TWO-WAY SATELLITE TIME TRANSFER (TWSTT): USNO OPERATIONS AND CALIBRATION SERVICES

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Abstract

The U.S. Naval Observatory maintains a large number of dedicated antennas, modems, and related hardware worldwide in support of high-precision DoD and non-DoD TWSTT time and frequency transfer users. This paper will present a small portion of our operations as an example. Recent TWSTT measured time and frequency comparison results, how we monitor the transmit and receive paths, some recent work done on evaluation of X-band high-power-amplifiers and effects on TWSTT, basics of calibration of high-precision time and frequency systems using TWSTT, and an estimate (~1.1 ns) for a recent co-located Ku-band TWSTT calibration are given.

INTRODUCTION

The U.S. Naval Observatory has been involved in two-way satellite time transfer (TWSTT) since the early 1960s [1]. The expansion of TWSTT at USNO over the last few years has been very rapid. At USNO alone we maintain approximately a dozen fixed and portable very small aperture terminals (VSATs) dedicated to operational world-wide TWSTT experiments linking in real-time remote timing centers to the USNO Master Clock (USNO MC).

The USNO now has two remote centers being compared to the USNO MC via nominal hourly TWSTT experiments. One is the U.S. Naval Observatory Alternate Master Clock (USNO AMC) (2374km, Ku-band) and the other is in the Persian Gulf region country of Bahrain (10,983km, X-band). The usefulness of the high-sampling-rate of TWSTT for these two centers confirms the viability and quality of both Ku-band and X-band TWSTT over worldwide distances. The USNO has developed a method of monitoring signal levels in both the transmit and receive paths that allow monitoring of each stage of the process and allows easy routine monitoring and optimization of signal levels at all times. Recent experiments at X-band allow the study of the effects of optimal and non-optimal signal level insertion into some components along the transmit and receive paths.

The basics of the USNO method of calibration of TWSTT and other timing links will be shown and the first estimate of TWSTT calibration accuracy is developed.

RECENT USNO - USNO AMC HIGH-SAMPLING RATE TWSTT

The performance of the USNO(MC2) - USNO AMC(MC1) Ku-band TWSTT link continues to be very good. The nominal sampling rate is @1h. On average we have about 19 to 20 successful TWSTT experiments during the day, out of 24 (79% to 83%). This number includes failed and numerically filtered experiments. In several months the USNO AMC will receive a software and modem upgrade which should allow close to 100% of the experiments to occur. Improvements include a more recent improved modem version, improved automated control and error detection software, remote autoreset, and tweaking of other related TWSTT systems. Figure 1 shows approximately the last 430 days of TWSTT. The rms is 0.536 nanoseconds.

Since the TWSTT is not yet exactly equally spaced, a simple one day time average is generated for each MJD. The simple one-day average data is then used to form fractional frequencies. The rms over the last 430 days is 2.09 parts in ten to the 15th. The precision in time and frequency given above are not the limit of the TWSTT method, since both these clocks are being steered. USNO(MC2) is steered to our USNO(Mean) real-time estimate of UTC(BIPM) once per day, while USNO AMC(MC1) is steered hourly to USNO(MC2). Figure 2 shows the daily fractional frequency performance estimated from the 1-day averaged data.

USNO maintains local atomic times at both USNO and USNO AMC. USNO(A.1) is made up of an ensemble of approximately 35 to 40 Cs and 10 H-maser clocks, while USNO AMC (A.1) is made up of an ensemble of approximately 10 Cs and 2 H-maser clocks. Using TWSTT we may compare the two free-running scales at high precision and accuracy. Figure 3 shows USNO AMC(A.1) - USNO(A.1) compared via TWSTT over about 400 days after removal of a rate of -62060.306 ps/d and a drift of 2.006 ps/d/d. The residual rms is 2985 picoseconds.

RECENT USNO - BAHRAIN HIGH SAMPLING RATE TWSTT

During 1998 a new X-band TWSTT station was installed in the Persian Gulf country of Bahrain. Improvements in hardware and software during October and November 1998 made it possible to sample this remote Cs at a nominal hourly sampling rate. The distance of 10,983km is the longest single-hop

TWSTT experiment ever performed. Figure 4 shows some recent time difference data.

TRANSMIT AND RECEIVE PATH MONITORING

For many years we have kept detailed log books on each antenna system, each timing link, and for each calibration trip. There is a wealth of information in these books that allow us to know what was done, what changes were made, what problems were encountered, how they were fixed, what the results were, etc.

The basic method of monitoring used is to generate baseline measurements when a system is first installed. Input signals are optimized at each stage along the transmit and receive paths.

Figure 5 shows the the transmit path. First from an on-time point a 5MHz and 1-PPS signal is sent to the modem for use in the formation of the transmitted 1-PPS. An oscilloscope is used to measure the clean peak-to-peak signal which is optimized to voltages that are optimal for the modem.

Next the 70MHz output of the modem is monitored with a spectrum analyzer just before insertion into the up converter in order to allow for all losses along the path. The signal into the up converter is optimized to manufacturer's specifications by adding or removing of attenuation pads, usually at the modem output.

The output of the up converter (GHz) is then sent to a high-power amplifier (HPA) or to a solid-state power amplifier (SSPA). The signal into the power amplifier is optimized again to manufacturer's specifications and is sampled at a test port and/or by using a power splitter and power meter system. More on this in a following section.

The receive path is monitored similarly (see Figure 6), except the satellite beacon is used as a signal reference for the baseline and subsequent monitoring measurements. The received signal may be sampled at the output of a low-noise amplifier (LNA) or in the case of a low-noise block amplifier (LNB) at any of the available intermediate frequencies.

The 70MHz output of the down converter is routinely monitored in day-to-day operations by use of a dedicated spectrum analyzer. Antennas are peaked periodically for fixed antennas, while steerable antennas are peaked either automatically by tracking the beacon or at the time of the TWSTT experiment by the operator.

TWSTT Calibration of High-Precision Time and Frequency Systems

The first fully calibrated TWSTT link was performed by USNO in December of 1992 at the U.S. Naval Observatory Time Service Sub-station (NOTSS)[2]. USNO has since calibrated many remote centers using the co-located TWSTT method. A great deal of experience has been gained during our remote field work. USNO has developed standard calibration methodologies, standard forms and spread-sheet forms to make processing of the data easy and accurate. The method gives a single "calibration value" to be applied to TWSTT experiments which is the sum of all the delay differences in the TWSTT (see Figure 7). The goal is to obtain a single value that describes accurately the sum of the delays between the two on-time points. The solid lines in Figure 7 show the delays at each station from the on-time point to the modem where the actual 1-PPS comparisons are made in the TWSTT modem and the dashed lines show the "RF delays".

