the TRIAD prn navigation experiments

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Introduction

THE PSEUDO-RANDOM NOISE (PRN) EXPERIMENT aboard the TRIAD satellite was designed to explore the possibility of obtaining improvements in satellite navigation through the use of highly precise timing signals. In potential application to Transit satellites, the timing signals would be obtained in the navigation receivers from the recovery of a precision time-signal modulation imposed on the satellite's 150- and 400-MHz carriers. The two main improvements sought over the current (and by now classical) integral doppler navigation systems were a reduction in the time span of the doppler data required for a navigation fix and a means for discriminating between covisible satellites.

The transmission of timing signals from a satellite and their reception at a navigation receiver involves the use of two timing devices (clocks). The events or "epochs" of time-signal transmission are under the control of the satellite clock; the observed epochs of signal reception are given time labels by the receiver clock. Either the satellite clock or the receiver clock is regarded as the master clock and as keeping "true" time.

Accuracy and precision are basic and independent aspects of time-signal transmission. Accuracy relates to the clocking of transmission and reception; timing precision or resolution derives from the time and bandwidth parameters of the timing-signal waveform.

The absolute accuracy of the master clock in satellite navigation must be such that its time error does not lead to significant errors in the calculated position coordinates of the satellite. Only the stability—not the accuracy—of the other clock is of importance since its epoch and rate errors relative to the master clock can be detected and removed in the navigation computation.

From the point of view of the navigator, the problem of clock accuracy is automatically solved and of no concern to him. However, the question of timing precision is a different matter and is a fundamental factor in establishing the accuracy of both doppler and ranging measurements.

Pseudo-Random Noise Codes—The time-signal transmission selected for TRIAD consists of Pseudo-Random Noise phase modulation. This choice was made for two principal reasons. First, PRN modulation is simple to generate and easy to add to an existing satellite RF system and second, the resulting frequency spectrum is so low that it cannot cause interference to other RF systems operating at the same frequency.

The following discussion of pseudo-random codes will, of necessity, be very brief; we refer the reader who desires greater insight to the excellent books by Golomb.[1,2]

A PRN code is represented mathematically by a periodic binary sequence of 1s and 0s where the elements of the sequence are related by a specific linear recursion relationship. Electronically, a code of 32,768 (2^{15}) elements can be generated using 15 binary storage elements and a few gates. Phase modulation is achieved by mapping the 1 and 0 elements of the code into advance and retard phase shifts of an RF carrier; the elements of the code are translated into phase-shift intervals of fixed length that are referred to as "chips."

The key feature which distinguishes a PRN code from any arbitrary periodic binary sequence and which forms the basis for precise time recovery is its autocorrelation function. The normalized autocorrelation function for a PRN code is nearly zero for all phase shifts except for a small interval in which it peaks to unit value. In a PRN receiver, the received code is continually correlated with the identical code generated in the receiver. By this process the point of maxi-

[1] S. W. Golomb et al, *Digital Communications with Space Applications,* Prentice-Hall, Englewood Cliffs, N.J., 1964.
[2] S. W. Golomb, *Shift Register Sequences,* Holden-Day, Inc., San Francisco, 1967.

Techniques for making highly precise timing measurements are needed to take full advantage of the accuracy of stable crystal oscillators and atomic frequency standards. In certain applications, Pseudo-Random Noise (PRN) codes with their remarkable autocorrelation property fill this need most effectively. The PRN-timing experiments conducted with the TRIAD satellite have pointed to several significant improvements and innovations now possible in satellite navigation.

mum correlation is determined with a time precision corresponding to a small fraction of a chip and the time-of-arrival of any chip pattern (epoch) in the code is measurable to the same precision.

TRIAD PRN Ranging—It is apparent that the availability of the PRN-timing pulses creates the potential for more than the precise timing and counting of doppler cycles. A measurement of slant range between satellite and receiver is implicit in the time interval between the transmission and receipt of epochs of the PRN code. Furthermore, once the slant range is known, the time of a satellite clock can be transferred to any receiver equipped to recover PRN.

The term "ranging" (i.e., the measurement of the distance between two locations) brings to mind the operation of a radar system. A pulse (or similar waveform) is transmitted at a known time and received, after reflection from a distant object, at a later time. The measured range is proportional to the measured time interval between pulse transmission and reception. Note that the epoch error of the radar clock does not appear in the time interval measurement. Clock rate errors are generally negligible in any single radar range measurement.

The one-way PRN-ranging measurements made with TRIAD differ from two-way radar measurements in that they are made over the one-way path between satellite and receiver and therefore require two clocks for the measurement of the transmission interval. In an operational PRN-ranging system the transmission epochs under the control of the clock in the satellite would be known; the instants of reception, measured by the receiver clock, would contain the time error in the receiver clock. The set of PRN-ranging intervals obtained over a satellite pass would contain a fixed clock epoch error and, to first order, a linearly-varying error due to clock rate error. In the TRIAD PRN experiment, the operational situation was simply inverted: the measurements of the received epochs were assumed to be free of clock error; the transmission epochs contained the epoch and rate errors of the uncontrolled clock in the satellite.

The availability of PRN-ranging measurements created the possibility of a new formulation for satellite navigation based upon instantaneous slant range rather than the slant range differences or changes measured in integral doppler. In integral doppler navigation, the three variables whose numerical values are determined are the two position coordinates of the navigator and the clock frequency. In ranging navigation, the value of an additional variable, clock epoch, is also determined.

