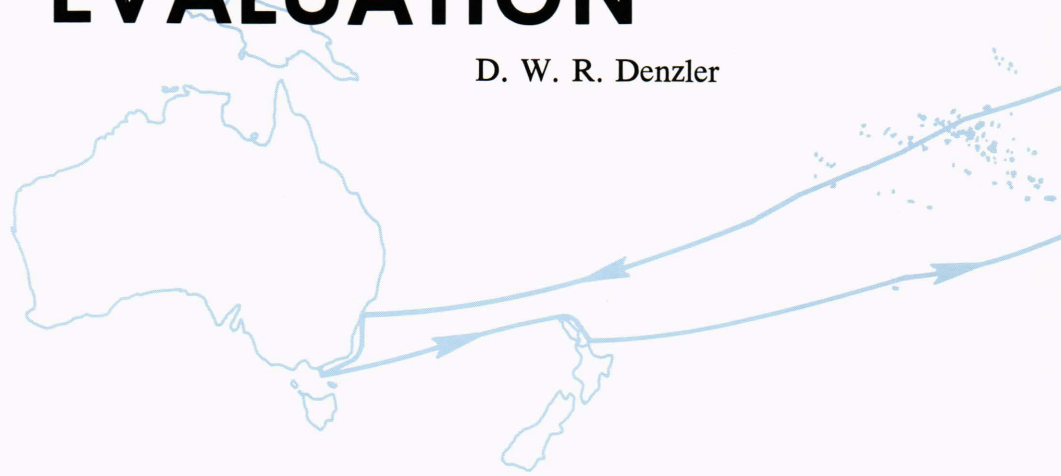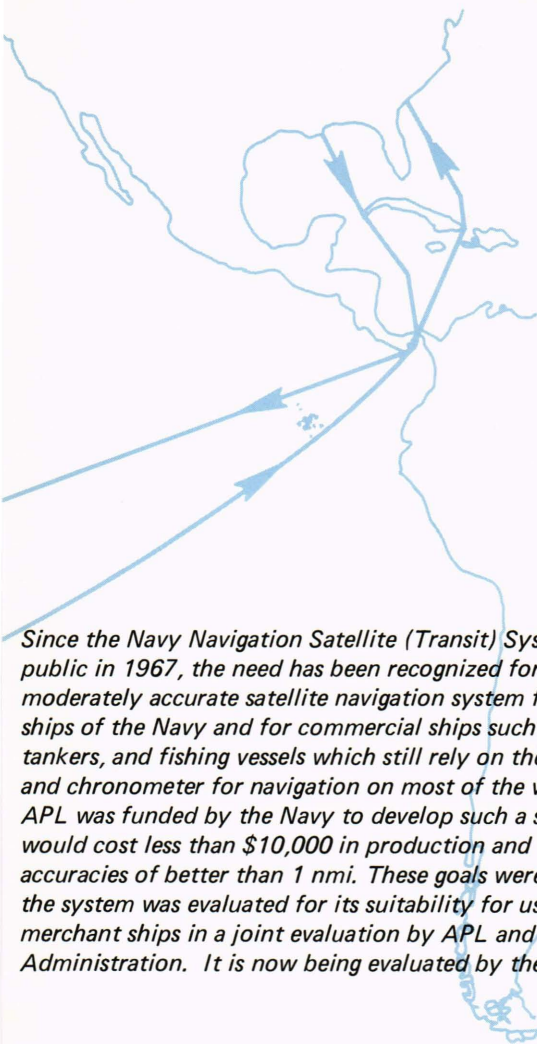# TRANSIM:
DEVELOPMENT AND EVALUATION

D. W. R. Denzler

IT IS POSSIBLE THAT SOME FUTURE HISTORIAN will write that the Transit navigation system[1] advanced the science of navigation as much as did the development of the sextant and the chronometer in the eighteenth century. However, today probably less than one percent of the ships at sea use Transit. The reason that wider acceptance of the system has not occurred in the decade since it became operational is probably primarily economic—the system is just too expensive to put on any except capital ships. At a time when both the Navy's and the Merchant Marine's fleets are shrinking because of lack of funds, it is difficult to justify spending from $30,000 to $100,000 per ship for better navigation, no matter how great the improvement. This problem of system cost has long been recognized, and early in 1969 the Ap-

plied Physics Laboratory began development of the Transim system under Navy sponsorship.

System Goals

The acronym Transim was a daily reminder to the individuals in the project to keep the system simple and inexpensive, for it is the conjunction of TRANsit and SIMplified. The design goals were to develop a system that would cost less than $10,000 in production and would provide fix accuracies of better than one mile with existing Transit navigation satellites. Receiver sensitivity was to be maintained because the ships for which Transim was being designed needed just as many fixes per day as did ships using the more expensive systems. In 1969 there were no U.S. merchant ships with permanent installations of Transit equipment aboard, so the design of Transim was directed toward meeting their needs. The design of the receiver had to provide for easy construction, maintenance, and operation to keep the cost

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[1] See R. B. Kershner, "Present State of Navigation by Doppler from Near Earth Satellites," *APL Technical Digest* **5**, No. 2, Nov.–Dec. 1965, 2–9.

