ENHANCEMENTS TO THE TTS-502 TIME TRANSFER SYSTEM

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ABSTRACT

Two years ago STI introduced an affordable, relatively compact time transfer system on the market -- the TTS-502, and described that system at the 1981 PTTI conference. Over the past few months, that system has been improved, and new features have been added. In addition, new options have been made available to further enhance the capabilities of the system.

These enhancements include the addition of a positioning algorithm and new options providing a corrected 5 MHz output that is phase coherent with the 1 pps output, and providing an internal Rubidium Oscillator.

The Positioning Algorithm was developed because not all time transfer users had the luxury of the Defense Mapping Agency's (DMA) services for determining their position in WGS-72 coordinates. The enhanced TTS-502 determines the GPS position anywhere in the world, independent of how many GPS satellites are concurrently visible. However, convergence time to a solution is inversely proportional to the number of satellites concurrently visible and the quality of frequency standard used in conjunction with the TTS-502. Real world solution results will be presented for a variety of cases and satellite scheduling scenarios. Typically, positioning accuracies were achieved better than 5 to 10 meters r.s.s. using the C/A code only at Sunnyvale, California.

A Time and Frequency Solution allows for the output of a time corrected 1 pps (to GPS time or UTC) and a frequency corrected 5 MHz (and 1 MHz) signal that is coherent to the 1 pps. This is offered as an inexpensive option.

To make the TTS-502 a stand alone system somewhat independent of GPS satellite visibility, an option is also offered where an internal

Rubidium Standard is included in the TTS-502, eliminating the need for expensive Cesium frequency standards.

This paper presents various details and results of the Positioning Algorithm and details of the new options available. In addition, details of other enhancements are described.

INTRODUCTION AND SUMMARY

The TTS-502 and its applications are described in detail in References 1, 2 and 3. It has been recently upgraded to the TTS-502B. A new computer board has made it possible to make various functional improvements in this Time Transfer System. These improvements are the addition of a Positioning Algorithm, a new Time and Frequency Solution and a series of new commands meant to aid the user in performing his time transfer.

The upgrade to the TTS-502B from the existing TTS-502's can be accomplished by simply purchasing the new computer board along with the new PROM's containing the new software.

In addition to the computer board and software upgrades, four new options are available. These options include two different internal Rubidium Oscillators, a coherent 5 MHz and corrected 1 pps output, and a custom length antenna cable.

The Positioning Algorithm, which is a square root information filter, has been tested at Sunnyvale, California and has consistently demonstrated accuracies of 5-10 meters. It also has the capability of positioning at locations where 4 satellites are never in view simultaneously.

The new Time and Frequency Solution uses the same type of filter as does the Positioning Algorithm. It provides a extremely stable time and frequency transfer capability.

THE POSITIONING ALGORITHM

The TTS-502B Positioning Algorithm was designed with the goal of solving for a stationary position anywhere on earth without much concern of how long it would take. Its primary purpose is to solve for that position for time transfer users who don't have or don't wish to have on outside service (such as DMA) to survey their position.

To solve for a position with GPS globally can't always be done in a short period of time. The system does not currently provide the required simultaneous visibility everywhere in this world. Not only is the Geometric Dilution of Precision (GDOP) bad, it doesn't even exist. However, for a stationary user, instantaneous good geometry is not required, as long as it exists over a reasonable period of time and provided that he has a reasonably stable clock. This is somewhat the concept of the TRANSIT system, except that that system uses Doppler measurements.

The TTS 502B algorithm relies on this concept. In that way it can position itself (actually, its antenna) anywhere on earth. It does so with a square root information filter version of a sequential Kalman Filter that is a natural algorithm for this sort of problem. the square root algorithm is known as the U-D (Upper Triangular Diagonal) Covariance Factorization method of Bierman.[4] However, for the purposes of this paper, the Kalman Filter implementation will be described because square root implementations are somewhat difficult to illustrate. The reader should refer to Reference 4 for those details.

The previous version of the TTS-502 software already processed measurements in a manner consistent with a Kalman Filter implementation. Corrected pseudorange measurements were computed every six seconds and compared with the equivalent computed range to derive a raw clock offset used in a polynomial smoothing algorithm. The Kalman Filter uses the same computation except that the corrected measurements are compared with a predicted pseudorange in order to define the measurement residuals for the Filter. So the structure was already there. The filtering procedures are as follows:

<u>Filter Initialization</u>

1) The initial position estimate $\hat{X}_0$, $\hat{Y}_0$, $\hat{Z}_0$ at t_0 in ECEF (Earth-Centered-Earth-Fixed) Coordinates (meters) is taken to be the position stored in the TTS-502B non-volatile memory, which could have been entered by the operator or saved from a previous solution.

2) The initial clock time offset and drift ($\Delta\hat{t}_{u_0}$, $\Delta\hat{\dot{t}}_{u_0}$) are taken to be zero, even if they had previously been estimated. Given the position described in 1), the filter will solve for these offsets very quickly.