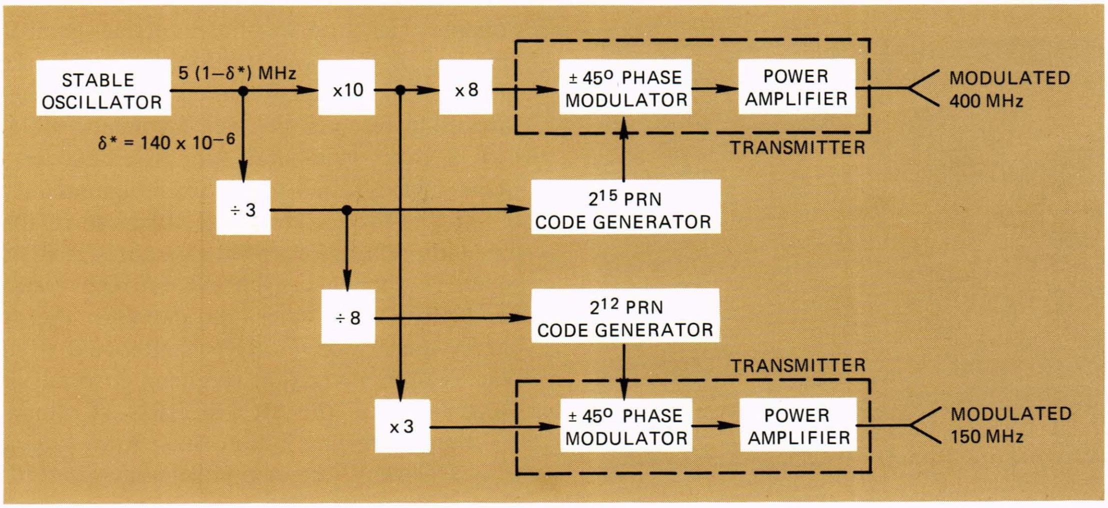

Fig. 1—TRIAD satellite RF system.

Satellite PRN Electronics

The TRIAD RF System generates two very stable carrier frequencies slightly below 400 and 150 MHz. As shown in Fig. 1, each carrier is phase-modulated by a different PRN code pattern. The parameters of the codes, listed in Table 1, were selected to make the code periods exactly the same. To establish a common transmission event or epoch, the code generators are cross-synchronized so that they are both clocked to the all-zero state at the same phase as the satellite's oscillator. The times at which this event occurs are referred to as "satellite epochs."

Table 1

PARAMETERS OF THE TRIAD PRN CODES

RF Channel	*Code Clock Rate (MHz)*	*Chip Length (μsec)*	*Code Length (chips)*	*Code Period (msec)*
400-MHz	1.66	0.6	32,768	19.66
150-MHz	0.208	4.8	4,096	19.66

The binary outputs of the code generators are used to biphase-modulate the RF carriers at a modulation index of 45°. This reduces the transmitted carrier energy by one-half and distributes the remaining energy uniformly around 400 and 150 MHz over bandwidths of about 3⅓ MHz and 416 kHz respectively.

Most of the satellite PRN hardware was realized using hybrid microelectronic techniques. The code generator was fabricated by the APL Microelectronics Laboratory on two ceramic substrates mounted in a 1¾-in. by 1¼-in. package shown unlidded in Fig. 2. The phase modulators consisted of simple phase shifters tuned for 90° at the carrier frequencies and switched alternately in or out of the carrier paths by diodes driven from the outputs of the code generators. The modulators are built on small ceramic substrates and inserted along the walls of transmitters which were designed previously for the Transit satellites. The 400-MHz phase modulator is shown in Fig. 3.

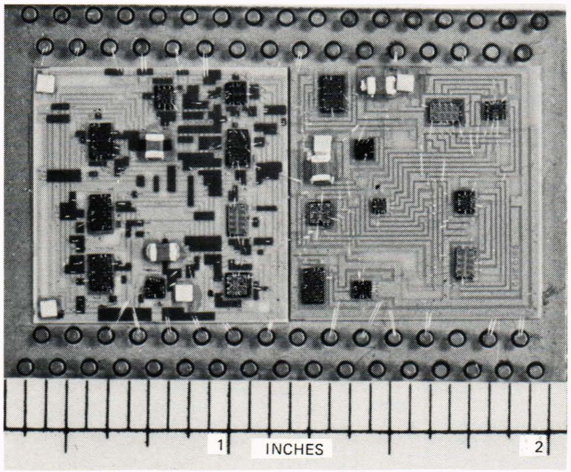

Fig. 2—TRIAD PRN digital generator.

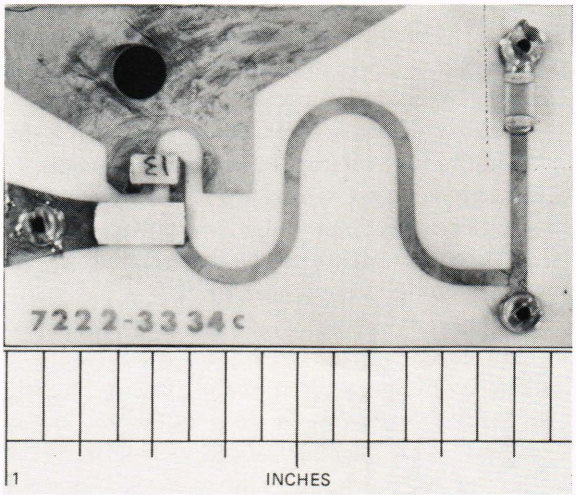

Fig. 3—TRIAD 400-MHz PRN phase modulator.

