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RFI-Source Location

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ABSTRACT

A method to determine unknown RFI-transmitter site coordinates based on Doppler-shift measurement using the LES-8 or LES-9 satellites and previously existing pieces of ground hardware and software is described. Test cases were run to evaluate the procedure. Several RFI sources have been located. A description is given of the satellites, ground hardware, and software (as they pertain to the location technique), along with results of the site-location experiments.

A second method of site location, the terminator-motion technique, is presented. It is based on a satellite rising and setting as seen from the unknown RFI-transmitter site. Restrictions on this technique are discussed and results of a test case are presented.

This report was originally Classified. It is being reissued with corrections of a few minor errors and misprints.

ACKNOWLEDGMENTS

The authors of this report wish to thank the many people involved in the RFI project, without whose help the work would have been impossible. In particular, we wish to thank W.W. Ward, who originally came to us asking for suggestions on how we might go about locating an RFI source with the resources available, and L.D. Collins for his suggestions and assistance in implementing the Doppler-shift technique with existing hardware and software. For their technical assistance with the software and post-processing of the data, we wish thank J.V. MacPhee, M.E. Ash, R. King, C.E. Small, and C.R. Curley. We also wish to acknowledge the data-gathering help provided by B.W. Barrett, H.H. Hoover, and A.P. Richard. Finally, we wish to thank W.W. Ward for his editorial assistance with this report.

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1. INTRODUCTION

In June 1977 there began a series of incidents in which use of the LES-9 wideband UHF-to UHF transponder (SCOPE DAWN operational mode) was interfered with by a strong uplink signal of unknown origin near 303.5 MHz. This RFI signal came and went with a semi-regular duty cycle. It was occasionally CW, but it was usually modulated in various ways. Estimates of the RHCP EIRP of the transmitting facility producing this RFI signal (made by the techniques used for the FLTSAT spectrum scans,) yielded as much as +25 dBW (~300 W) at times. This RFI signal had ceased to bother LES-9 by September 1977, perhaps because of the continued slow eastward drift of the satellite during that period*. In December 1977 LES-9 began its 0.3°/day transfer from approximately 34° west longitude to its newly assigned station at 95° west longitude. A few weeks after this thrusting, the uplink RFI signal near 303.5 MHz commenced to give trouble again, perhaps because LES-9 had moved back into a region where this transmitting facility was radiating significant power. The RFI signal became quite strong, although it could be overwhelmed in LES-9's transponder limiter by a brute-force signal from Lexington (transmitter power up to 1 kW, 30-ft-diameter/23-dBI-gain antenna atop Building B).

After the initial occurrence of this RFI, ESD/DCKT (the office responsible for the LES-8/9 Joint Test Program, in progress at that time) submitted two MIJI incident reports (#77-492) to AFEWC/EWI. Following the reappearance of the RFI, TROC (the segment of AFCS that manages LES-8 and LES-9 on a day-to-day basis in their SCOPE DAWN operational phase) submitted an additional MIJI incident report (#78-039). TROC pointed out that LES-9 would have limited usefulness if this RFI could not be mitigated.

Shortly after this RFI problem first arose, LL began to develop special techniques to locate its source, assuming the RFI signal to come from a single fixed ground facility of some sort. The approach is basically an inversion of the Navy's TRANSIT navigation-satellite system. In that system, a receive-only terminal (such as a ship) records the Doppler-shift curve as it listens to stable CW radiation of known frequency from a satellite passing within view in a comparatively low-altitude polar orbit. The satellite also transmits its current orbital elements. The terminal then crunches all the numbers together and estimates where it must have been during the satellite pass in order to have experienced the Doppler-shift curve that was actually observed. U.S. Patent #3,063,048 (Figure 1), which was filed early in the TRANSIT era, proposed a similar technique. In that system (known as SARUS — search-and-rescue using satellites), the CW signal from a transmitter at an unknown location (specifically, a locater beacon in a life raft or downed aircraft) is relayed through a polar-orbiting satellite. Subsequent data-processing makes possible determining the location of the transmitter. The SARUS concept has been revived recently and will apparently be realized by NASA using piggyback packages on satellites such as TIROS (Reference 1). There will be wide international participation (Canada, France, USSR, etc.) in this program for satellite search-and-rescue (SAR).

