NBSIR 75-827

REPORT ON NBS DUAL MIXER TIME DIFFERENCE SYSTEM (DMTD) BUILT FOR TIME-DOMAIN MEASUREMENTS ASSOCIATED WITH PHASE 1 OF GPS

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January 1976

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Based on a previous work reported at the 1975 Frequency Control Symposium, the National Bureau of Standards was asked to build a Dual Mixer Time Difference (DMTD) measuring system. This report includes the design, construction, and testing of this DMTD system in fulfillment of this request. The precision of time difference measurement with this system was shown to be about 0.1 picosecond and the accuracy about 10 ps; similarly, the frequency stability precision was shown to be described by $\sigma_y(\tau) \simeq 10^{-13}\ \tau^{-1}$, $0.1\text{s} < \tau < 10^3\text{s}$ and equal to 10^{-16} at τ equal about half a day.

The request for this DMTD system was for measuring the clocks that will go on board the satellites for Phase I of the Global Positioning System (GPS) program. The DMTD system described in this report is the only system that can easily meet all of the time-domain measurement requirements for this program.

KEY WORDS: Frequency measurement; Frequency mixing; Global Positioning System; Isolation amplifiers; Low-noise amplifiers; Precision frequency measurements; Precision time measurements; Time difference measurements; Time-domain frequency stability; Time interval.

Having gained additional insights from the prototype DMTD system reported on at the 1975 Frequency Control Symposium we made appropriate changes in designing and building a DMTD system to fulfill a request for a time-domain measuring system to be used in Phase I of GPS. These included: a pair of NBS designed isolation amplifiers for splitting the signal from the common oscillator, the signal from the common oscillator is fed through isolation transformers to the isolation amplifiers; an improved low-pass filter following each mixer; an additional and lower noise stage of amplification following each low-pass filter, better bandwidth control included in the 2nd stage of amplification; a driver to feed each pulse isolation transformer for an improved pulse shape; the ability to use or not use the phase shifter in one leg of the system; both electric and magnetic shielding properly displaced to reduce capacitive coupling, and non-battery operation using well isolated, regulated, and decoupled DC power supplies.

A local subcontractor was sought and obtained to do the layout, assembly, and overall construction.

Attached are the block and circuit diagrams of the DMTD system as prepared by the subcontractor (No. 75008-A1 through 75008-A6). The phase shifter in A-1 has $\sim 100\ \Omega$ input impedance and 10 dB insertion loss. The inputs to the mixers, should not exceed ~ 3 mW. The low-pass filter (LPF) has a roll-off at about 10 kHz. The bandwidths f_h of the amplifiers are ganged and discretely variable (1, 3, 10, 30, 100, 300, 1000 Hz). The isolated output pulses corresponding with the zero crossings of the beat frequency have about 4 volts output into a high impedance with 20 ns rise time. On sheet 1 of A-2 test point 1 (TP-1) should read ~ 600 mV peak-to-peak for near optimum signal-to-noise performance out of the mixers. The common oscillator input shown in A-4 should not exceed ~ 1 mW (0.6 V peak-to-peak at input of isolation amplifiers A-5); the amplifier will distort at higher drive levels.

II. Testing and Measurement of DMTD System Noise

A 10.23 MHz quartz crystal oscillator lent to NBS for testing was used to drive both mixer one and two to estimate the system noise. The oscillator output was insufficient to obtain optimum signal-to-noise conditions, but adequate for testing. The R-port of each mixer was driven with about 0.6 volt peak-to-peak and the L-port with about 0.36 volt peak-to-peak giving a mixer output of only 170 mV peak-to-peak, i.e., the signal-to-noise could be about 3 or 4 times better with higher drive levels.

The common oscillator employed was a low-noise synthesizer. One can graphically see the effects of common oscillator noise by tuning the phase of the two beat signals to near zero. The attached sheet headed with the date 8 October 1975 page 1 is a copy of the lab notes during the testing. The left column of data are all taken with the bandwidth, f_h, set to 1 kHz and the beat frequency at 10 Hz -- giving a time difference measurement every 0.1s. The Δt indicates the degree of synchronization of the phases of the beat signals, and it is obvious that as they are moved from near zero phase difference toward large phase difference the phase noise increases considerably. The right column shows the same effect only with a 10 Hz bandwidth.

The DMTD system noise was measured by setting the phase difference between the beat signals near zero to reduce the effects of common oscillator noise and then using a computing counter to measure the fractional frequency stability in terms of $\sigma_y(\tau)$ for various bandwidths and beat frequencies. These results are summarized in the attached $\sigma_y(\tau)$ vs τ diagram.Also shown on this diagram are some values translated from some data taken in the frequency domain. These data were obtained by removing both covers to the instrument so that a lead could be attached to test point 2 (TP-2 in drawing A-2) on mixer 1 and then later on mixer 2. A signal from the 10.23 MHz test oscillator was fed into the mixer port through the phase shifter and also into the common oscillator port; the phase was shifted to obtain quadrature (0 volts out of the mixer). The signal from TP-2 was fed into a low-noise amplifier and into a spectrum analyzer to deduce the frequency domain stability $S_\phi(f)$ of the phase for this much of the circuit, which should be the critical noise contributor. The results using mixer 2 were essentially the same. Some 60 Hz sidebands were present at a level of -116 dB, but these apparently disappear when the shielding lids are put back, because such a level would give $\sigma_y(\tau = 1\text{s}) = 7 \times 10^{-12}$, but instead we obtain a 1 second stability better than 1 part in 10^{13}, and with no apparent 60 Hz present when the beat frequency is set to that value in order to filter it out if it were present. Attached also is a sheet headed with the date 8 October 1975 page 2 which shows the time difference stability over a couple of minutes with f_h = 1 Hz and with a 1 second beat, $\nu_b = 1/\tau$. A slight phase drift is observed. A test was conducted from a cold start of the instrument to ascertain the long-term time difference stability of the unit. During the first hour it drifted $\sim$ 50 ps and then in an overnight run the phase stayed within a peak-to-peak deviation of $\sim$ 10 ps with ambient temperature fluctuations of about $\pm$ 2C°. This would correspond to a worst case one day sample time fractional frequency departure of about one part in 10^{16}.

