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A PROBLEM WITH EXTERIOR BALLISTIC MEASUREMENTS--AN EXPLORATION OF <NS LEVEL PRECISION>GROUP DELAY MEASUREMENT METHODS

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ABSTRACT This article makes a simple description of GPS (global positioning system) positioning precisions as well as its measurement methods. It elucidates test measurement levels reached domestically and existing problems. It puts forward effective pulse modulation and demodulation technologies to determine test measurement precisions and opts for the use of measurement duration intervals to replace phase measurements. This is capable of effectively making systems with the same frequencies and different frequencies reach ns level group delay measurement precisions. In conjunction with this, it gives test measurement method schematic diagrams as well as key equipment and explains that this system is capable of resolving a difficulty associated with GPS system zero calibration.

I. INTRODUCTION

In the realm of space navigation, speaking in terms of rocket and missile technology, precise determinations of the flight tracks is extremely important. The global positioning system (GPS) is the global, all weather, continuous radio positioning, navigation, and time transmission system developed by the U.S. Department of Defense. The GPS system's navigation and positioning accuracies are very high. Making full use of the GPS system's resources of high precision positioning technology is extremely beneficial with regard to missile and rocket exterior measurement systems. As far as research associated with the applying of GPS positioning information to carry out missile exterior measurements for the fixing of tracks is concerned, it is through transmiters installed on missiles sending GPS NAVSTAR (navigation satellite) transmited L wave band signals and ground measurement receiving equipment receiving at the same time GPS satellite signals as well as GPS signals transmited from missiles. Following this, through data processing and calculations, pseudo ranges and pseudo range rates of change are measured in order to precisely determine the position and course of missiles.

GPS system positioning opts for the use of a multiple satellite high orbit range measurement system, using distance as the basic measurment observed. The basic prinicple of range measurement systems is to precisely determine propogation delays (propogation times) associated with radio signals over the distances measured in order to calculate range, that is

$$\rho = C \cdot \tau \qquad (1)$$

In this, τ is the difference between the instant of transmission of a signal coming from a certain satellite and the instant the receiver receives it. C is the speed of propogation of electromagnetic waves in air. However, in reality, τ also includes receiving system and transmiting system delays. In this way, errors will then be brought into measured distances, thereby influencing the precision of measured ranges. As a result, during actual calculations, it is necessary to calibrate zero in order to eliminate this partial delay quantity. With regard to measurements of delay quantities associated with receiving systems and transmiting systems themselves, they then become key elements in missile exterior measurements. The precision associated with measurements of these directly influence the precision of range measurements. From equation (1), it is possible to know that, if C is selected as the speed of light at 3x10-8 m/sec, and the error τ is selected as 1ns, then, the error

τ is 0.3 meters. At the present time, there is some engineering which requires precisions of 1 meter. Looking then from the viewpoint of present technological levels and forces, there is still a certain error between those adequate to be used in actual engineering test measurements and test measurement methods reaching ns level precisions. As a result, determining high precision group delay test measurements becomes an urgent matter. Our telemetry center laboratories go through domestic investigative research and search for data. Use is made of laboratory advanced equipment and rich practical operating experience. On the foundation of large amounts of experimentation and analysis, one type of group delay test measurement system came out of research. The system in question is not only capable of reaching the ns level in terms of precision. It, moreover, provides a preliminary solution for the difficulties associated with frequency variation system group delay test measurements, providing a technological basis for increasing missile exterior measurement precision. /145

II. BASIC CONCEPTS AND PRINCIPLES

1. Group Delay

Group delay is one type of special transmission parameter unique to linear systems and networks. It has two areas of significance. The first is that the magnitude of group delays themselves determine the magnitude of system and network signal transmission delays. This is also nothing else than the absolute group delay people often talk about. The second is that there is a close relationship between group delay characteristics and signal transmission distortion. This is also nothing else than relative group delay.

Here, the significance of "group" has two layers of meaning. On the one hand, transmission signals must be group signals. Monochromatic wave transmissions can be said to have no group delays. What are called group signals are complex signals or wave groups made up, in accordance with certain forms or patterns, from a number of frequencies quite close to each other. Various types of already modulated signals produced by the carrying out of modulation on high frequency carrier waves using telemetry coding (AM, FM, PM) are group signals. Such commonly seen signals as telemetry transmissions, as well as radar signals, and so on, are all group signals. On the other hand, groups refer to system delays which must be delays associated with wave groups as a whole and are not phase delays associated with certain frequencies among them. Even less are they mean values.

A mathematical expression associated with group delays is:

$$\tau = -d\Phi(\omega)/d\omega \qquad (2)$$

The geometrical meaning of group delay is as shown in Fig.1.

