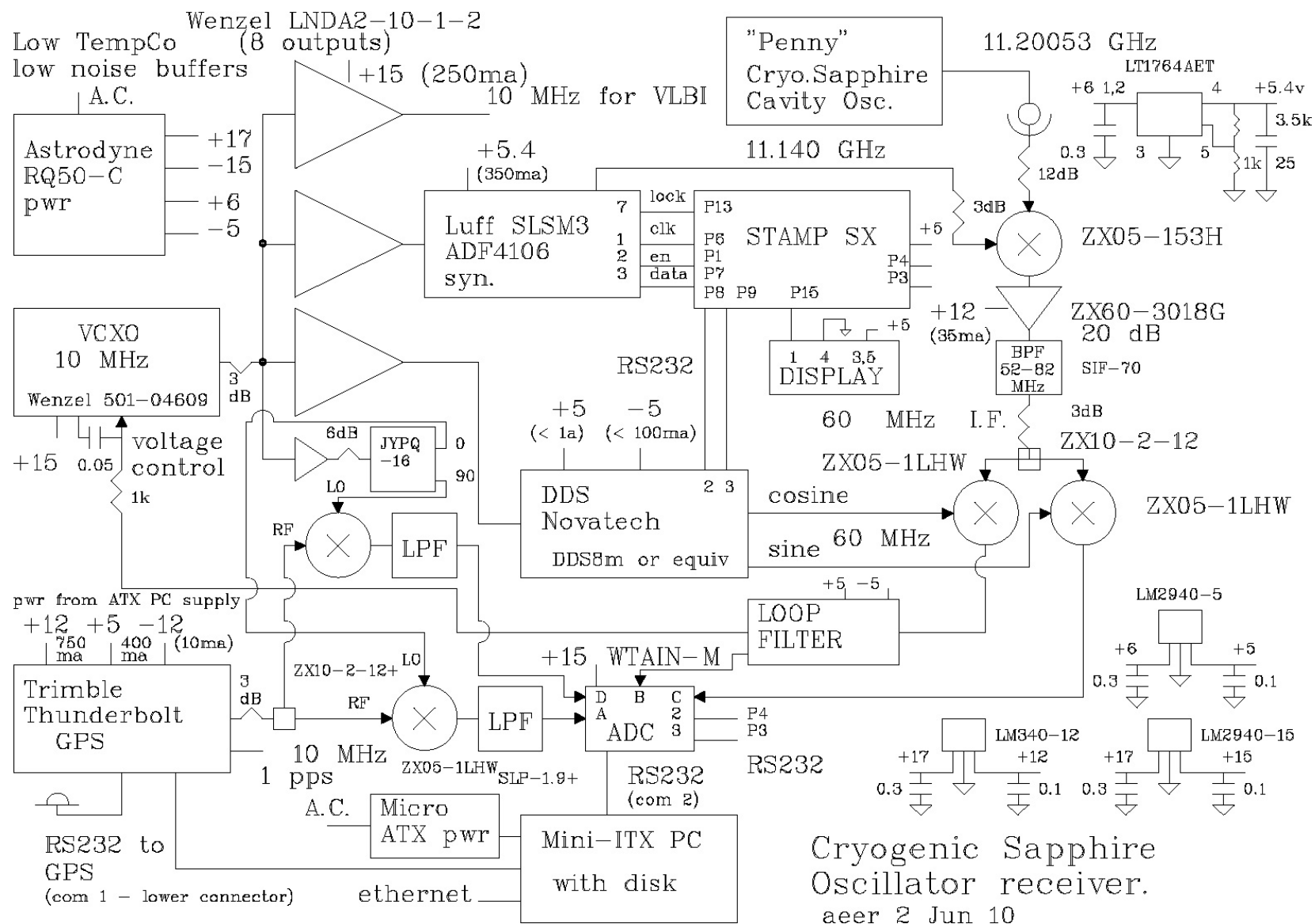
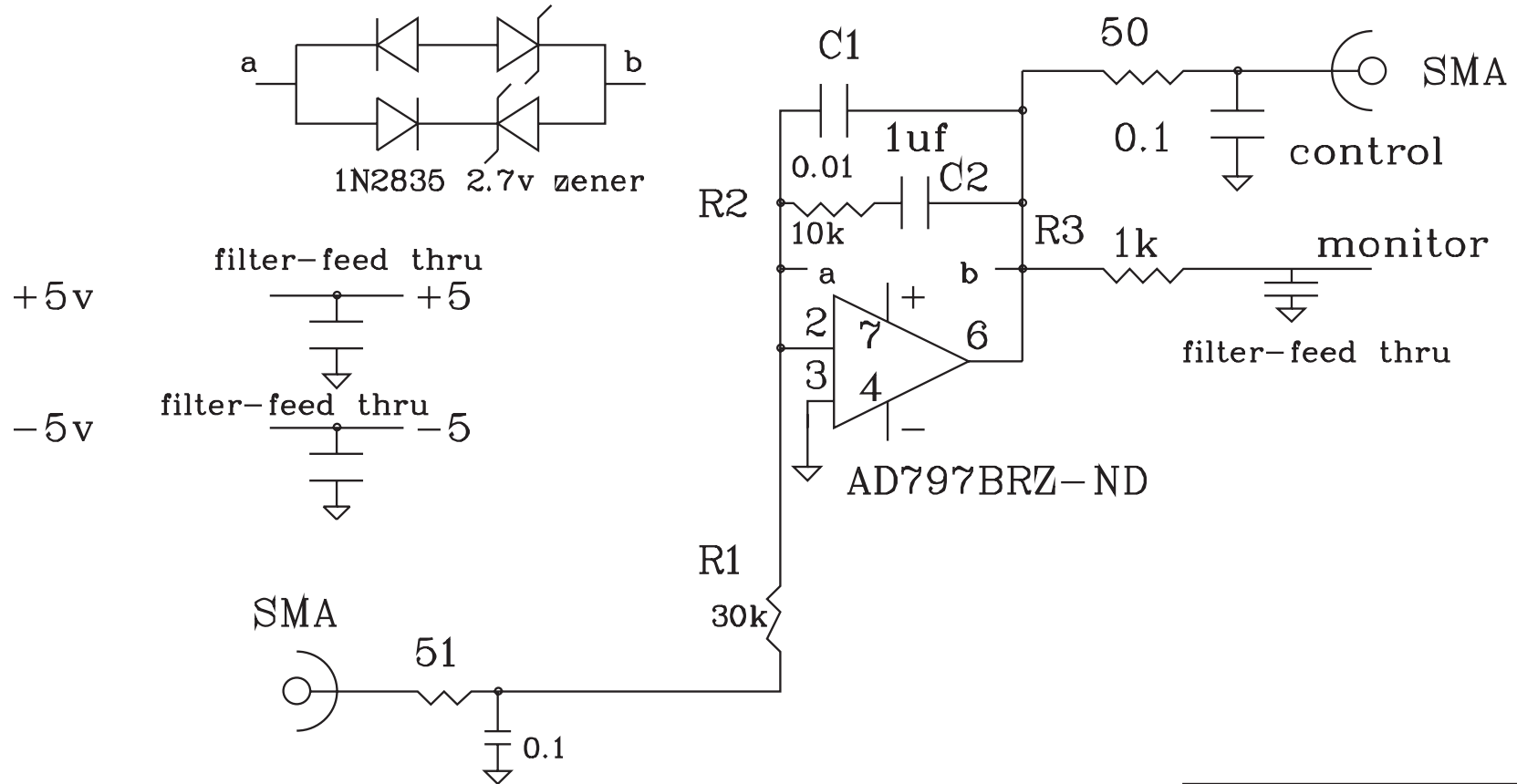