Since the Navy Navigation Satellite (Transit) System was made public in 1967, the need has been recognized for a simplified moderately accurate satellite navigation system for the smaller ships of the Navy and for commercial ships such as freighters, tankers, and fishing vessels which still rely on the sextant and chronometer for navigation on most of the world's oceans. APL was funded by the Navy to develop such a system that would cost less than $10,000 in production and would provide accuracies of better than 1 nmi. These goals were met, and the system was evaluated for its suitability for use aboard merchant ships in a joint evaluation by APL and the Maritime Administration. It is now being evaluated by the Navy.

in 1969 as soon as funds were available. Within ten months a breadboard version of the RF section was tracking satellites. By June 1970, a breadboard of the simple digital section displaying doppler counts, which was mentioned in the preceding paragraph, had also been built. To demonstrate that the simple digital section, the "beep word detector" as it was called, provided doppler counts of sufficient quality to be used with the proposed satellite, a number of passes were tracked and navigated using doppler counts from this digital section. The results of these navigations are shown in Fig. 1.

By January 1971, the receiver and beep word detector had been completed as a proof-of-principle unit. Figure 2 shows the receiver with the detector installed. The detector is contained behind the plate labeled "Doppler Readout", and the doppler counts are displayed for the operator in the rectangular window above this legend.

During 1970 two studies were made to select the data processor that would perform the navigation calculations for the system using currently operating satellites. The objective of the first study was to find a minicomputer costing less than $5000 that would be capable of solving the problem and would have built-in (or at least included in the cost) a keyboard, display, and program

of ownership to a minimum. Finally, the computational routines were to be designed to minimize operator training and maximize ease of use.

Another goal of the development effort was to build a device that could replace the digital section of the receiver (the section that communicates the received signals from the satellite to the data processor) with a very simple digital section that would only recover doppler counts and display them to the operator. This configuration, which would cost perhaps half as much as the present Transim, looks toward a future in which more precisely controlled satellite orbits would permit Transim navigation with special charts analogous to Loran charts. This system would require that a special satellite be placed in an orbit with long-term predictability and that the satellite make an exactly integral number of orbits each sidereal day.

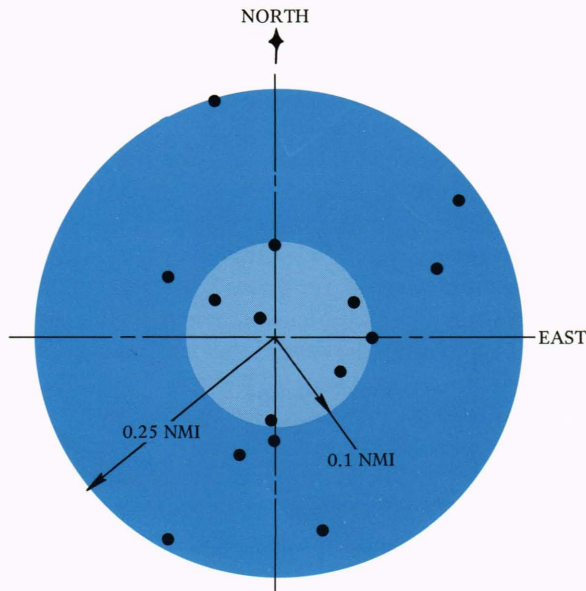## Development

Development of the Transim receiver began

Fig. 1—Transim receiver performance.

Fig. 2—Transim receiver.

loader. Several computers within the price range had the computational capability to solve the navigation calculations, but when appropriate peripheral devices were added, the cost was always greater than $6000. One programmable electronic desk calculator was found that would provide all the desired auxiliary functions for $5000, but the investigators questioned whether its limited 120-word memory was large enough to handle the navigation computations. The goal of the second study was to see how much the navigation equations could be simplified without an unacceptable loss of accuracy. The study indicated that navigation computations yielding 1-mile accuracies could be performed with the electronic desk calculator. Therefore, a Wang Laboratories 700B calculator, the type studied, was purchased early in 1971.

As soon as the calculator was delivered (in February 1971), parallel efforts were begun to write the calculator program and to develop a digital section that would extract the satellite message and send it to the calculator. The digital section was completed late in July, and the program was ready early in August when the first pass was navigated. The initial program, the Mk I, did not use the ephemeral words portion of the satellite message and yielded accuracies of approximately one mile, as the study had predicted. While writing this program, however, the programmer believed that he saw a way to "squeeze" more complex equations, including the ephemeral words, into the calculator's small memory. As a result, writing of the Mk II program began almost immediately. By mid-November the Mk II program was operating, and seventy passes were tracked and navigated to verify system accuracy. The results of these navigations are shown in Fig. 3. The center of this plot represents the survey position

of the antenna, and the small triangle shows the average position computed. The ellipse was generated from the latitude and longtitude standard deviations. The RMS of these two standard deviations is 0.07 nmi.
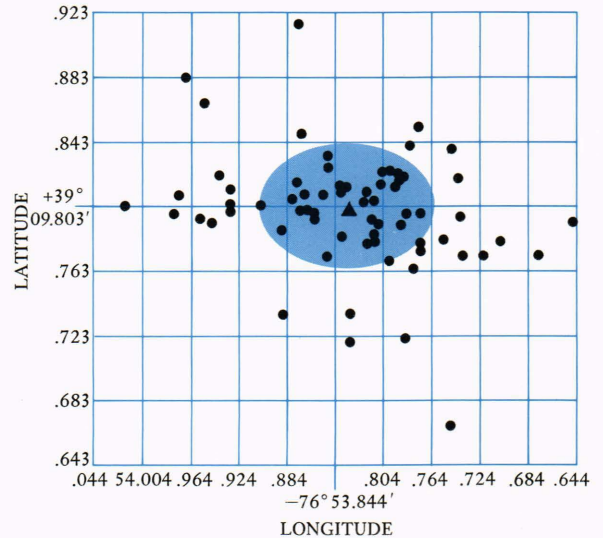

Fig. 3—Plot of Transim system accuracy.