*Also, the site producing this signal might have gone out of operation at that time.

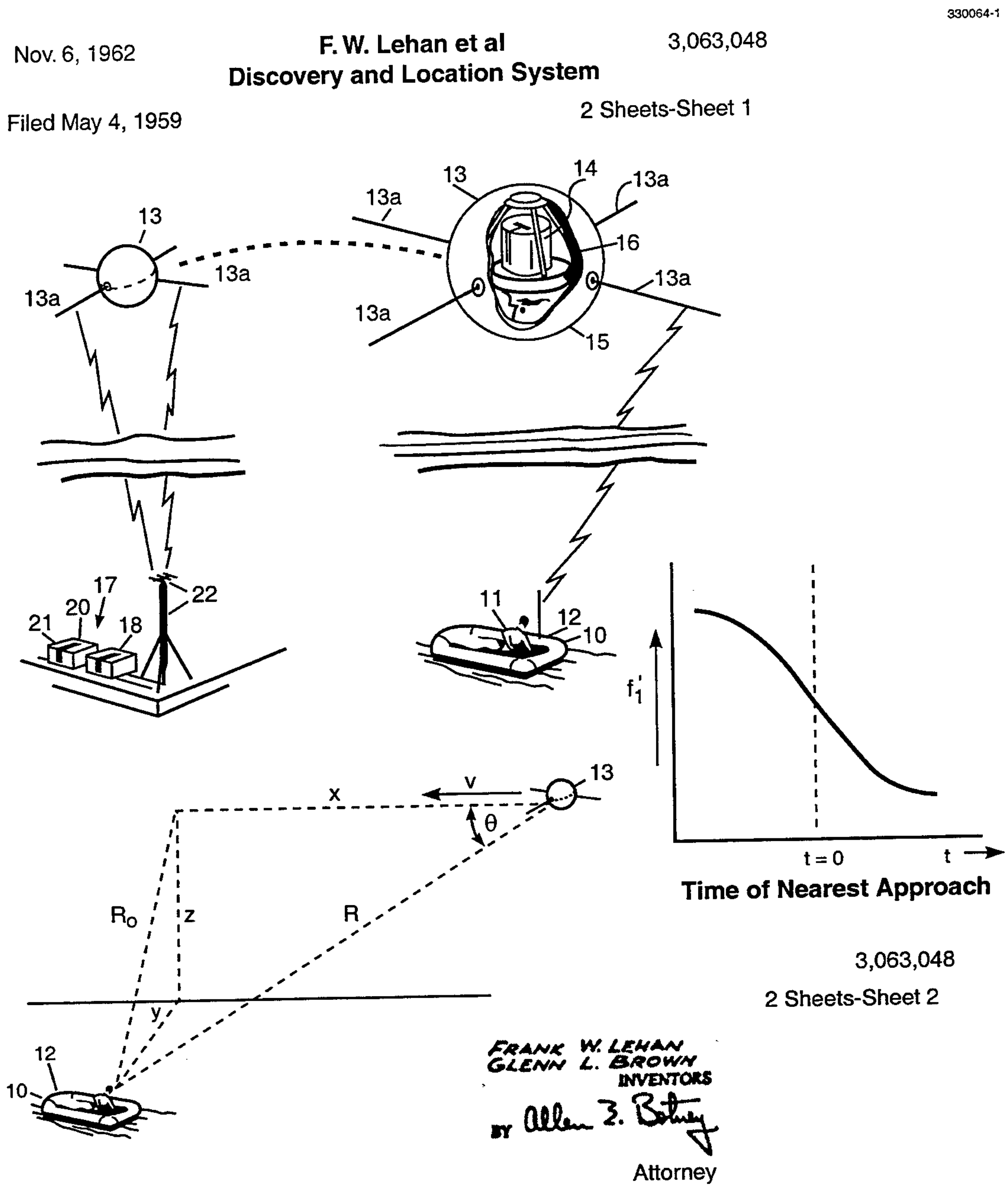


Figure 1. Diagrams from the SARUS patent.

