A TRANSIT SATELLITE TIMING RECEIVER

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ABSTRACT

The development of a time transfer instrument employing a TRANSIT satellite receiver and a microprocessor based computer is described. This instrument has been tested at the U. S. Naval Observatory measuring the time difference between the USNO Master Clock and the timing receiver. Data from these tests are presented which show the system can provide time referenced to UTC accurate to 25 microseconds or better.

The paper treats principles of operation, time transfer capabilities of the satellite system, projected system capabilities, system errors, and features of the timing receiver.

INTRODUCTION

The T-200 Satellite Timing Receiver uses signals from the Navy Navigation Satellite System (NNSS) or TRANSIT. Time marks in the satellite signal are referenced to UTC (USNO). This allows an earth station to derive accurate time from NNSS if the following functions are implemented:

1. Recover the satellite time
2. Reference a local clock to the received time
3. Correct the local clock for offset

The Satellite Timing Receiver was developed to accomplish these tasks and to provide a synchronized 1 pulse/second output and UTC in hours-minutes-seconds format.

The time-keeping ability of the operational NNSS is superior to that required for the navigation function, but up to the present time no instrument has been available to make full use of this fact. NNSS can provide unique and desirable features for time transfer. For example, the system is fully operational now and has been since 1964. The system is fully funded and maintained by the U. S. Navy. A polar orbit satellite configuration provides world-wide coverage. Transmission from the satellites is at VHF with essentially no unpredictable signal propagation effects.

THE NAVY NAVIGATION SATELLITE SYSTEM

TRANSIT (NNSS) is an operational system of five satellites and associated ground support stations. The satellites are in almost circular polar orbits of approximately 7500 km radius. The system was funded by and is supported by the U. S. Navy, and although the system continues to have widespread military use, the U. S. Government released details of the system for uncontrolled use world-wide in 1967.

Conventional (i.e., navigational) use of the NNSS is accomplished by a passive earth station receiving the ~~signals~~ from a single satellite with an omnidirectional antenna. The received messages describe the satellite orbit to an accuracy of approximately ±5 meters. Included in the message is a digital signal called the fiducial time mark (FTM) that delimits two-minute periods in the satellite transmission. Ground stations monitor each satellite and uplink new orbital data and clock adjustments to keep the onboard satellite clock FTM synchronized to the USNO master clock. Integration of the frequency difference between received signals and a stable internal oscillator frequency (doppler) between FTMs provides a measure of the change in slant range between the satellite and the earth station.

Using an assumed position on Earth and the received orbital data, a theoretical change in slant range can be computed. Using several such calculations and their measured analog from the doppler, the error in the assumed position can be deduced. This yields the "satellite fix".

RECOVERY OF TIME

Major functional elements of the timing receiver are shown in block diagram form in Fig. 1. The key elements are:

1. NNSS receiver
2. FTM detector
3. Microsecond clock
4. Microcomputer

The receiver gives orbital information from the satellite message to the microcomputer and, in turn, is controlled by the microcomputer. The receiver also drives the fiducial time mark detector from its phase detector output.

Precise time (to 1 microsecond) is kept in a 6 digit decade counter driven by 1 MHz derived from the precision local oscillator. The overflow from this counter generates a 1 pps signal - the primary output from the timing receiver. This microsecond register can be advanced or retarded by the computer in increments of 1 microsecond. Hours-minutes-seconds time is kept by the computer and displayed in a seven segment LED display on the front panel.

Transfer of the microsecond clock to the microcomputer is done by a latch which the microcomputer can read at any time. The microsecond clock continues to run when the latch is strobed.

Every two minutes the satellite transmits a sync word of 23 "ones" followed by a "zero" and 400 Hz modulation. The FTM is defined to be that transition between the final binary zero in the sync word and the beginning of the 400 Hz "beep". Fig. 2a shows the end of one two-minute message and the beginning of the next showing the FTM. The microprocessor generates an enable signal for the FTM detection circuitry that allows detection of the first zero crossing after the last bit of the message. This zero crossing occurs 1/16 of a bit time (1229 microsecond) after the FTM at the detector. The FTM is delayed through the receiver by 435 microseconds. Timing relationships of the derived FTM (FTM') are shown in Fig. 2b.