System Description

The preceding description of the Transim development effort indicates that the system has been made to work within the constraints of the pre-established goals. It has also indicated, in very general terms, how the system works. Before we describe the sea trials of the system, it will be well to give a more detailed description of just how Transim operates.[2]

Receiver RF Section—To minimize cost, the design of the receiver, the computational device, and even the programming, used techniques that were new to the Transit system. The low cost of the receiver results from:

1. Using only one channel (400-MHz) instead of the two that are transmitted by the satellite,

2. Eliminating the need for automatic gain control by using a hard-limiting IF amplifier,

3. Using a doppler recovery system that avoids the generation of UHF frequencies,

[2] A complete description of the Transim system design is contained in APL/JHU Reports TG 1204A and 1204B, *Transim—A Low-Cost Satellite Navigation System*, Oct. 1972, by D. W. R. Denzler, J. R. Norton, and J. A. Trennepohl.

4. Minimizing the number of components and shortening assembly time by using integrated circuits wherever possible, and

5. Screening all components to make sure that each was the least expensive one available to perform the required function.

In addition, a simple form of automatic acquisition was included so the system could be operated easily without satellite alerts.

A modular block diagram of the RF section of the Transim receiver is shown in Fig. 4. Each group of blocks that is enclosed in a colored box represents a module that performs a major function within the receiver. We will trace the functioning of the RF section around the block diagram in a clockwise direction starting in the upper left corner.

The front-end module contains an RF amplifier and a mixer. It receives the weak 399.968 MHz signal from the satellite through the Transim antenna, amplifies the signal, and converts it to a frequency of 10.5 MHz. The performance of this amplifier is critical to the performance of the whole system because the receiver's sensitivity is set by the noise figure of this RF amplifier.

The mixer in the front-end module is essential to the basic design of the receiver. It is a dual-conversion superheterodyne design in which the first local oscillator (LO) (block A in Fig. 4) is phase-locked (the heavy line in the block diagram indicates the phase-lock loop) to the satellite signal. Because of this phase-locking, which is accomplished in the front-end mixer, it is possible to use a narrowband crystal filter (block B in Fig. 4) immediately after the mixer to minimize
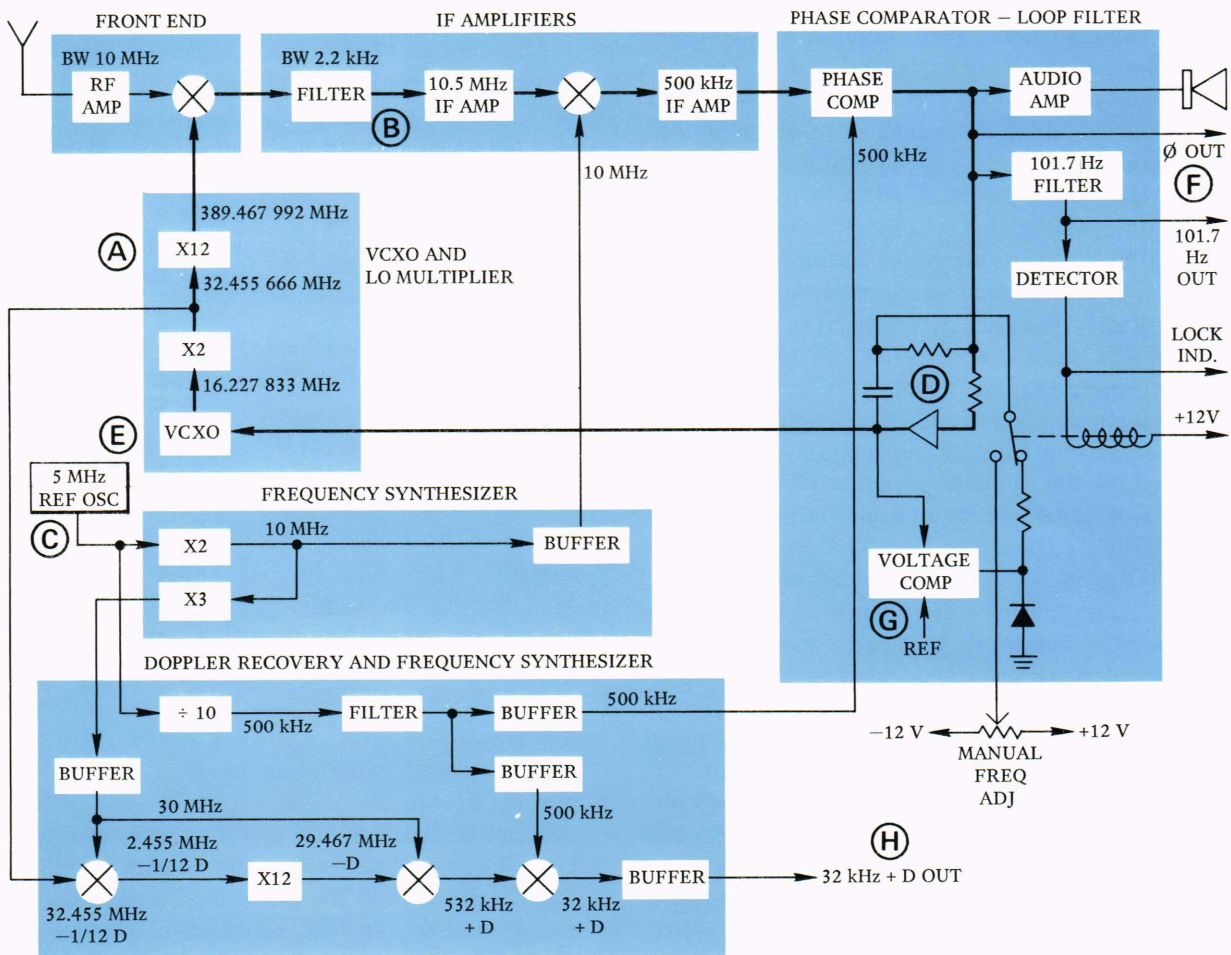