The calibration process begins by making measurements with the portable antenna using matched and measured cables. The experiments at USNO are designed to precisely and accurately measure the time time difference between the on-time point of the USNO MC2 to operational USNO modem. The portable/calibration antenna/modem is then shipped to the remote center. Once the portable/calibration system is set up at the remote center and optimized after the method mentioned in the section above, experiments are obtained to isolate the local on-time point to the modem and the field modem to USNO modem. Typically experiments are made over several days to have full confidence that the calibration system is working well. Upon return of the equipment closure experiments are made and the experiment means compared for closure errors--typically 0.5 to 1.0 ns overlaps and better than the 1-sigma level.

The calibration data are then averaged and the sum of the delays is computed and a single calibration time is applied in the routine processing of the operational TWSTT. The details of the mathematics depends on each unique setup.

Once the first system is calibrated it is a simple matter to calibrate backup modems and antenna combinations. if a failure of a component requires it. In critical operational links information is passed in the data files, which allows automatic delay determination with each calibrated antenna/modem combination when the data are processed. Figure 8 shows the basic TWSTT link calibration showing the sequence of events.

TWSTT CALIBRATION OF GPS TIMING SYSTEMS

If a remote station has additional high precision equipment for time and frequency, such as GPS Carrier-Phase (GPS CP) in addition to TWSTT, it is rather easy to use the TWSTT calibration to calibrate a co-located GPS system to be calibrated at the same level of accuracy as TWSTT. A single bias value may be determined to put the uncalibrated GPS on-time with TWSTT. This assumes that the same on time source is used at each timing center (see Figure 9).

FIRST TWSTT CALIBRATION ACCURACY ESTIMATE

A recent, summer 1998, Ku-band syntonization and single-shot synchronization was made at Naval Command, Control, and Ocean Surveillance Research and Development Center (NRaD), San Diego, CA, USA. The data from all the USNO and in the field TWSTT experiments were combined to give an estimate of the accuracy reached. No closure experiments were made for this calibration. The combined error estimate gives an rms of 1.057ns for this calibration (Figure 10). Several methods were employed to obtain intermediate data for the calibration and all seem to give similar results. No experiments were filtered to determine this calibration error. The results are quite good especially those in the field. Improvements in the measurement schemes should allow sub-nanosecond calibrations to be achieved in some cases.

X-BAND TRANSMIT POWER OPTIMIZATION AND CHARACTERIZATION

Recent work allowed us to characterize the performance of a 40-watt high-power amplifier (HPA) for optimization for X-band work. Power meter measurements were made using a power splitter (attn: 50db) in the wave-guide path after the HPA. We inserted various signal levels into the HPA to find the optimum input level in order to reach the full 40-watt output of the HPA. We varied the attenuation in the up converter from 0db to 30db and measured the output power of the HPA through the power splitter. Figure 11 shows the power meter measurements. The optimum up converter attenuation was found to be 10db. When the HPA was over-driven the power dropped, since more power was put into side-bands (dashed lines indicating side-bands in top diagram of Figure 5). When under-driven the full output power of 40 watts was not reached. Figure 12 shows the conversion of the power meter readings to actual power in watts.

This work allowed us to see the effects of over-driving and under-driving an HPA by monitoring TWSTT experiment means and scatter changes in the 1-PPS measurements. Figure 13 shows the variation of the rms scatter of the experiment means with HPA output as the input signal to the HPA was being varied by changing the attenuation in the up converter. The scatter goes up when over-driving the HPA, since nonlinear distortion is introduced. When under-driving the HPA the scatter is increased due to low S/N on the receive side. Figure 14 shows that the mean of the TWSTT experiments varies fairly linearly from the over-driven case to the under-driven case. The approximate relationship is a change of 650 ps per db attenuation change. Most samples were performed at the optimal settings with only a few measurements made in the non-optimal regions.

CONCLUSIONS

TWSTT continues to be a fascinating and useful high precision time and frequency transfer method. The high sampling rate (@1h) experiments continue to prove their worth over distances reaching nearly 11,000 km. Experiments show that TWSTT is stable and able to be calibrated routinely to the 1ns level. New hardware components have been characterized which allow optimal set up and routine monitoring of the TWSTT system in order to reach and maintain the best possible TWSTT precision and accuracy.

ACKNOWLEDGMENTS

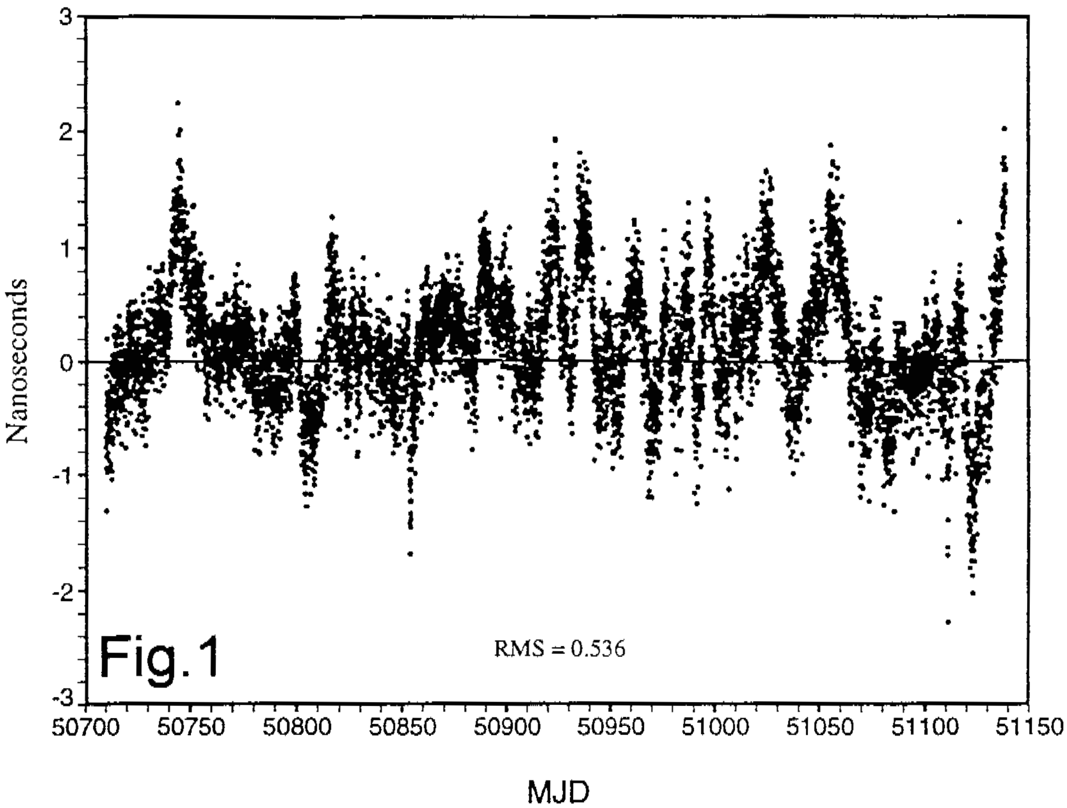
This paper could not have been written with out the outstanding hardware work, some of it very physical and sometimes done in very hot and difficult field conditions, of Phu Mai, Angela McKinley, George Luther, and Paul Wheeler.

