NAVIGATION TECHNOLOGY SATELLITE (NTS) LOW COST TIMING RECEIVER DEVELOPMENT*

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ABSTRACT

A compact timing receiver which receives and processes NTS ranging sidetones has been developed. In its prime operating mode, the receiver outputs a spacecraft-receiver range measurement in time units once each minute. The format of the output is compatible with the NTS data processing system, which determines the time difference between the user's clock and a reference clock at the Naval Observatory.

The receiver, which operates at P-band (335 MHz), is designed to use a minimum of RF and analog circuitry. The received ranging signals are quickly converted to low frequency, digital signals for processing under the control of an INTEL-8080 microprocessor. Receiver operation is primarily automatic, requiring only initial operator setup via front panel controls.

This paper describes the receiver and its operation, points out its advantages to a user requiring precise time at remote sites at an economical price, and describes a typical application.

*The receivers were jointly developed with NASA funding by the Applied Physics Laboratory, JHU and the Naval Surface Weapons Center.

INTRODUCTION

The NASA Goddard Laser Ranging Network, which is presently being implemented, has a world wide clock synchronization requirement of ± one microsecond to support various projects. At the present, the Network consists of one stationary Laser system located at Goddard and three Mobile systems. In addition, five more Mobile systems are being built. These eight Mobile systems will be deployed, at various times, at the locations indicated on the map. (Fig. 1) The Laser systems will have an overall ranging accuracy or capability of several centimeters.

In order to make use of the highly accurate ranging data, it is necessary to time tag the data very accurately. In applications where the data from two or more stations will be merged to determine baselines, polar motion, crustal motion, etc., it is necessary that the Laser clocks at the several stations be synchronized to within ± one microsecond.

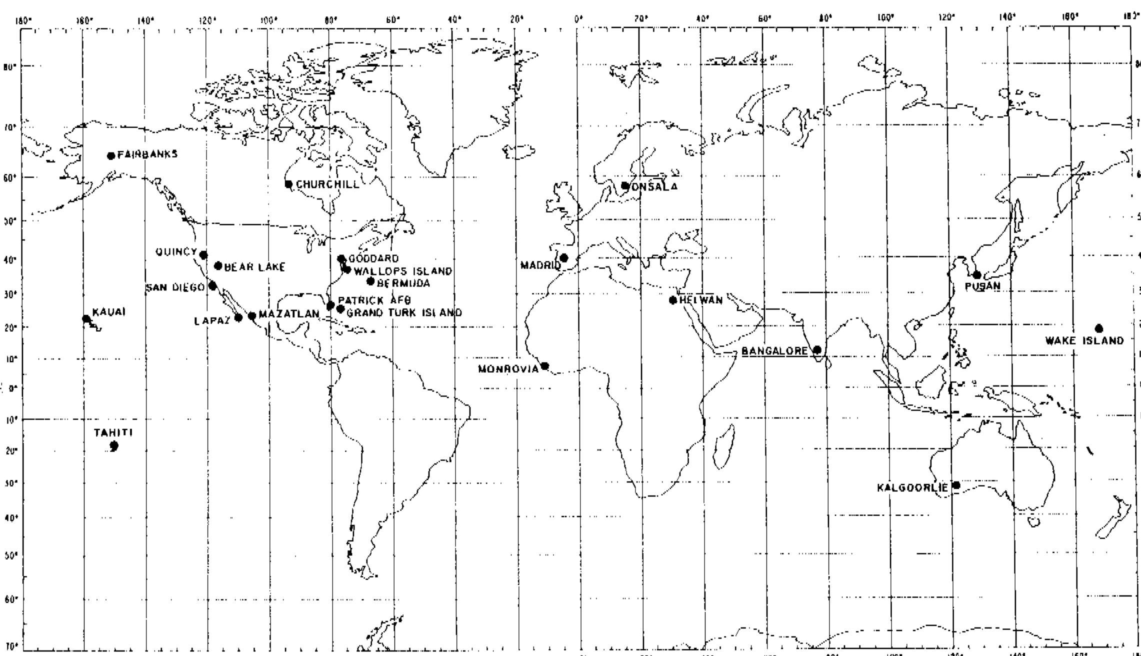

Figure 1. Tentative Laser Network

This requirement arises from the fact that a satellite moving in a typical low orbit travels about 0.7 cm per microsecond. Thus, if time is known to within one microsecond the peak error in spacecraft position due to time will be 0.7 cm.

Goddard personnel have over the years evaluated and used many techniques of time transfer including HF, VLF, dual VLF, radio navigation systems, the use of satellites such as GEOS, ATS and more recently the Navigational Technology Satellite to mention a few.

Recognizing, on a global basis, that microsecond clock synchronization is not practically achieveable by conventional means such as Loran-C or extended portable clock trips, Goddard concluded that between now and the early 1980's that the use of the NTS satellites would best provide the global coverage needed and the degree of clock synchronization required. Beyond the early 1980's NASA hopes to use either its own Tracking Data Relay Satellites (TDRSS) or the Global Positioning System to meet submicrosecond needs.

In 1975 NASA initiated the development of a signal frequency receiver for use with the NTS satellites for time transfer to within a microsecond. These receivers will be used in the Laser Ranging Timing Systems. A Laser Ranging Timing System is shown in Figure 2 and consists of a Cesium Beam Frequency Standard (004 Option), WWV and LORAN-C receivers and the NTS time transfer receiver plus signal distribution, etc.

This paper describes the NTS satellite time transfer receiver and the technique by which a user determines his time with respect to a master clock such as the U.S. Naval Observatory.