Fig. 4—Block diagram of Transim RF section.

interfering signals and noise from the high-gain IF amplifiers in the IF amplifier module.

The bulk of necessary receiver gain is provided by the IF amplifier module. IF amplifiers operating at frequencies of 10.5 MHz for the first IF and 500 kHz for the second IF were chosen to be near IF frequencies of commercial FM (10.7 MHz) and AM (455 kHz) receivers to take advantage of integrated circuits and filters developed for the commercial market. Following the initial filter, which determines the receiver's video bandwidth, is the first IF amplifier and a second mixer, which converts the signal to the second IF frequency of 500 kHz. The second IF amplifier hard-limits the incoming signal, thus producing a constant output level of signal plus noise. The overall gain of the receiver is sufficient to produce full limiting from receiver noise alone.

From the IF amplifier, the signal flows to the phase comparator-loop filter module. One function of this module is to close the phase-lock loop already mentioned. The phase comparator compares the phase of the incoming signal with a 500 kHz reference derived (via the doppler recovery and frequency synthesizer module) from the reference oscillator (block C in Fig. 4) and generates a DC voltage, which is proportional to the phase difference between the two signals. This DC voltage is filtered by an active integrator circuit (circuit D in Fig. 4) whose output is applied to a voltage-controlled crystal oscillator (VCXO) (block E in Fig. 4) to phase-lock the first LO (block A) to the incoming satellite signal.

Another function of the phase comparator is to demodulate the orbital information that is impressed on the satellite carrier as phase modulation. This demodulated information is one of two basic outputs (item F in Fig. 4) from the RF section to the digital section of the Transim receiver. An audio amplifier is also connected to the phase comparator output to help with manual phase-locking of the receiver and to indicate to the operator that the receiver is functioning properly.

Automatic acquisition is accomplished by using a voltage comparator (block G in Fig. 4) in conjunction with other circuitry to generate and control a DC voltage that is applied to the integrator of the loop filter to produce a voltage ramp causing the VCXO to sweep the frequency band in which the satellite signal will appear. When a satellite signal is detected, the DC voltage is removed and the receiver assumes a phase-locked mode.

The VCXO (block E) is located in the VCXO and LO multiplier module. A series of frequency multipliers increases the VCXO output frequency to 389.468 MHz, which is the first LO (block A). An output at 32.5 MHz is taken from the multiplier chain for use in the doppler recovery process.

The doppler shift of the passing satellite signal, which is the second basic output (item H in Fig. 4) to the digital section, is reconstructed in the doppler recovery module. A heterodyning and frequency synthesis process compares a signal synthesized from the reference oscillator (block C) with a 32.5-MHz signal from the VCXO and LO multiplier module. This process effectively compares the signal from the reference oscillator with the incoming 399.968-MHz satellite signal. The result is a nominal offset signal of 32 kHz around which the doppler frequency varies ±10 kHz. (As a packaging convenience, the 500-kHz signal used in the phase-lock loop is also synthesized from the reference oscillator signal in this module.)

The number of different frequencies that must be generated are held to a minimum in the Transim receiver, but those required (except for the 500 kHz signal just noted) are generated in the frequency synthesizer module. A 5-MHz signal from the reference oscillator (block C) drives frequency multipliers to generate 10-MHz and 30-MHz signals for use in other modules of the RF section.

Each doppler count collected by Transim is a count of the frequency difference between the received satellite signal and an indirectly generated 400-MHz signal from the reference oscillator. Therefore, each doppler count and the system's accuracy are directly related to reference oscillator stability. The oscillator used in Transim was purchased from Austron Inc. Its output frequency is so stable that aberrations in the reference oscillator will contribute less than 0.02 nmi to navigation fix errors.