REFERENCES

[1] http://tycho.usno.navy.mil/twstt.html

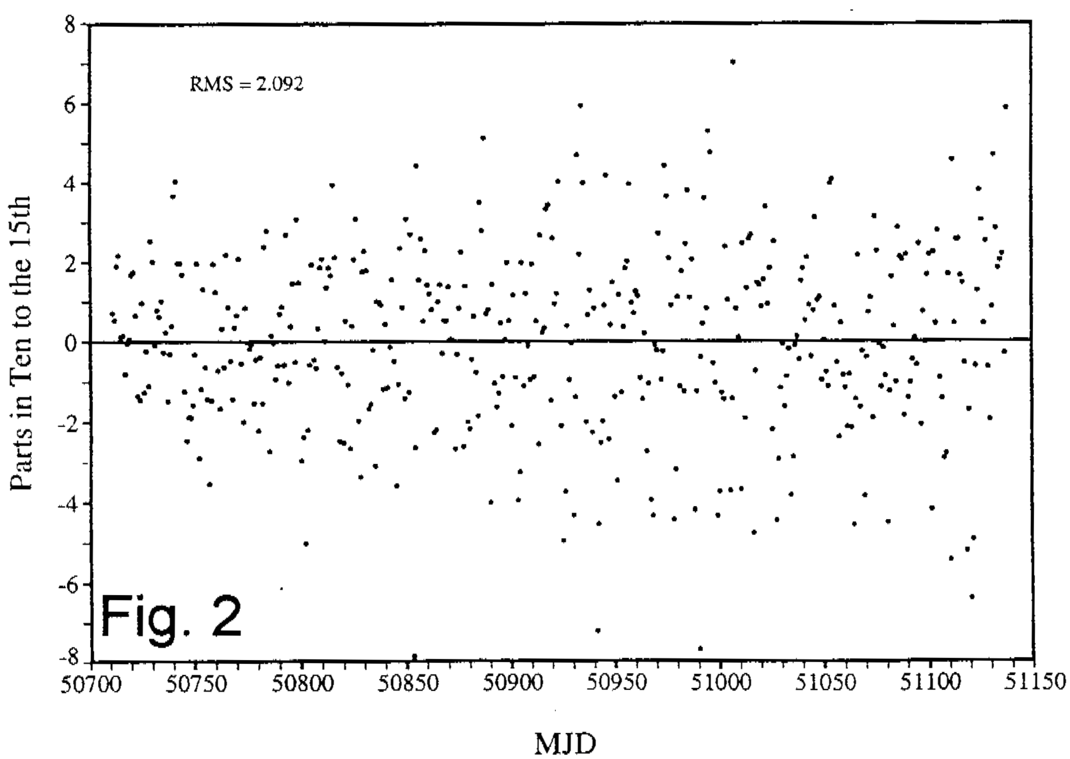
[2] J. DeYoung and R. J. Andrukitis, 1994, "Remote Clocks Linked by a Fully Calibrated Two-Way Timing Link," Proceedings of the 25th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, November 29-December 2, 1993, pp. 285-292.

USNO(MC2) - USNO AMC(MC1) Via Nearly Hourly TWSTT



USNO(MC2) - USNO AMC(MC1) Via TWSTT

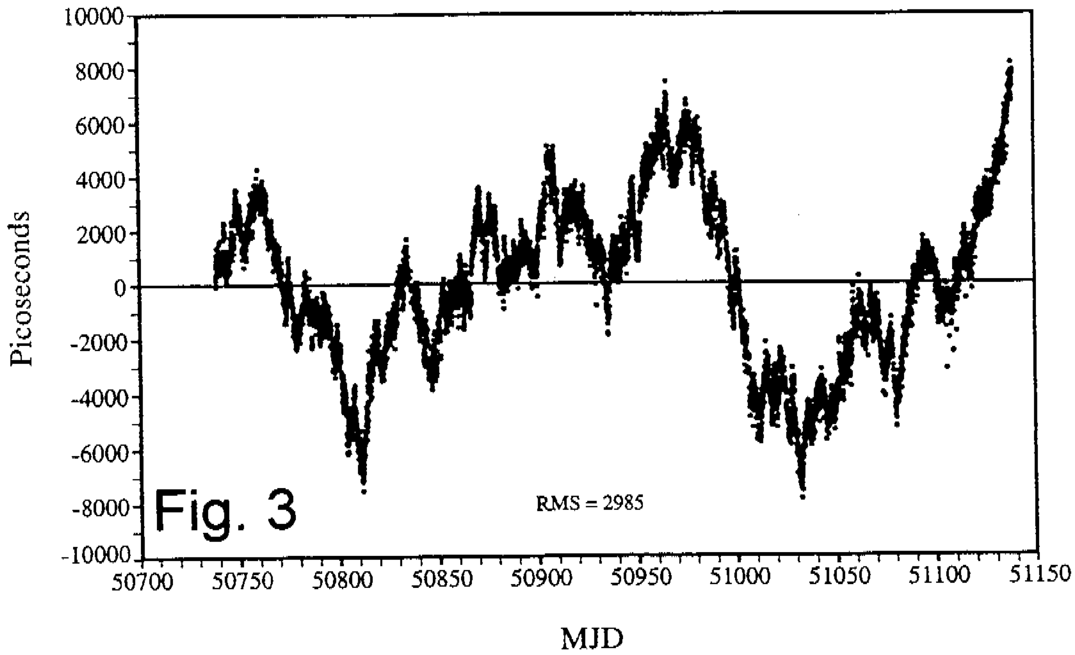
Frequency @1d from Simple 1d Time Averages