III. Usage of the NBS DMTD Instrument

Attached are four sequential photographs of the instrument: 1) Front panel; 2) Top view with electric shield cover removed; 3) Top view with electric and magnetic shield covers removed; and 4) Close up of contents in magnetic shield compartment. The instrument is broadband ($\sim$ 1 MHz - 60 MHz) except for the phase shifter which covers $\pm$ 1 MHz about 10.23 MHz. One may conveniently choose whether or not to use the phase shifter. If used it provides a convenient method of setting the output time difference to any desired point, and if the common oscillator noise is excessive one can set the beats in phase ($\Delta T \simeq 0$), so that one obtains a reduction of the noise contribution coming from the common oscillator. The phase shifter has the disadvantage that it has $\sim$ 10 dB insertion loss.

The mixer inputs go directly to the low noise Schotcky barrier diode double balanced mixers and optimally should be driven with about 1 to 3 mW. CAUTION: excessive drive levels (maximum current 40 mA or about $2V_{rms}$) on the mixers will burn them out. About 1 volt peak-to-peak input is a good operating point. The common oscillator port can be driven up to about 0.6 volts peak-to-peak ($\sim$ .3 mW) before the isolation amplifiers, which feed the other ports of the mixers, start to distort.

The measurement bandwidth f_h should always be greater than or equal to the beat frequency ν_b. It is sometimes convenient to change the bandwidth and see its effect on the stability to get an idea of the kind of noise process that may be dominant. If the bandwidth is set too small, the stability determined will be too good for sample times less than $1/f_h$.

The output pulses have about a 20 ns rise time and about 4 volts height into a high impedance. The steepest slope and ideal trigger point is a + slope at about + 1 volt. The pulses will work into a 50 Ω load with the amplitude and rise time degraded by about a factor of 2. These output pulses are respectively tied to the phases of oscillator 1 and oscillator 2, and the time difference x(i) between the zero crossings of these two oscillators for the i^{th} measurement is given by

$$x(i) = (T_1 - T_2) \frac{\nu_b}{\nu_o} + \frac{\phi}{2\Pi\nu_o} \qquad (1)$$

where $T_1 - T_2 = \Delta T$ is the actual time difference read on a time interval counter with T_1 connected to the start jack and T_2 to the stop jack, where ϕ is the total phase difference between the two halves of the dual mixer time difference system--most of which will be that due to the phase shifter, and where ν_b and ν_o are the nominal beat frequencies and carrier frequencies respectively. As an example suppose that $\Delta T = 25.3\mu s$ for the i^{th} measurement and $\nu_b = 10$ Hz and $\nu_o = 10$ MHz, then the time difference of osc 1 - osc 2 = 25.3 ps $+ \frac{\phi}{2\Pi\nu_o}$. Suppose, for the $(i+1)^{th}$ measurement, we get 25.6 ps $+ \frac{\phi}{2\Pi\nu_o}$, which is 100 ms later, then the average fractional frequency difference over that interval is given by:

$$y(i) = \frac{x(i+1) - x(i)}{\tau} \tag{2}$$

$$= \frac{0.3 \text{ ps}}{100 \text{ ms}} = 3 \times 10^{-12}$$

The stability may be computed from the frequency or the time data as follows:

$$\sigma_y^2(\tau) \simeq \frac{1}{2(M-1)} \sum_{i=1}^{M-1} [y(i+1) - y(i)]^2 \tag{3}$$

or

$$\sigma_y^2(\tau) \simeq \frac{1}{2(M-1)\,\tau^2} \sum_{i=1}^{M-1} [x(i+2) - 2\,x(i+1) + x(i)]^2 \tag{4}$$

where there are M+1 time readings in a sequence. If one wishes to take the square root and compute $\sigma_y(\tau)$ direct from the ΔT readings of a time interval counter then:

$$\sigma_y(\tau) \simeq \frac{\nu_b}{\sqrt{2(M-1)} \cdot \tau\, \nu_o} \left\{ \sum_{i=1}^{M-1} [\Delta T\,(i+2) - 2\,\Delta T(i+1) + \Delta T(i)]^2 \right\}^{1/2} \tag{5}$$

where τ (the interval between time difference measurements) can be any integer multiple of $1/\nu_b$; i.e., one does not have to measure at every cycle of the beat frequency. Equation 5 can be approximately summarized for the measurement noise of the DMTD system as:

$$\sigma_y(\tau) \simeq \frac{0.1 \text{ ps}}{\tau}, \quad 0.1\text{s} \leq \tau \leq 10^3\text{s}$$

with only a slight degradation for longer times due to apparent temperature induced phase drifts and for shorter times due to white noise as the bandwidth f_h is opened up.

IV. Maintenance

The unit should be free of need for any maintenance procedure. The OP-05 operational amplifiers were DC balanced during the NBS testing phase, and their specifications of 3.5μV per month should be low enough to give no difficulty in the foreseeable future unless the ultimate finesse is wanted from this DMTD instrument. These operational amplifiers are zeroed by simply grounding the input test point, and while monitoring the output test point of that operational amplifier adjusting the trim pot associated with it for zero volts DC output.