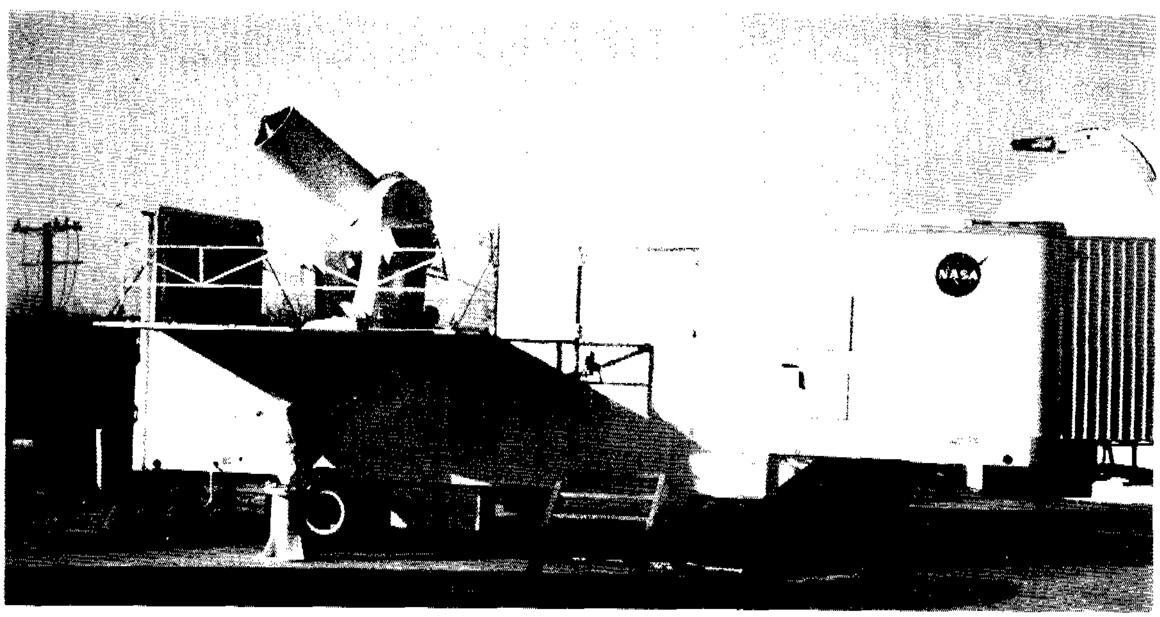

Figure 2. Laser Van

NTS Satellites

The NTS-1 spacecraft is the third satellite in a series of advanced research and technology satellites built and operated by the Naval Research Lab. Table 1 presents pertinent information of each spacecraft. The primary objectives of the missions are advanced clock development, satellite navigation and orbit determination; but a natural by-product of such work is the precise transfer of time using remote receiver sites.

For a precise time transfer to obtain maximum accuracy the following parameters are required to have minimum uncertainity:

1. Radial Location of Satellite
2. Satellite Clock
3. Ground Station Clock
4. Ground Station Antenna Position
5. Transmission Path

Any or all of the above five parameters could be solved for, but should be readily available in time transfer experiments.

TABLE 1

TECHNOLOGY SATELLITES

	T-I	T-II	T-III	
			NTS-1	NTS-2
LAUNCH DATE	5/31/67	9/30/69	7/14/74	1977
ALTITUDE (N. MI.)	500	500	7400	10,900
INCLINATION	70°	70°	125°	63°
ECCENTRICITY	0008	002	007	0
WEIGHT (LBS)	85	125	650	950
D.C. POWER (W)	6	18	100	300
FREQUENCIES	UHF	VHF/UHF	UHF/L BAND	UHF/L_1L_2
OSCILLATOR	QTZ	QTZ	QTZ/RB	C_S
Δ F/F(DAY) PP10^{13}	300	100	5-10	2-5

Figure 3 depicts a typical ground station time transfer configuration. Range observations are made at two or more sites by processing signals transmitted from the spacecraft. When the observations are combined and the satellite

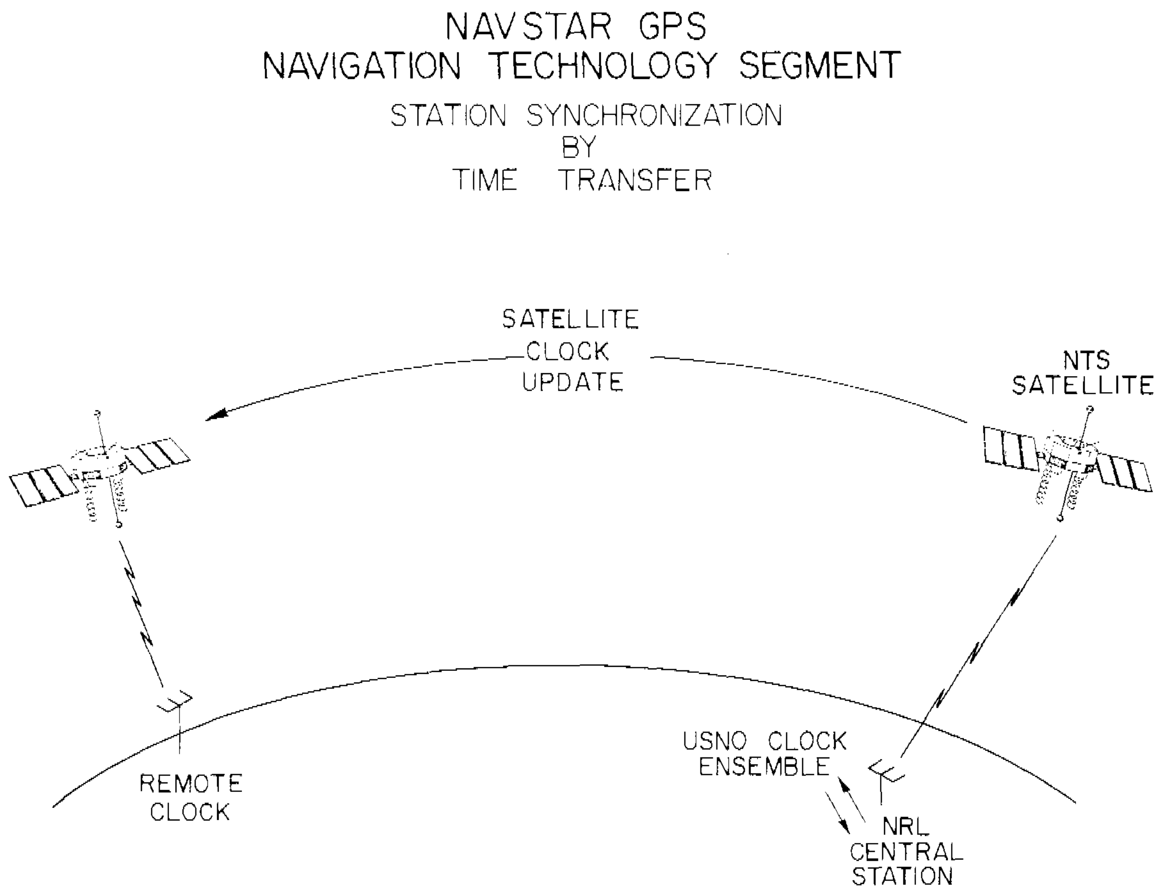

Figure 3. Time Transfer Configuration

oscillator drift is updated to allow for the time difference of the observations, the difference between the two ground clocks is obtained.