Features of the TRIAD Signals—Each of the signals transmitted from TRIAD can be thought of as the sum of two independent signal components: (a) a narrow-band carrier signal that is identical to the signal transmitted by the Transit satellites and uniquely suited to the recovery of satellite-to-receiver doppler frequency shift, and (b) a new wide-band suppressed-carrier PRN signal that is suited to the unambiguous recovery of satellite-to-receiver range. Because of the significantly different spectral signatures of these two signal components, each can be recovered independently of the other. As shown in Fig. 4, the energy density of the PRN component is so low that Transit navigation receivers currently in the Fleet (such as the SRN-9, BRN-3) cannot tell it's there. During initial shakedown operations with TRIAD, these equipments navigated in their normal way, experiencing no interference from the PRN component.

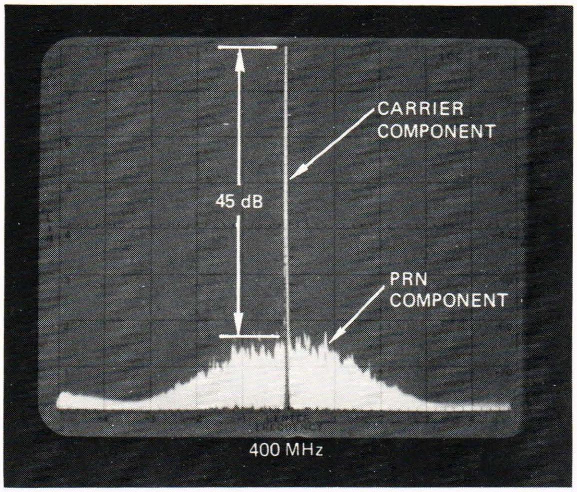

Fig. 4—Frequency spectrum of 400-MHz TRIAD transmission.

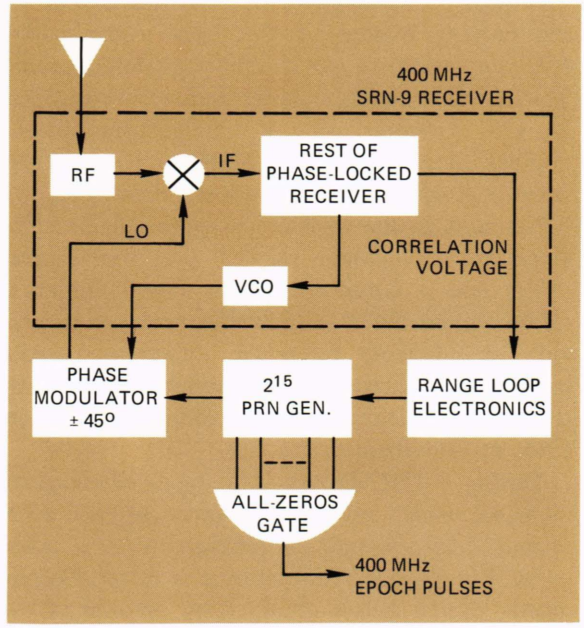

Fig. 5—Modification to SRN-9 400-MHz receiver for PRN signal tracking.

PRN Receiver Implementation

To recover the PRN signals from TRIAD, it is necessary to reproduce the code on the ground and correlate the locally-generated code with the received signal. While this process can obviously form the basis for the design of an entirely new receiver, we wanted to demonstrate that PRN recovery could readily be added to an existing navigation receiver. The SRN-9 receiver was selected for this purpose because of its widespread use in the Fleet.

The basic SRN-9 equipment contains two independent phase-locked receivers which track the 400- and 150-MHz carriers, recover the doppler frequency shifts and demodulate the satellite position information which is carried as narrowband phase modulation of the carriers. Each receiver was modified for independent PRN recovery with very similar electronics; therefore, only the 400-MHz receiver implementation will be discussed.

PRN Signal Tracking—The capability to track PRN modulation is added to the 400-MHz receiver by obtaining a correlation product between the received and locally-generated codes at the front end of the receiver, where the bandwidth is wide enough to encompass the full code spectrum. As shown in Fig. 5, the local code is applied to the receiver's local oscillator (LO) as phase modulation and then multiplied by the received 400-MHz signal in the first mixer. The resulting correlation product is carried as amplitude modulation of the difference frequency (IF) at the output of the mixer and detected, after further amplification, by a correlation detector within the SRN-9.

In the conventional (non-PRN) operation of the SRN-9, the correlation detector output is due solely to the multiplication product of the unmodulated LO signal with the 400-MHz carrier component in the received signal. By adding the PRN capability, an increase in detector output is obtained when the received and local codes are matched in time-phase. Initially, the local code is shifted in phase until the proper time-match is found; the correlation peak is then actively tracked by generating an error signal when a change from maximum is detected. The error signal is filtered to reduce noise and then used to modify the phase of the local PRN code and keep it in time-step with the received code throughout the pass. As a result of this tracking operation, the local PRN code generator progresses through its states in precise time-step with the received modulation. In particular, the all-zeros state of the generator is sensed by means of an "all zeros" gate. The times at which this gate fires are referred to as "receiver epochs."