REVISIONS			
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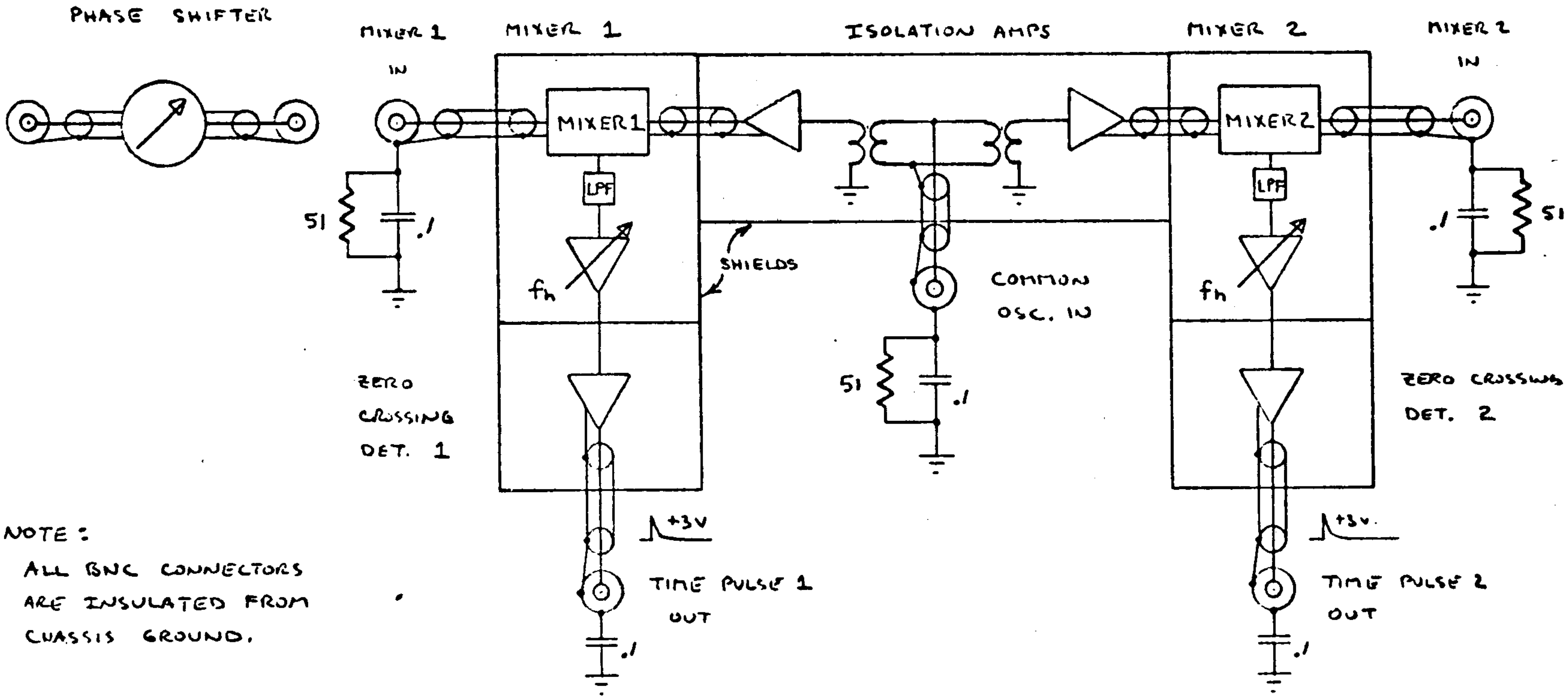
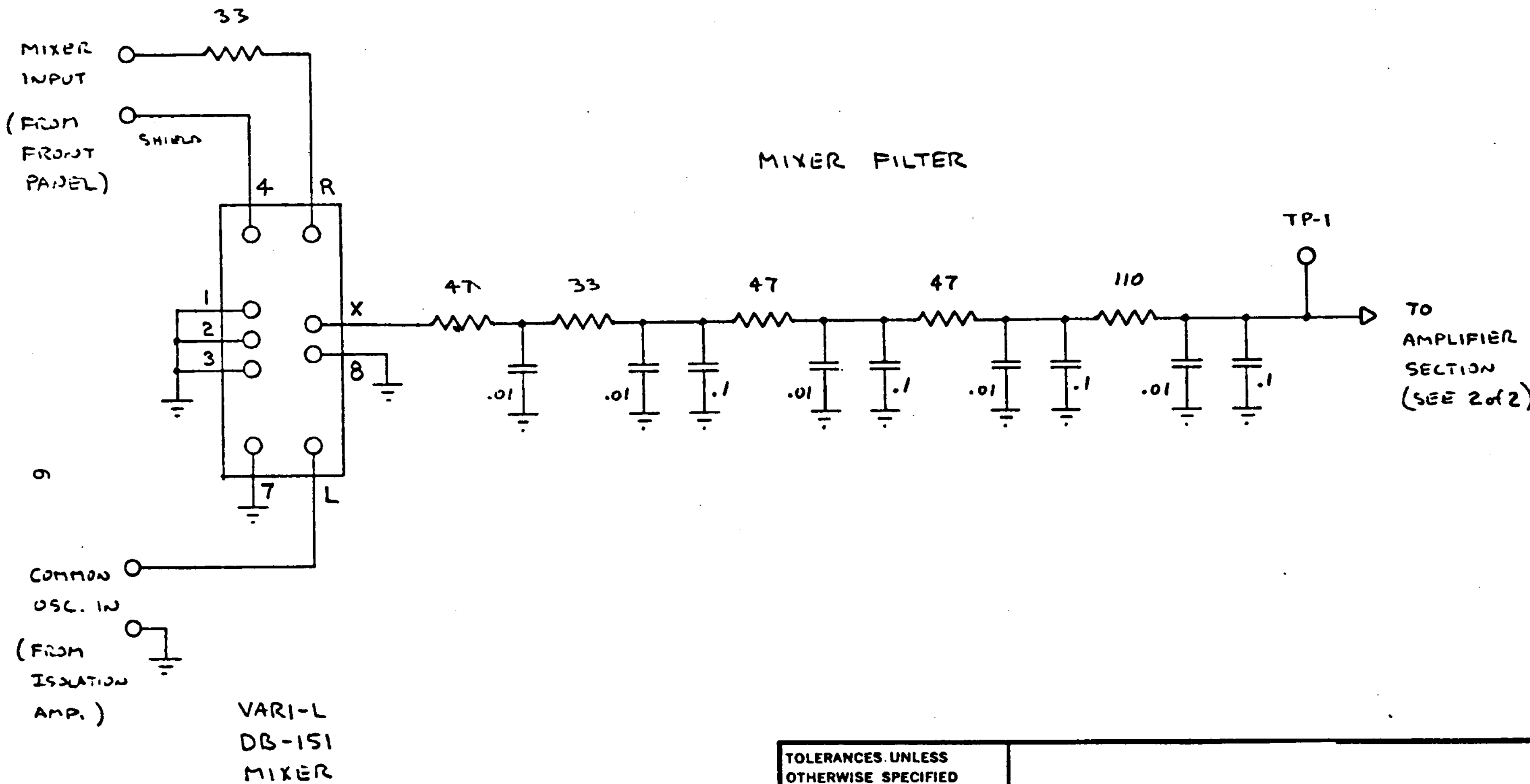


NOTE: ALL BNC CONNECTORS ARE INSULATED FROM CHASSIS GROUND.