USNO AMC(A.1) - USNO (A.1) via TWSTT

USNO AMC ---> 10Cs + 2 H-maser

USNO ---> 35Cs + 10 H-maser

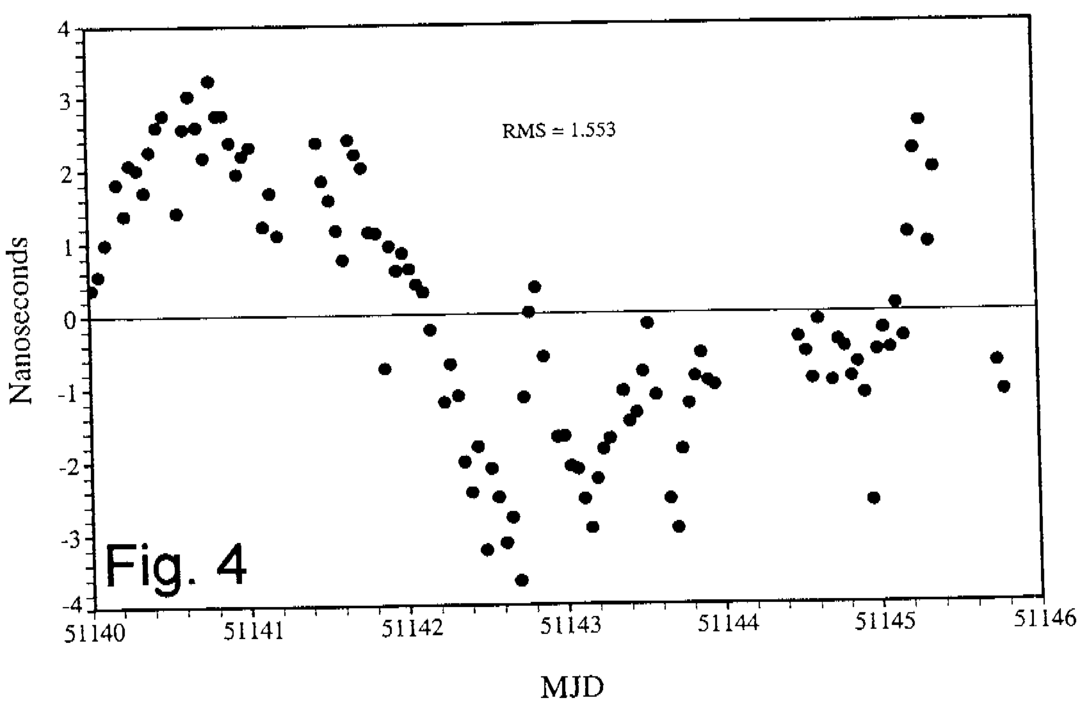


Removed: 1st Order -62060.306 ps/d, 2nd Order 2.006 ps/d/d

USNO(MC2) - BAH(Cs) via TWSTT

10,983km Single Hop X-band

Rate of +9.847 ns/d Removed



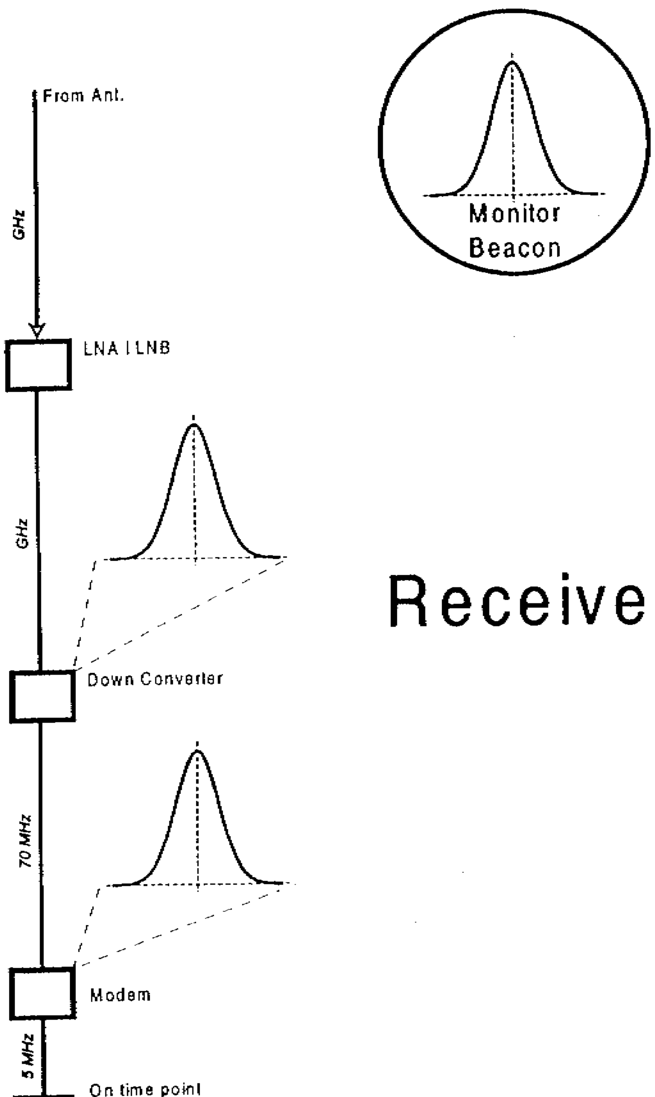

From Ant.
GHz
LNA | LNB
GHz
Down Converter
70 MHz
Modem
5 MHz
On time point
Monitor
Beacon
Receive