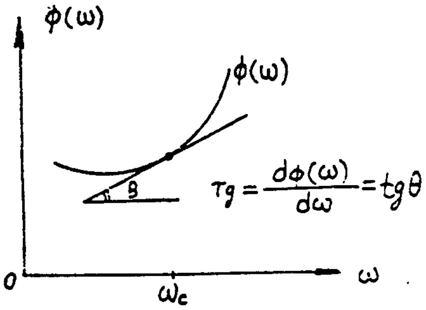

Fig.1

The group delay expressed by equation (2) refers to entire delays produced on system or network signals when going through linear systems or networks. They are also called signal energy transmission delays or absolute group delays. They represent time periods required from system input terminals to system output terminals by wave group signal energies. They are a measure of the magnitude of energy transmission time periods.

Due to the fact that group delays are phase specific first order differentials, and phase specific linearities are also closely related to signal distortion, as a result, group delay characteristics are also capable of acting as signal distortion indices and are used in order to express system or network capabilities for signal transmission with minimum distortion.

2. Envelope Delays

When signals go through systems, system output signal envelopes show a certain time delay with regard to input signal envelopes. This time delay is called system envelope delay. Due to the fact that system envelopes are loci associated with maximum amplitude values for composite signals from various wave group components as they change over time, under certain conditions, therefore, envelope delays can stand for wave group signal energy transmission delays. Also, because envelope wave forms associated with already modulated signals and modulation signal wave forms are the same, as a result, envelopes also represent group signal information components. Therefore, envelope delays have a very important significance with regard to signal energy transmission. Moreover, under certain conditions, they are also capable of taking the place of group time delays. This is also very important with regard to group delay test measurements.

Below, taking modulated signals as an example, we derive a mathematical expression for envelope delay.

Assume a1(t) is a simple modulated signal. Its analytical form is:

$$a_1(t) = A_0(1 + m\cos\Omega t)\cos\omega_c t \tag{3}$$

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Taking form (3) and expanding it, one obtains:

$$a_1(t) = A_0\cos\omega_c t + \frac{mA}{2}\cos(\omega_c t + \Omega)t + \frac{mA}{2}\cos(\omega_c - \Omega)t \tag{4}$$

Assuming that, in the system in question, $A(\omega) = 1$, , $\Phi(\omega)$ is any curve as shown in Fig.2.

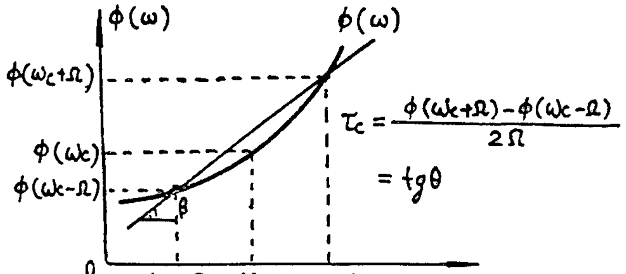

Fig.2

The phase shifts produced on signals by the three system components are, respectively, $\Phi(\omega_c - \Omega)$, $\Phi(\omega)$, and $\Phi(\omega_c + \Omega)$. Assuming that the modulated system output signal is ao(t), then

$$\begin{aligned} a_0(t) &= A_0\cos[\omega_c - \Phi(\omega_c)] + \frac{mA_0}{2}\cos[(w_c + \Omega)t - \Phi(\omega_c + \Phi)] \\ &+ \frac{mA_0}{2}\cos(\omega_c - \Omega)t - \Phi(\omega_c - \Omega) \\ &= A_0[1 + m\cos(\Omega t = (\Phi(\omega_c + \Omega) - \Phi(\omega_c - \Omega))/2)] \\ &\cos[\omega_c t - \Phi(\omega_c)] \end{aligned} \tag{5}$$

Comparing equations (3) and (5), it is possible to see that the envelope shift between output signals and input signals is Φ_e :

$$\Phi_e = [\Phi(\omega_c + \Omega) - \Phi(\omega_c - \Omega)] / 2 \tag{6}$$

From equation (6), it is possible to see that envelope phase shifts produced by systems are identical to one half the difference between upper boundary frequency phase shifts and lower boundary frequency phase shifts. This has no parallel with whether or not phase characteristic $\Phi\,(w)$ is linear or curvalinear. Rewriting equation (5), one obtains:

$$a_0(t) = A_0[1 + m\cos\Omega(t - \frac{\Phi_{(\omega_c+\Omega)} - \Phi_{(\omega_c-\Omega)}}{2})]\cos[t - \Phi(\omega_c)/\omega_c]\omega_c \tag{7}$$

Comparing equation (3) and equation (7), it is possible to clearly see system output signals and input signals in comparison to each other. It is also possible to see that the output signal envelope is delayed a time τ_e:

$$\tau_e = [\Phi(\omega_c + \Omega) - \Phi(\omega_c - \Omega)] / 2\Omega = \Phi_e / \Omega = \mathrm{tg}\theta \tag{8}$$

τ_e is defined as being the system envelope delay at location ω_c .