FTM' is used to latch the microsecond clock during the satellite pass. The latch reading is transferred to the microprocessor after each FTM (i.e., every two minutes). Data stored in the microcomputer memory represent the clock reading at each FTM' during the pass.

To detect any microsecond clock offset, it is necessary to modify these readings so they are referenced to the <u>transmitted</u> FTM. The two sources of difference between the transmitted FTM and FTM' are propagation path (a function of slant range) and detection delay (a constant). Corrections to the latched clock readings are therefore of the form:

$$\text{Corr} = A_0 + A_1 S \qquad \text{(Equation 1.)}$$

$$A_0 = 1664\ \mu s$$

$$A_1 = 3.3356405\ \mu s/km$$

Where S = slant range in km

Using orbital information transmitted by the satellite and location of the instrument read from internal registers, the slant range to the satellite is computed for each point. Microsecond clock readings are adjusted backwards by a number of microseconds indicated by Equation 1. Because the FTM was transmitted on a second mark (every two minutes UTC), the difference between corrected clock readings and zero (ahead or behind) is the clock error indicated by that FTM reception. Between 3 and 9 of these corrections are available for each usable satellite pass.

After data have been reduced to form a single clock correction amount, the microsecond clock can be advanced or retarded accordingly.

SOURCES OF ERROR

The primary sources of error are caused by (1) time jitter in FTM detection and (2) offset in the FTM transmitted by the satellite. The user has no control over the latter except to average clock corrections over several satellites. The limiting factor in satellite FTM error is the ability of the controlling agency to monitor satellite performance. Corrections to satellite clock are straightforward once the offset is determined. Summaries of offset data published by USNO show FTM accuracies in the ±30 μs range. The T-200 allows averaging over several satellites to reduce time-keeping error at the expense of correction response time. Filtering algorithms are discussed in the next section.

Reduction of time jitter in the FTM detection was an important part of the development of this instrument. A combination of careful hardware design and microcomputer control permits detection with very low jitter considering the narrow bandwidth and low signal to noise ratio (S/N) of the receiver. Fig. 3 shows the jitter as a function of signal strength. These data were obtained in the laboratory by using a NNSS Test Set.

Using an omnidirectional antenna, full limiting signals are not always possible. However, the 20 μs peak-to-peak jitter for satellite elevations above 10° allows good performance for most of an average satellite pass. Editing of FTM detection for elevation angle is done by using corresponding slant ranges as described in the next section.

EDITING, AVERAGING, AND FILTERING

Although the clock correction corresponding to one FTM detection could be used, the mean of an edited ensemble of the corrections from a single pass yields significantly superior accuracy.

Editing of the points corresponding to a pass of a single satellite is done after satellite set time and is a two-step process. The first step removes clock corrections corresponding to slant ranges greater than 2800 km (elevation angles less than 10°). The mean and variance of the remainder of the clock error points are computed. If the standard deviation does not exceed 24 μs, the ensemble is accepted. Otherwise, all points more than 1 standard deviation from the mean are deleted. If the ensemble has 3 or more points after all editing, a clock correction is computed as the mean ("best estimate") of the points.

Fig. 4a shows a computer printout of data from the T-200 for a single pass of satellite 30120 on 23 October at 1648 UT. These data were taken with intrapass editing disabled. The clock correcting subroutine was disabled to permit data acquisition of the indicated corrections under a variety of conditions.

As can be seen, the data have a high standard deviation primarily due to two data points (#0, #6). The mean clock error was -445 μs, and would have caused a 445 μs clock advance if it had been used.

Fig. 4b shows the same pass processed using the intrapass editing algorithm described. Point #0 was eliminated because slant range was greater than 2800 km, and point #6 was eliminated because it differed from the mean by 1391 μs (2.27 σ). The new mean, -74 μs, was computed from the remaining points and the standard deviation improved to 15 μs.