What LL has done is to make use of the daily round-trip excursions of either LES-8 or LES-9 between 25° north latitude and 25° south latitude, that motion corresponding to the motion of the SARUS/SAR satellite in its polar orbit. The problem is more difficult using LES-8/9 because the range and angle rates for those satellites are much lower, with correspondingly lower Doppler shifts. However, LES-8/9 observation intervals can extend over much more that the several minutes for a SARUS/SAR pass within view of the transmitting facility.

The technique used to locate a transmitter site is based on the fact that, knowing the orbital path of the LES-8 or -9 satellite, there exists a unique Doppler-shift curve for each point on the Earth visible to the satellites. The actual mechanics of determining the transmitter site coordinates involves extracting, recording, and computer-processing Doppler-shift data from the RFI signal (see Figure 2). The RFI signal is first received by the satellite, by tuning the satellite uplink frequency-synthesizer to the desired frequency in the STOP mode. Using the sample channel in the satellite, the received signal at IF is separated into two quadrature components, each of which is one-bit quantized. The resultant I and Q bits are then multiplexed onto the K-band downlink. The Lincoln Laboratory K-band ABNCP terminal receives this downlink signal and recovers the I and Q bits exactly as they were in the satellite. The IF signal is reconstructed by using the I and Q bits to modulate an appropriate LO signal. The resulting reconstructed IF signal can be displayed on a spectrum analyzer to show bandwidth, spacing, modulation, etc. As this signal is a reasonably faithful replica of the uplink signal received by the satellite (aside from the frequency translation from RF to IF), it can be recorded, demodulated, and otherwise studied in any manner desired. In effect, a private listening post has been established within the satellite, for the uplink signal is not transponded to the Earth terminal in a readily recognizable form.

For the purposes of RFI-source location, the reconstructed IF signal is further processed to extract Doppler-shift and frequency-offset data, which are recorded on magnetic tape. The tape is then read into the planetary-ephemeris compute program (PEP) (Reference 2) which, when given sufficient data, can remove any frequency offset and fit the Doppler-shift signature to determine a specific transmitter location on the Earth's surface.

The sections that follow give a more detailed description of the hardware and software at Lincoln Laboratory used for RFI-source location purposes.