In equation (8), assume $\Phi(\omega_c + \Omega) - \Phi(\omega_c - \Omega) = \triangle\Phi$, and $2\Omega = \triangle\omega$, . Then, $\tau_e = \triangle\Phi / \triangle\omega$, . When $\Omega \to 0$, that is, envelope frequencies are extremely small relative to carrier wave frequencies, then:

$$\tau_e = lim\triangle\Phi / \triangle\Omega = d\Phi / d\omega \tag{9}$$

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Equation (9) is a special form of envelope delay and is not a universal expression. However, it has an important role in the measurement of group delay. Although the derivations above, relevent to envelope delays, use modulated waves as signals, they are appropriate in the same way with regard to angle modulation signals. As a result, the concept of "envelope delay" is a generalized one, and it is established in all cases--whether one reaches the conclusion from AM, FM, or PM.

Going through the discussions above, it is possible to reach this type of conclusion: under certain conditions, signal envelope delays are equal to group delays. This is the main foundation for our setting up group delay test measurement systems.

III. BASIC PRINCIPLES OF GROUP DELAY TEST MEASUREMENTS

Due to the definition and concept of group delay, group signal delay time periods are not capable of measurement by the use of simple methods. On the basis of different principles of test measurement, delay period measurement techniques are divided into two types. One type is called the phase shift characteristic curve slope measurement technique and is also called the static measurement method. The other type is a modulation demodulation technique and is also called the dynamic measurement method.

In the first type of situation, group delays are obtained through calculations. These calculations are capable of being completed from static measurements of phase characteristics. Phase delay measurement instruments, which have already become commercial products--for instance, vector network analyzer instruments (HP8510C, Willtron 360B), impedance analyzer instruments, and so on--are all based on this method. Opting for the use of test measurement systems composed of vector voltage meters or other high precision phase meters, also makes use of this type of principle. In all cases, they derive group delay through the slopes of phase characteristics at location w. The test measurement schematic diagrams are as shown in Fig.3 and Fig.4. System absolute group delay can be shown in a closely similar way as:

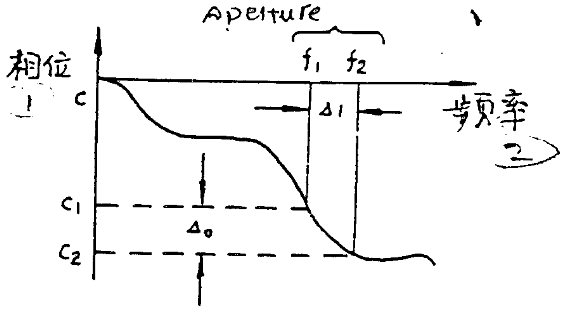

Fig.3 (1) Phase (2) Frequency

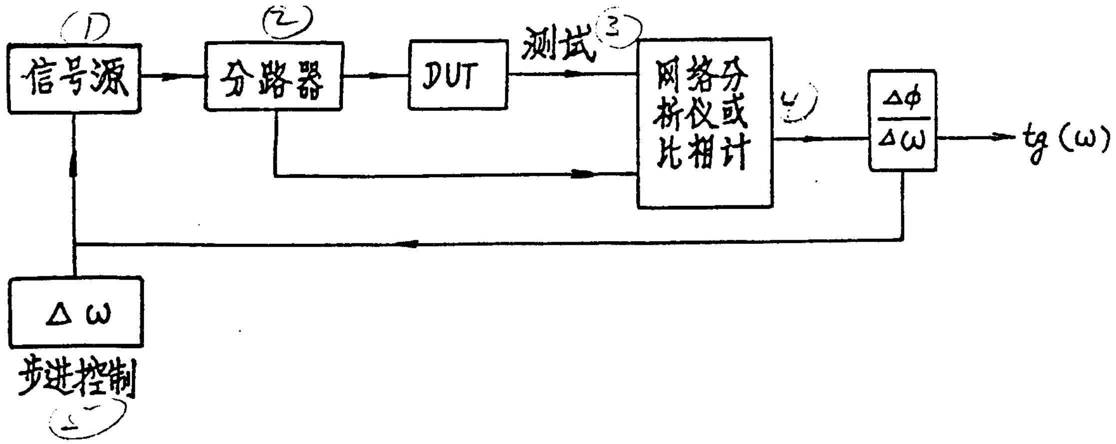

Fig.4 (1) Signal Source (2) Shunt (3) Test Measurements (4) Network Analyzer Instruments or Relative Phase Meters (5) Step Control

Due to static methods opting for the use of approximate calculations, they bring with them certain limitations to measurement techniques. If delta f or delta w (called window apertures) are selected, there is a direct influence on measurement results. In accordance with the principles, the smaller delta f is the better it should be. However, with delta f too small, due to Φ resolution powers being limited, there is no way to obtain accurate phase values. In doing this, it is possible to increase frequency resolution. However, there is no way to eliminate phase error. With regard to given phase /148 resolution, enlarging delta f is capable of making group delay resolution increase. However, test measurement precision goes down, and there exist time phenomena potentially making measurement results turn uniform.