Receiver Digital Section—The digital section of the Transim receiver consists of an interface section that converts the phase modulation and doppler signal outputs of the RF section into signals that can be accepted and used by the Wang calculator. The interface section also receives a 100-Hz signal derived from the phase-lock loop in the RF section and the RF lock signal. A block diagram showing how these signals are used in the interface section is presented in Fig. 5.
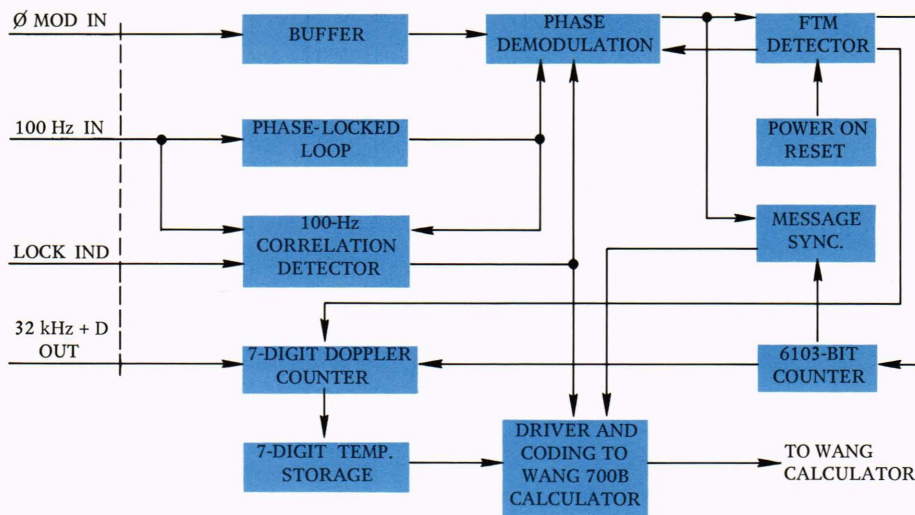
Fig. 5—Block diagram of Transim interface.

The 100-Hz signal derived from the phase-lock loop of the RF section is immediately injected into a phase-locked loop in the interface section. The use of this phase-locked loop prevents loss of bit synchronization during brief fades in the satellite signal. The 100-Hz signal from the RF section is also compared with the output of the interface section phased-locked loop in a correlation detector. Before a satellite message can be decoded, the correlation detector must indicate that these two signals are in phase quadrature.

When the signals are in phase quadrature, the phase modulation decoder decodes half-bits until half-bit synchronization is achieved. The half-bits go into the fiducial time mark (FTM) detector, which detects the last 25 bits of word 2 of the satellite message thus achieving simultaneous bit and message synchronization. When this dual synchro-

nization occurs, signals are sent to both the seven-digit doppler counter and to the 6103-bit counter to make them ready to receive a new set of data.

The fiducial time detection mechanism used in the Transim interface section is an entirely new development. The time mark is transmitted by the satellite every two minutes. It is used to identify the beginning of the message and to control the doppler counters. In the Transim interface section, complexity is reduced by searching the stream of digital half-bits coming in from the satellite for two adjacent half-bit "ones." When they are found, a counter is started that counts the number of times adjacent half-bits differ. If the counter reaches 43 and if two adjacent half-bit "zeros" are then detected, timing and full-bit synchronization have been achieved. This detection technique can be used because of the distinctive character of
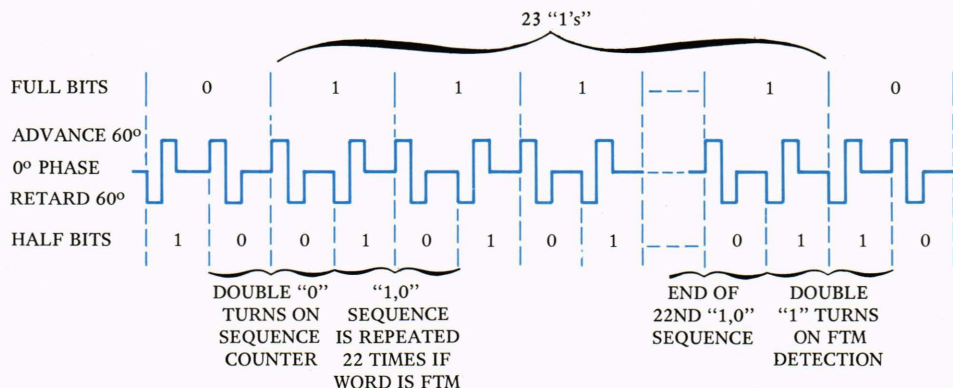

Fig. 6—Fiducial time mark detection.

THE SEQUENCE "0" FOLLOWED BY 23 "1's", FOLLOWED BY A "0" IS UNIQUE IN THE SATELLITE MESSAGE AND ISOLATES THE FIDUCIAL TIME MARK FROM THE REST OF THE WORDS.

the fiducial time mark in the satellite message. Figure 6 shows the time mark graphically and indicates why the technique just described works.

As we have indicated, the FTM detector is used to achieve simultaneous bit and message synchronization. Message synchronization is used to select from the satellite message the eighth word and every sixth word thereafter because these are the words that contain navigation information. The 6103-bit counter provides the necessary gating signals so that only the desired words are sent to the calculator. The 6103-bit counter is also used to reset itself and transfer the contents of the doppler counter to the calculator. After this transfer, the counter is reset so that the doppler count for the next two-minute interval may be generated.