Fig. 6

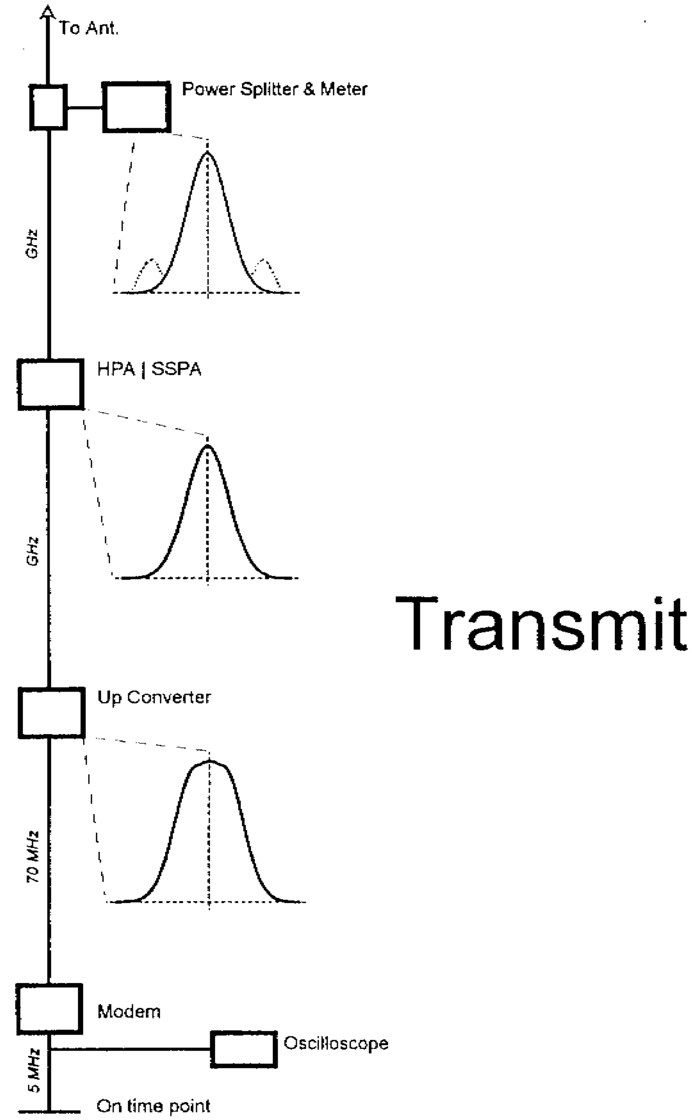

To Ant.
Power Splitter & Meter
GHz
HPA | SSPA
GHz
Up Converter
70 MHz
Modem
Oscilloscope
5 MHz
On time point
Transmit