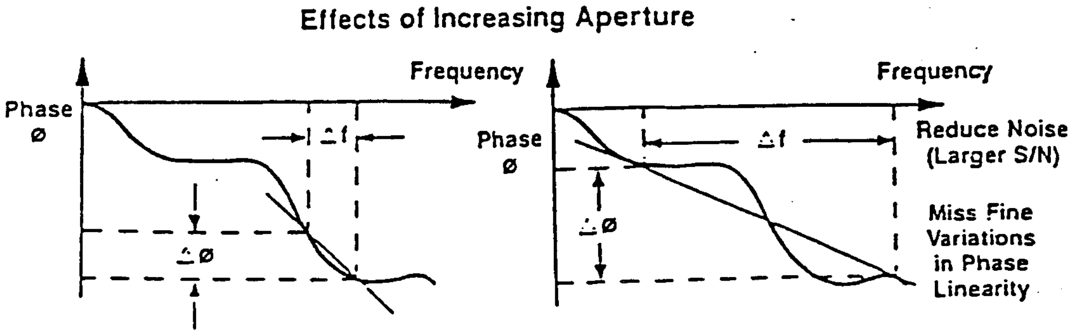

Fig.5

Low signal to noise ratios will also influence Φ resolution. The reason is that signal to noise ratios being low will introduce phase confusion, thereby leading to the introduction of phase measurement blurriness. The table below explains--under conditions with given apertures--the relationships between phase resolution and group delay resolution.

Signal to Noise Ratio	Resolution	τ_g
80dB	+0.006°	+0.06ns
60dB	+0.06°	+0.6ns
40dB	+0.6°	+6.0ns
20dB	+6.0°	+60.00ns

f=278KHz $\tau_g = \triangle\Phi / 360.\triangle f$

Besides this, with regard to group delay test measurements associated with frequency conversion systems, static methods are clearly powerless. The reason is that they go through frequency measurements and phase comparisions in order to calculate group delays. However, only when frequencies are the same is it then possible to compare phases. When frequencies change, there is no way to carry out phase comparisions. Thus, there is no way to obtain phase difference values in order to calculate group delay. In actual engineering, frequency convertors, signal transmiters, and so on, are often used. They are systems in which input and output frequencies are different. At the present time, with regard to group delay test measurements produced by this type of system, in world terms, it is still a problem. In a search of the data, there are no reports in this area. There are only experts with an interest in this.

Another type of measurement technology opts for the use of already modulated signals to act as test measurement signals. After going through the network being measured and being demodulated, comparisons are made to modulation signals, measuring group delay values. The principles are as shown in Fig.2 and equation (9). The test measurement schematic diagram is as shown in Fig.6. This type of test measurement technology, due to opting for the use of test measurement signals which are group signals, is, therefore, capable of approaching even closer to real group delays and truly reflected system group delay characteristics.

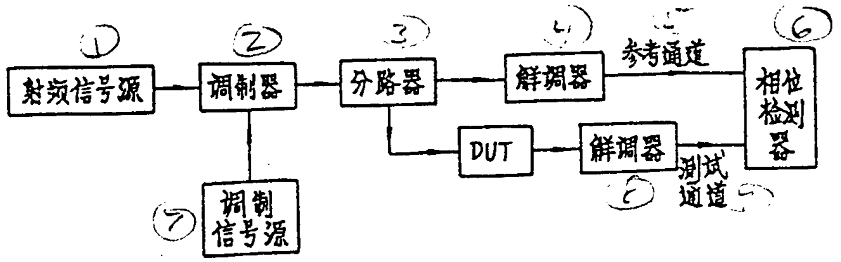

Fig.6 (1) Radio Frequency Signal Source (2) Modulation Device (3) Shunt (4) Demodulation Device (5) Reference Channel (6) Phase Detector (7) Modulation Signal Source (8) Demodulation Device (9) Test Measurement Channel

Opting for the use of modulation and demodulation technologies, it is also possible to carry out group delay test measurements associated with frequency conversion systems. When general option is made for the use of sine wave modulation, time delay resolution is very severely limited. If option is made for the use of 20KHz to act as modulation signal, phase meter /149 resolution is 0.01°. By contrast, minimum group delay resolution is 1.5ns.