The calculator periodically indicates to the interface section that it is ready to receive data. The message data are then transmitted, a character at a time, to the calculator through circuitry that reformats and recodes the data appropriately. (The data in the satellite message are in a binary coded decimal excess three (BCDXS 3) format. To be accepted by the calculator, they must be converted to another code.) After each word is transferred, control is returned to the calculator.

Calculator Program.—In order to use the Wang calculator, which, by comparison with even a small computer, has a very limited memory, the calculations required to derive a navigation solution from the satellite data have been organized in a series of steps each of which can be completed before the next step is started. At the beginning of each step, the controlling Loader program loads the program for the next step into the calculator's memory from the cassette tape. This stepwise technique permits the small calculator to cope with a relatively complex navigation computation.

The steps in the calculator program are shown in the flow chart in Fig. 7. The Loader program is loaded into the calculator by commands to the cassette drive from the keyboard. As already noted, the Loader program is then in control of the calculation procedure; each step ends by referring the calculator back to the Loader program so that it can load the program for the next step into the calculator's memory.

The Initialize program sets all of the data registers in the calculator that do not contain the program itself to zero. This procedure allows maximum use of the memory by the Real Time

program. Its job is to sort the data that are received from the satellite, correct errors resulting from RF noise and fades, store appropriate data, and eliminate redundancies. It operates in real time as the satellite pass is being observed.

Once the satellite is no longer visible, the Sequence Data program is loaded. It checks the message data to make sure that enough are available for navigation. Then it arranges the data in sequence so that the doppler counts and ephemeral-words, which are both time dependent, are both keyed to the same time sequence. The Convert Data program then converts the satellite data
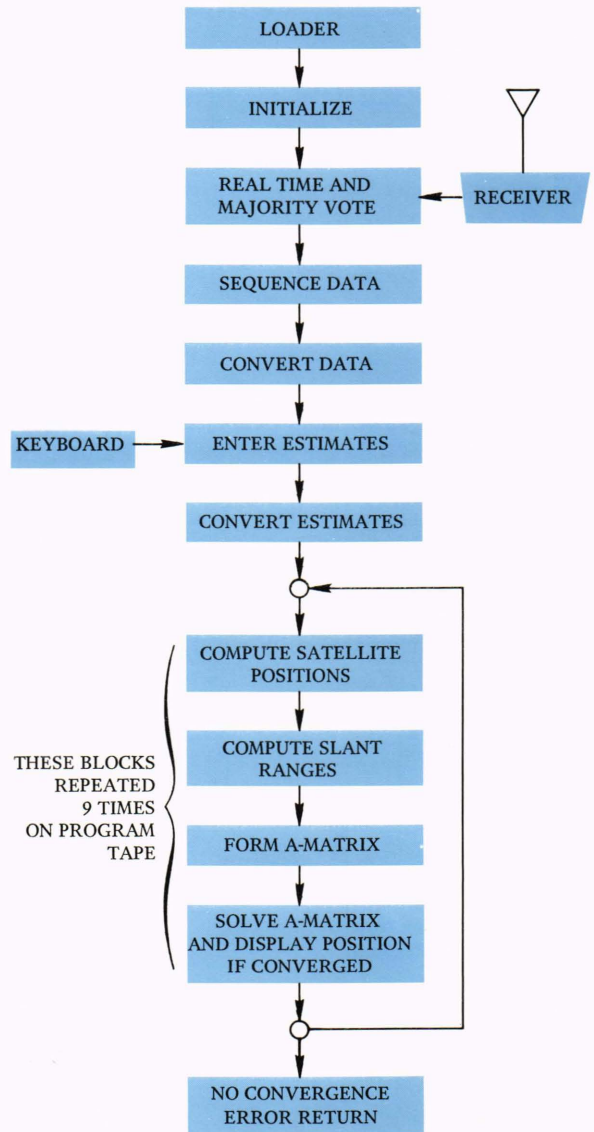

Fig. 7—Flow chart of navigation program.

to working units with proper signs and decimal points.

At this point, the operator, in connection with the Enter Estimates program, must use the calculator keyboard to enter his best estimate of the ship's position, velocity, and time. He must also enter accurate values of the Transim antenna's altitude. The Convert Estimates program then converts all the estimates to working units.

Now, all the data that are necessary for obtaining a navigation solution are in the proper format and in the correct locations within the calculator's memory. From this point on, the system is iterative. Four programs are repeated nine times each on the program tape. Repeated execution of those four programs amounts to a least-squares fitting process, with the four programs being repeated until convergence occurs.

The first of the iterative programs, Compute Satellite Positions, calculates the position of the satellite at each time mark for which usable data were obtained during the pass. The Compute Slant Ranges program calculates the navigator's positions at these same times and computes the slant ranges between the navigator and the satellite. The satellite positions are then replaced in the calculator memory by the slant ranges and their partial derivatives with respect to latitude and longitude. The Form A-Matrix program compares the calculated slant ranges with the observed slant range changes (the doppler data) and forms an A-matrix. The fourth program, true to its name, solves the A-matrix to obtain values for delta latitude, delta longitude, and delta frequency. These values are compared to the estimates and tested for convergence. If convergence has not been achieved, the iteration cycle is repeated. If it has, the updated values of latitude and longitude are displayed on the calculator display panel, and the computation cycle ends. If, after nine iterations, convergence has still not occurred, the No Convergence Error Return program tells the operator that a navigation fix could not be achieved.