PRN and Doppler Measurements—To make a definitive assessment of PRN-ranging navigation, it was necessary to obtain a reference position for each pass which would be effectively free of errors not directly related to the PRN transmission/receiving system (e.g., errors in the satellite orbit). This function could be easily obtained by navigating with each pass using the conventional integral doppler data which were obtained concurrently with the PRN data. Although the doppler counting circuits in the SRN-9 are quite adequate for shipboard navigation, we felt that the doppler errors due to count truncation and timing-noise effects within the receiver were too large to provide an adequate reference; therefore external hardware was designed for making higher precision doppler measurements in addition to the new PRN measurements.

During a TRIAD pass, two types of measurement are made: integral doppler counts and PRN receipt times. A pair of measurements is made every 4.6 seconds. This interval is established by master timing pulses obtained by division of the recovered 400 PRN epoch pulse stream. Although a number of different interval lengths can be selected within the hardware, the 4.6-second interval was used for all the data reported herein.

A doppler measurement consists of three parts: a "main doppler count," an "auxiliary doppler count," and a "phase count." The timing associated with the doppler measurement is shown in Fig. 6. The main doppler count is a nontruncated count of the zero crossings in the offset doppler signal recovered by the 400-MHz phase-locked receiver. The count begins on the first positive zero-crossing following a master timing pulse and ends on the first positive zero-crossing following the next master timing pulse. The exact interval of the count is established by recording the reading of a local GMT clock at the beginning (time t_1) and the end (t_2) of the count. The auxiliary count is a truncated count of the zero crossings in the offset doppler signal recovered by the 150-MHz phase-locked receiver after it has been scaled in frequency by 8/3. This count is started and stopped at precisely the same time as the main doppler count but, because the two doppler signals are not coherent, a random truncation error of up to ± 1 count can occur. This error is largely eliminated by measuring the phases between the zero crossings of the 400- and (scaled) 150-MHz doppler signals at the beginning (δt_1) and end (δt_2) of each count interval and applying them as software corrections to the auxiliary counts. The three components of the doppler measurement are used (together with the clock readings t_1, t_2) to derive a high precision "vacuum" doppler count which is subsequently used in the navigation software to compute the conventional, dual-frequency doppler position fix. Only the 400-MHz doppler count data are used to compute the single-frequency fix.

A PRN receipt-time measurement is also initiated at the occurrence of each master timing pulse and consists of three parts: an "early time-difference," a "receiver epoch time," and a "late time-difference," indicated by δt_3, t_3, and δt_4 respectively in Fig. 7. The early time-difference is a measure of the difference in arrival times of the first pair of 150- and 400-MHz epoch pulses occurring after the master timing pulse. The late time-difference is a similar measure made on the third pair of epoch pulses. The receiver epoch

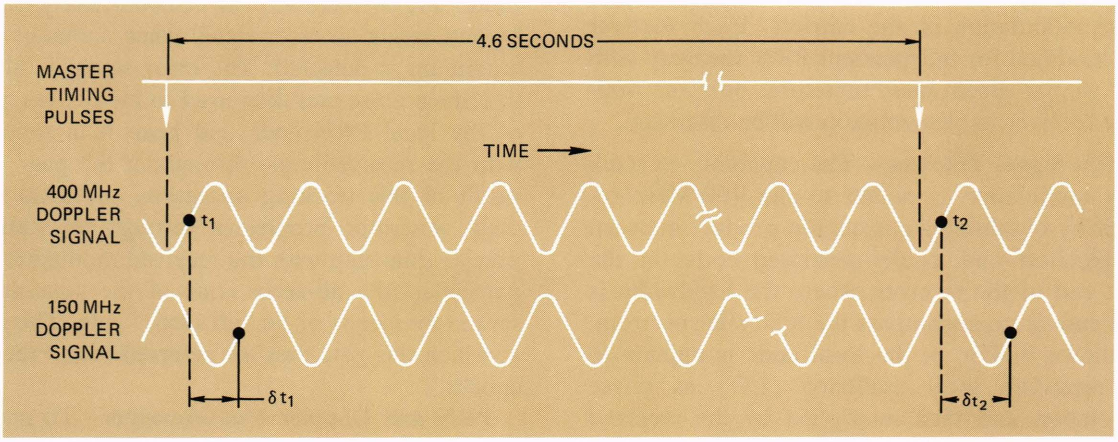

Fig. 6—Doppler measurement timing.