From the analysis above, it is possible to know that the precisions of test measurement systems in which there is option for the use of phase measurements can be calculated from the formula below:

$$\Delta\tau = \Delta\Phi / 360 \cdot \Delta f$$

In this, delta Φ is phase measurement precision. It is very greatly influenced by amplitude. The smaller ranges are, the lower phase measurement precisions are. If phase measurement precision is 1°, when delta f is 1MHz, the time delay precision is 1ns. When delta f is reduced to be 100KHz, phase measurement precision is 10ns.

Besides this, opting for the use of phase measurement techniques will also be limited by the band width of measured systems. Speaking in terms of narrow band systems of under a few megs, due to it not being possible to select apertures too large, this will then lower test measurement precision.

Due to it being very difficult for test measurement precisions associated with phase measurements as well as phase comparision methods to reach the ns level, measurement time intervals, however, are still capable of reaching very high precisions. The preceding derivations prove that, under certain conditions, envelope delays are equal to group delays. Based on this presupposition, we set up test measurement systems. The schematic diagram is as follows:

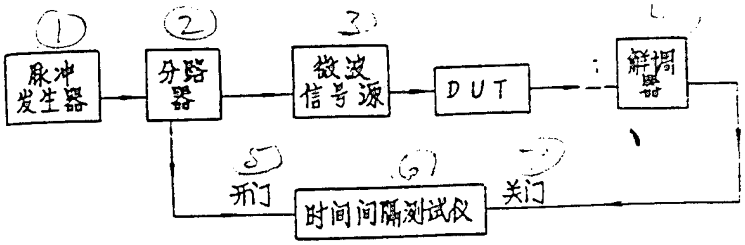

Fig.7 (1) Pulse Generator (2) Shunt (3) Microwave Signal Source (4) Demodulation Device (5) Open Switch (6) Time Period Interval Test Measurement Instrument (7) Close Switch

Pulse signals produced by pulse generators are divided into two circuits. One circuit acts as the open switch signal directly sent to the time period interval test measurement instrument. The other circuit goes to the modulation microwave signal source. Microwave signal sources output already modulated waves to components being measured. Components being measured output already modulated waves with the occurence of carrier wave frequency changes. Going through demodulation, obtained pulse signals act as close switch signals sent to the time period interval measurement instrument. The time period interval test measurement instrument measures the time interval between the open switch signal and the close switch signal, thereby measuring group delay. Group delay test measurements are just on the verge of turning into time interval test measurements. Time interval test measurements opt for the use of simulated interior difference methods to eliminate ±1 errors. General calculation devices are then capable of reaching ns level precisions. The test measurement principles are as follows.

The time period interval associated with measured signals is Tx. From Fig.8, it is possible to know that Tx=Tn+T1-T2. Tn is the time interval between the first time base pulse after pulse activation and the first time base pulse after pulse termination. T1 is the time period interval between pulse activation and the first one after it. T2 is the time period between the termination pulse and the first pulse after it. As far as measuring Tn is concerned, a total is made for the NO counting pulses (time base signals) which appear in the time period intervals in question. With regard to the measurement of T1 and

T2, by contrast, first use is made of interpolation devices to enlarge them 1000 fold. Then, ordinary counting devices are used for measurements. With regard to this expanded time period T1', it is possible to use a total for the standard count pulse number N1 which appears within T1' in order to make precise determinations. At the same time, T2 also goes through the same sort of interpolation device to enlarge 1000 times. In conjunction with this, it makes T2'=1000T2, totaling the standard count pulse number N2 within this time period in order to precisely determine T2'. In this way, counting devices respectively count the pulses numbers NO, N1, and N2. TO is the standard pulse counting cycle. Then

Tn=NoTO, T1'=N1TO, and T2'=N2TO

Measured time period intervals are: Tx =[NO+(N1-N2)/1000]TO
Although +1 errors exist at T1 and T2 levels, the magnitude is reduced to 1/1000th. Counting device resolutions are three /150 orders of magnitude. For example, TO=100ns. fO(10NHz) general counting devices will not exceed 1000 fold. After opting for the use of interpolation techniques, increases of 0.1ns are possible, equivalent to opting for the use of 10G standard count frequency signals.