3) The filter is a five state filter. Its initial state estimate is

$$\underline{\bar{X}}'_o = \begin{bmatrix} X'_o \\ Y'_o \\ Z'_o \\ \Delta t'_{u_o} \\ \Delta \dot{t}'_{u_o} \end{bmatrix}$$

4) The initial covariance matrix P'_o is defined based on position uncertainties entered by the operator and constants stored in the TTS-502B for the time and frequency offsets. Since the TTS-502B initially sets its time from the HOW word, the initial time uncertainty is based on the uncertainty in that setting. The frequency uncertainty is based upon worst case offsets that might prevail with the frequency standard to which the TTS-502B is being slaved. The type of frequency standard is entered by the operator (crystal, Rubidium or Cesium). the initial error covariance matrix is defined as a diagonal matrix

$$P'_o = \begin{bmatrix} \sigma^2_{x_o} & & & & \\ & \sigma^2_{y_o} & & O & \\ & & \sigma^2_{z_o} & & \\ & O & & \sigma^2_{\Delta t_{u_o}} & \\ & & & & \sigma^2_{\Delta \dot{t}_{u_o}} \end{bmatrix}$$

Filter Measurement Application

1) The measurement matrix $H_k(\underline{\hat{X}}_k)$ is computed at time t_k as a 5x1 column vector (T = transposed)

$$H_k(\underline{\hat{X}}_k) = [\overline{1}_{LOS_k}, c, 0]^T$$

where the 1x3 line-of-sight vector is

$$\overline{1}_{LOS_k} = \left[\frac{\hat{X}_k - X_{s_k}}{\hat{R}_k}, \frac{\hat{Y}_k - Y_{s_k}}{\hat{R}_k}, \frac{\hat{Z}_k - Y_{s_k}}{\hat{R}_k} \right]$$

where X_{s_k}, Y_{s_k} and Z_{s_k} are the ECEF coordinates of the satellites at time t_k less signal transmission time; $\hat{X}_k$, $\hat{Y}_k$ and $\hat{Z}_k$ are the position estimate predicted from the time of the last measurements t_{k-1}, where

$$\hat{X}_k = X_{k-1}$$
$$\hat{Y}_k = Y_{k-1}$$
$$\hat{Z}_k = Z_{k-1}$$

and the range estimate $\hat{R}_k$ is

$$\hat{R}_k = \sqrt{(X_{s_k} - \hat{X}_k)^2 + (Y_{s_k} - \hat{Y}_k)^2 + (Z_{s_k} - \hat{Z}_k)^2}$$

and c is the speed of light in meters per second.

2) Compute the pseudorange measurement residual variance α_k as

$$\alpha_k = H_k(\underline{\hat{X}}_k) \hat{P}_k H_k^T(\underline{\hat{X}}_k) + \sum$$

where P_k' is the predicted error covariance matrix at time t_k and $\sum$ is the pseudorange measurement noise variance taken to be a constant at $(15 \text{ meters})^2$.

3) Compute the Kalman Filter gains vector K_k (5x1) where

$$K_k = P_k' H_k(\underline{\overline{X}}_k')/\alpha_k$$

4) Update the error covariance matrix incorporating the measurements at time t_k

$$P_k = [I - K_k H_k (\underline{\overline{X}}_k')] P_k'$$

where I is a 5x5 identity matrix.

5) Compute the measurement residual δm_k at time t_k as

$$\delta m_k = PR_k - \hat{PR}_k$$

where PR_k is the pseudorange measurement at time t_k and $\hat{PR}_k$ is the predicted pseudorange measurement, where

$$\hat{PR}_k = R_k' + (\Delta t_{u_k}' + \tau_k - \Delta t_{sv_k}) \cdot c$$

where τ_k is the sum of pseudorange corrections (ionospheric and tropospheric delay and earth's rotation correction, all in seconds) and Δt_{sv_k} is the satellites time offset at time t_k.

6) Update the estimate of the state vector $\underline{\overline{X}}_k$ at time t_k, where

$$\underline{\overline{X}}_k = \underline{\overline{X}}_k' + K_k \delta m_k$$

At this time the TTS-502 computes the change in state since the first iteration (t_o) as

$$\Delta\underline{\overline{X}}_k = \underline{\overline{X}}_k - \underline{\overline{X}}'_o$$

and the filter one sigma position uncertainty σ_{P_k}, where

$$\sigma_{P_k} = \sqrt{P_{11_k} + P_{22_k} + P_{33_k}}$$

where P_{ii_k} is the iith entry of the error covariance matrix. The TTS-502B then outputs these values on the screen, to a printer (if option is chosen) and to the auxiliary output port (if option is chosen).

Filter Time Update

1) At the time of the next measurement (t_{k+1}), the TTS-502 computes

$$\Delta t_k = t_{k+1} - t_k$$

and sets

$$t_k = t_{k+1}$$

It then updates the estimates (predicts), where

$$\underline{\overline{X}}'_k = \Phi_k \, \underline{\overline{X}}_{k-1}$$

where Φ_k is the state transition matrix at the time t_k given as

$$\Phi_k = \begin{bmatrix} 1 & & & & \\ & 1 & & \bigcirc & \\ & \bigcirc & 1 & & \\ & & & 1 & \Delta t_k \\ & & & 0 & 1 \end{bmatrix}$$