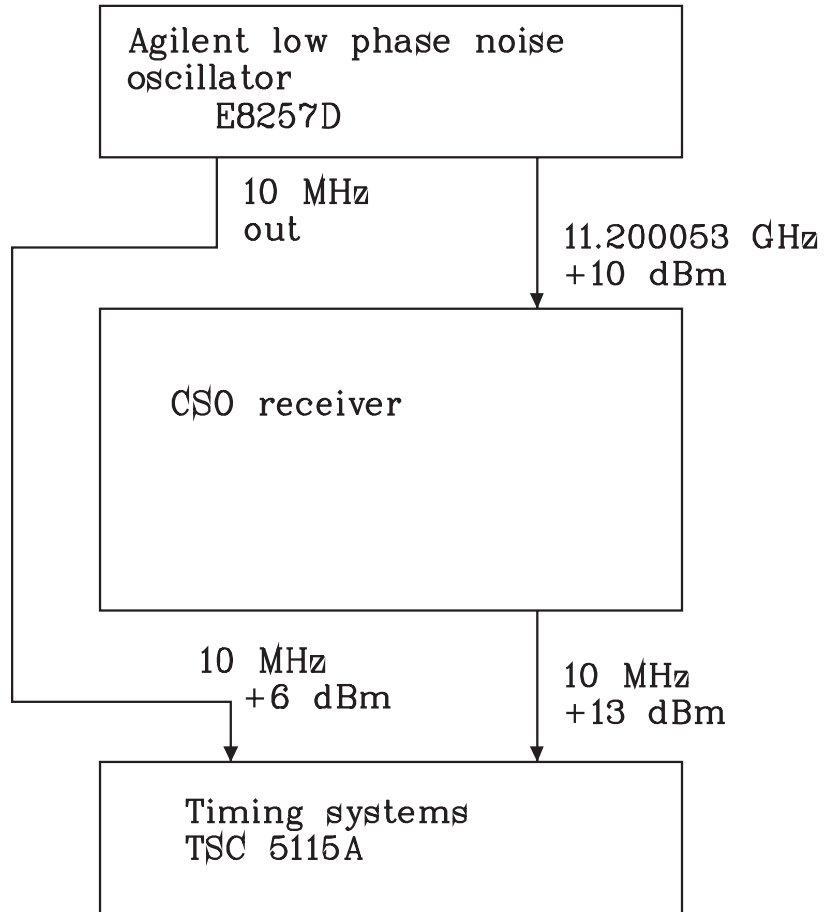
Figure 1. Block diagram of CSO receiver



Notes:

Loop Filter
for Cavity
Oscillator
aeer 22Apr10

Figure 2. Loop filter



CSO receiver tests

aeer 26Apr10

Figure 3.