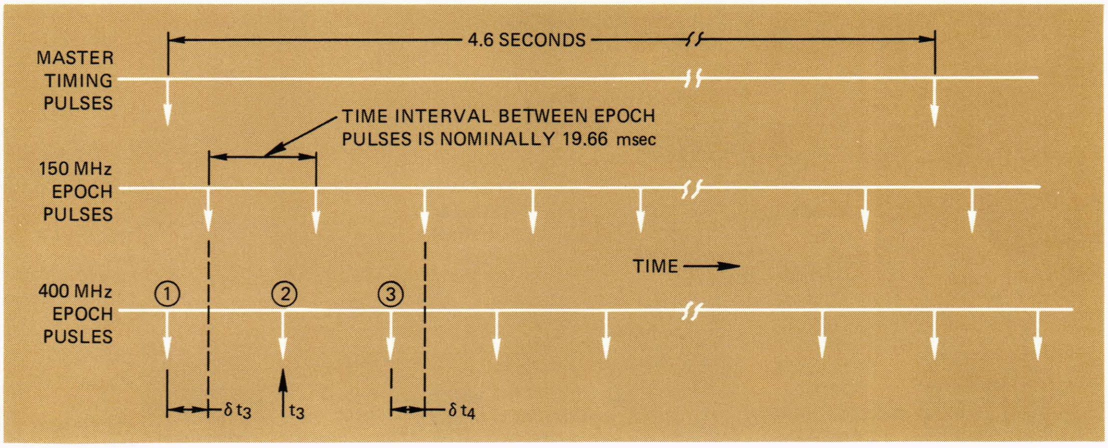

Fig. 7—PRN-ranging measurement timing.

time consists of the reading of the local GMT clock at the instant of reception of the second 400-MHz epoch pulse following the master timing pulse. The time-difference data are used in the software to correct the receiver epoch time for ionospheric refraction. The corrected epoch time is subsequently used in the navigation software to compute a dual-frequency PRN ranging position fix. Only the uncorrected receiver epoch time data are used to compute the single-frequency fix.

Data-Gathering System

In order to obtain a position fix using either range or doppler measurements from an orbiting satellite, it is necessary to know where the satellite was at the time the measurements were made. This information is transmitted by the Transit satellites as modulation on the 400- and 150-MHz carriers. The timing of the Transit modulation is controlled so that the modulation words, transmitted at time t_0, contain the position of the satellite at time t_0. The navigator, therefore, receives all the information necessary to compute a position fix from the RF navigation link.

During the periods of PRN data-gathering, TRIAD did not transmit its positions nor did it have any level of accurate time control. These two pieces of information had to be obtained by other means. Figure 8 shows all the functional subsystems involved in the complete experimental evaluation. The SRN-9/PRN receiver obtained the range and doppler measurements which were recorded on magnetic tape. This subsystem is pictured in Fig. 9. The TRIAD carrier transmissions were continually monitored by TRANET stations around the world. The TRANET data were used at APL to compute the satellite ephemerides. The APL Time and Frequency Laboratory provided the common time reference which allowed the satellite positions to be determined (after-the-fact) at the range and doppler measurement times with negligible error.

The final step of navigating the data was carried out on the System/360 Model 91 computer using the newly-developed range navigation programs as well as conventional integral doppler navigation programs.[3]

Experimental Results

Three new experimental results have been identified and demonstrated by means of the integral doppler and PRN-ranging measurements made at APL on the transmissions from TRIAD. These are:

1. PRN-timed, dual-frequency integral doppler measurements permit a reduction in navigation data span for SRN-9 type receivers to about the two-minute level without serious degradation in navigation accuracy.

2. Dual-frequency PRN-ranging navigation gives nearly the same navigation accuracy as dual-frequency integral doppler navigation when the full-pass span of navigation data is used.

3. Single-frequency (400-MHz) Doppler Ranging (DOPRAN) fixes are essentially equivalent to dual-frequency (150/400-MHz) integral doppler

[3] V. Schwab and E. F. Prozeller, *Single-Frequency, Refraction-Free Satellite Navigation*, APL/JHU Report TG 1221, Jan. 1974.

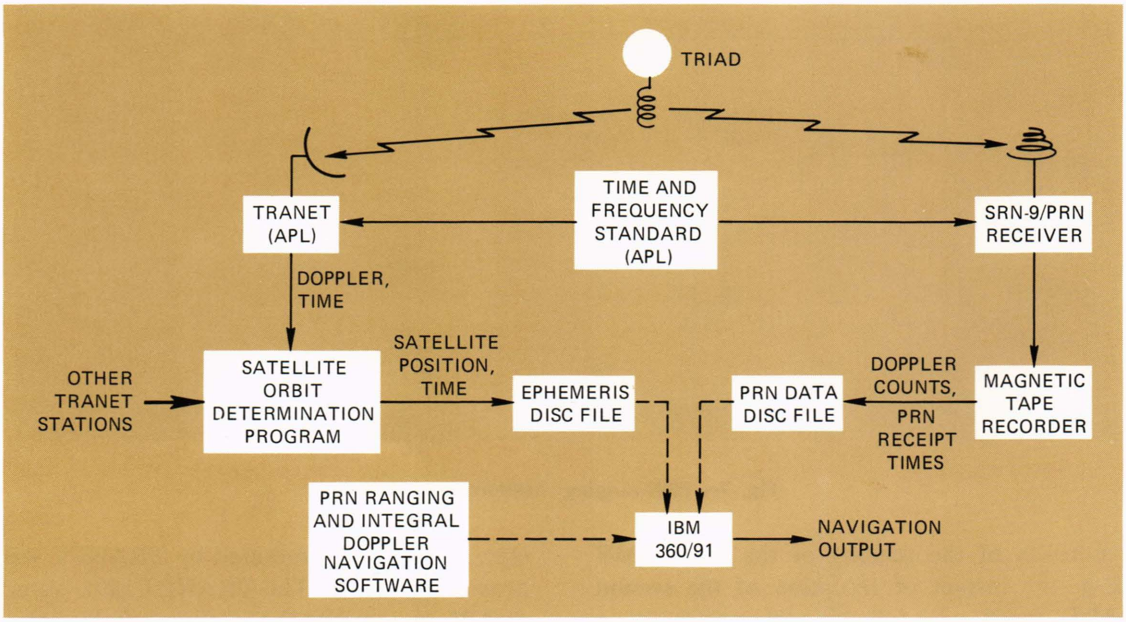

Fig. 8—Elements of the PRN data-gathering system.