2) The error covariance matrix P_k' is then updated as

$$P_k' = \Phi_k P_{k-1} \Phi_k^T + Q_k$$

where Q_k is the process noise matrix modeling the characteristics of the frequency standard to which the TTS-502B is slaved. That is,

$$Q_k = \begin{bmatrix} 0 & & & & \\ & 0 & & \bigcirc & \\ & & 0 & & \\ & \bigcirc & & q_{44} & q_{45} \\ & & & q_{45} & q_{55} \end{bmatrix}$$

where, in general,

$$q_{44} = \frac{h_0}{2} \Delta t_k + 2h_{-1} \Delta t_k^2 + \frac{2\pi^2}{3} h_{-2} \Delta t_k^3 + \sigma_D^2 \frac{\Delta t_k^4}{4}$$

$$q_{45} = 2h_{-1} \Delta t_k + \pi^2 h_{-2} \Delta t_k^2 + \sigma_D^2 \frac{\Delta t_k^3}{2}$$

$$q_{55} = h_{-1} \ln \Delta t_k + 2\pi^2 h_{-2} \Delta t_k + \sigma_D^2 \Delta t_k^2$$

where h_0, h_{-1} and h_{-2} are Allan variance spectral density coefficients (5) and σ_D is the one sigma frequency standard drift rate in seconds/second^2. These variables are stored in the TTS-502B as typical constants for each type of frequency source (good crystal, Rubidium and Cesium).

Filter Operation

Starting with the initial estimates and error covariance defined above, at the time of the first measurement (t_0), the TTS-502B processes a measurement in the filter every six seconds sequentially by first applying the time update from the time of the previous measurement to the time of the current measurement, and then performing the measurement update. Whenever a satellite changeover occurs, the time between the last measurement from the previous satellite to the first measurement of the current satellite could be as long as 90 seconds.

SOME EXPERIMENTAL RESULTS

The algorithms presented above were verified experimentally prior to modifying the software in the TTS-502. This was relatively easy to do because of the auxiliary port data category output options available. The data required for the filtering operations were available without modifying the unit.

The algorithms were tested using data from Category 2 - Auxiliary Time Transfer Data [6]. This data was read via GPIB into an HP-85 desk top computer. Matrix manipulation PROMs augmented the HP-85 to enhance its accuracy. Even then, the square root formulation of the Kalman Filter was required to provide the numerical stability of the Positioning Algorithm. However, this provided a good test in that if the HP-85 could solve for the position of the TTS-502, then surely the MC68000 could with its double precision (64 bits) mathematics package.

The purpose of the algorithm tests using the HP-85 was not only to check out the algorithms themselves and the numerical technique of implementing them, but to test concepts for scheduling measurements from satellites, even in cases when good instantaneous GDOP is not achievable.

All tests were run using a crystal oscillator as the frequency source.

Algorithm Stability

Whenever four satellites are available with good GDOP for the Positioning Algorithm, the rate of convergence to a solution is directly proportional to the rate of switching between satellites. This is evident from the plots of R.S.S. position error in Figure 1, where

$$P_{RSS} = \sqrt{(X_K-X_T)^2 + (Y_K-Y_T)^2 + (Z_K-Z_T)^2}$$

where X_T, Y_T, Z_T is the DMA surveyed position at Sunnyvale, CA. In this plot, a filter iteration normally took 12 seconds, as the HP-85 could not keep up with the TTS-502 six second measurements when the square root algorithm was used. Additionally, there was approximately 60-90 seconds between measurements any time a satellite change was made.

When satellites were changed every 4 minutes, ultimate convergence to better than 10 meters accuracy was achieved in about 45 minutes. In contrast, if satellites were changed every 1/2 hour, convergence took up to 3 hours or so while it obviously takes at least 3 hours for one hour changes. But then, this slower change rate more closely represents the case when four satellites with good GDOP are never available simultaneously.

This is the reason why the square root filter was mechanized. Sometimes when the TTS-502 was scheduled to dwell on a particular satellite for an extended period of time before the filter converged when the conventional Kalman Filter was used, the filter becam unstable. This is because the error ellipsiod, which was initialized as a spheroid, became very flat along the line-of-sight to the satellite, and very high correlations (near 1 or -1) between errors occurred. This tended to cause numerical problems. Correlations creeped over 1 or below -1, causing the covariance matrix to become eventually nonpositive definite. The square root algorithm improved the situation significantly. However, it could also have numerical problems in extreme cases. Thus, it is important to not schedule a single satellite for too long a period. This restriction is not serious, however, since in general a time of day can be selected when at least 2 or 3 satellites are visible for filter initialization.

The Case Where Fewer Than Four Satellites are Ever Visible

Unfortunately, in California at least four satellites are visible for an extended period of time for some time each day. Therefore, one could always take advantage of fast convergence. In order to simulate the case when four satellites (with good GDOP) are never visible at a given location, a schedule was derived where all but three satellites was purposely deleted from the schedule. When this is done, the tracking schedule must be stretched in order to effectively achieve a good geometry over a period of time, taking advantage of the movement of the satellites. Figure 2 illustrates such an example when only three satellites were tracked. The R.S.S. position is compared to that of a four satellite solution. In each case the satellites were changed once an hour. The convergence time for this particular case of three satellites is about 4.5 hours and about 80 minutes longer than that for the four satellite case. The R.S.S. error is 10 meters as opposed to the 5 meter R.S.S. error for the four satellite case. However, that error comparison is somewhat non-conclusive, since the solutions occurred on different days.

As it turns out, the four satellite solution presented in Figure 2 also simulates a solution at a location where four satellites are not visible simultaneously because the fourth satellite was acquired three hours after the first satellite. Full accuracy was achieved with one sequence through the satellites, so the first one or two satellites need not be visible any longer. In the three satellite case, it is probably necessary to come back to previously tracked satellites.