Data presented in this paper was obtained using the NTS-1 spacecraft. The receiver described will also operate with the NTS-2 satellite which is to be launched in early 1977. A more detailed explanation of the time transfer technique can be obtained in ref (1).

Time Transfer Receiver, Functional Description

The purpose of this receiver is to determine the range to a satellite in terms of the time required for its transmitted signal to reach the receiver. This is accomplished by the technique of sidetone ranging. In sidetone ranging phase comparisons are made between satellite transmitted tones and receiver generated tones of the same frequency. Both sets of tones are derived from very stable frequency sources so that the phase differences represent mostly propagation delay with some error due to small frequency drifts in the sources, ionospheric diffraction, and propagation of the signal through receiver components. Propagation delay in the receiver is significantly constant for each tone and is calibrated out. The other errors are dealt with in the data processing performed external to the receiver.

There are three basic subsystems within the receiver. These three subsystems perform separate but interrelated functions which, acting together, derive the ultimate output data. The functional diagram (Figure 4) depicts the receiver broken down into the three basic subsystems. The major data path through the receiver is indicated in this diagram along with the output parameters of each subsystem.

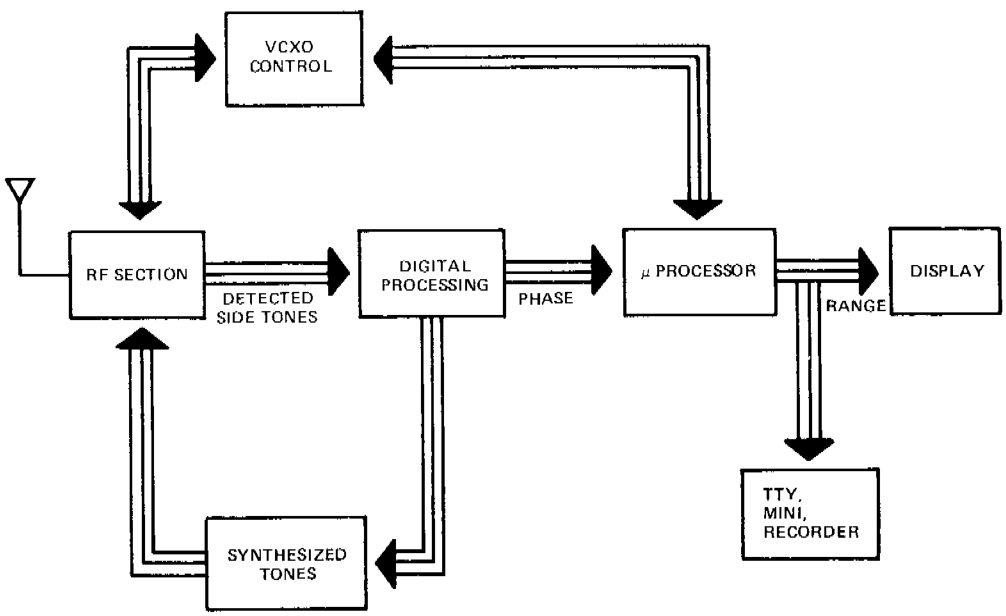

Figure 4. Rx Functional Diagram

The radio frequency (RF) subsystems's major function is to acquire and lock onto the signal transmitted by the satellite and to extract a stable intermediate frequency (IF) for subsequent mixing to the final output signal.

The digital subsystem performs two major functions. One is to synthesize the various sidetones at the proper time and in the same sequence as the satellite's transmitter. In order to do this, the digital subsystem must maintain precise time correlation with the ground station clock. The synthesized sidetones are used by the RF subsystem to extract an output signal containing phase information. The second major function of the digital subsystem is to measure the phase of this signal and send the data to the microprocessor.

The microprocessor subsystem performs a large number of functional tasks. Its major task is to accept, analyze, and store data. Recall that the receiver's ultimate output is the range of the satellite expressed in terms of time. The microprocessor derives this range by solving a rather complex equation involving phase data.

The microprocessor performs another major task which is to control the various modes of operation of the receiver. In this task the microprocessor acts as a man-machine interface allowing the operator to select and control several functions and options including tests and calibration.

This receiver is compatible with the NTS family of satellites. These satellites transmit tones once a minute on both UHF and L bands. The UHF signals are the ones accepted by this receiver. The time of transmission by the satellite can be controlled from the ground, that is to say that the tone burst may be selected to be transmitted at any time during the minute. This means that the receiver must be initially synchronized to the time of transmission of the satellite, hence the connection to the station or master clock.

The NTS satellite's signal format is depicted in Figure 5. The receiver synthesized tones are compared to those of the satellite to get phase information.

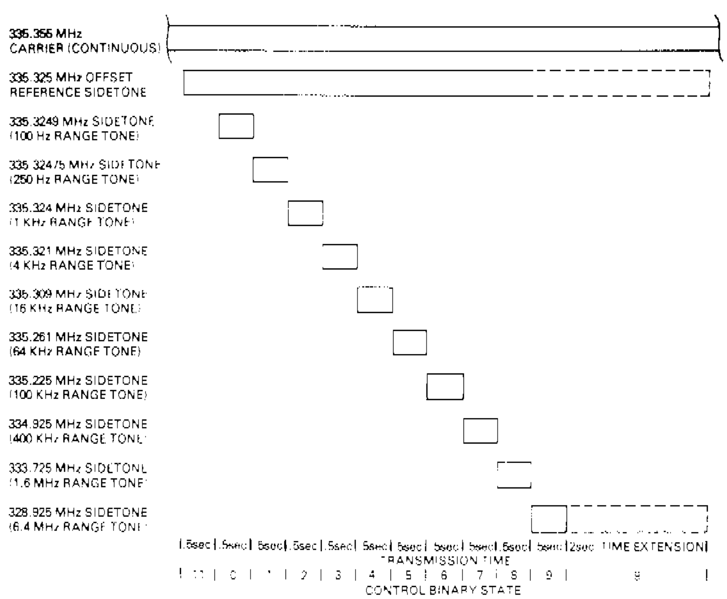

Figure 5. NTS Signal Patterns

That data is used to derive the range, which is then displayed. Phase data may also be displayed at the option of the operator.