Fig. 5

Fig. 7

Detail of Portion of Calibration by Co-Located TWSTT Method

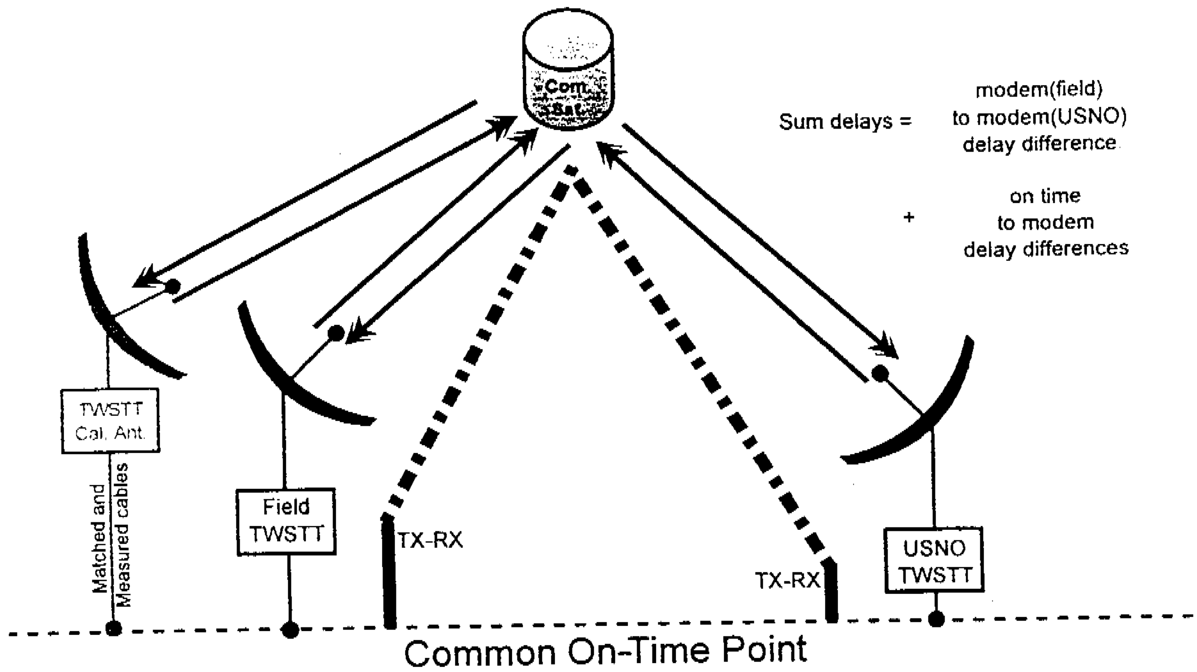


Fig. 8

TWSTT Link Calibrated by Co-Located TWSTT Method

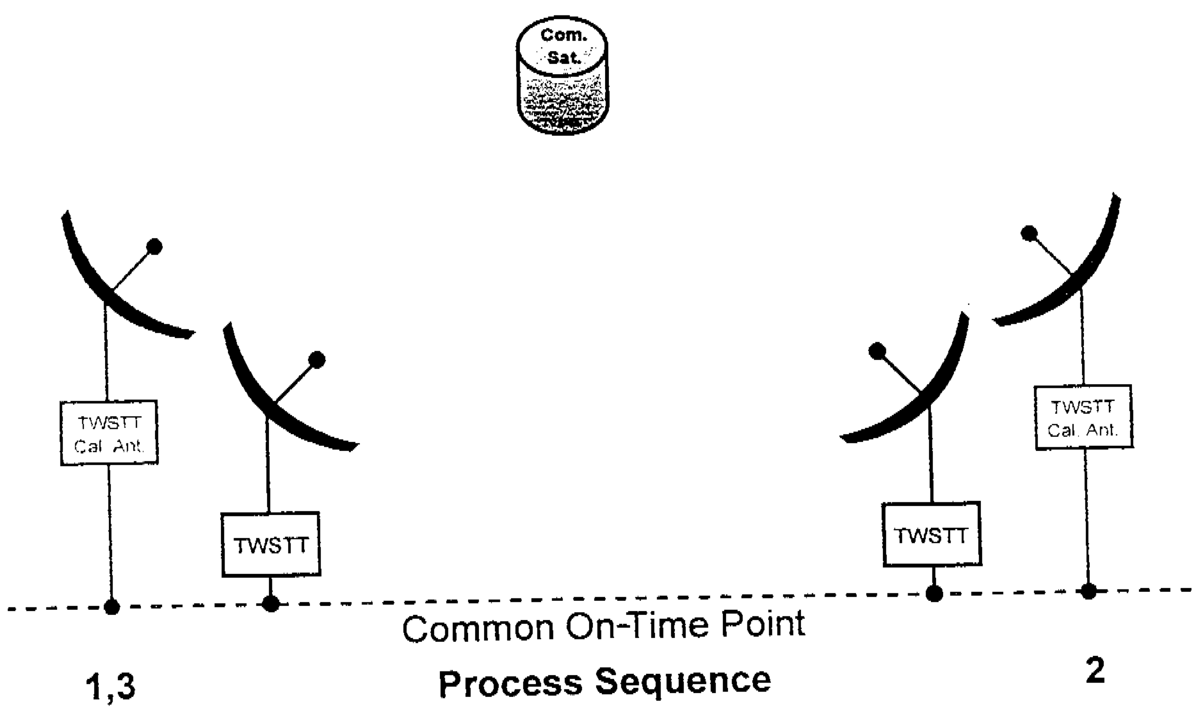


Fig. 9 **GPS Receiver Link Calibrated by Co-Located TWSTT Method**

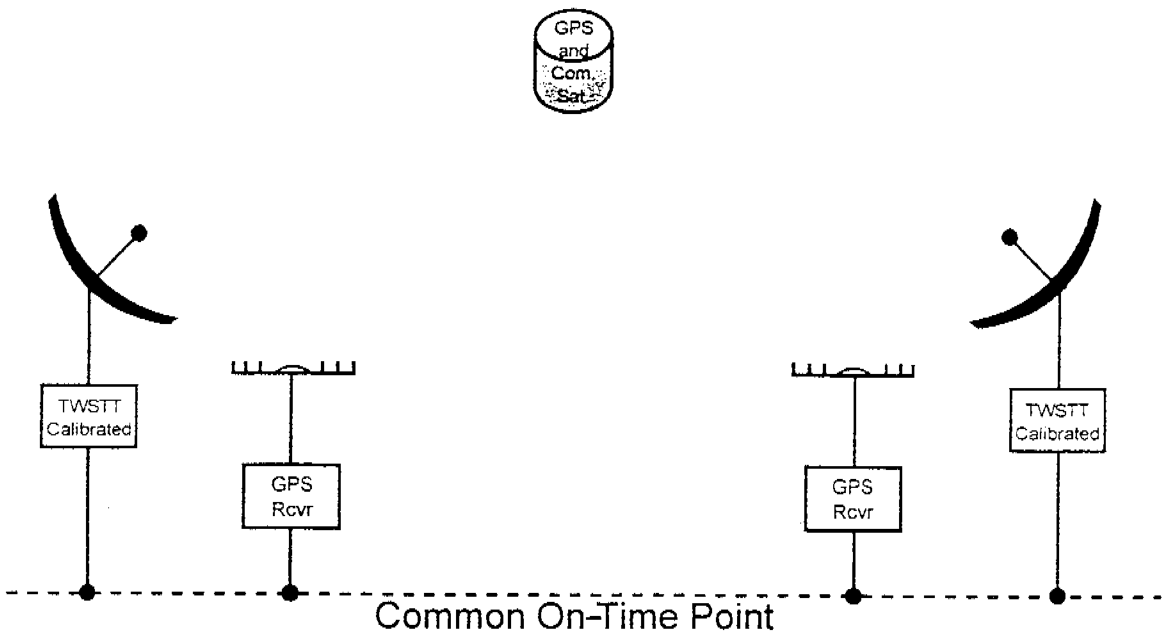
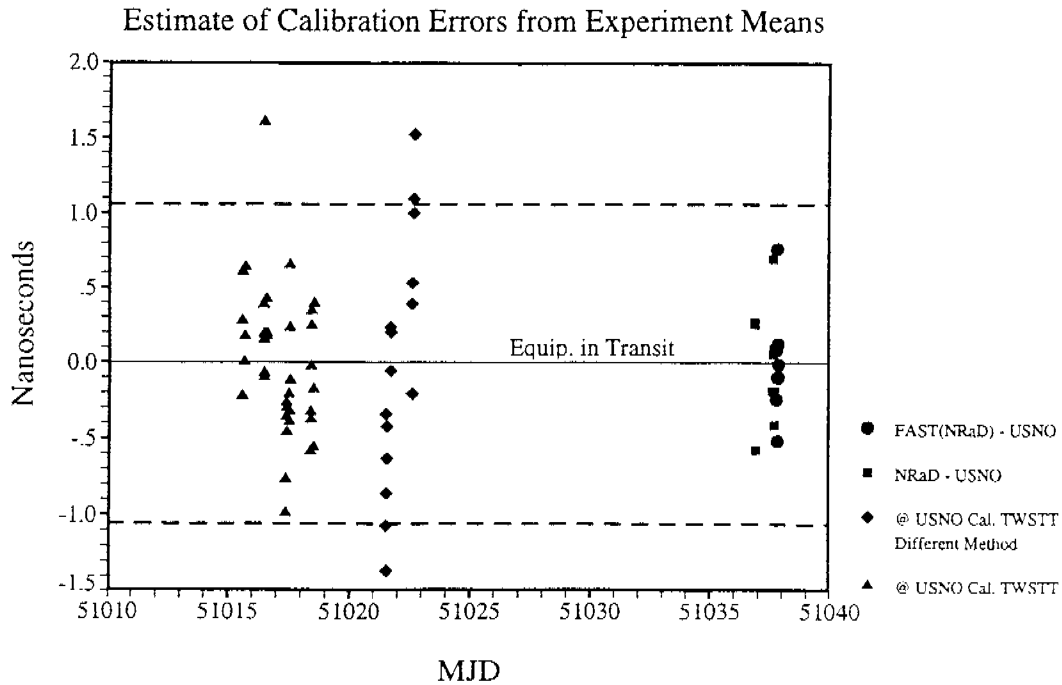