Convergence Criteria

Fortunately, for testing purposes, the location of the TTS-502 antenna was known for the results described above. However, that would never be the case in the field for those using TTS-502B for determining their position. Therefore, a criteria was established for determining convergence, which is described below under the heading "How to Use the Positioning Feature of the TTS-502B." That procedure states to let the Positioning Algorithm run until the uncertainty level in the SIGMA column drops down to 2-3 meters, where SIGMA is the filter sigma σ_{P_k} defined in the equations presented earlier. Figures 3 and 4 illustrate two examples of how that sigma compares to the RSS position error. In those figures σ_{P_k} never gets to the 2-3 meter level because the positioning estimates were turned off when a σ_{P_k} of 5 meters was reached, solving for the time only after that. That does not occur in the actual implementation, however. The "time only" solution in the actual implementation is described below.

A NEW TIME-FREQUENCY SOLUTION

The TTS-502 has always had a Time-Frequency Solution although only the time solution was displayed. The frequency solution was available via the auxiliary output port. These solutions were a function of a sliding polynomial fit (zero, first or second order) over a specified period. That fit period had a maximum value of 4 minutes (40 six second samples).

Actually, that Time-Frequency Solution is relatively noisy, especially the frequency solution. Because of that, a new Time-Frequency Solution has been implemented in the TTS-502B. That new solution is a fall out of the Positioning Algorithm defined above. In fact, a Time-Frequency Solution is part of the state vector of the positioning filter (Δt_u, $\Delta \dot{t}_u$). It is not desirable, however, to solve for a position during time and frequency transfers, primary because, as stated earlier, positioning is not always possible. Besides, the time solution is diluted by TDOP (Time Dilution of Precision) when solving for a position.

Therefore, a "time-only" filter solution has been implemented in the TTS-502B. This solution uses the same algorithms (5 state filter) and software used in the Positioning Algorithm with the following modifications. First of all, a position is assumed, taken to be those coordinates stored in non-volatile memory, which may have been entered by the operator or with a replace command following a positioning solution. Then, the 5-state filter is re-initialized and a "time-only" solution is selected. From that time on, the measurement matrix is defined as

$$H(\underline{\hat{X}}_k) = [0\ 0\ 0\ 1\ 0]^T$$

indicating that the measurements from that time on only measure time offsets. Since the initial covariance matrix P_0 has no state cross-correlation entries, there will be no cross coupling of the measurements into the positioning states, except for the definition of the range estimate R_k used to define the measurement residuals.

Using the definition of the process noise matrix Q_k, the time constant of this time-frequency filter adapts to the type of frequency standard being used. In fact, the solution will be near optimum given that the Q_k realistically models the characteristics of the frequency standard. The fact is, however, that the parameters were selected to be somewhat pessimistic so that the filter does not become unstable. In any event, no matter which frequency standard is used, the filter has a short time constant to start with, and a relatively long time constant as the filter converges on the time frequency solution. This time constant adapts to the type of frequency standard being used and is much longer than the maximum 4 minute fit span of the previous, but still available, polynomial fit. In fact, previously noticeable measurement quantization effects are no longer noticeable using the new Time-Frequency Solution.

HOW TO USE THE POSITIONING FEATURE OF THE TTS-502B

There are two modes of operation: semi automatic and full automatic, activated by the SP and FP command, respectively. These two modes are identical except that the semi-automatic operation uses the user-setup satellite tracking schedule, while the full-automatic operation computes its own schedule.

The full automatic schedule algorithm implemented in the TTS-502B software is still experimental and does not always provide the best schedule. It is recommended that the semi-automatic mode of operation be used for positioning. Steps 2 and 3 of the following procedure will show how to set up a good tracking schedule.

Procedures

1. Use the DB command to enter the best estimate of antenna location. The location may be entered in either the Earth-Centered Earth Fixed (XYZ) coordinates or the geodetic (latitude, longitude, and height) coordinates. Also set the elevation angle mask to less than 10 degree to get more visibility and better geometry.

2. Use the HV command with P (print) option to get a copy of satellite visibility histogram to help set up a tracking schedule.

3. The best schedule would have the maximum number of satellites over the shortest time interval.

   If possible, do positioning over an interval where there are four or more satellites since the position solution converges faster in this case. Over this interval, a tracking schedule may be set up that "rotates" among these satellites, with about 4 minutes per satellite. Even when four or more satellites are simultaneously visible over some time interval, one may not want to wait until such time to do positioning. In such case, a schedule may be set up that will eventually cover four or more satellites, using 4- to 30-minute time slots. At some locations this could be the only choice since there may never be more than 3 satellites simultaneously visible with the current GPS constellation of only 5 working satellites.

After setting up a schedule, use the IS command to enter the tracking schedule. The allotted time of some time slots may have to be stretched if the schedule requires more than 79 time slots.

4. Use the SP command, with P (print) option if desired, to activate the semi-automatic positioning operation. Specify three parameters as follows:

   a. The kind of frequency standard (crystal, Rubidium, or Cesium) that is being used in positioning. This input is used to select the appropriate clock model. The kind of standard that is being used has to be specified since the system may have been configured with more than one standard, e.g., an internal crystal standard and an external Cesium standard.

   b. A uncertainty level in the best estimate of the location. It could be as small as 10 meters if it is a very good estimate, or as big as 20,000 meters if the estimate is picked from a map. This parameter should be specified in meters even if the location is entered in geodetic coordinates.

   c. Enter the selection of XYZ or geodetic coordinates for display. To conserve space on the screen display, only the difference between the computed position and the initial position is displayed.