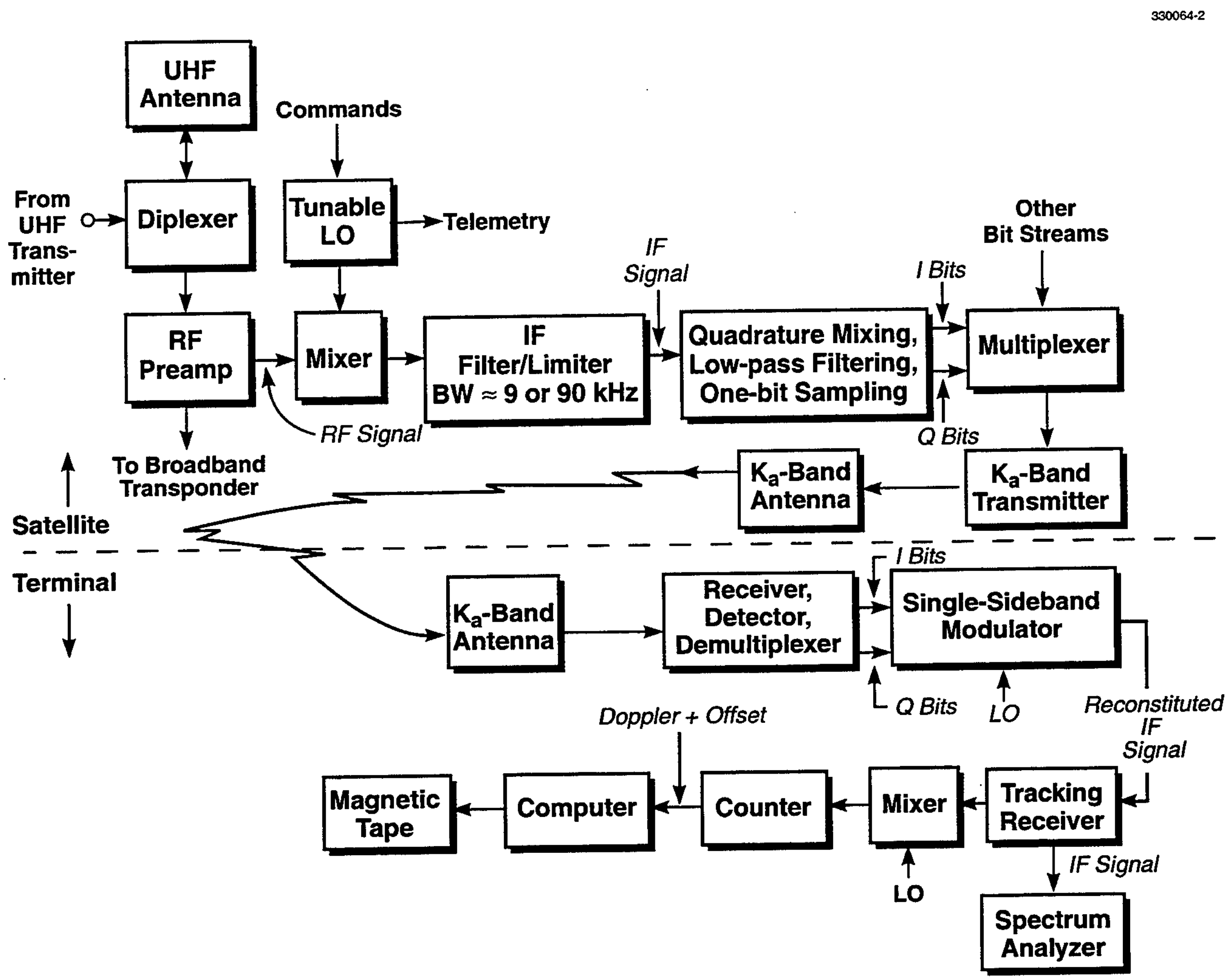


Figure 2. UHF-to-K_a-band analog transponding by LES-8/9 for RFI-source location.

2. HARDWARE

No provisions were made in the design of the LES-8 and -9 satellites to directly measure Doppler shift and telemeter this data to a receiving station. The hardware used in the RFI-source location effort was pieced together from existing equipment which had been built for other projects, but was adapted to the task with only minor reconfiguration. As previously discussed, the Doppler-shift recording technique employed involves sampling the received uplink signal in the satellite and retransmitting the information content of the uplink signal back to Earth at a different carrier frequency, where it is received, reconstructed, and processed. Figure 2 shows the essential portions of the measurement technique.*

In the satellite portion of the hardware, the received UHF uplink signal is mixed with a tunable local oscillator (LO) which can be programmed via ground command over the ~102.4 MHz band of LES-8/9 in steps of ~195 Hz. [Since the finest resolution of the tunable synthesizer is ~195 Hz, a constant error up to (+) or (–) ~100 Hz can be introduced which must later be removed in the post-processing.] The limiting UHF uplink frequencies for which the frequency synthesizer can be set by command are 297.2 MHz and (399.6 MHz – 195 Hz).