The T-200 permits the net clock correction at each pass to be filtered over a number of satellite passes that is user selectable. Filtering the correction over a number of satellites smooths the offset and improves instrument performance at the expense of response time. Using a filter time constant of one satellite average period will allow a correction at every satellite that produces an acceptable result. Using a larger time constant places more emphasis on the correction of the satellite constellation and less on any one satellite. Also, a large error in one satellite would not grossly effect the instrument error if filtering was used.

SYSTEM PERFORMANCE

Transmission accuracy of the satellite FTM determines timing accuracy in the T-200 receiver. Currently, NNSS satellites are controlled by the U. S. Navy Astronautics Group (NAG), Point Mugu, California. Under NAG control, FTM measurements are made at five different ground stations. All stations receive data from each satellite for at least four passes per day. Each pass contains an average of seven FTM measurements, or a total number of about 150 data points per day, thus, statistics on FTM measurements are very good.

Synchronization between NAG and USNO is maintained to within 5 microseconds by portable clock trips. Under present time-keeping procedures, satellite time is maintained within about ±30 microseconds of UTC, but it should be emphasized that satellite navigation does not require time with greater accuracy. A change in operating procedures can yield timekeeping within ±15 microseconds at little or no additional expense, and a joint program between NAG and USNO is now underway to implement this improvement.

Tests on the prototype T-200 receiver were performed at the U. S. Naval Observatory during May and June, 1977, with results given in Fig. 5. The receiver reference clock during these tests was an atomic source and all measurements were relative to the USNO Master Clock. The results of these tests were used to improve the correction algorithm and to determine the exact equipment delays. The value used for equipment delay during these tests was 1702 μs, whereas the correct value is actually 1664 μs. This caused the 38 μs bias shown in the receiver performance of Fig. 5c and 5d.

Fig. 5a shows USNO published time differences(1) for the period May 20, 1977 through June 7, 1977. Fig. 5b shows raw T-200 Satellite Timing Receiver measurements (T-200 clock - USNO Master Clock) for the same time period. Fig. 5c and Fig. 5d show the T-200 and USNO time difference after application of computed filter corrections during this test period.

From Fig. 5a it can be seen that satellite clock differences are randomly distributed with mean zero. Since T-200 clock corrections can be filtered over all satellites in the constellation, the satellite clock errors are integrated such that the receiver clock at any given time may be closer to UTC than any individual satellite time. This result is shown in Fig. 5c and Fig. 5d. Improvements in control of satellite time would, of course, improve the T-200 receiver clock.

OPERATOR CONTROLS

Two inputs are required to start the receiver: receiver location and initial clock time. An internal receiver printed circuit contains decimal switches for the input of latitude, longitude, and antenna height. Once set, these switches need not be changed unless the receiver is moved to a new site.

The UTC clock must be set, but initial clock error may be up to 15 minutes without effecting the T-200 accuracy after its first satellite correction. At completion of the first satellite pass, hours, minutes, and seconds are corrected to actual UTC, and the microseconds clock is corrected for the computed error without filtering. This should place the 1 pps output to within 50 microseconds of UTC. Each succeeding satellite correction will have filtering applied if this has been selected.

The microprocessor in the receiver design has made the T-200 automatic for most operations. The microcomputer (1) sets initial parameters at turn-on, (2) controls receiver message recovery, (3) edits FTM data based on quality criteria, (4) computes and applies clock corrections, and (5) automatically self-tests once each hour.

Although the receiver can operate without attention, features are incorporated in the design to permit operator adjustment of the clock

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(1)Average values for time difference between NNSS satellites and USNO are published by USNO in "TRANSIT Satellite Report, Series 17". Data shown are from Reports No. 265, 26 May 1977; No. 266, 2 June 1977; No. 267, 9 June 1977, and No. 268, 16 June 1977.

(prior to the first satellite only), to delete corrections from specific satellites, and to change the filter function.

An optional feature for the T-200 is a module which determines receiver position. This design is useful on ships at sea or on vehicles which are expected to move between locations. Another option provides a summary printout of correction data at each satellite pass. Optional internal oscillators are available with accuracies of 1 x 10^{-9}/24 hours or 5 x 10^{-11}/24 hours.