The receiver includes several features. Meters are included to display received signal level and receiver tracking error. An alphanumeric display presents data and indicates the operational mode, data entry, clock synchronization and other functions. There is also a keyboard and a set of function switches provided for operator interaction with and control of the receiver. The keyboard and display are functionally related in that the display provides a means of monitoring push-button entries prior to that entry's insertion into the microprocessor memory.

This brief functional description should provide some preparation for the detailed explanations which follow. Insofar as it is possible each functional section of the receiver will be treated separately for clearer appreciation of the detail.

RF Subsystem

The RF subsystem was designed to accept the UHF transmitted from the spacecraft and convert the ranging sidetones to a form suitable for processing in the digital subsystem. The subsystem uses a frequency tracking phase locked loop to generate the necessary internal signals to remove carrier doppler from the received ranging sidetones. Signals generated by the digital subsystem are then used to convert the received sidetones to a common 30 kHz frequency, containing individual sidetone doppler and in TTL waveform for processing by the digital subsystem.

The RF subsystem is capable of operating in either of two modes: The normal "carrier" mode in which the continuous carrier is tracked and used as the doppler reference; or in a "reference" mode. In this mode, whether the carrier is present or not, the RF subsystem acquires and tracks the received reference tone which is present only during the 5.5 or 7.5 second tone burst. In either of these modes, the tracking loop voltage controlled crystal oscillator (VCXO) may be tuned by either the digital subsystem or manually for quick acquisition.

The RF subsystem also outputs to the digital subsystem:

(1) an indication that the tracking loop has acquired the signal

(2) a short pulse signal indicating each time the tracking loop loses lock;

(3) the tracking loop VCXO frequency for use by the VCXO tuning function within the digital subsystem.

For purposes of verifying proper functioning of the digital subsystem, the RF section has capability for inserting calibration sidetones into the sidetone channel. These are generated from signals derived from the digital subsystem.

A simplified block diagram of the RF subsystem is shown in Figure 6. The signals appearing at the antenna terminals consist of the carrier at 335.355 MHz, a reference tone at 335.325 MHz and ten sequentially occurring tones from 335.324900 MHz through 328.925000 MHz. These signals may contain doppler proportional to frequency.

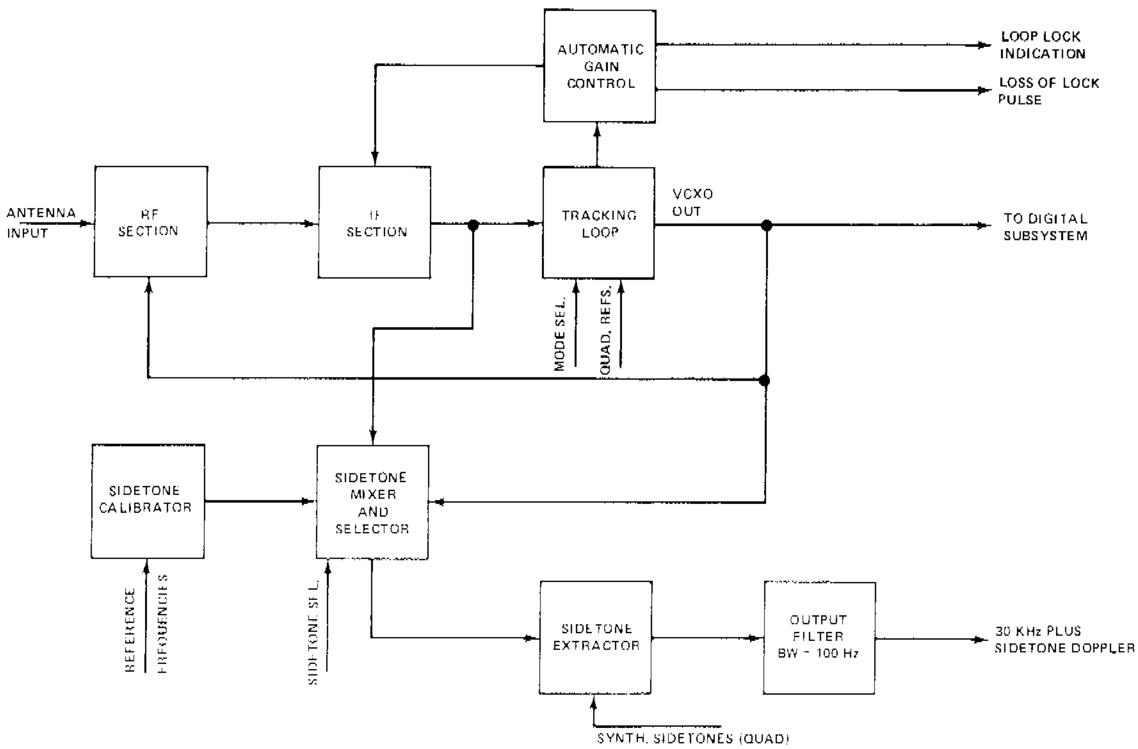

Figure 6. RF Subsystem

RF Section:

In the RF section, this band of frequencies is amplified, passed through an image and interference reject filter, and converted to an IF in which the tracked component frequency and its doppler are reduced by about 9/10. This reduction in doppler comes about because the local oscillator for the first conversion mixer is obtained by frequency multiplying the tracking loop voltage controlled crystal oscillator (VCXO) by 9.

IF Section:

In the IF section, a 9MHz bandpass filter establishes the IF bandwidth, and AGC is applied to the composite signals. The IF outputs the full band of frequencies to both the tracking loop and the sidetone mixer.

Tracking Loop:

Two functions are performed by the Tracking Loop. The first is to provide a coherent frequency reference for use as a local oscillator by the RF and the Sidetone Mixer and Selector sections. The second is to provide a dc voltage proportional to received signal level which can be used as a source of automatic gain control voltage for the IF section.

The Tracking Loop is configured to track either the carrier or the reference frequency by selection of one of two narrow passband predetection filters. The tracked component is then downconverted a second time, amplified and applied to the loop phase detector whose output controls the VCXO. The VCXO output is used directly as the local oscillator for the second conversion.