RFI source location using the Doppler-shift technique and LES-8 or LES-9 would be possible at K_a-band over the respective different ~102.4-MHz hopping bands of these satellites. The limiting K_a-band uplink frequencies are

	Lower	Upper
LES-8	(36.7364 GHz + 195 Hz)	36.8388 GHz
LES-9	38.0412 GHz	(38.1436 GHz – 195 Hz).

As the Doppler-shift coefficient [Hz/(meter/sec)] at K_a-band is about 100 times that at UHF, the technique should work quite well in that frequency range. Up to this time, Lincoln Laboratory has not carried out any source-location experiments at K_a-band, however.

The mixed output is bandpass-filtered (BPF) to help reject unwanted signals and is limited for gain-control purposes. Figure 3 shows the IF block diagram in more detail. The choice of the 8.9 or the 88-kHz filter to provide better selectivity and sensitivity depends on the bandwidth of the uplink signal. The approximate uplink signal frequency (f_0) can be determined by appropriately programming the uplink synthesizer. Figure 4 shows the implementation of the procedure, which is useful in the initial stages of system set-up. Using the 8.9-kHz BPF and monitoring the receiver output power on real-time telemetry

*The actual recorded data represents Doppler shift plus any drift of the transmitter oscillator, plus technique-introduced offsets. Given sufficient data and a reasonable transmitter-oscillator drift rate, the post-processing program can extract the pure Doppler shift. UHF uplink Doppler-shift precorrection by a transmitting site is highly unusual and would cause this set-up to yield erroneous results. The term Doppler shift in this report refers to Doppler shift plus offsets.

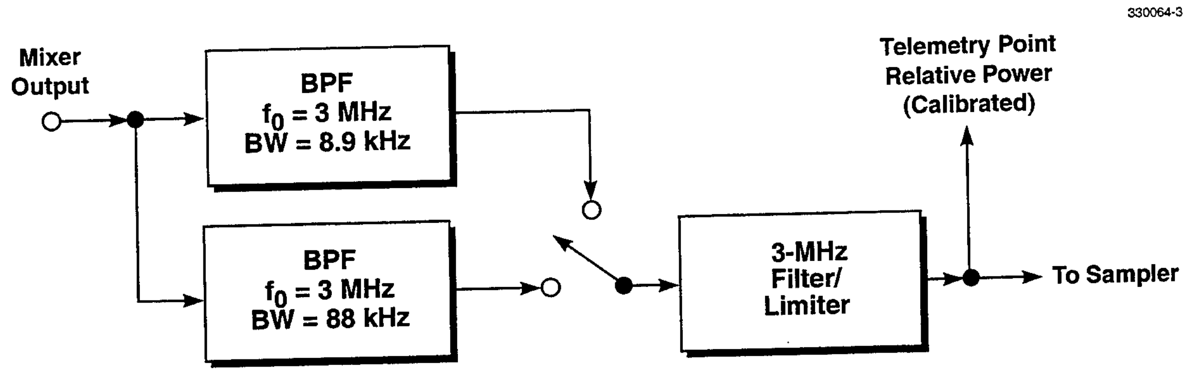
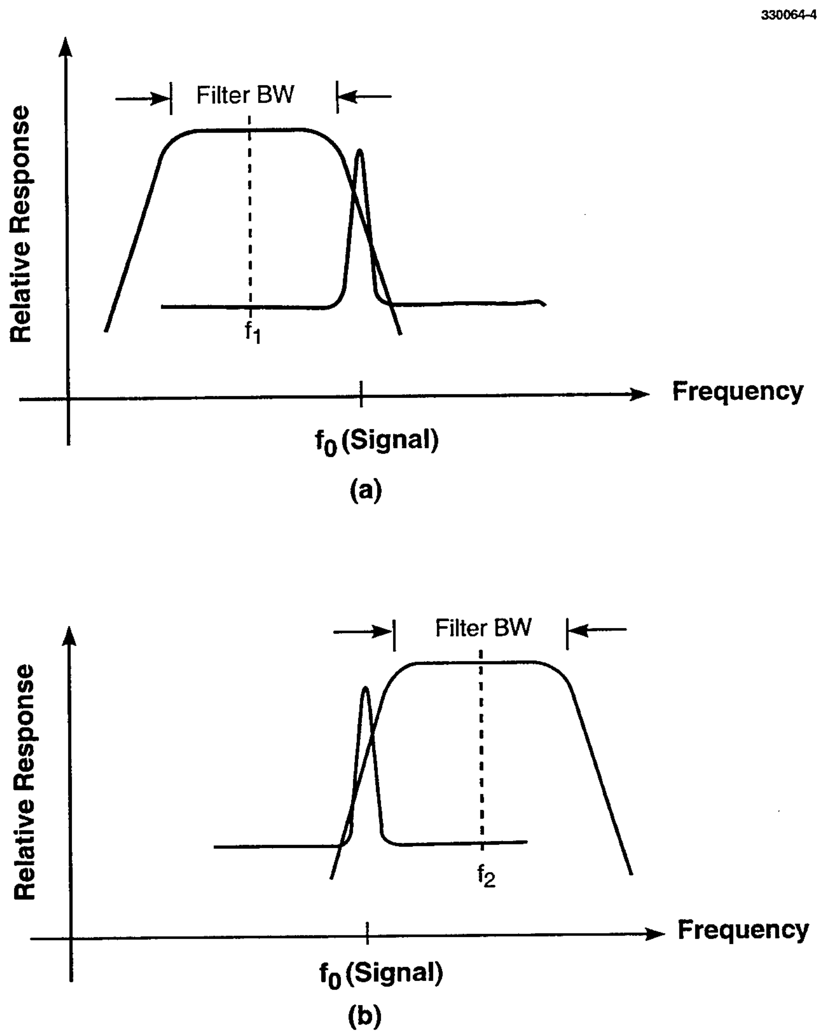