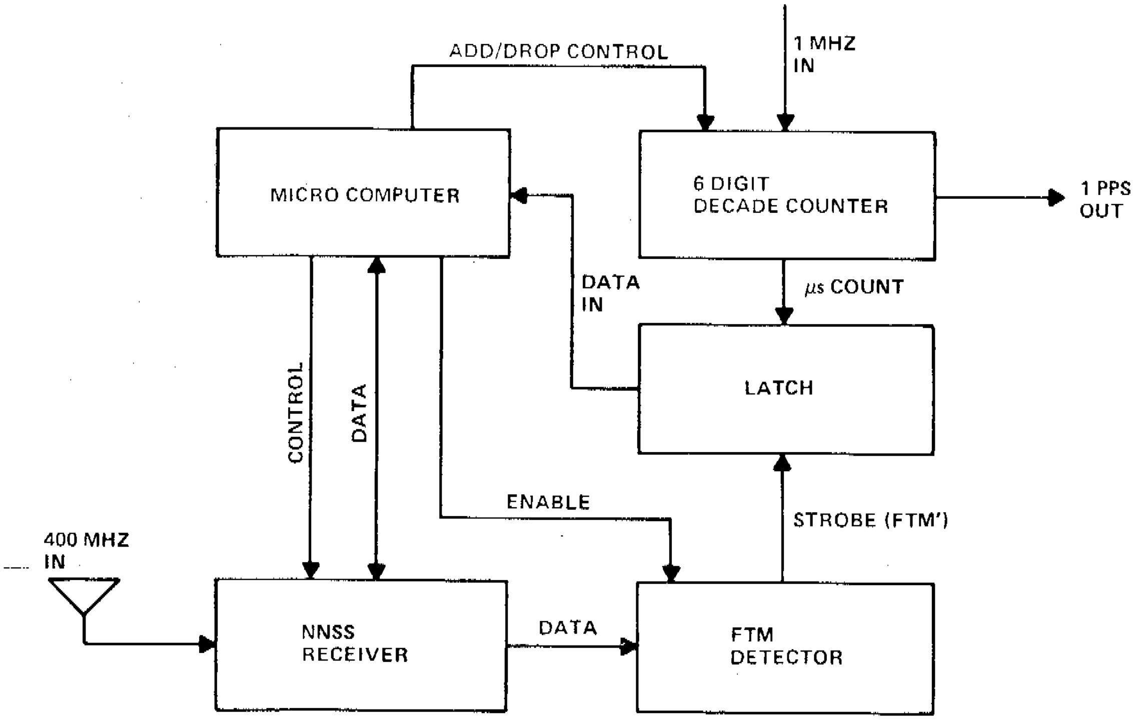

Fig. 1. Timing Receiver Block Diagram

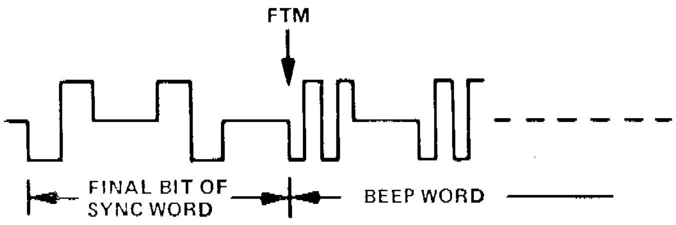

Fig. 2a. Data Pattern at FTM

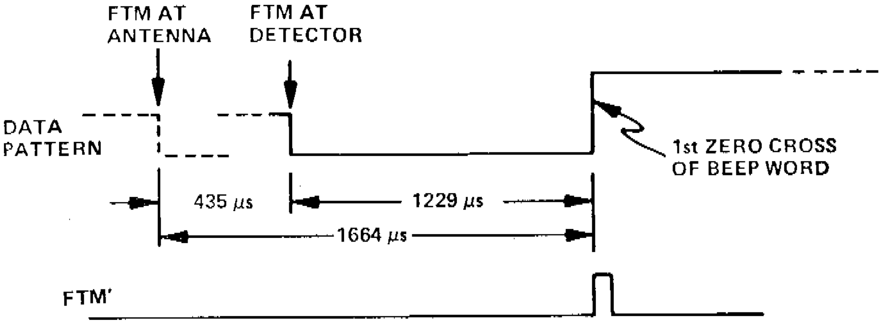

Fig. 2b. FTM' Derivation

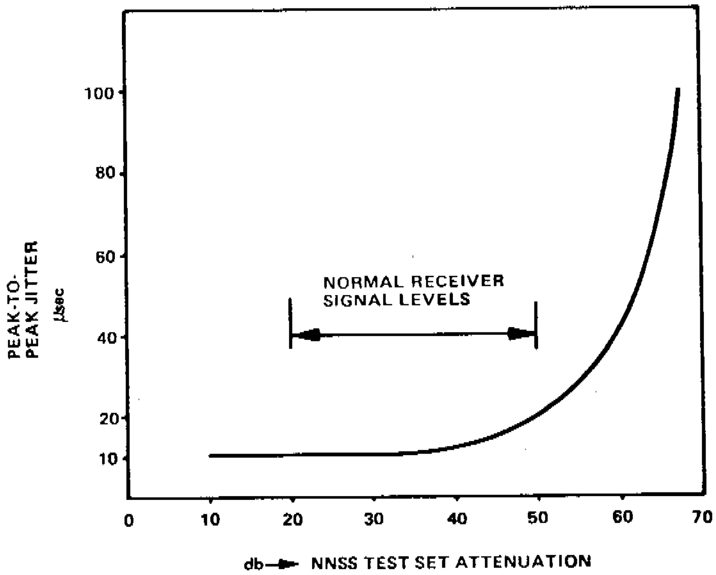

Fig. 3. FTM Detection Jitter

```
SAT =30120
LOCK 1008 MIN UT


                SLANT          CLOCK
INDEX           RANGE          CORREC
                   KM          USEC
   0             2832          - 160