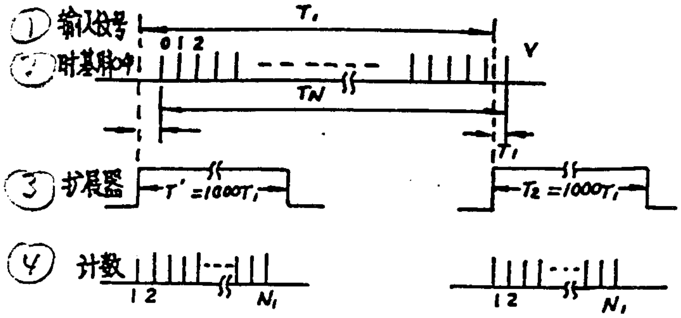

Fig.8 (1) Input Signal (2) Time Base Pulse (3) Multiplier (4) Count

EXPLANATIONS OF A FEW KEY QUESTIONS

(I) Design of System Components

1. Modulation and Demodulation Systems:

Speaking in theoretical terms, opting for any type of system is alright (AM, FM, ΦM all belong to group signals). During actual test measurements, hardware level is relied on to select modulation systems. Because the various components in test measurement sytems all require ns level leading edge response, they possess quite large difficulties. Telemetry center laboratories are only equiped with experimental conditions for modulation systems. Therefore, system designs opt for the use of modulation methods. The system shown in Fig.7 is appropriate for use with any type of modulation. In engineering applications, it is best to opt for the use of phase modulation methods. It is not only possible to decrease the influence of signal to noise ratios. Moreover, it is possible to regulate test measurement signal band widths in order to adapt to the requirements of measured systems.

2. Signal Sources

During group delay test measurements, high stability, low phase noise frequency sources are indispensible prerequisite conditions. Because GPS system input signals on missiles are -130dBm, in this electrical power level status, if test measurement systems want to operate normally, it is necessary to install the corresponding modulation devices, demodulation devices, and amplifiers. However, ns level requirements make hardware enter into microwave frequencies. The corresponding hardware index requirements are even stricter. Otherwise, noise will give rise to unstable system operation, causing time period test measurements to have no way to be carried out and produce extremely large deviations.

(II) Test Measurement Results

As far as test measurement systems composed of this type of multivarious components are concerned, going through detailed adjustment, systems are capable of reaching levels of stability at less than 0.5ns as shown in Fig.9.

Horizontal axses shown in Fig.'s above represent time periods used in test measurements. Vertical axses represent measured time period intervals. Overall, SPAN=1ns. Resolution is 125ps each grid. Changes in test measurement results do not exceed four grids. That is nothing else than to say that the system absolute delay is 14ns with stability of 0.5ns.

The time period interval test measurement instruments we make use of at the present time opt for the use of this type of technology. The crystal vibration is only 5MHz, but the resolution still reaches 20ps.

Fig.'s 10 and 11 are experimental group delay measurement systems set up on the basis of the principles and analyses discussed above. Fig.11 (sic) is a system with the same frequencies. Fig.11 is a system with different frequencies. With regard to test measurement systems with the same frequencies, it is possible to reach very high precisions and resolutions. Making use of the test measurement systems in question, comparative test measurements were carried out on institute 203 standard delay curves in order to check the reliability of test measurements by the systems in question. Test measurement results were as follows.

Standard delay curve theoretical delay calculations are 42.6ns. Institute 203 measured 42.8ns. The results we obtained were as shown in Fig.12. The frequency range for standard delay curves was 10M-18GHz. Due to our test measurement systems being limited by LNA, test measurements were only carried out within the range 2200-2300MHz. The resolving powers and stabilities were all very high. Both were followed with equal interest.