With, hopefully, a more comprehensive understanding of how the Transim system operates, we are now ready to look at the system's demonstration of its capability in a working environment.

At-Sea Testing

Transim first went to sea in February 1972 aboard one of the small sailing craft used in the Laboratory's underwater sound work. Although aboard for only a short time, the system was considered a success.

In March, the U.S. Maritime Administration requested that the Laboratory conduct evaluation tests of Transim in the Atlantic and Pacific oceans. The purpose of the tests was to demonstrate the suitability, adequacy, and feasibility of this type of low-cost equipment for U.S. merchant ships and to determine the optimum configuration for future equipment of this type. Particular emphasis was placed on determining how well the equipment could be operated by regular shipboard personnel. The tests were conducted in three phases: the first aboard a research ship assigned to the National Maritime Research Center, the second aboard a coastal freighter, and the third aboard a transoceanic freighter.

Late in March, the equipment was placed in service for several weeks at the National Maritime Research Center at Kings Point, New York, to familiarize the personnel there with its operation. After two weeks, it was installed on the *R. V. Nereid* primarily for testing the operator instructions. The equipment was operated only by cadets from the National Merchant Marine Academy, which is also located at Kings Point. The majority of the operators had never operated the equipment until the tests; they provided many comments which resulted in substantial improvement of the operator instructions.

A minor modification was made to the Transim receiver before the second phase of the tests. Since merchant ships operate with only two men on the bridge, the deck officers on duty, who are also the Transim operators, do not have time to monitor the system continuously. Therefore, the headphones were replaced by an audio amplifier. However, because the amplifier noise can become annoying when a satellite is not being tracked, a circuit was designed that keeps the audio off until the receiver automatically locks onto the satellite and the first beep word is recognized. Then, when the audio comes on, an officer can monitor the pass.

With this modification, the system was installed aboard the S.S. *Eric K. Holzer* for the second phase of the at-sea tests in mid-May. This ship is in service between New York and San Juan, Puerto Rico. She was selected because her route is

almost completely within Loran coverage, and it was desired to accumulate a large amount of data to demonstrate to the maritime community Transim's inherent accuracy aboard ship. More than 90 passes were collected aboard the *Holzer*, which also had Loran fixes. All of the fixes agreed within the accuracy of Loran. Some difficulty with both the antenna and the calculator was experienced early in the tests, but the problems were solved by replacing the antenna with one of a slightly different design and by having the vendors modify the calculator circuitry somewhat. (The changes in the calculator have been incorporated in recent production models.) Unfortunately, testing on the *Holzer* was terminated ahead of schedule because of a problem completely unrelated to the Transim program.

The third phase of at-sea testing was conducted aboard the S.S. *African Meteor* (Fig. 8) from mid-July through late December 1972. The equipment (Fig. 9 shows the calculator and receiver; Fig. 10 shows the Chu Associates antenna) was aboard for two voyages; the first from her home port of New York to Australia and New Zealand and back (mid-July through late September) and
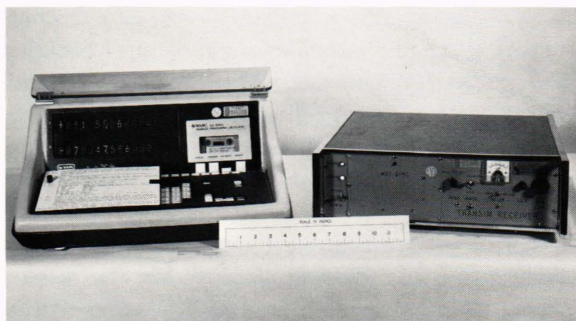

Fig. 8—The S.S. *African Meteor.*

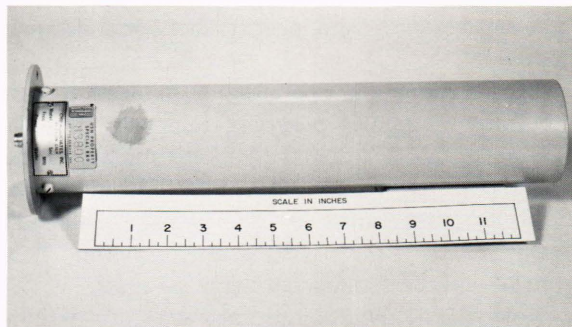Fig. 9—Transim calculator and receiver.

Fig. 10—Transim antenna.

the second from New York to South Africa and Mozambique and back (early October through late December).

Not all of the data from the *African Meteor* voyages have yet been analyzed. However, preliminary analysis of the Australian voyage (Fig. 11) indicates that the system is fully usable and suitable for use on merchant ships.[3] To evaluate usability, the officers were observed and interviewed during the return trip from Balboa, C.Z., to Charleston, S.C. Two of the three officers operated the system completely from memory, while the third used a short checklist attached to the calculator. The average amount of time they spent per navigation fix was less than 6 minutes, which is a significant reduction in time spent compared to a celestial fix. During the Pacific portion of the voyage, approximately 347 fixes were achieved during 197 4-hour watches, giving an average of 1.75 fixes per watch or a fix about every 2.27 hours.