5. Wait until the uncertainty level on the SIGMA column of the display drops down to 2-3 meters, and then stop the operation by entering CONTROL X. This level of uncertainty indicates that the position solution has converged.

6. Use the LP command with the R option to have the initial position estimate in non-volatile memory replaced by the last position solution.

NEW OPTIONS

There are four new options available that can be added to the TTS-502B. These options are:

1) Option 001-RL - an Internal Rubidium Oscillator

2) Option 001-RH - an Internal High Precision Rubidium Oscillator

3) Option 008 - - Coherent 5 MHz and Corrected 1 pps Output

4) Option 009 - - Antenna Cable with Customized Length up to 200 ft.

Internal Rubidium Oscillators

The first two options are identical except for the stability of the oscillator. These options are in addition to the internal crystal oscillator option previously available. Their function is the same. However, they provide a capability with the TTS-502B where it is truly a stand-alone unit as a precise time-frequency standard. This is because the Rubidium Oscillators are stable enough to provide continuous precise time even during periods of time when no GPS satellites are visible.

Currently, Option 001-RL includes the Efratrom FRK-L Rubidium Oscillator with the LN (Low Noise) option, whose stability (σ_τ) at τ=100 seconds is 3×10^{-12}. Option 001-RH includes the Efratrom FRK-H, where $\sigma_\tau = 1\times10^{-12}$ at τ = 100 seconds. For a nominal five hour period of satellite nonvisibility, those numbers translate into time drifts of about 65 and 22 nanoseconds (one sigma) for the RL and RH options, respectively, essentially making the TTS-502B a continuous stand-alone 100 nanosecond timekeeping devise.

Coherent 5 MHz and Corrected 1 pps Output

This option provides the capability of having a time-frequency source that is slaved to UTC or GPS Time. With this option the TTS-502B computed time and frequency offsets are used to correct the phase and frequency of the 5 MHz source (internal or external) and the time of the 1 pps output. In addition, the 1 pps output is coherently derived from the corrected 5 MHz. A block diagram of this option is presented in Figure 5.

When this option is being used, any external 1 pps is ignored. The TTS-502B generates its own 1 pps and corrects it so that there is no time offset in its solution. In addition, the frequency of the 5 MHz output is corrected so that there is no frequency offset in the TTS-502B's solution. Since that corrected 5 MHz is used to derive the corrected 1 pps output, they are coherent and the frequency of the 1 pps is also correct. In effect, the TTS-502B provides a very low bandwidth second order 1 pps Phase Lock Loop.

In addition to the corrected 5 MHz and 1 pps outputs, a corrected 1 MHz output is provided. Both the 5 MHz and 1 MHz outputs are passed through crystal oscillator phase lock loops to reduce the harmonics and spurious components of the signals.

Antenna Cable

The standard length of the TTS-502B antenna cable is 82 feet (25 meters). Option 009 provides customized antenna cable lengths of up to 200 feet for a nominal charge. However, the receiver time calibration is performed with whatever cable, customized or not, is provided with the unit. If the cable or its length is changed, recalibration is required.

USER COMMAND UPGRADE

Hardware-wise, the only difference between the TTS-502 and the TTS-502B, except for options, is a new computer board. The new board is the Omnibyte OB68K1A with 96K of PROM. This board with more memory made it possible to implement the Positioning Algorithm described above. In addition, the number of user commands was increased from 17 to 32. These 32 commands are listed in Figure 6. Some of those new commands are associated with the new Positioning Algorithm and new Time-Frequency Solution. Others were added to further assist the user in operating the TTS-502B. Also, some of the original commands were improved. A summary of these user command upgrades follows.

General Upgrade

In general, three options were added to some of the commands. These are the "Replace" option [R], the "Print" option [P] and the "Output" option [O]. The Replace option is used to replace data in non-volatile memory with the corresponding data shown on the screen display. The Print option is used to output the image of the displayed data to the auxiliary RS-232-C bus. A user-provided RS-232-C printer can be used to obtain a hard copy of the screen display. The Output option is used to output a formatted data category associated with the given command to the auxiliary RS-232-C and/or the GPIB busses.

In addition, for the user's convenience most commands that require a time input will now default to system time if the time input is omitted.

New Commands

The following is a summary of new commands:

1) DD - Displays all operational data base parameters -- see example in Figure 7.

2) UT - Displays UTC/GPS parameters.

3) UG - Computes UTC-GPS time difference at a particular time.

4) HV - Displays visibility histogram, i.e., the number of visible satellites and their ID's. See example in Figure 8.

5) DV - Displays elevation angle, azimuth angle and Doppler of a particular satellite as a function of time on a particular date.

6) CD - Displays a snapshot of elevation angle, azimuth angle and Doppler of all satellites at a particular time and date.

7) SS - Displays, for review only, the semi-automatic tracking schedule adjusted to any particular date.

8) CP - Computes a fully automatic tracking schedule for positioning such that each satellite (except priority 0) is to be scheduled at least once a day.

9) SK,FK - Perform time transfer operation using square root filter to produce time and frequency estimates. SK uses semi-automatic schedule; FK uses fully-automatic schedule.

10) SP,FP - Perform positioning function using semi-automatic or fully-automatic schedule, respectively. Displays difference between updated and initial

position in XYZ or geodetic coordinates. See example in Figure 9. A new data category #12 is output every 6 seconds, if selected.