(III) Calibration Techniques

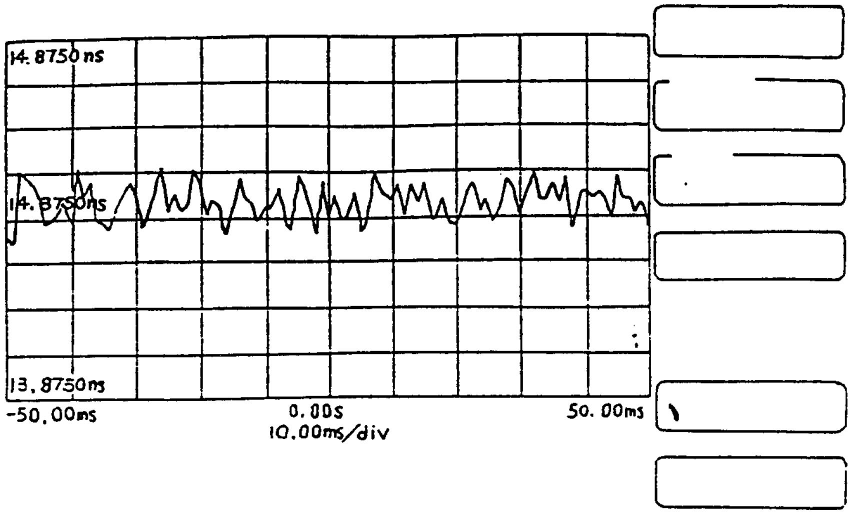

Fig.9

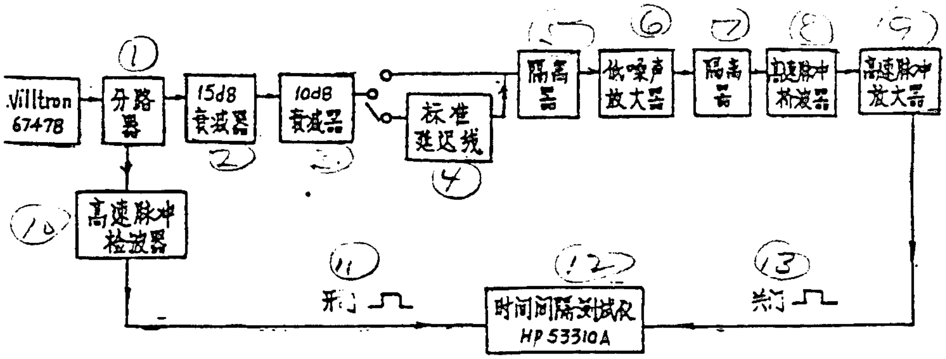

Fig.10 For Input and Output Frequencies that Are the Same (1) Shunt (2) & (3) Attenuation Device (4) Standard Delay Curve (5) Isolator (6) Low Noise Amplifier (7) Isolator (8) High Speed Pulse Detector (9) High Speed Pulse Amplifier (10) High Speed Pulse Detector (11) Open Switch (12) Time Period Interval Test Measurement Instrument (13) Close Switch

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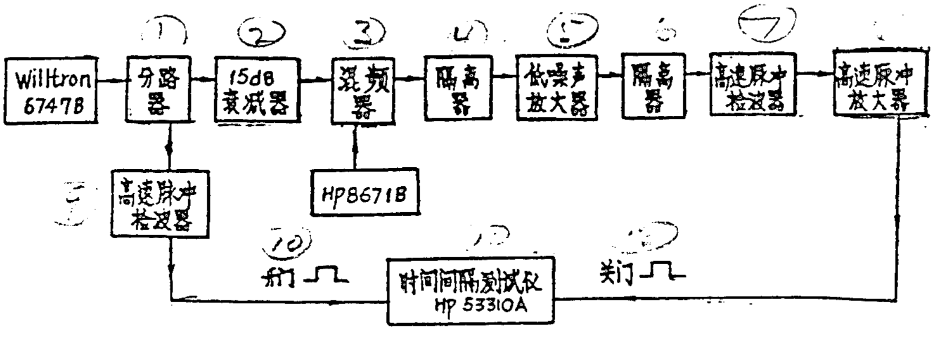

Fig.11 For Different Input and Output Frequencies (1) Shunt (2) Attenuation Device (3) Frequency Mixing Device (4) Isolator (5) Low Noise Amplifier (6) Isolator (7) High Speed Pulse Detector (8) High Speed Pulse Amplifier (9) High Speed Pulse Detector (10) Open Switch (11) Time Period Interval Test Measurement Instrument (12) Close Switch

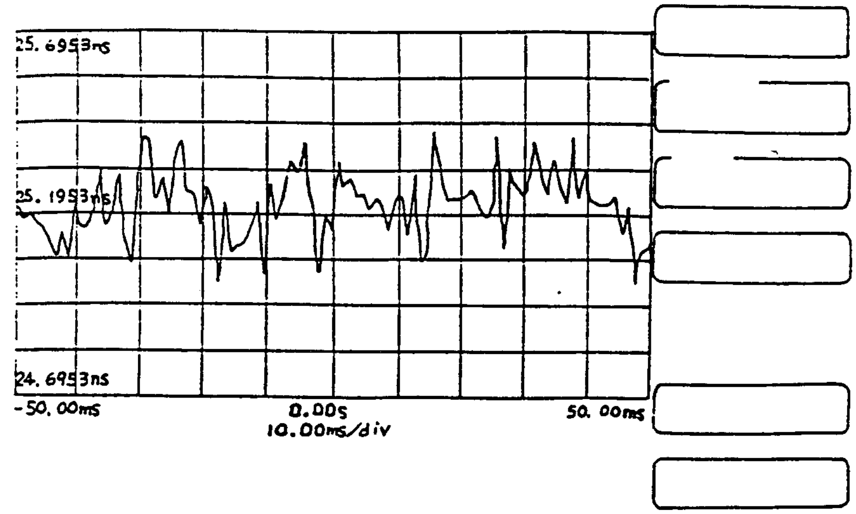

Fig.12(a)