   1             2186          -   92
   2             1673          -   77
   3             1451          -   74
   4             1648          -   78
   5             2149          -   52
   6             2792          -2299
   7             3494
   8             4217
MEAN        -405 USEC
STD DEV      836 USEC
```

Fig. 4a. T-200 Pass Without Editing

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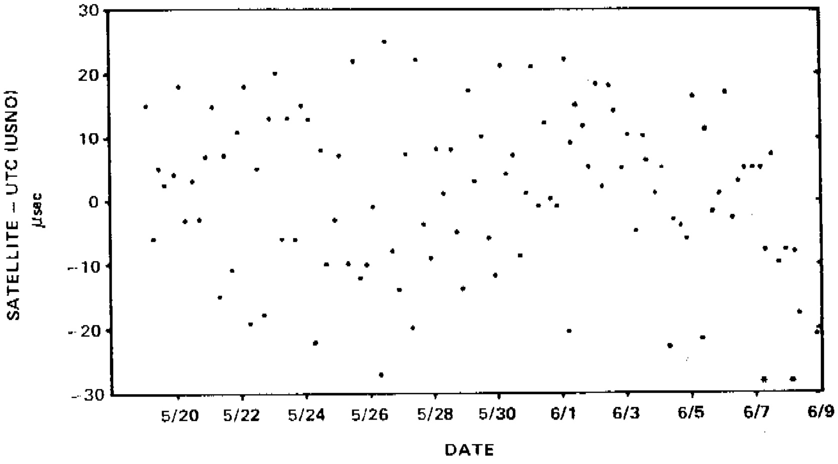
SAT =30120
LOCK 1008 MIN UT