11) LP - Displays the last position computed by the previous SP or FP command. With Replace option, that position will be stored in non-volatile memory to be used as reference position.

12) CB - Stops the "beeping" alarm.

13) ?? - Displays format of a particular command.

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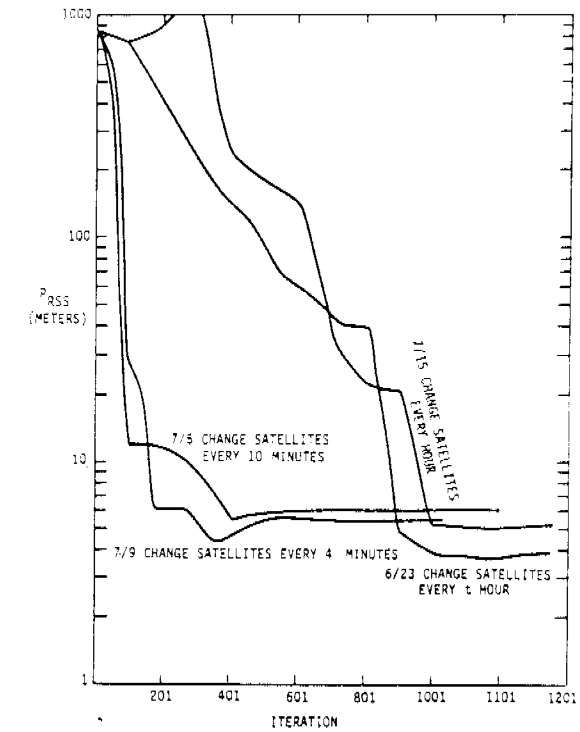