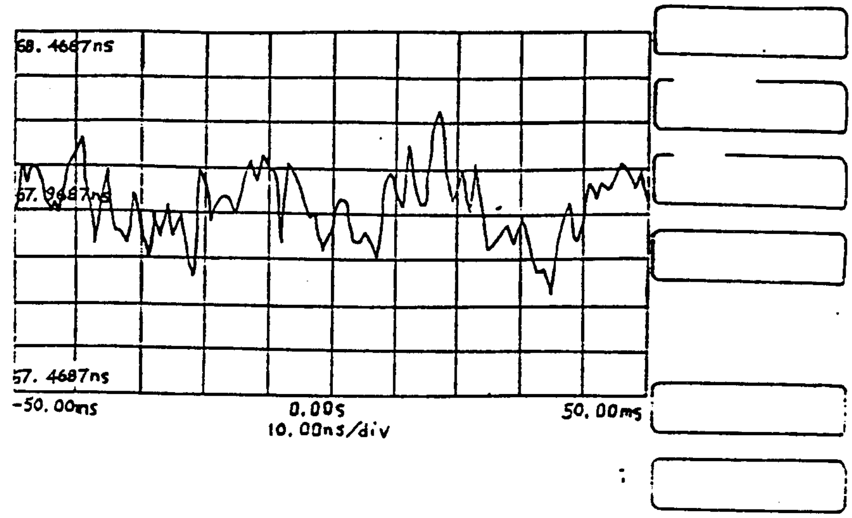

Fig.12(b)

Before introducing calibration techniques, we will explain a conceptual chromatic dispersion system. Due to the fact that delays are phase specific derivatives, but phase characteristics are functions of frequency, absolutely linear systems do not exist. As a result, delay characteristics are also nothing else than functions of frequency. Delays being functions of frequency led to by phase specific linearity being bad is called chromatic disperision. Any transmission system has chromatic dispersion. The difference is only the magnitude of the chromatic dispersion, and that is all. The institute 203 standard delay curve chromatic dispersion is very small. From 2200MHz-2300MHz, the delay changes are only 0.5ns. Moreover, the influences of amplitude and frequency characteristics are not considered. Therefore, it comes very close to a system without chromatic dispersion.

Due to the key point associated with absolute group delay test measurements--in regard to systems having different frequencies--laying in calibration, that is nothing else than to say that, due to the system's chromatic dispersion characteristics, system delay values take some frequency point as datum.

In measurement receiving systems associated with the carrying out of the positioning of flying targets with the use of GPS satellite signals, GPS missile borne transmiters are frequency conversion systems. System delay differentials associated with ordinary GPS test measurement receivers, which receive direct GPS signals, can reach close to 200ns. GPS transmiters include two parts--receiving and sending. Moreover, they are also connected into the entire test measurement system. Speaking in terms of GPS positioning systems, this is a system parameter which must be calibrated.

At the present time, GPS transmiters have three types of zeroing designs. In these, group delay measurement method errors are minimal. However, domestic engineering units still have a number of problems and difficulties with regard to the use of this type of method in zeroing. The test measurement systems which our telemetry center laboratories have studied are as shown in Fig.'s 11 and 12. Opting for the use of pulse modulation methods to measure time period intervals, group delay test measurement difficulties were resolved, effectively raising system zeroing precision.

IV. TENTATIVE IDEAS AND CONCLUSIONS

Following along with unceasing increases in range finding precision requirements and the unending applications of GPS, the need for high precision group delay measurements--in particular, group delay measurements associated with systems with different frequencies--becomes more pressing day by day. This set of group delay test measurement systems set up by telemetry center laboratories is capable of reaching very high precisions. This is particularly the case with regard to frequency conversion systems capable of giving 1ns instability group delay test measurement values, which are rare in China.

This system is only a model system. If one wants to use it in actual engineering test measurements, it is also necessary to deploy application specific hardware and software.

At the present time--on the foundation of currently existing research--our telemetry center laboratories carried out certain probes of group delay test measurements in signal transmission systems of frequency expansion set ups. Due to group delay distortion leading to related distortion in relevent receivers, thereby giving rise to increases in erroneous code rates, GPS satellite signals are also modulated by false random codes. It is possible to receive signals drowned in noise. This cannot be achieved by traditional modulation systems. Therefore, it is very important that use is made of false random code modulation signals to act as test measurement signals in carrying out component or system group delay test measurements.

V. CONCLUSIONS

Under the impetus of equipment model mission requirements, we developed the study of group delay test measurement methods and achieved certain progress. Following along with unceasing increases in exterior measurement precision requirements, high precision frequency conversion system group delay test measurements have become more and more important. Relevent theory and actual test measurements associated with group delay test measurements will also achieve further perfecting and strengthening.

Above are only a few attempts and experiments we made in the area of frequency conversion system group delay test measurements. We humbly request corrections from other specialists.

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