                SLANT          CLOCK
INDEX           RANGE          CORREC
                   KM          USEC

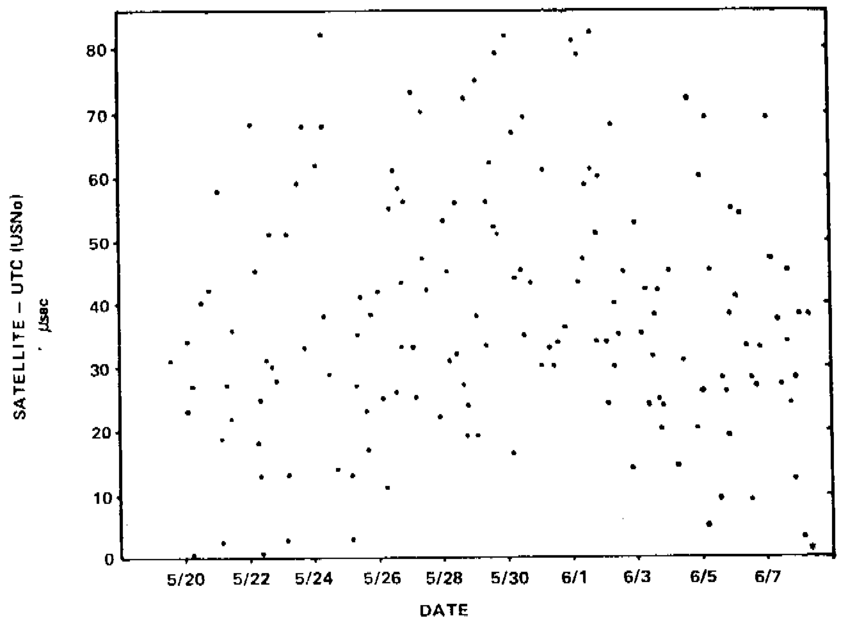
   0             2832
   1             2186           - 92
   2             1673          - 77
   3             1451          - 74
   4             1648          - 78
   5             2149          - 52
   6             2792
   7             3494
   8             4217
MEAN        - 75 USEC
STD DEV       14 USEC
```

Fig. 4b. T-200 Pass After Editing



*6/7
30140 error = −429
*6/8 30190
30190 error = −39

Fig. 5a. Average Satellite Error



*JUN 8
140 = −18

Fig. 5b. T-200 Raw Clock Error

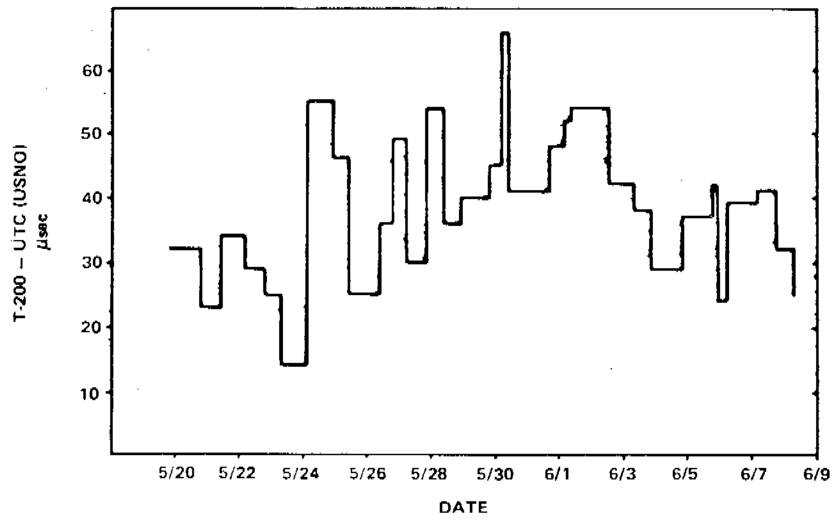


Fig. 5c. T-200 Computed Clock Error (Filter Factor = 5)

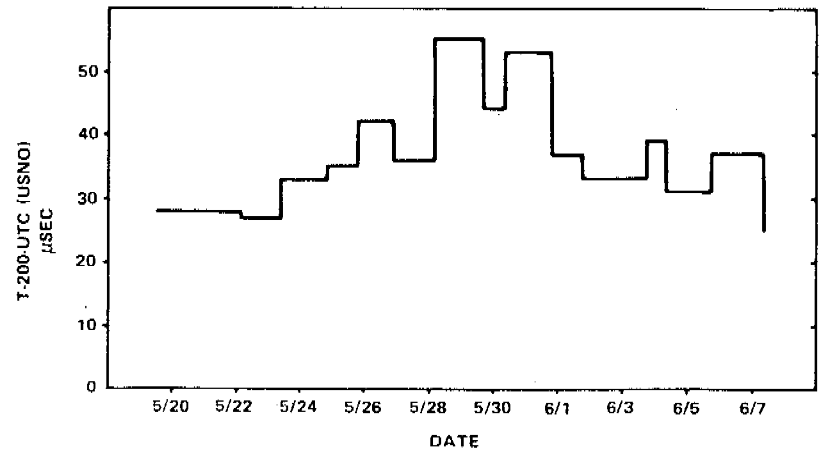


Fig. 5d. T-200 Computed Clock Error (Filter Factor = 10)

QUESTIONS AND ANSWERS

MR. GEORGE OJA, U. S. Naval Representative Office:

For the maximum interval between satellite passes, what would you expect the accumulated error to be into the internal oscillator?

MR. HUNT:

Knowing the precision and stability of your reference clock, it can be computed directly. It is a function only of the clock. The timing receiver removes the offset from the time. The precision of time between satellite fixes is a function of the accuracy of the clock, obviously, so it depends on how good your oscillator is. If you work on a microsecond-a-day clock, which is very common, your maximum error due to the non-continuous operation of the satellite system would be 1 microsecond if it were a day. The Constellation, as I understand it, is in a particularly bad phase right now. It is working its way out. We are getting satellite passes one after the other for a few times and then go several hours without them. So given the maximum time of several hours, what is your oscillator stability? You can answer your own question.

MR. OJA:

Yes, that's what I mean. What oscillator are you using?

MR. HUNT:

We provide no oscillator. I am sorry I didn't make this point clear. You use your own oscillator. Or, there are two optional oscillators, both of which offer microsecond-a-day type stability.

MR. LAUREN RUEGER, Johns Hopkins University Applied Physics Lab:

Have you tried reconciling the published excursions of the satellite system time with the data that you have presented?

MR. HUNT:

Yes. We see some correlation, but not a whole lot. Frankly, the controlling agency has the same problem we do in measuring the offset to the USNO master clock. We can see some correlation, however. When the satellite indicates it is very far off in one direction--20 or 30 microseconds one way or the other--we can see that in our data also, although we can't measure it precisely to that. Removing the satellite offset from our data after the fact using USNO Publication 17 improves it somewhat but doesn't remove all that we think it could.

MR. RUEGER:

Is there a limitation in the resolution if the satellite system does get control down to ± 5 microseconds? Will you be able to see it?

MR. HUNT:

That I don't know. Perhaps the gentleman from NAJ or the Navy can tell us. On one pass, we are looking at, typically, between 8 and 12 microseconds standard deviation. The slide I made showed 14. We are doing better than that now because we have improved our fiducial time mark detector. We are computing the position of the satellite to well within 25 meters, which obviously is down in the noise as far as microseconds are concerned. So, I think the resolution available ultimately goes back to how well the satellite system can be controlled down to a floor in the 10-microsecond region.

MR. RUEGER:

You would be able to see 1 microsecond if we were holding the mean to that value?

MR. HUNT:

If you were holding the mean to that value and we filtered, we would be in our floor of around 10 microseconds due to the jitter in the fiducial time mark detector, although some of that could be removed with additional filtering. How much we don't know yet because we don't have the Navy satellite system correctable to that point. Hopefully, this new procedure will improve it enough so that we can see these factors.

DR. GERNOT M. R. WINKLER, U. S. Naval Observatory:

I would like to comment. The Naval Astronautics operations and the timing control of the satellite system, as it is executed now, is more than sufficient to satisfy navigational requirements. The use which we see here represents additional potential of a national resource. It is now up to us to tighten these operational procedures, to tighten up the timing. I am confident that we will be able to do that to make that national resource more readily available.

MR. ROGER EASTON, Naval Research Laboratory:

What is the cost of the receiver?

MR. HUNT:

I don't know the price. I can give a range. It is on the GSA schedule, and the price depends, of course, on quantity. I believe the price for quantity one is in the vicinity of $13,000 to $14,000.