FIGURE 1 P_{RSS} VS ITERATION FOR VARYING LENGTH FOUR SATELLITE SCHEDULES

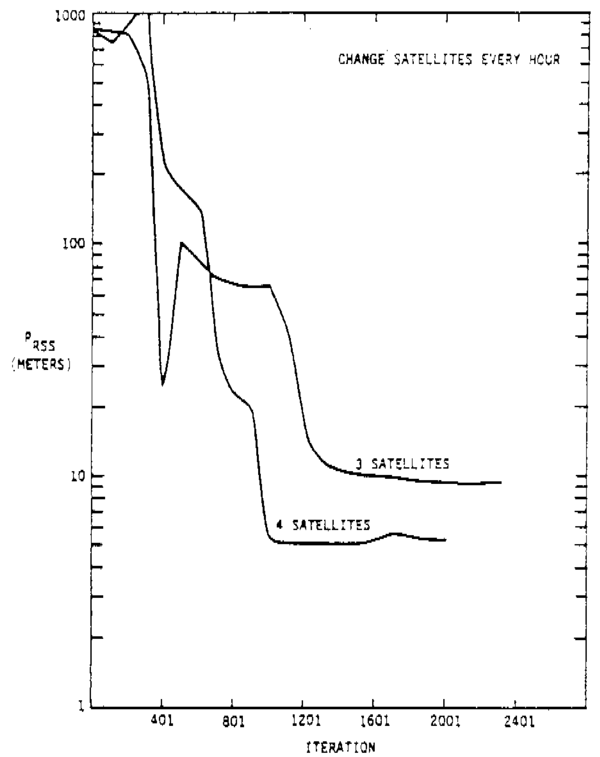

FIGURE 2 A THREE SATELLITE SCHEDULE AND FOUR SATELLITE SCHEDULE COMPARED

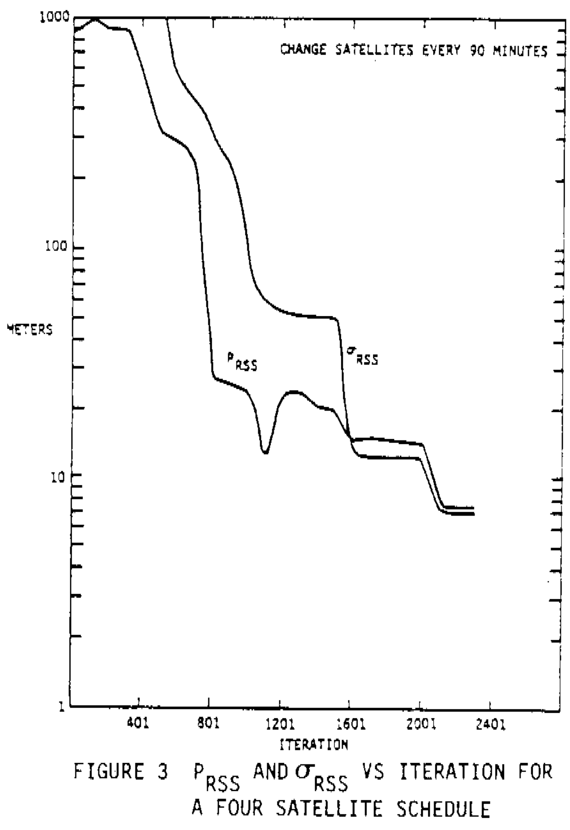

FIGURE 3 P_{RSS} AND σ_{RSS} VS ITERATION FOR A FOUR SATELLITE SCHEDULE

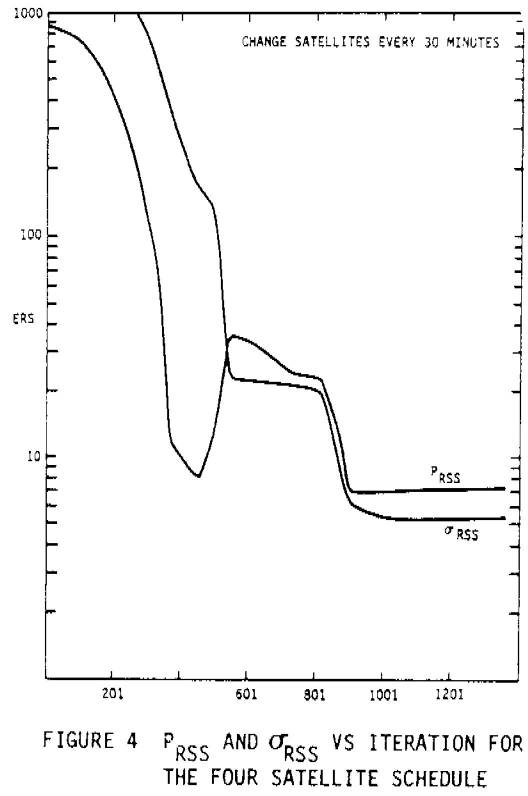

FIGURE 4 P_{RSS} AND σ_{RSS} VS ITERATION FOR THE FOUR SATELLITE SCHEDULE

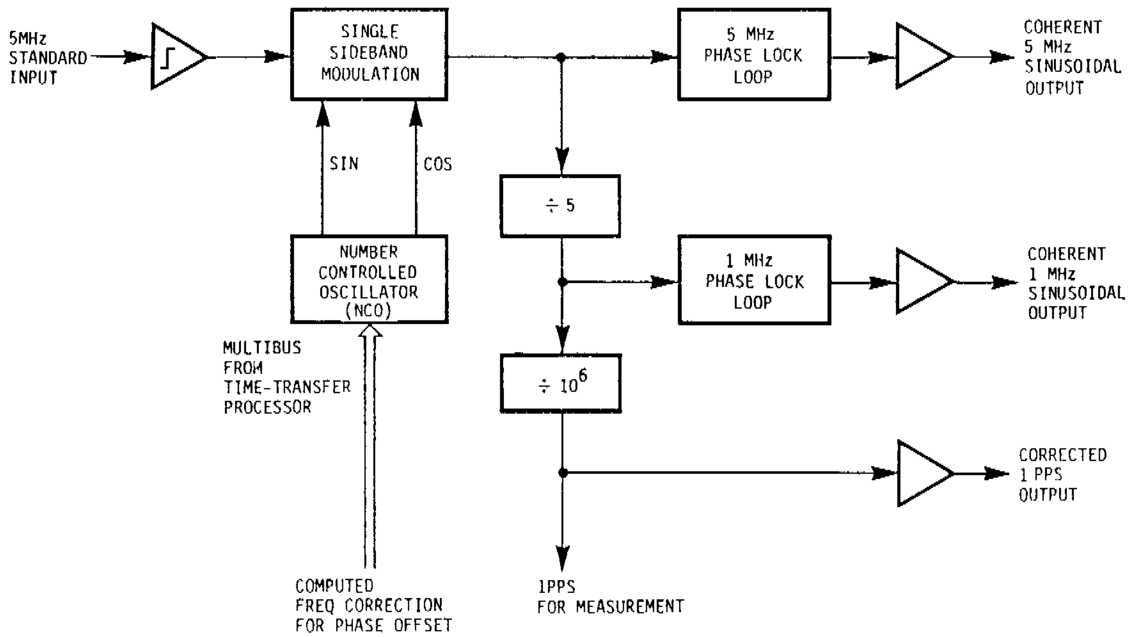

FIGURE 5. TTS 502B OPTION 8, COHERENT CORRECTED 1 PPS

ST	..... Set Time	IS	..... Input Schedule [P]
RT	..... Request Time [P]	SS	..... Shift Schedule [P]
DB	..... Data Base Input [O]	CS,CP	.. Compute Schedule [PR]
DD	..... Data Base Display [PO]	SA,FA	.. Time Transfer (Poly) [P]
AC	..... Almanac Collection	SK,FK	.. Time Transfer (Kalman) [P]
HS	..... Health & Status [P]	SP,FP	.. Positioning [PO]
HC	..... Health & Configuration [P]	LP	..... Last-Computed Position [R]
SM	..... SV Special Message [P]	OM	..... Operator Message
UT	..... UTC/GPS Data [P]	RM	..... Receiver Monitor
UG	..... Compute UTC-GPS [P]	BC	..... Bias Calibration
RV	..... SV Visibility [PO]	DT	..... Diagnostic Table
HV	..... SV Visibility Histogram [P]	CB	..... Cancel Bell
DV	..... Daily Elv/Azm/Doppler [P]	HE	..... Print Command List
CD	..... SV Elv/Azm/Doppler [P]	??	..... Command Format

FIGURE 6. TTS-502B's 32 COMMANDS

```
Latitude .................. N [illegible] 27m 24.889s
Longitude ................. W 121d 58m [illegible]
Height (meter) ...........     -7.161
Receiver Bias (nsec) .....  160
SMOOTHING:        Order ....  1    Size ... 20
Time Reference ........... GPS
Elevation Mask (deg) ..... 10
STANDARDS:     Primary .... LOVE  Secondary ... HAIL
SV IDENTIFIER AND PRIORITY:
04-00   05-01   06-01   08-01   09-01   11-01
DATA CATEGORIES SELECTED:
1. Primary Time Transfer
2. Auxiliary Time Transfer
3. SV Ephemerides
4. SV Special Message
5. SV Tracking Schedule
6. SV Almanac
7. Receiver Fault and System Anomaly
8. Ionospheric Correction and UTC-GPS
9. SV Health and Configuration
```