Fig. 10 USNO - NRaD Syntonization and Single-Shot Synchronization



Combined Error: 1.057ns

Fig. 11

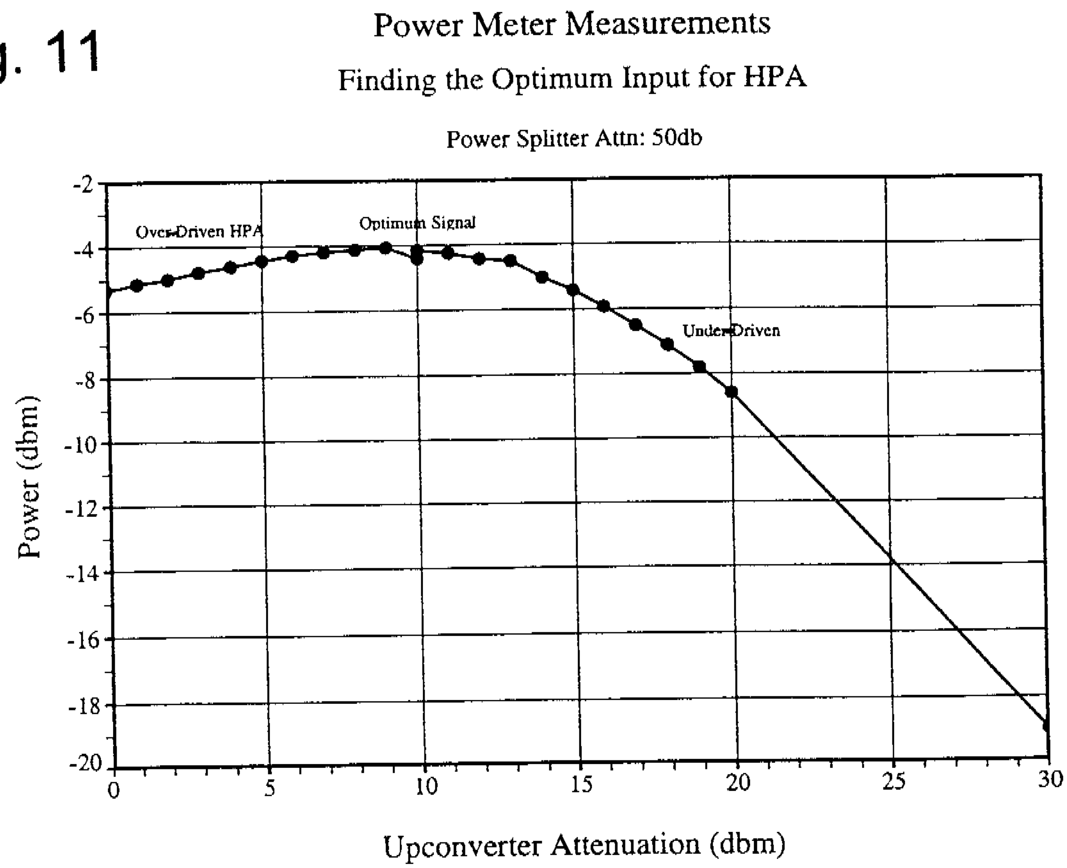

Power Meter Measurements
Finding the Optimum Input for HPA
Power Splitter Attn: 50db
Over-Driven HPA
Optimum Signal
Under-Driven
Power (dbm)
Upconverter Attenuation (dbm)
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
5
10
15
20
25
30

Fig. 12

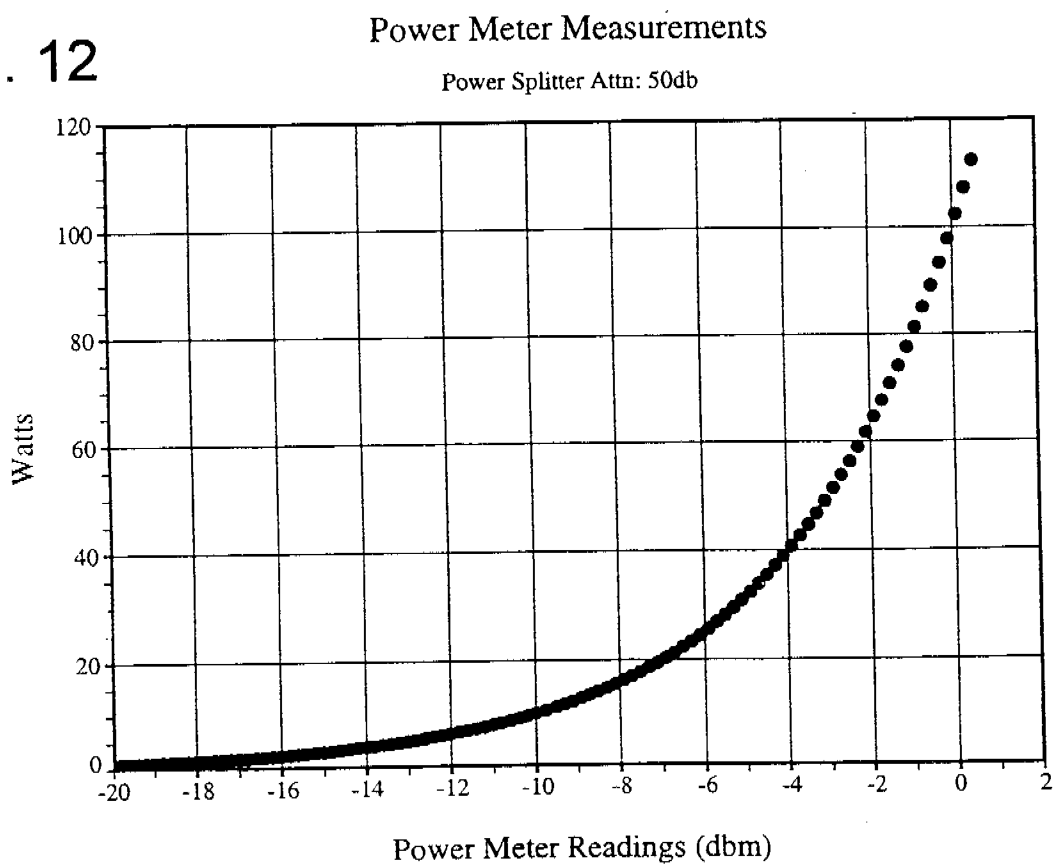

Power Meter Measurements
Power Splitter Attn: 50db
Watts
Power Meter Readings (dbm)
120
100
80
60
40
20
0
-20
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
2