Fig. 9—PRN ground system.

fixes in eliminating the large first-order effect of ionospheric refraction.

Short Data-Span Integral Doppler Navigation— The most accurate navigation fix uses all of the measured data gathered over the interval of the full pass of the satellite. If additional fixes are computed using less than the full data set, a different, and therefore more erroneous, navigated position will be obtained. The changes in navigated position (relative to the full-pass navigated position) with changes in the length of measurement data span are illustrated in Fig. 10.

Each of the plotted points in Fig. 10 represents RMS values obtained in dual-frequency integral doppler fixes obtained in 55 passes of TRIAD at APL. The first point plotted at 23.0-sec data span represents a fix based on only the five 4.6-sec doppler intervals best centered about the instant of closest approach of the satellite. Subsequent points represent fixes obtained by adding 4.6-sec intervals to each end of the original five-interval data set.

The solid curve in Fig. 10 connects points which represent fixes based on the full-accuracy doppler data. The dashed curve represents fixes in which the full-accuracy doppler counts were purposely truncated as they are in conventional SRN-9 integral doppler receivers. The navigated positions obtained from conventional receivers

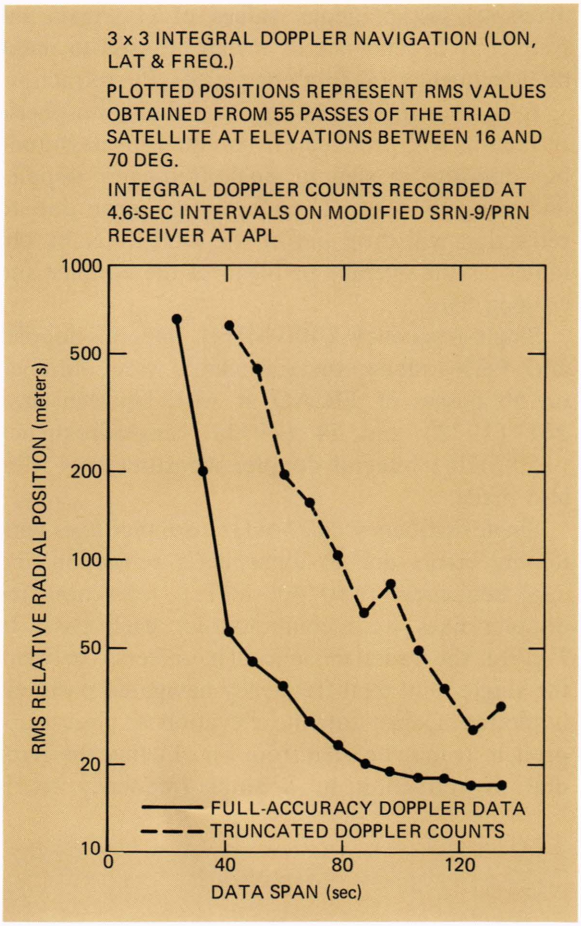

Fig. 10—Observed changes in navigated position versus data span.

would even lie above the dashed curve since the doppler measurements would have less precise timing.

The change in navigated position for an 80-second data span is only 20 meters for the PRN-timed, non-truncated doppler data but nearly 100 meters when the truncated doppler data are used. Even larger changes would be expected were the timing precision degraded to the level existing in many conventional integral doppler receivers.

Comparison of Dual-Frequency Integral Doppler and PRN-Ranging Navigation—PRN-ranging data at 150 and 400 MHz were obtained on five of the early passes of TRIAD. Thereafter, a malfunction of the computer on TRIAD prevented the 150-MHz PRN code generator in the satellite from being turned on. However, 400-MHz PRN-ranging data have been obtained on more than 80 passes of TRIAD. The loss of the 150-MHz PRN channel has not significantly impaired the demonstration that PRN-ranging navigation—both single- and dual-frequency—offers nearly the same high accuracy as that obtained in integral doppler navigation.

The available dual-frequency ranging navigation results obtained with five passes of TRIAD at APL are summarized in Table 2. For each of the five passes there are listed the coordinates at closest approach: year; day; hour (GMT); min; satellite elevation; and quadrant (N and S for north- and south-going satellites; E and W for passes east and west of the navigation station). Also given: the minimum elevation cutoff limit in degrees for data used in the doppler and ranging fixes; the total number of data intervals and points used in the doppler and ranging fixes, respectively. The relative longitude and latitude coordinates in Table 2 give the coordinates of the PRN-ranging navigation fix relative to the integral doppler fix.

The first navigation results obtained with TRIAD (Passes 1, 2, and 3 in Table 2) were very encouraging. The good results of Pass 2 did not seem to be accidental and this belief was greatly strengthened when the results of Passes 4 and 5 were obtained on the following day.