Figure 3. Satellite IF block diagram.



$$\text{Bandwidth} \approx |f_1 - f_2| - (\text{Filter BW})$$

$$f_0 \approx \frac{f_1 + f_2}{2}$$

Figure 4. Center-frequency and bandwidth estimation.

(Figure 3), the uplink synthesizer is moved until the signal is no longer detectable and the receiver uplink center frequency is recorded (f_1). The synthesizer is then moved in the opposite direction through the signal peak, until the signal is again not detectable (f_2). The carrier (f_o) is thus approximately

$$f_o \approx \frac{f_1 + f_2}{2} \tag{1}$$

A rough estimation of the uplink signal bandwidth (BW) can be determined by

$$(\text{signal BW}) \approx [f_1 - f_2] - (\text{filter BW}) \tag{2}$$

This approximation is sufficient to determine if the 8.9 or 88-kHz BFP should be used. Programming the uplink synthesizer to f_o and choosing the proper filter assures easier signal lock-on at the ground station.

The IF signal out of the BPF/limiter circuit is then quadrature-mixed, low-pass filtered, one-bit quantized, and sampled to produce a digital stream of I/Q bits. Figure 5 shows a more detailed diagram of this block. Sampling theory states that if the sampling rate is greater than twice the maximum-frequency component in the signal being sampled, then the original signal can be exactly reproduced from the samples. The sampling rates in the satellites are 5 k or 50 k samples per second (depending on the choice of the 8.9 or 88-kHz BPF respectively). Because of the quadrature mixing which precedes the sampling and the fact that I and Q are simultaneously sampled, the effective sampling rate is 10 ksps and 100 ksps. Thus sampled signals with bandwidths up to 5 or 50 kHz can be reconstructed.