Fig. 13

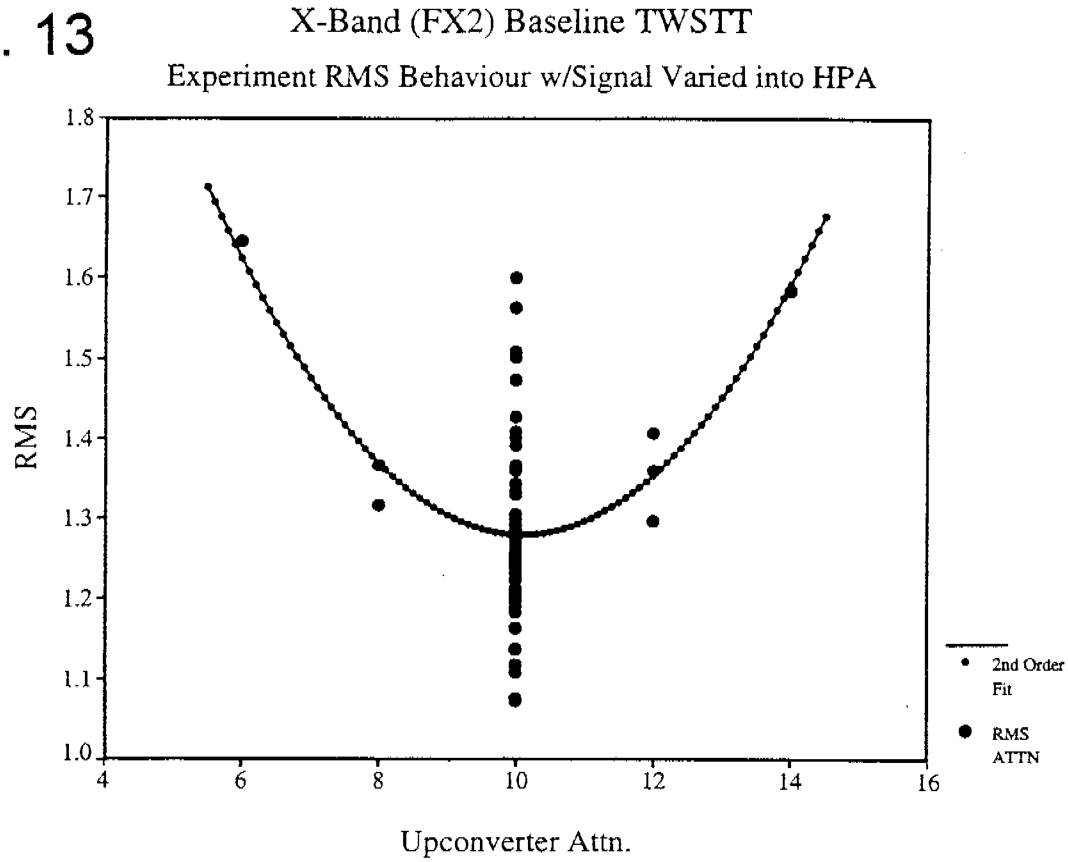
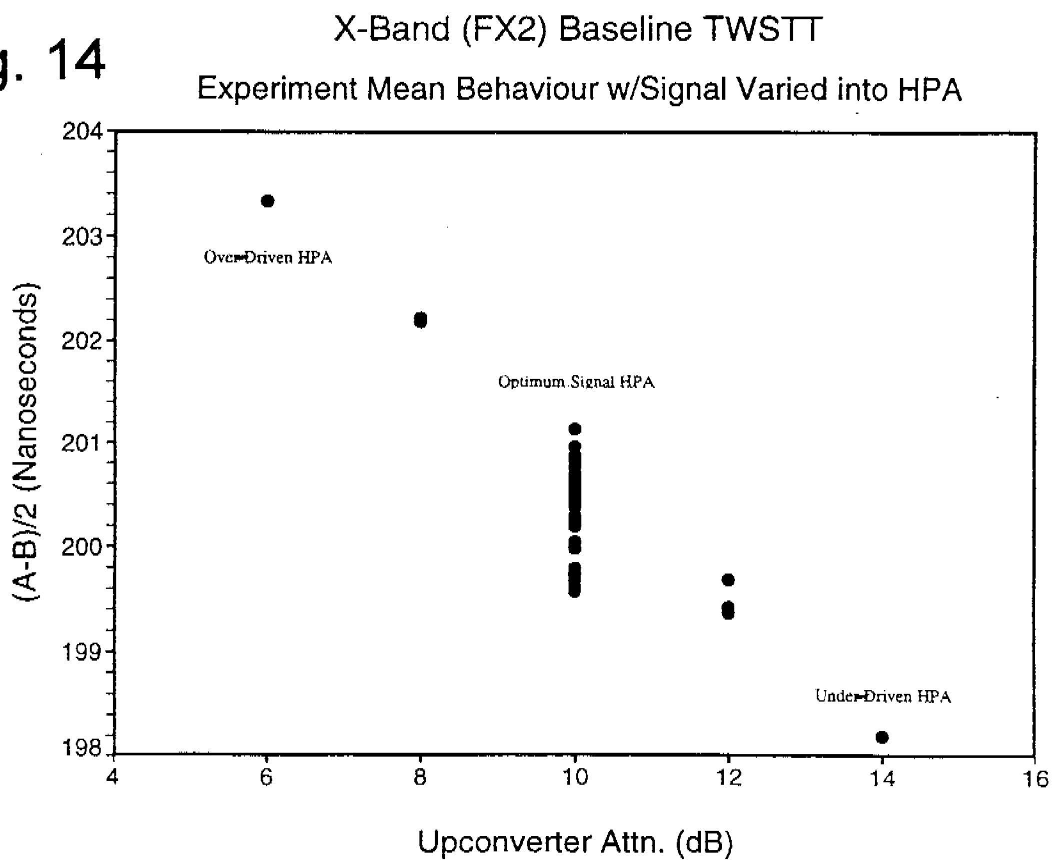

X-Band (FX2) Baseline TWSTT
Experiment RMS Behaviour w/Signal Varied into HPA
RMS
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
4
6
8
10
12
14
16
Upconverter Attn.
2nd Order Fit
RMS ATTN

Fig. 14


X-Band (FX2) Baseline TWSTT
Experiment Mean Behaviour w/Signal Varied into HPA
(A-B)/2 (Nanoseconds)
204
203
202
201
200
199
198
Over-Driven HPA
Optimum Signal HPA
Under-Driven HPA
4
6
8
10
12
14
16
Upconverter Attn. (dB)