Table 2

NAVIGATED DUAL-FREQUENCY PRN-RANGING POSITION RELATIVE TO NAVIGATED DUAL-FREQUENCY DOPPLER POSITION IN FIVE PASSES OF THE TRIAD SATELLITE AT APL

Coordinates at Closest Approach							*Elevation Cut-Off (°)*		*Data Pts.*		*Rel. Position (m)*	
Pass	*Year*	*Day*	*Hour*	*Min.*	*El*	*Quad*	*Dop*	*Ran*	*Dop*	*Ran*	*△Lon*	*△Lat*
1	72	261	1	24	42	NE	0	0	143	135	−138.6	−7.3
2	72	261	13	38	59	SE	7.5	0	135	105	7.9	2.3
3	72	261	15	20	16	SW	7.5	0	65	61	−53.0	−102.2
4	72	262	2	38	37	NW	7.5	0	106	99	−32.1	−19.5
5	72	262	14	48	28	SW	7.5	0	121	111	−6.4	5.6

The relatively poor showing in Passes 1 and 3 is explained in part by the fact that the 416-kHz PRN code was used on both carriers in Pass 1 (for the only time) and in Pass 3 about one-half of the ranging data points fell below 7.5°.

The results from the five passes in Table 2 standing by themselves may not be wholly persuasive as to the near-equivalence of dual-frequency doppler and dual-frequency PRN-ranging. However, the DOPRAN results in fifty passes to be presented next, consistently imply PRN-ranging performance comparable to that observed in Passes 2, 4, and 5.

Comparison of Single-Frequency (400-MHz) DOPRAN Navigation and Dual-Frequency (150/400-MHz) Integral Doppler Navigation—The technique employing dual coherent frequencies to eliminate the measurement errors due to the first-order ionospheric refraction effect in integral doppler navigation has been proven to be very effective. It does, however, require the use of dual-frequency antennas and navigation receivers. An alternative single-frequency scheme, discovered in the course of the TRIAD navigation experiments (DOPRAN navigation) is almost equally effective in compensating for the first-order refraction effect.

The physical reason for the success of DOPRAN arises from the difference (in the ionosphere) between two fictitious variables called the phase path length, denoted by *P*, and the group path length,[4] denoted by *G*. The variables *P* and *G* differ from *S*, the true slant-range between satellite and receiver, by the first-order ionospheric range error *R*. The approximations in

$$P = S - R \text{ and } G = S + R \qquad (1)$$

are correct to within a few meters[5] at 400 MHz.

The refraction error $R \geqq 0$ in Eq. (1) is proportional to the integrated density of electrons over the vacuum path between satellite and receiver and also inversely proportional to the square of the transmitted carrier frequency.

Integral doppler measures changes $\triangle P = \triangle S - \triangle R$ in the phase path length. The frequency dependence of $\triangle R$ is exploited in making dual-frequency integral doppler corrections for ionospheric refraction. PRN-ranging on the other hand measures instantaneous values of *G*. Again the frequency dependence of *R* can be used to make dual-frequency ranging corrections for refraction.

It is also implied by Eq. (1) that ionospheric refraction will produce errors equal in magnitude but opposite in sign in single-frequency doppler and ranging fixes. Therefore, the error due to refraction will drop out of the DOPRAN fix obtained as the average or mean of the doppler and ranging fixes.

Single-frequency (400-MHz) integral doppler and PRN-ranging measurements were obtained on 50 passes of TRIAD at APL between days 261 (1972) and 54 (1973). Single-frequency (150-MHz) integral doppler measurements were also made.

Single-frequency (400-MHz) doppler fixes containing errors due to ionospheric refraction and dual-frequency (150/400-MHz) refraction-free doppler fixes were computed for each pass. In Fig. 11 the radial distance (in meters) between the single- and dual-frequency navigated positions is plotted against satellite elevation at closest approach. It may be seen from Fig. 11 that the error due to refraction in a single-frequency fix is

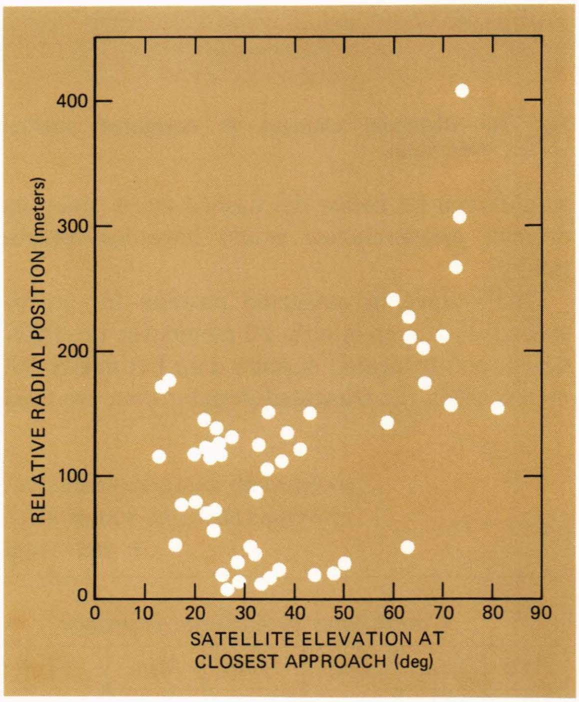

Fig. 11—Single-frequency (400-MHz) integral doppler navigated position relative to dual-frequency (150/400-MHz) integral doppler navigated position in 50 passes of the TRIAD satellite at APL.