Since the phase detector is referenced by signals generated by, and which are coherent with, digital subsystem timing, all doppler is removed from the tracked component at the second downconversion mixer. The proper phase detector reference frequency is automatically selected when the predetection filter is selected.

The VCXO is then output directly for use as a frequency reference by the Side-tone Mixer and Selector Section. Additionally, a sample of the VCXO frequency is output to the digital subsystem.

The Tracking Loop circuitry also contains a coherent amplitude detector which generates a low level unfiltered dc voltage proportional to the amplitude of the tracked signal. This voltage is output to the Coherent AGC Section.

Automatic Gain Control:

The output of a coherent amplitude detector in the tracking loop is routed to the Coherent AGC section where it is filtered and amplified. When the loop is tracking (or "locked"), the AGC circuit establishes a control voltage proportional to received power of the tracked frequency. This voltage is used to control the gain of the IF AGC amplifier. When the loop is not locked, the gain of the IF amplifier is limited to that corresponding to the weakest expected received signal level.

The AGC section also generates a loop lock signal which is sent to the digital subsystem and a front panel light which is lit continuously when the loop is tracking. This section also generates a short TTL pulse when the loop loses lock. This pulse is also output to the digital subsystem.

Sidetone Mixer and Selector:

The IF output is routed to the Sidetone Mixer which uses the tracking loop VCXO frequency as its reference. The output of the Sidetone Mixer consists of components corresponding to and bearing the doppler and phase information contained in the received reference and ranging sidetones. It should be noted that the doppler remaining on the sequentially received sidetones is proportional to the difference between the transmitted sidetone frequency and the transmitted frequency of the component tracked by the loop. This is because the RF portion of the doppler (or "carrier doppler") has been removed in the coherent down-conversion processes. A switch selects either the sidetones from the receiver or calibration sidetones derived from the digital subsystem. The selected sidetones are distributed to the sidetone extractor and filter section.

Sidetone Extractor:

The sidetones output sequentially by the Sidetone Mixer and Switch are routed to the Sidetone Extractor and Filter where they are converted to a common 30 kHz frequency. This is accomplished by a combination of double sideband and single sideband mixing processes using synthesized sidetones from the digital subsystem. The synthesized sidetones, which are coherent with digital subsystem timing and therefore contain no doppler, are switched sequentially with the received sidetones. Thus the output frequency is offset from the nominal 30 kHz by the doppler associated with the received sidetones. The phase of the output is directly related to the phase of the received sidetone. The 30 kHz sinusoidal signal is converted to TTL and output to the ditital subsystem as the primary output of the RF subsystem.

Sidetone Calibrator:

The Sidetone Calibrator provides a means of supplying calibration tones to the digital subsystem. This section generates a burst of tones similar to the received burst but which are controlled in phase since they are derived from the digital subsystem.

Detailed Processor Description

The following description will refer to the processor functional block diagram in Figure 7. In the diagram the microcomputer is shown as one block and is connected by inputs and outputs to various digital subsections. The microcomputer controls these subsections which interface the processor to the RF subsystem, station clock, and operator.

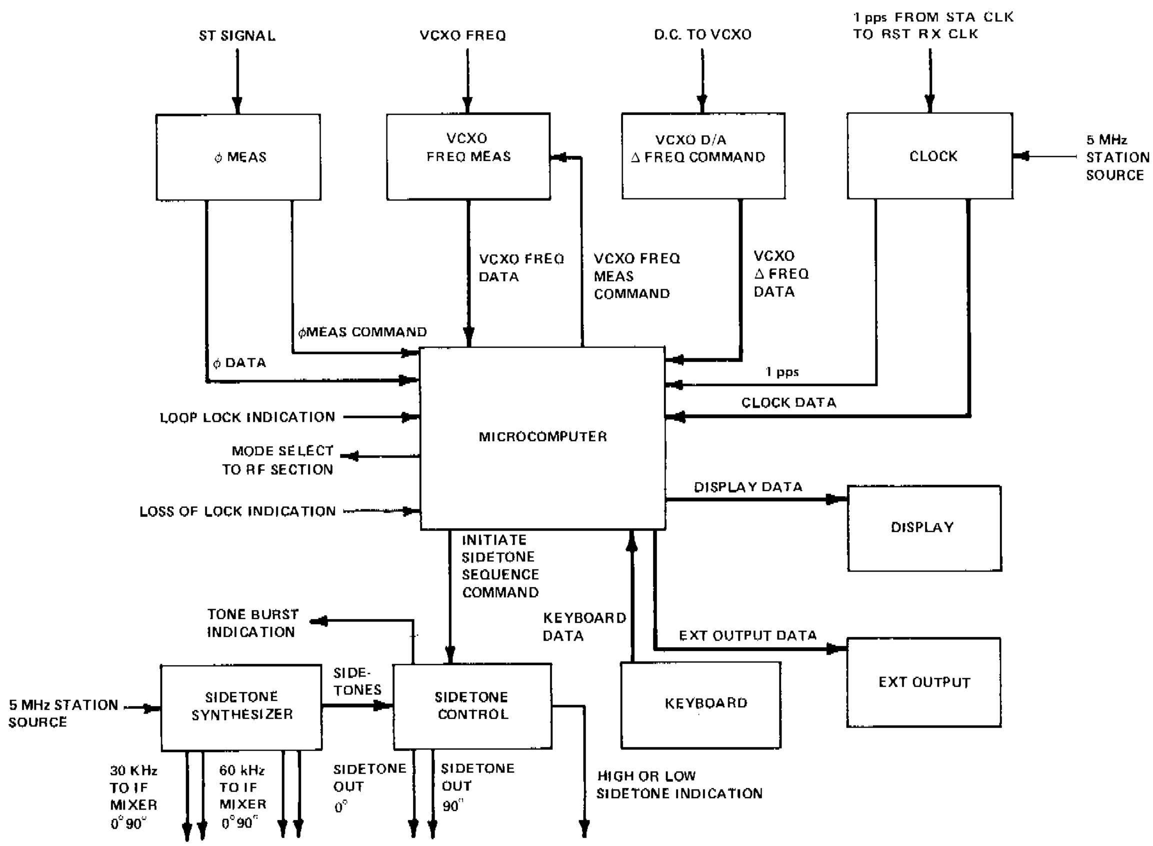

Figure 7. Processor

Phase Measurement

The signal input to the processor from the RF subsystem is at 30 KHz and contains the doppler of the sidetones. The phase of this signal is measured by a time-interval counter at the command of the microcomputer. The data upon conclusion of the measurement is available at a microcomputer input.