To better understand the sampling process, consider a CW transmission with Doppler shift (f_o+f_d). The uplink synthesizer is first tuned to the transmitter frequency, assuming no frequency-standard or tuning offsets. Figure 6a shows the signal (f_o+f_d) into the quadrature mixer. The LPFs following the mixer eliminate all products except the difference frequencies, which are shown in Figures 6b and 6c. These signals are related to the phase differences between the uplink signal and 0° and 90° mixer LOs. Assuming that $f_o = f_{LO}$, then the I and Q difference frequencies are entirely due to Doppler-shift. The I and Q signals are next one-bit quantized by zero-crossing detectors (Figures 6d and 6e) and sampled. The samples are then combined into a single bit stream (Figure 6g) and multiplexed with other bit streams and telemetry within the satellite. This multiplexed bit stream DPSK-modulates a K-band downlink carrier signal.

The ground portion of the Doppler-shift measurement technique (Figure 7) begins with the reception of the K-band downlink signal from the satellite via a 4-ft-diameter paraboloidal antenna. The signal then proceeds through a receiver, a DPSK demodulator, and a demultiplexer to recover the I and Q bit streams as they appeared in the satellite. The demultiplexed I and Q signals are used to QPSK-modulate a carrier signal. The key to this entire technique is the fact that the output of this modulator is a signal equivalent to the IF signal at the output of the IF filter/limiter in the satellite (Figure 2) except for the phase quantization introduced by the one-bit I/Q quantization. The actual LO frequency used in the modulation is unimportant provided it is stable, so as not to introduce any frequency errors.

The reconstructed IF signal is then fed into a tracking receiver which locks onto and tracks the center of the spectrum. The tracking receiver provides an IF output signal suitable for viewing on a spectrum analyzer, as well as outputting a signal which has the tracking-LO frequency plus Doppler-shift.

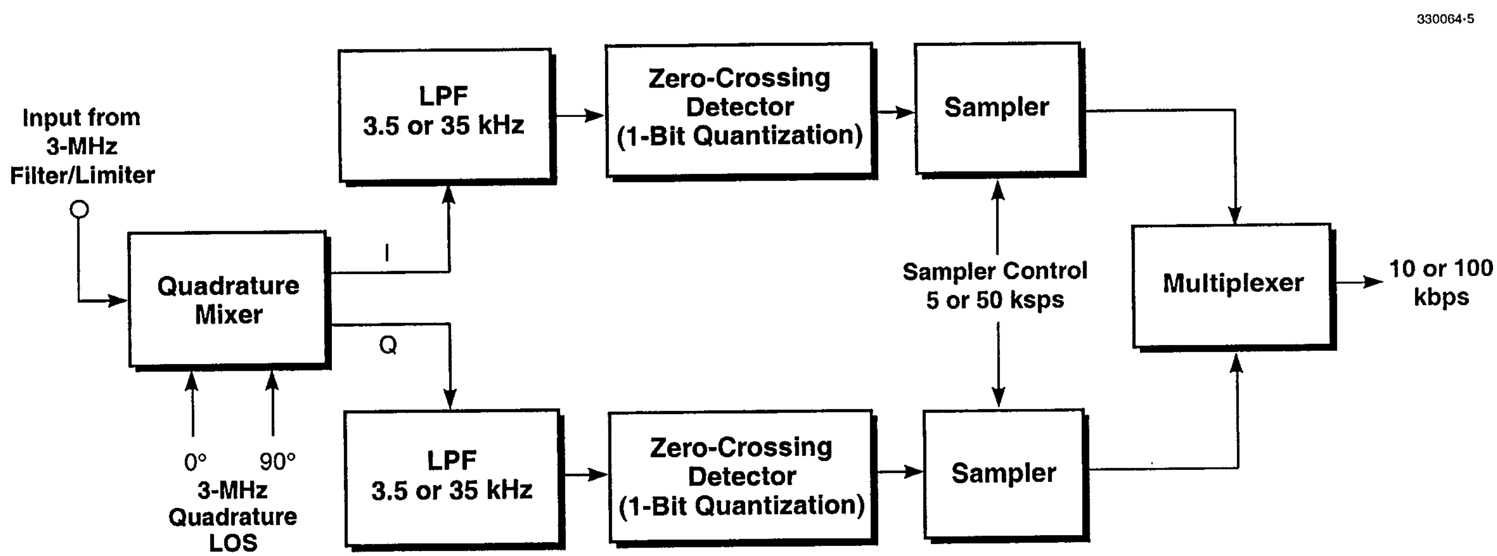


Figure 5. Satellite sampling.