[4] R. S. Lawrence, C. G. Little, and H. J. A. Chivers, "A Survey of Ionospheric Effects Upon Earth-Space Radio Propagation," *Proc. IEEE* **52**, 1964, 4–27.

[5] V. Schwab, *Phase, Ray, and Group Path Lengths in the Ionosphere*, APL/JHU Memo S1A-177-71, Aug. 1971.

greater than 100 meters in more than half of the passes. The error tends to be larger at high elevations, and in one pass at 74° the error is greater than 400 meters.

For each of the same 50 passes a single-frequency (400-MHz) PRN-ranging navigation fix was computed. The single-frequency doppler and ranging fixes were then averaged to produce a 400-MHz DOPRAN fix. The radial distance between the 400-MHz DOPRAN-navigated position and the dual-frequency (150/400-MHz) integral doppler position is plotted against satellite elevation in Fig. 12 for each of the 50 passes. Note that the vertical scale in Fig. 12 is ten times larger than the scale in Fig. 11.

In more than half of the 50 passes, the agreement between the 400-MHz DOPRAN and 150/400-MHz integral doppler fixes is better than 10 meters. The agreement is consistently poorer at low elevation angles due to the higher noise sensitivity of ranging navigation in this region. The reason for the exceptional "wild point" at 81° elevation has not been determined.

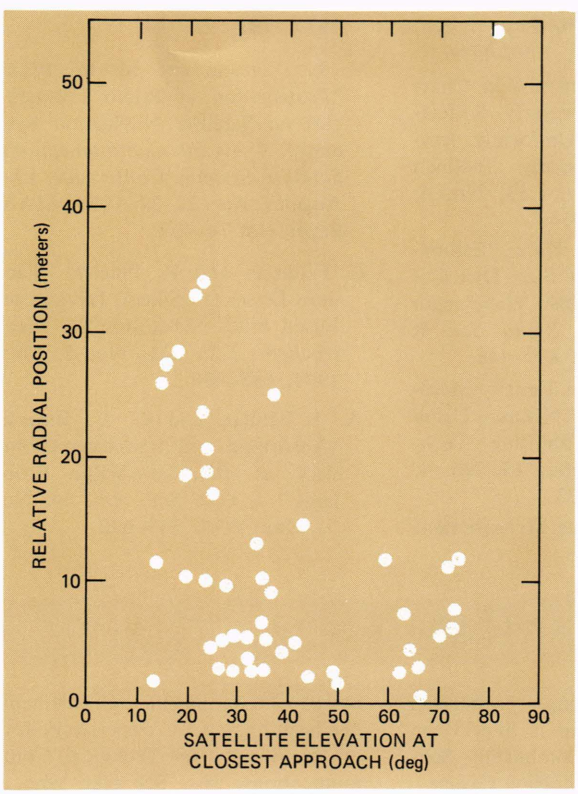

Fig. 12—Single-frequency (400-MHz) DOPRAN navigated position relative to dual-frequency (150/400-MHz) integral doppler navigated position in 50 passes of the TRIAD satellite at APL.

Figure 13 is a bullseye plot of the same 400-MHz DOPRAN-navigated positions relative to the 150/400-MHz integral doppler navigated position.

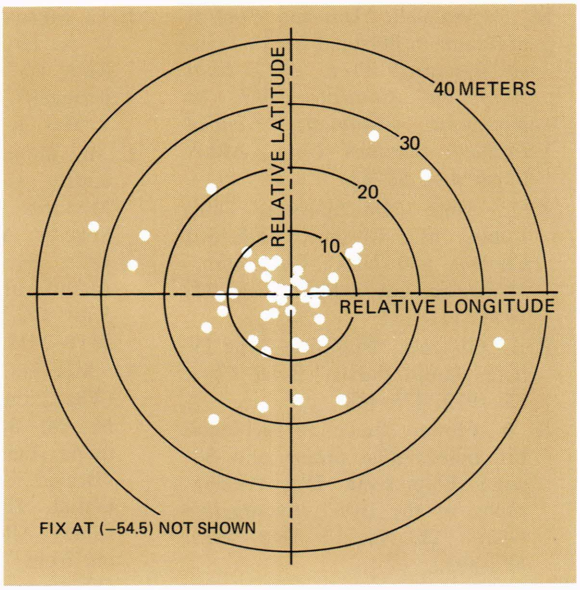

Fig. 13—Cartesian plot of single-frequency (400-MHz) DOPRAN navigated position relative to dual-frequency (150/400-MHz) integral doppler navigated position in 50 passes of the TRIAD satellite at APL.

Conclusions

The significance of the PRN results reported here lies in the influence they may have on the evolution of future satellite navigation systems. There appear to be many uses for precise timing in navigation and time transfer, although all are not yet formally defined.

The TRIAD experiments also demonstrate that, by means of PRN modulation, satellite timing signals can be transmitted and received with nanosecond precision and still be compatible with the relatively crowded frequency channels at 150 and 400 MHz.

Acknowledgement

The measurement and data recording portions of the SRN-9/PRN receiver were designed by R. J. Heins and built by R. Yost. C. J. Monahan produced many of the computer programs required to handle the measurement data. Finally, R. E. Jenkins and S. C. Dillon computed the TRIAD ephemerides required by the navigation programs.