VCXO Control

The microcomputer has the capability of controlling the VCXO frequency through the use of a VCXO frequency measurement counter and a digital to analog converter. Upon command of the microcomputer, the VCXO frequency measurement counter counts the number of VCXO cycles which occur in one second. This VCXO frequency data is made available to the microcomputer at an input after the one second measurement. The analog output of the D/A converter is continually summed with the VCXO control voltage. The digital input to the D/A is controlled by an output which remains constant until changed by the microcomputer.

Sidetone Synthesizer and Sidetone Control

The sidetone synthesizer derives from the station 5 MHz source all the necessary mixing signals required by the RF subsystem to mix out the desired signal. The 30 KHz and 60 KHz signals are available to the RF subsystem continually for IF mixing. The synthesized sidetones are continuously fed into a sidetone control circuit which selects and sequences the tones at the command of the microcomputer. The sequence first provides a d.c. level for a half second then ten tones ranging from 100 Hz to 6.4 MHz for a half second each. The selected tone is provided to the RF subsystem in quadrature for the lower four tones and in duplicate for the upper six tones. When the sequence is complete, a d.c. level is maintained at the sidetone output to the RF subsystem. The tone burst indication output lights a front panel LED during the sidetone sequence. The high or low sidetone output is provided to indicate to the RF subsystem when the low four sidetones are sequenced.

Clock

The clock derives seconds and milliseconds data from the station 5 MHz source. An external reset provides the capability of synchronizing the receiver 1 pps to the station source 1 pulse per second (1 pps) to within an accuracy of 200 nanoseconds. The milliseconds data is fed into an input and the 1 pps into an interrupt of the microcomputer.

Mode Select, Loop Lock, and Loss of Lock

The mode select output is an indication to the RF subsystem and front panel LED as to whether the carrier or reference only mode of the receiver has been selected. The loop lock indication is an input from the RF subsystem and is active whenever the receiver is locked on a signal. The loss of lock is another input from the RF subsystem that provides a pulse whenever the receiver loses lock.

Keyboard/Display, and External Output

A sixteen button hexidecimal keyboard is provided for inputting data to the microcomputer. A four button keyboard provides the additional input functions "interrupt", "clear", "enter", and "continue". A thirty-two character alphanumeric gas discharge display is provided to output data and messages to the operator from the microcomputer. The external output duplicates all data and messages that appear on the display and is intended to be used in interfacing the receiver with an external device.

Phase Determination

The receiver's primary mode of operation for processing data is in the reference mode using automatic acquisition. This is the mode in which the data processing will be described. First the microcomputer waits until the time at which the tones are transmitted. While waiting it holds the VCXO at the desired initial acquisition frequency previously entered. When the tone transmission occurs, the VCXO D/A output is left at its last value and the synthesized tone burst sequence is initiated in the receiver. The microprocessor begins to sample the phase of the first tone through the phase measurement circuit. For each tone 81 samples of phase are taken at a 200 Hz rate, and a linear least squares fit is made to these points. In this fit the following equation is realized.

$$\phi_i = M_i t_i + B_i \tag{1}$$

where ϕ_i is the phase of the ith sidetone, M_i is the phase rate of the ith sidetone, B_i is the phase of the ith sidetone at the time its sampling was begun, and t_i is the time of the phase relative to when the sampling was begun. Time is normalized to one unit equals 5 msec for simplicity. In equation (1) the values of M_i and B_i are calculated from the least squares approximation as follows:

$$M = \frac{S_0S_4 - S_1S_3}{S_0S_2 - S_1^2} \qquad B = \frac{S_2S_3 - S_1S_4}{S_0S_2 - S_1^2}$$

where,

S_0 = number of samples = 81

S_1 = sum of the times for each sample
= 0 + 1 + 2 + 3 + . . . + 80
= 3240

S_2 = sum of the times squared for each sample
$= 0^2 + 1^2 + 2^2 + 3^2 + \ldots + 80^2$
= 173,880

S_3 = sum of the phases including integer wavelengths as measured from the time of the first sample

S_4 = sum of the phases multiplied by the sample times

Substituting for the constants that result from fixing the number of samples gives,

$$M = .00002258\ S_4 - .0009033\ S_3 \tag{2}$$

$$B = .0484\ S_3 - .0009033\ S_4 \tag{3}$$

The values of S_3 and S_4 are accumulated during the sampling of each tone, and B_i is calculated and saved for each tone. Since M_i is the phase rate of each tone due to doppler, if the doppler is assumed to be constant throughout the tone burst sequence, then all of the tone phase rates are equal to the phase rate of the highest tone multiplied by a constant as follows,

$$M_i = K_i M_{10} \tag{4}$$

where K_i is a constant unique for each tone, and M_{10} is the phase rate of the 6.4 MHz tone. M_{10} is calculated and saved for the 6.4 MHz tone.

In determining range the phase of each sidetone is projected to the point in time that the range is desired. Equations (1) and (4) may be combined to give,

$$\phi_i = K_i M_{10} t_i + B_i \tag{5}$$

The ϕ_i in equation (5) must be corrected for propagation delay through the receiver so an error term is added giving,

$$\phi_i = K_i M_{10} t_i + \phi_{Ei} + B_i \qquad (6)$$

where ϕ_{Ei} is the calibration error. Equation (6) is used to determine the phase of each sidetone at the end of the tone burst, and these in turn are used to determine a range.

Range Determination

The phase differences determined represent propagation delay and clock error between the satellite clock and the receiver clock. These phases are interpreted in terms of observed range to the satellite in milliseconds. The phases of the lower tones are used to get a rough range and those of the higher tones are used to resolve range to nanosecond accuracy. In resolving range equation (7) is used:

$$R_i = \frac{\phi_i + \text{INTEGER}\ [R_{i-1} f_i + \frac{1}{2} - \phi_i]}{f_i} \qquad (7)$$

where,

> ϕ_i is the phase of the ith tone
> f_i is the frequency of the ith tone
> R_i is the range in seconds whose accuracy is based on the phase of the ith tone.