Determining suitability is somewhat more difficult, since the only known requirements for merchant ship navigation accuracy state that fix accuracies should be better than 4 nmi 95% of the time and should occur at least every 2 hours.[4] Since Transim's accuracy is an order of magnitude better than this but less frequent than desired, it is difficult to compare it to these requirements. Any navigation system that does not give continuous fixes assumes some knowledge by the navigator of his course and speed between fixes so that the maximum error uncertainty in his position can be computed. Unfortunately, N P N does not

[3] D. W. R. Denzler, *Quick-Look Report for Phase IV Testing of Transim First Voyage,* APL/JHU Memo S3R-72-178, Oct. 11, 1972.
[4] *Department of Transportation National Plan for Navigation,* (NPN) Department of Transportation, Washington, D.C., Apr. 1972.
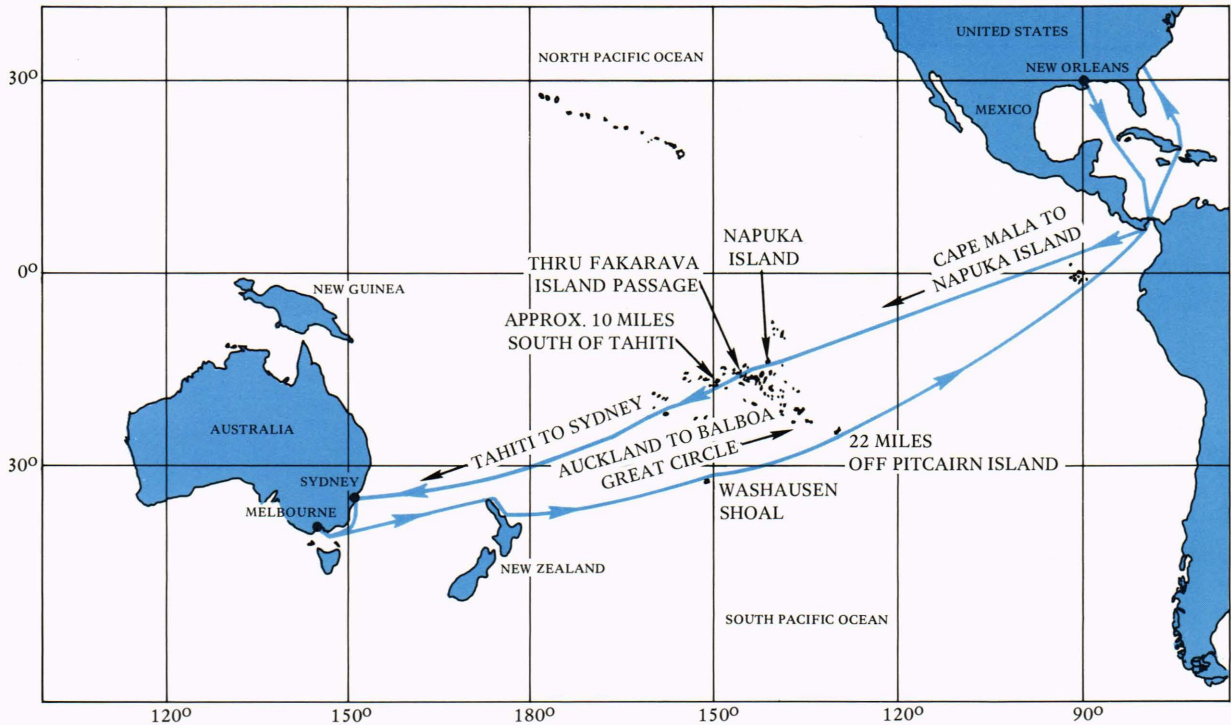
Fig. 11—*African Meteor* voyage 40.

specify the allowable limits of position uncertainty. Therefore, the suitability analysis of Transim assumed the worst case with respect to accuracy requirements, i.e., that the navigator's position should be allowed to be greater than 4 nmi only 5% of the time. The data for the portion of the voyage from Balboa, C.Z., to Sydney were examined, and it was found that the uncertainty in the position of the S.S. *African Meteor* during that leg of the voyage was less than 4 nmi 98% of the time if it is assumed that she knew her course to 1°, her speed to ½ knot, and that fix errors were always less than 0.2 nmi.

These statistical results of the shipboard testing of Transim indicate the utility of the system using the current satellite constellation and the electronic calculator. Although the special satellite that would permit mariners to navigate using only the beep-word detector has not been orbited, the beep-word mode of navigation is being used on a delayed basis by the National Oceanic and Atmospheric Administration (NOAA).

The Laboratory built for NOAA four Transim receivers that incorporate beep-word detectors. These units have been installed on four drifting NOAA buoys. NOAA is now tracking the buoys by combining the doppler counts that the buoys transmit directly to the NOAA laboratories in Mississippi with satellite messages that are provided to NOAA daily by the Navy Astronautics Group. This project is demonstrating that it is possible to obtain fixes with the beep-word-detector system with the present satellite constellation.

Despite all the statistics, the variety of tests, and the accuracy plots, probably the most telling evidence of Transim's acceptability to the Merchant Marine are these words sent back from Australia by one of the officers of the *African Meteor:* "Your satellite unit has our A-1 gold star stamp of approval;" he writes, "our sextants are now museum pieces."

Acknowledgment