TOLERANCES UNLESS OTHERWISE SPECIFIED FRACTIONS ± DEC ± ANGLES ±	NBS DUAL MIXER SYSTEM SYSTEM DIAGRAM
APPROVALS / DATE DRAWN LAE 10-75 CHECKED	SCALE / SIZE / DRAWING NO. 75008-A1
	DO NOT SCALE DRAWING — SHEET 1 of 1

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED



TOLERANCES UNLESS OTHERWISE SPECIFIED		
FRACTIONS ±	DEC ±	ANGLES ±

NBS DUAL MIXER SYSTEM
MIXER-AMPLIFIER

APPROVALS	DATE
DRAWN LAE	10-95
CHECKED	

SCALE	SIZE	DRAWING NO.
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DO NOT SCALE DRAWING

SHEET 1 of 2

REVISIONS			
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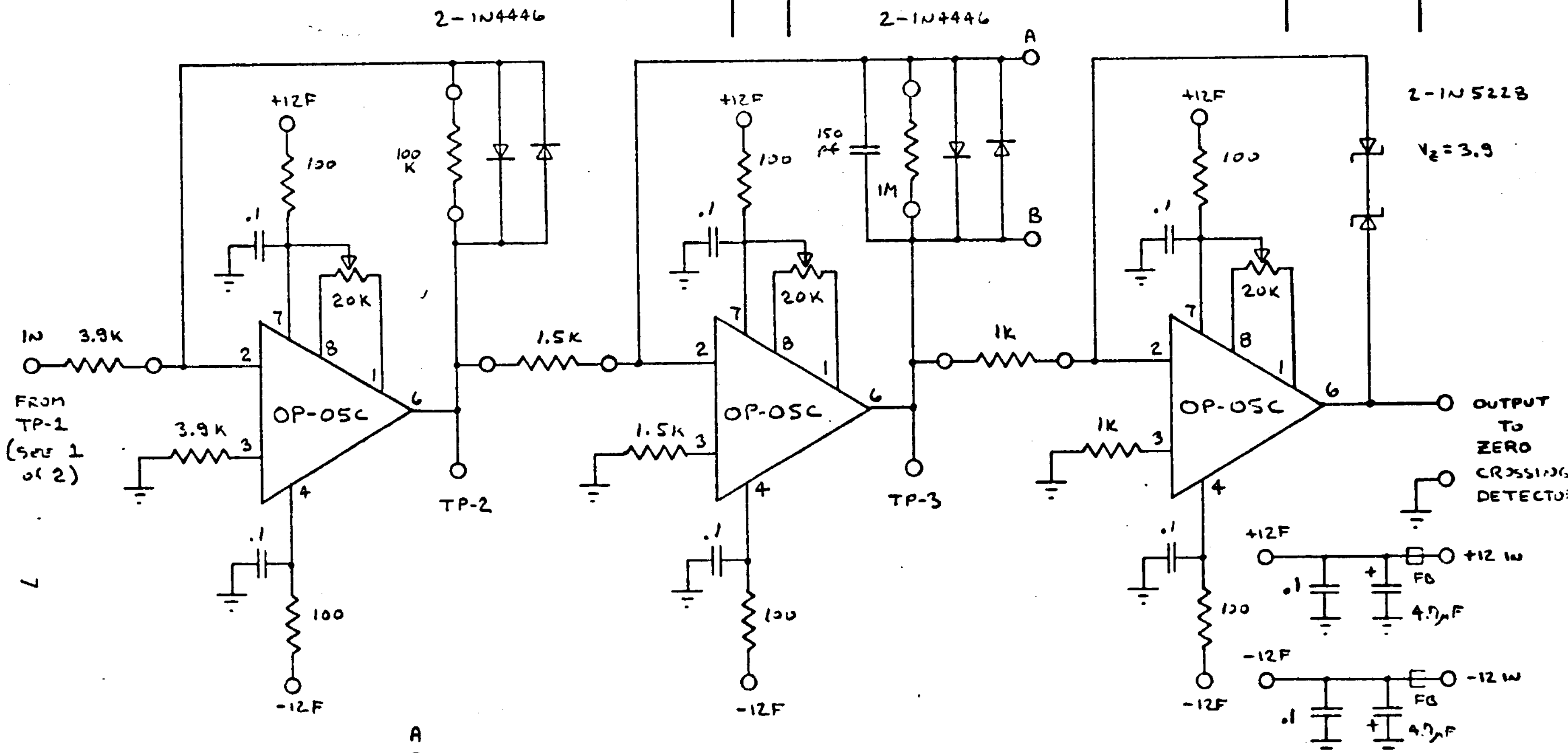
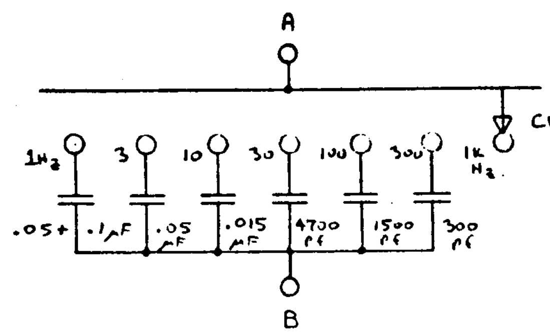