The phases of each tone are determined to an accuracy of 1%, and the accuracy of a range based on the phase of a tone is 1% of the tone's period. The accuracy of the final range is 1% of the 6.4 MHz tone period or 1.56 nsec. After the range is calculated, the phase of each tone may be displayed as well as range if the operator desires. Upon conclusion of display of the phases, real time and the last range are continually displayed until the next sequence of data is processed.

Operation

The receiver is shown in Figure 8. Inputs required are 1 pps and 5 MHz from the station clock. The receiver's final output is observed range to the satellite in milliseconds. This data is displayed on the front panel and also appears at an external output which may be interfaced with a teletype, minicomputer, or data recording device.

When the receiver is initialized, the operator first synchronizes the receiver clock with the station clock, enters a predicted satellite frequency which is

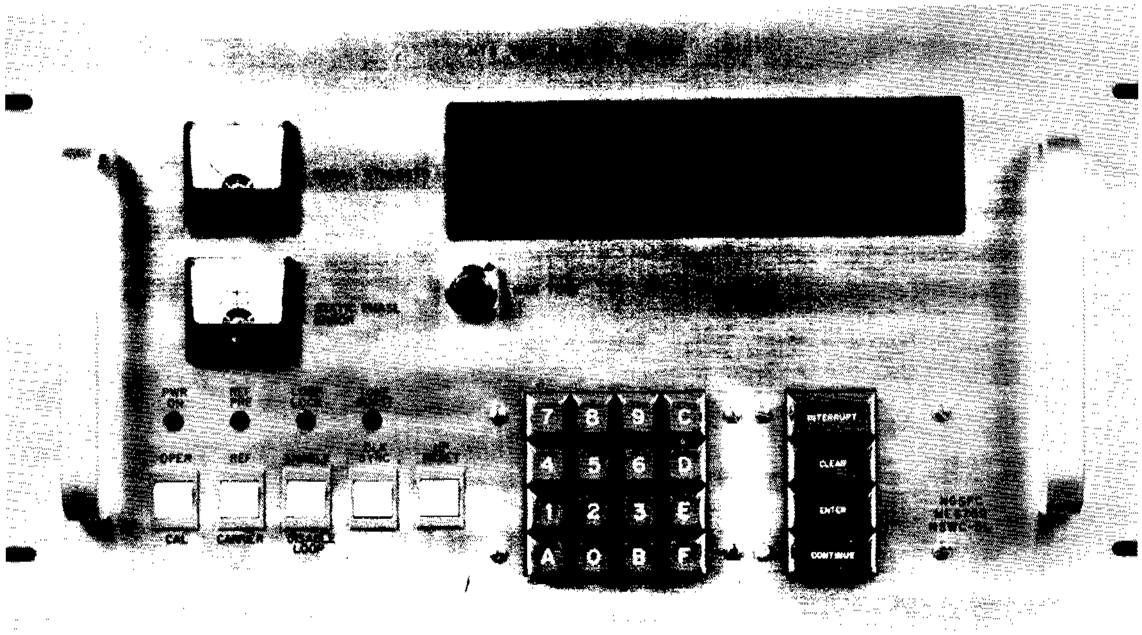

Figure 8. Rx

maintained by the microcomputer, and then waits for aquisition of the satellite. During the tone burst if there is an affirmative lock indication, the VCXO frequency is measured and replaces the initial frequency input by the operator. The VCXO is held to this frequency by microcomputer control until time for the next burst of data. Again upon lock of the signal a new frequency is measured, and the sequence continues enabling the receiver to track the satellite throughout its doppler range. The microcomputer continues the sequence of taking data until interrupted by the operator.

Field Test

The receiver shown in Figure (8) was taken to a NASA tracking station at Rosman, N.C. A time transfer was performed as shown in Figure 9. Time at Rosman was compared to that at an NRL tracking station at Chesapeake Beach, Md. Time at the NRL site was known relative to USNO time by portable clock measurements. In performing a time transfer, a range observation is made at Rosman and at Chesapeake Beach. The observation at Rosman is corrected for oscillator drift in the satellite clock during the time between the two measurements. The observation at Cheasceapeake Beach is corrected to USNO time and the difference is taken between the two stations.