FIGURE 7. OPERATION DATA BASE DISPLAY
(DD COMMAND)

```
SATELLITE VISIBILITY ON: [illegible] 287 (10-degree MASK)
FROM  TO     N     SATELLITE ID'S
hhmm  hhmm
0000  0038   1 :   4
0038  0621   0 :
0621  0818   1 :   8
0818  0934   2 :   8  11
0934  0957   1 :  11
0957  1413   0 :
1413  1442   1 :   6
1442  1551   2 :   6   8
1551  1632   3 :   6   8  11
1632  1724   4 :   6   8   9  11
1724  1804   5 :   5   6   8   9  11
1804  1908   6 :   4   5   6   8   9  11
1908  2049   5 :   4   5   6   9  11
2049  2108   4 :   4   5   9  11
2108  2216   3 :   4   5   9
2216  2331   2 :   4   5
2331  2400   1 :   4
```

FIGURE 8. VISIBILITY HISTOGRAM
(HV COMMAND)

TIME hh:mm:ss	DX meter	DY meter	DZ meter	SIGMA meter	DF/F 10**-14	ELEV deg	AZIMTH deg	DATA AGE d.hh.mm
18:56:12	0.00	-0.00	0.00	1732	0.000	53.52	122.58	0.02.2[illegible]
18:56:18	0.12	0.70	2.95	1731	0.003	53.48	122.65	0.02.2[illegible]
18:56:24	-0.16	-0.92	-3.90	1729	-0.004	53.44	122.71	0.02.21
18:56:30	0.79	4.44	18.67	1726	0.019	53.40	122.78	[illegible]
18:56:36	0.73	4.11	17.30	1720	0.018	53.36	122.85	[illegible]
18:56:42	0.33	1.91	7.99	1712	0.008	53.32	122.91	[illegible]
18:56:48	1.21	6.76	28.53	1701	0.030	53.28	122.98	[illegible]
18:56:54	0.30	1.78	7.37	1688	0.007	53.24	123.05	[illegible]
18:57:00	-1.58	-8.46	-36.40	1673	-0.038	53.21	123.11	0.02.21
18:57:06	-2.36	-12.67	-54.43	1656	-0.057	53.17	123.18	0.02.21
18:57:12	-1.43	-7.69	-32.98	1638	-0.035	53.13	123.24	0.02.22
18:57:18	-1.41	-7.62	-32.71	1620	-0.034	53.09	123.31	0.02.22
19:57:24	0.65	3.28	14.65	1602	0.015	53.05	123.37	0.02.22
19:57:30	-1.14	-6.07	-26.17	1585	-0.027	53.01	123.44	[illegible]
19:57:36	0.54	2.59	11.87	1568	0.013	52.97	123.51	0.02.22
18:57:42	4.91	24.78	109.87	1553	0.118	52.93	123.57	[illegible]
18:57:48	5.66	28.53	126.57	1539	0.136	52.89	123.64	0.02.22
18:57:54	6.03	30.36	134.60	1526	0.145	52.85	123.70	[illegible]
18:58:00	8.16	40.66	181.43	1515	0.196	52.81	123.77	[illegible]
18:58:06	10.40	51.31	230.18	1504	0.249	52.77	123.83	[illegible]
18:58:12	10.24	50.55	226.64	1495	0.245	52.73	123.90	0.02.2[illegible]
18:58:18	11.61	56.78	255.88	1487	0.277	52.69	123.96	0.02.2[illegible]
18:58:24	13.37	64.56	292.97	1480	0.319	52.65	124.03	0.02.2[illegible]
18:58:30	12.60	61.22	276.79	1473	0.301	52.61	124.09	0.02.2[illegible]
18:58:36	12.45	60.61	273.77	1468	0.297	52.58	124.16	0.02.2[illegible]
18:58:42	10.34	52.20	231.27	1462	0.249	52.54	124.22	0.02.23
18:58:48	9.57	49.25	216.00	1458	0.231	52.50	124.29	0.02.23
18:58:54	10.60	53.01	236.05	1454	0.254	52.46	124.35	0.02.23
18:59:00	9.17	48.04	208.72	1450	0.222	52.42	124.41	0.02.23
18:59:06	7.94	43.97	185.60	1447	0.195	52.38	124.48	0.02.23
18:59:12	6.28	38.86	155.32	1444	0.158	52.34	124.54	0.02.24
18:59:18	4.05	32.43	115.46	1442	0.109	52.30	124.60	0.02.24
18:59:24	3.74	31.60	110.04	1440	0.102	52.26	124.67	0.02.2[illegible]
18:59:30	2.83	29.35	94.47	1437	0.083	52.22	124.73	0.02.24
18:59:36	2.46	28.54	88.40	1436	0.075	52.18	124.79	0.02.2[illegible]
18:59:42	1.72	27.06	76.45	1434	0.059	52.14	124.86	0.02.2[illegible]

FIGURE 9. POSITIONING DATA DISPLAY (SP OR FP COMMAND)

QUESTIONS AND ANSWERS

None for Paper #9.