AMPLIFIERS



BANDWIDTH SWITCH

TOLERANCES UNLESS OTHERWISE SPECIFIED		
FRACTIONS	DEC	ANGLES
±	±	±

NBS DUAL MIXER SYSTEM
MIXER-AMPLIFIER

APPROVALS	DATE
DRAWN LAE	10-75
CHECKED	

SCALE	SIZE	DRAWING NO.
		75008-A2

DO NOT SCALE DRAWING — SHEET 2 of 2

REVISIONS			
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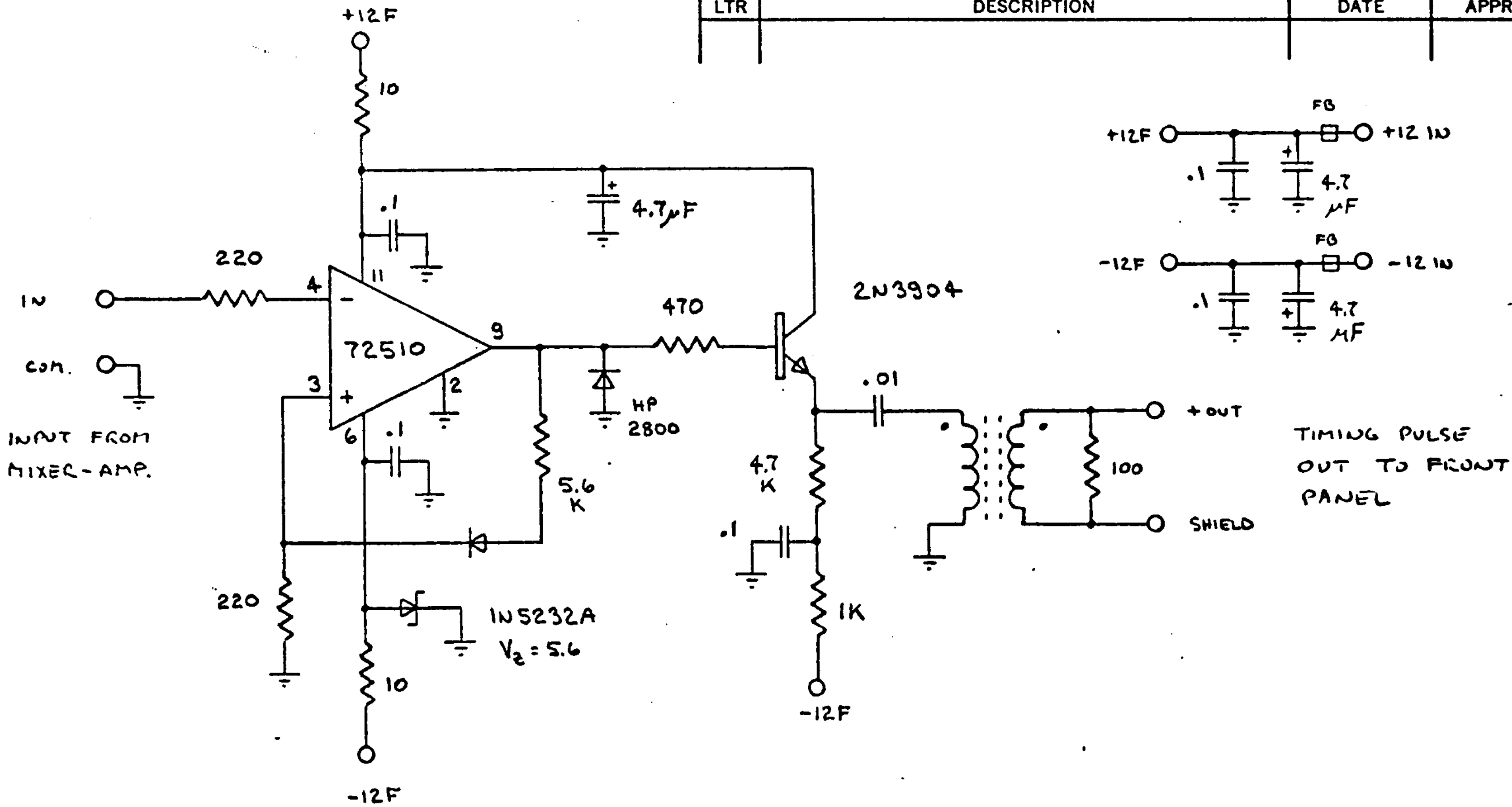


TOLERANCES UNLESS OTHERWISE SPECIFIED

FRACTIONS	DEC	ANGLES
±	±	±

APPROVALS		DATE
DRAWN	LAE	10-75
CHECKED		

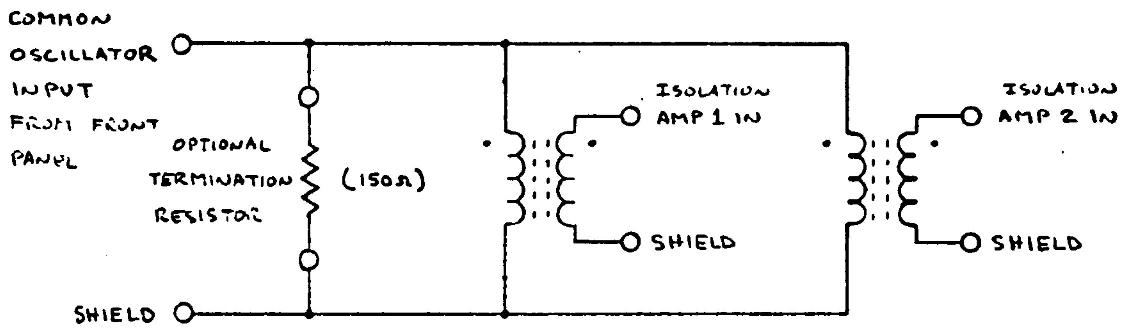
NBS DUAL MIXER SYSTEM
ZERO CROSSING DETECTOR

SCALE	SIZE	DRAWING NO.
		75008-A3

DO NOT SCALE DRAWING

SHEET 1 OF 1

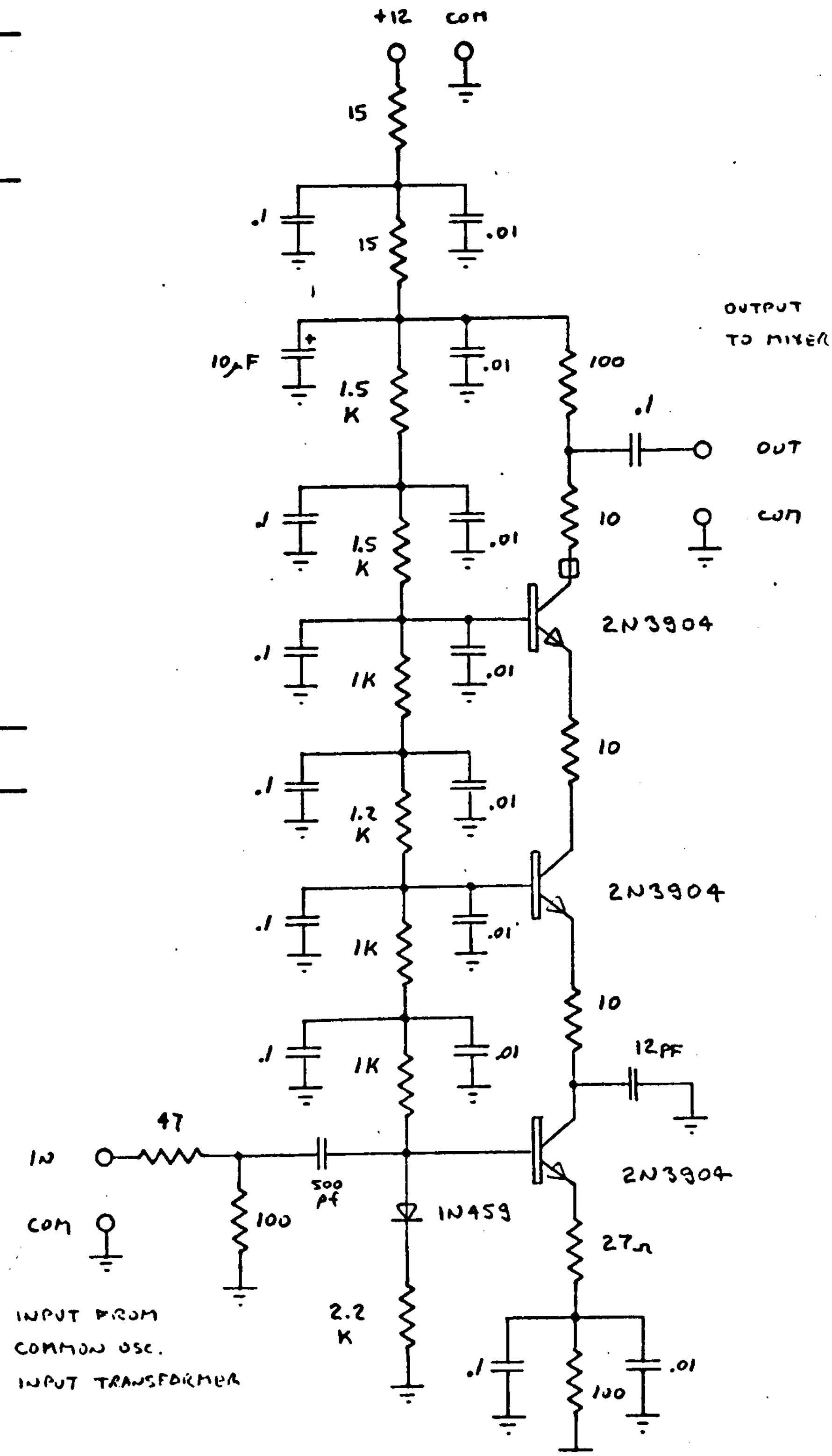
REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED



6

TOLERANCES UNLESS OTHERWISE SPECIFIED FRACTIONS ± DEC ± ANGLES ±		NBS DUAL MIXER SYSTEM COMMON OSC. INPUT XFORMER
APPROVALS	DATE	
DRAWN LAE	10-75	
CHECKED		SCALE / SIZE / DRAWING NO. 75008-A4
		DO NOT SCALE DRAWING / SHEET 1 OF 1

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED



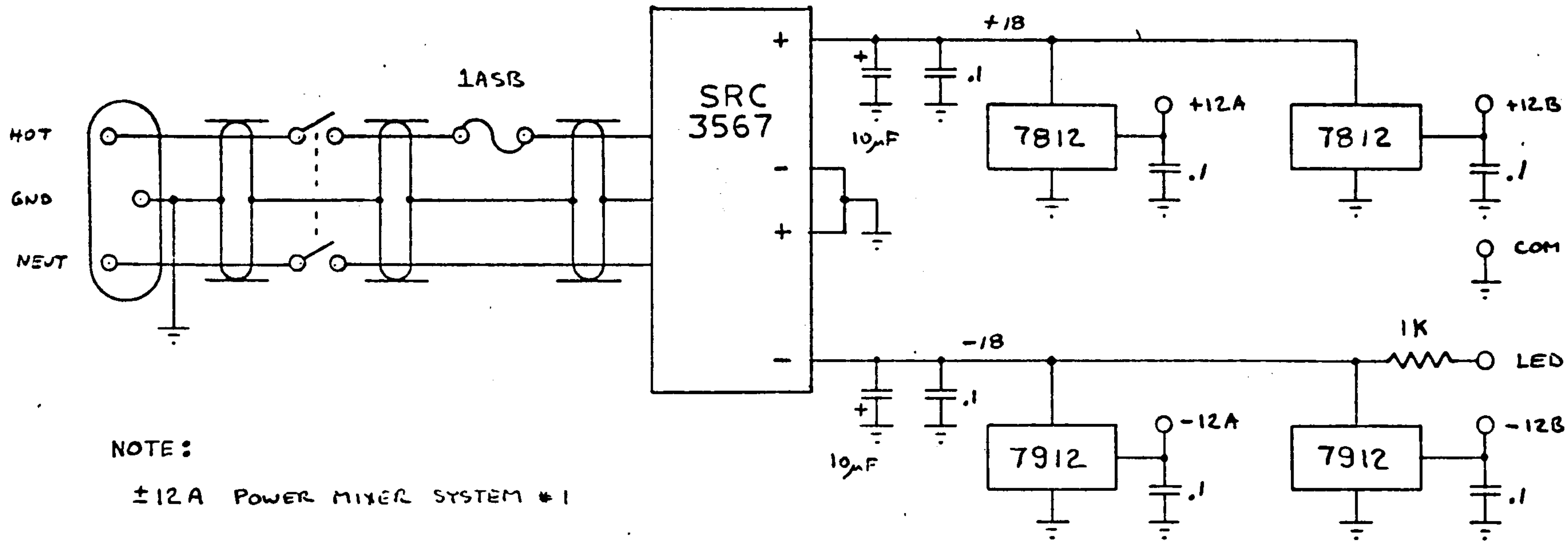
NBS DUAL MIXER SYSTEM
OSC. ISOLATION AMP.

TOLERANCES UNLESS OTHERWISE SPECIFIED		
FRACTIONS ±	DEC ±	ANGLES ±
APPROVALS	DATE	
DRAWN LAE	10-75	
CHECKED		

SCALE | SIZE | DRAWING NO. 75008-A5

DO NOT SCALE DRAWING | SHEET 1 OF 1

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED



NOTE:

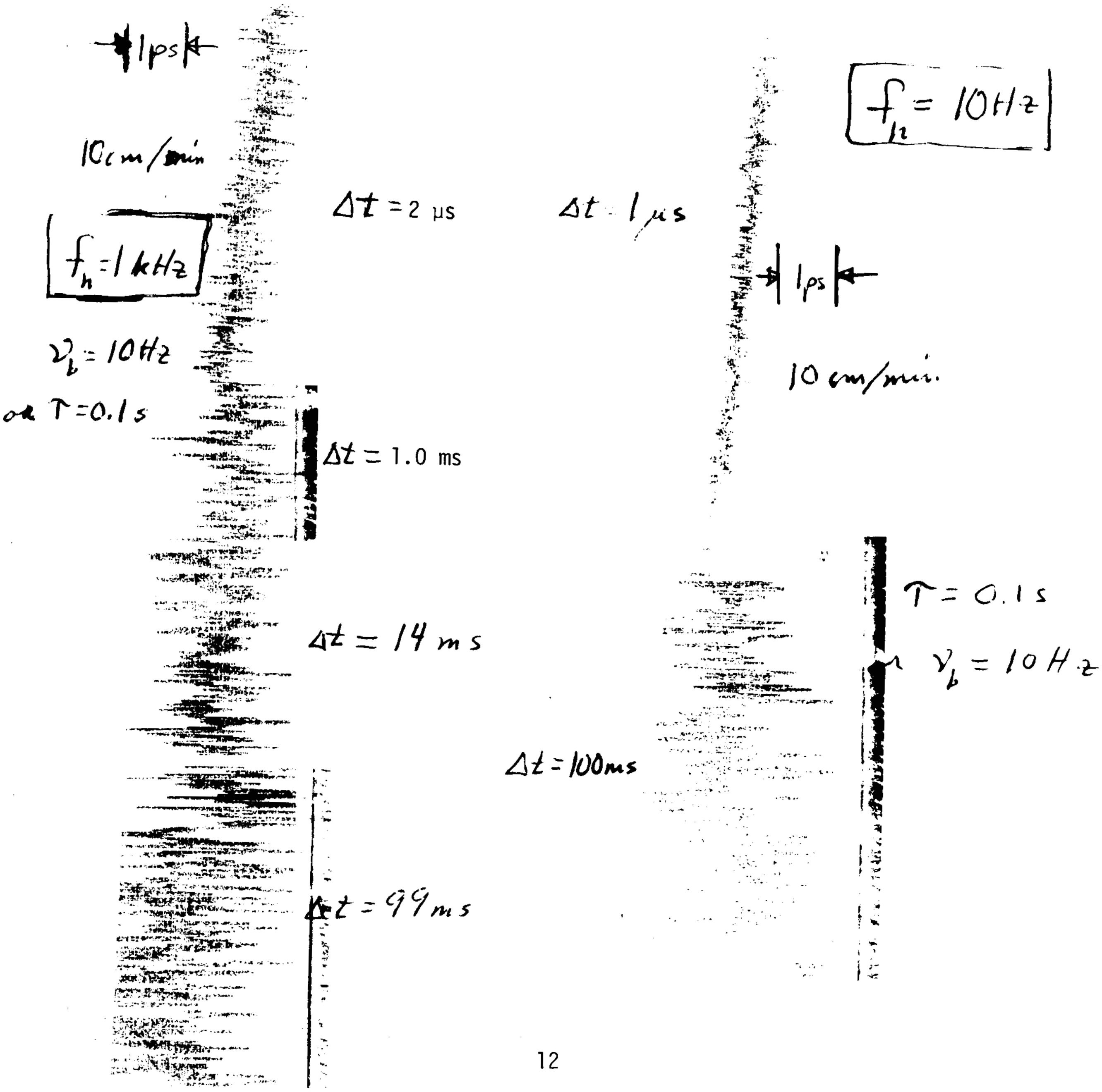
±12A POWER MIXER SYSTEM #1

±12B POWER MIXER SYSTEM #2

TOLERANCES UNLESS OTHERWISE SPECIFIED		NBS DUAL MIXER SYSTEM POWER SUPPLY		
FRACTIONS ± DEC ± ANGLES ±				
APPROVALS	DATE			
DRAWN LAE	10-75	SCALE	SIZE	DRAWING NO. 75008-A6
CHECKED				
		DO NOT SCALE DRAWING		SHEET 1 OF 1

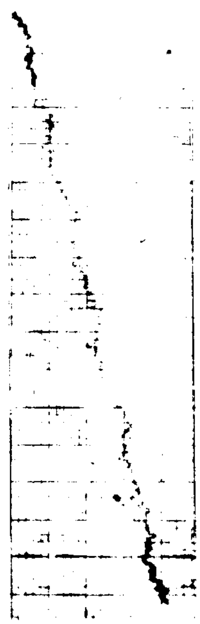
8 October 75

DMTD test of system noise as a function of common oscillator rejection
10.23 feed through ϕ-shifter to mixer 1
and split before ϕ-shifter to mixer 2
Same levels as yesterday. Set the beat ν_b = 10 Hz
$\therefore$ τ = 0.1s and plotted the phase for various shifts
or Δt readings on counter. Chart speed = 10 cm/min
Sensitivity 1 ps per cm



8 October 75

Same oscillator drive levels and condition as before. $\Delta t \sim$ few μs to reduce common oscillator noise contribution to test measurement system noise and phase drift.