NTS REMOTE CLOCK SYNCHRONIZATION

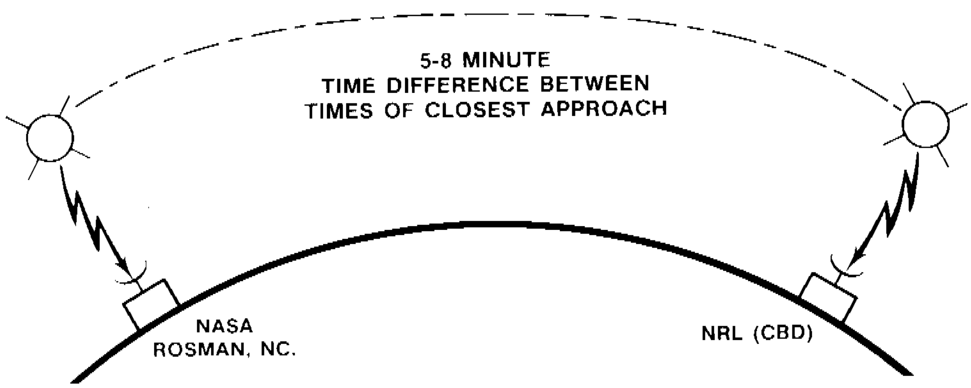

Figure 9. Time Transfer with Rosman

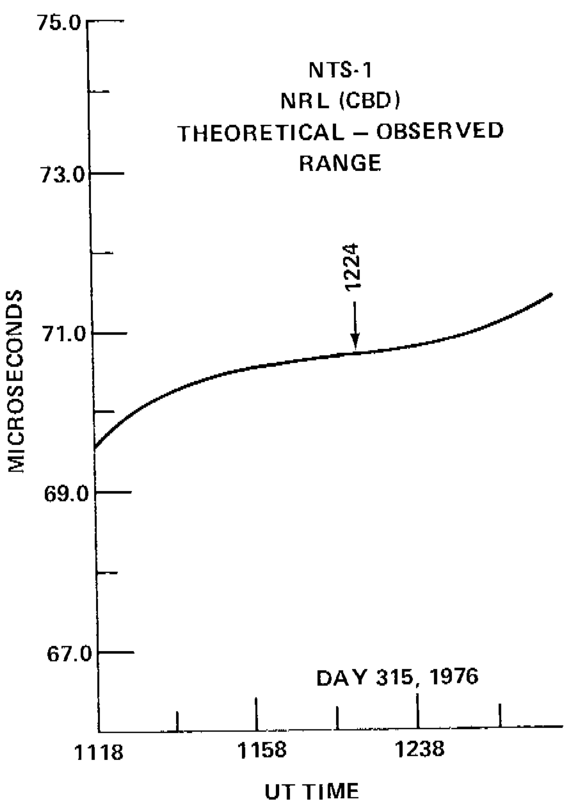

Figure 10. CBD Pass

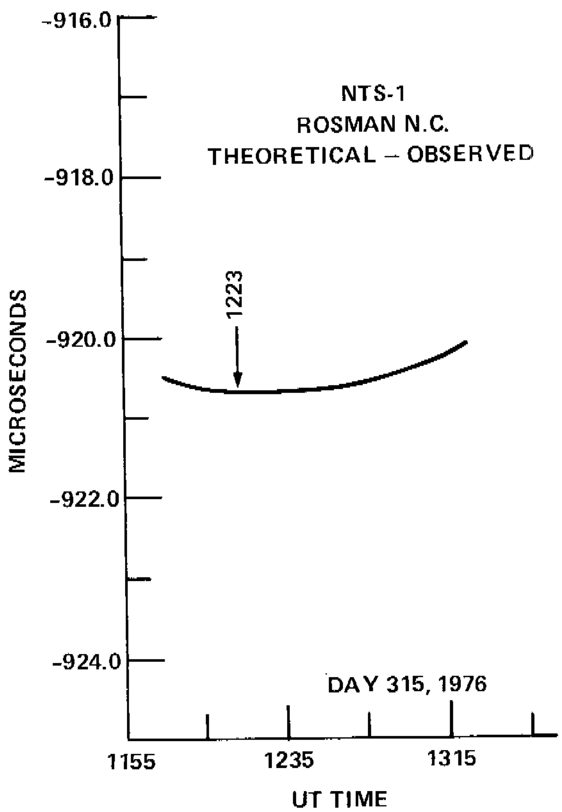

Figure 11. Rosman Pass

Figure 10 and Figure 11 show one particular satellite pass with observations made at Rosman and Chesapeake Beach during the test. The data used in the time transfer are taken at the time of closest approach and are pointed out with arrows. Twelve such passes were taken and each time transfer is plotted in Figure 12. The noise in the data has a RMS of 86 nsec. A portable clock measurement was made before and after the field test. These points are plotted and a line drawn between the two falls very close to the time transfer data. The conclusion of the test was a time transfer accuracy better than 100 nsec.

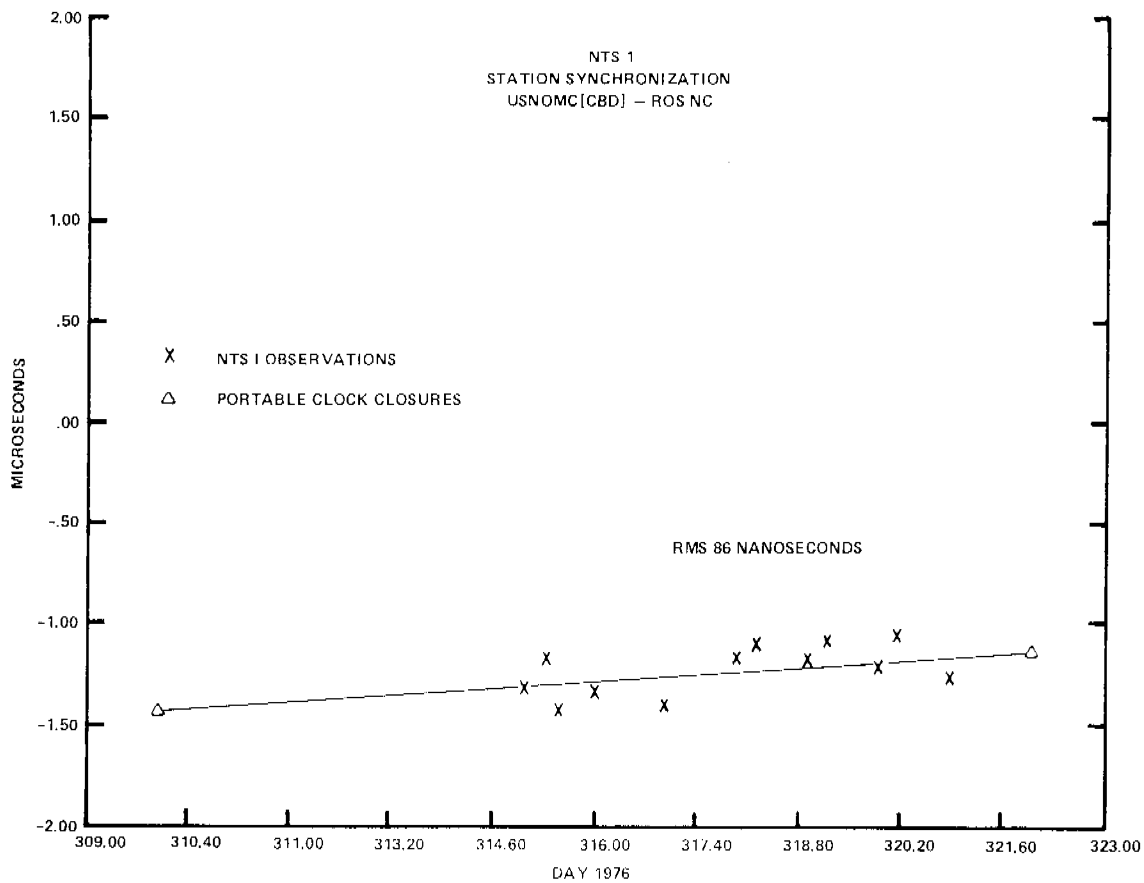

Figure 12. Time Transfer Plot

Reference:

1. NRL Report 7703, April 18, 1974 "International Time Transfer Between USNO and RGO via TIMATION 2 Satellite"; R. Easton, D. Lynch, J. Buisson and T. McCaskill.