→ 1 ps ←

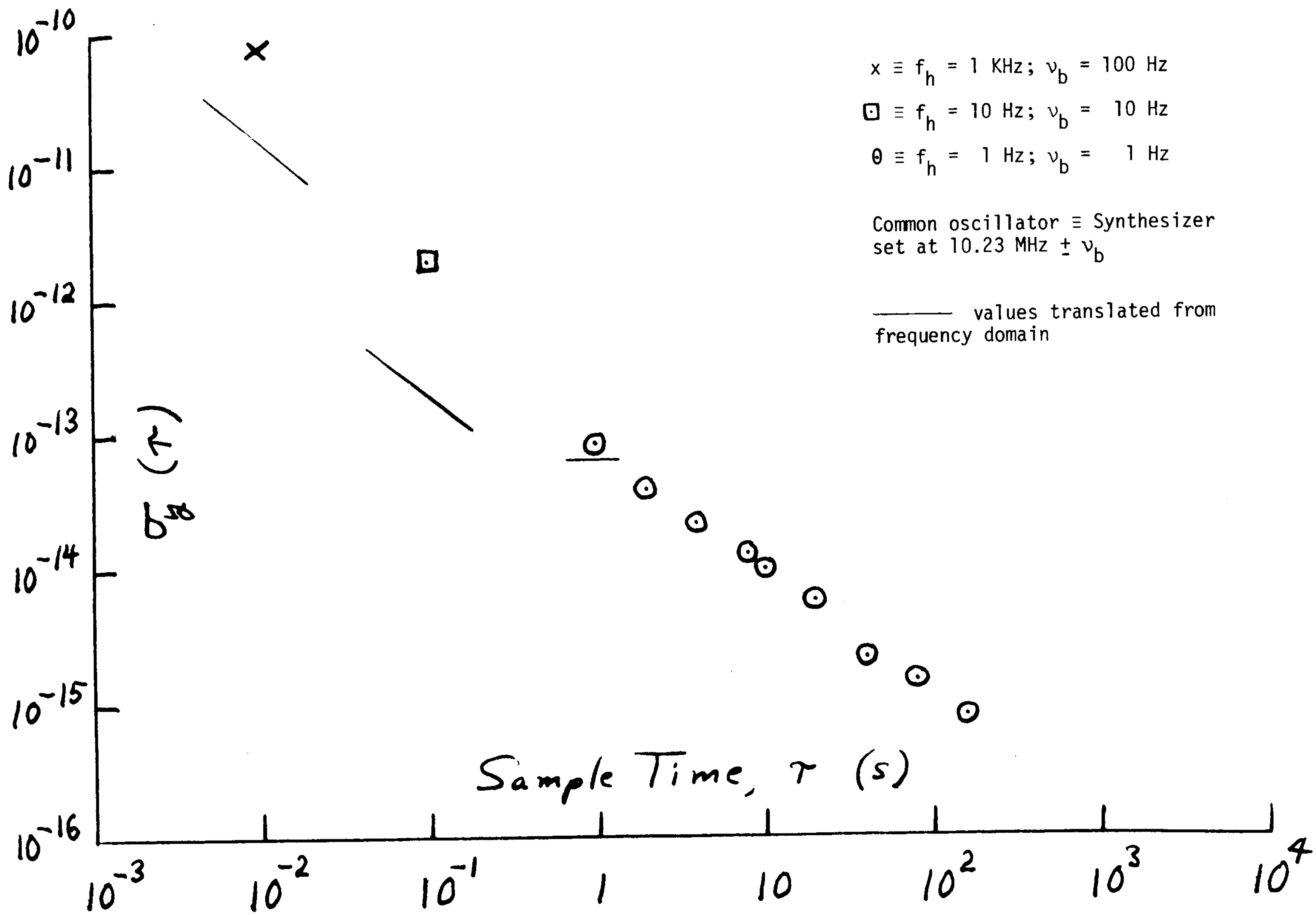
τ = 1s

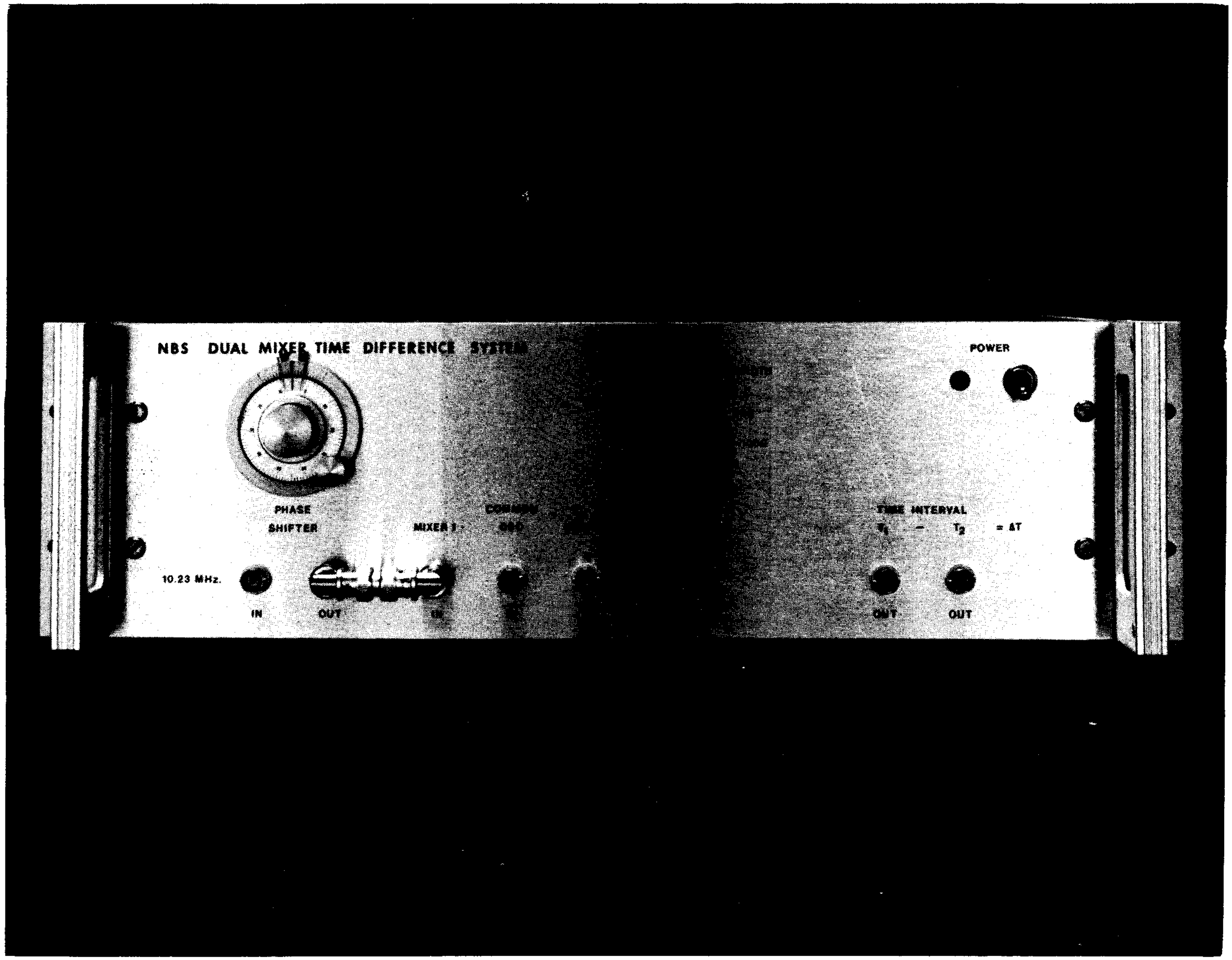
f_h =1 Hz

2.5 cm/min

Warm up phase drift was about 50 ps over the first hour; but stabilizing to a peak of about 10 ps thereafter in an overnight run with ± 2° C ambient temperature fluctuations.

NBS DUAL MIXER TIME DIFFERENCE SYSTEM
MEASUREMENT NOISE




NBS DUAL MIXER TIME DIFFERENCE SYSTEM
POWER
PHASE
SHIFTER
MIXER 1
10.23 MHz.
IN
OUT
TIME INTERVAL
= ΔT
OUT
OUT