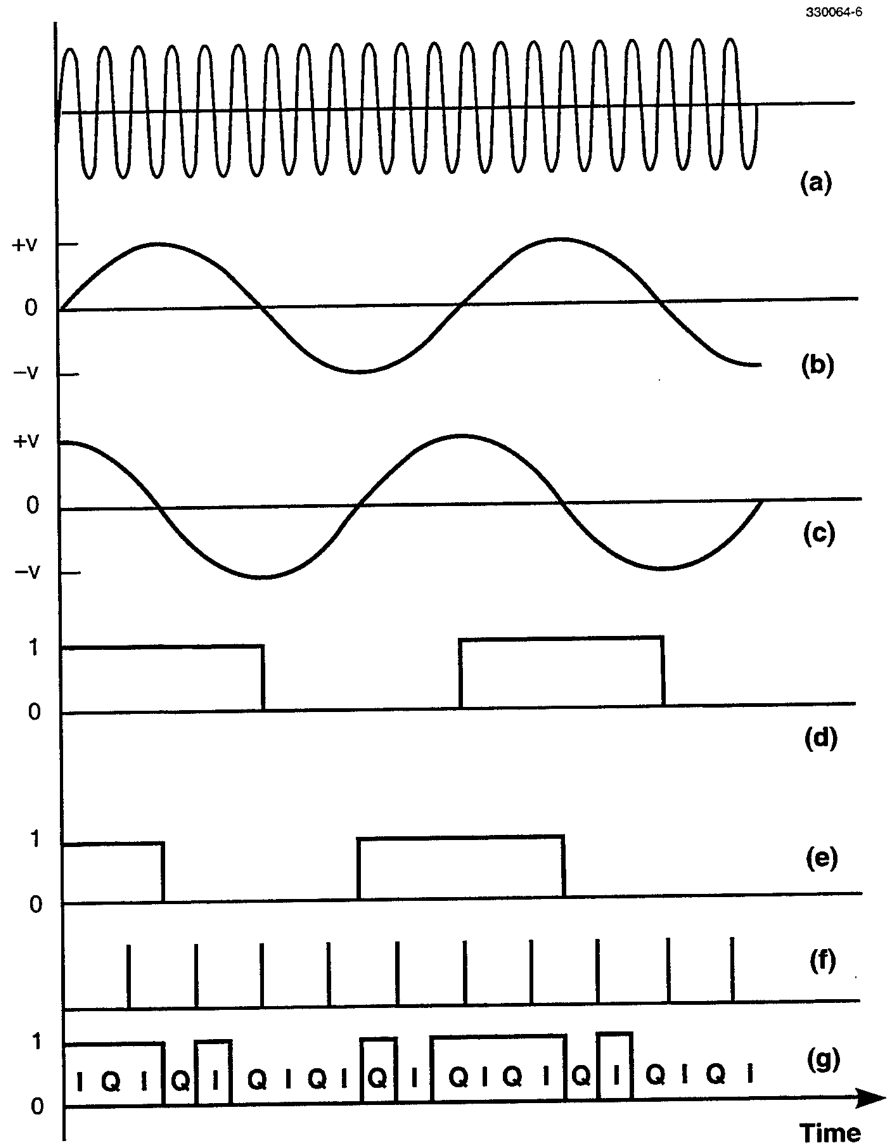


Figure 6. Satellite processing of CW signal with Doppler shift.

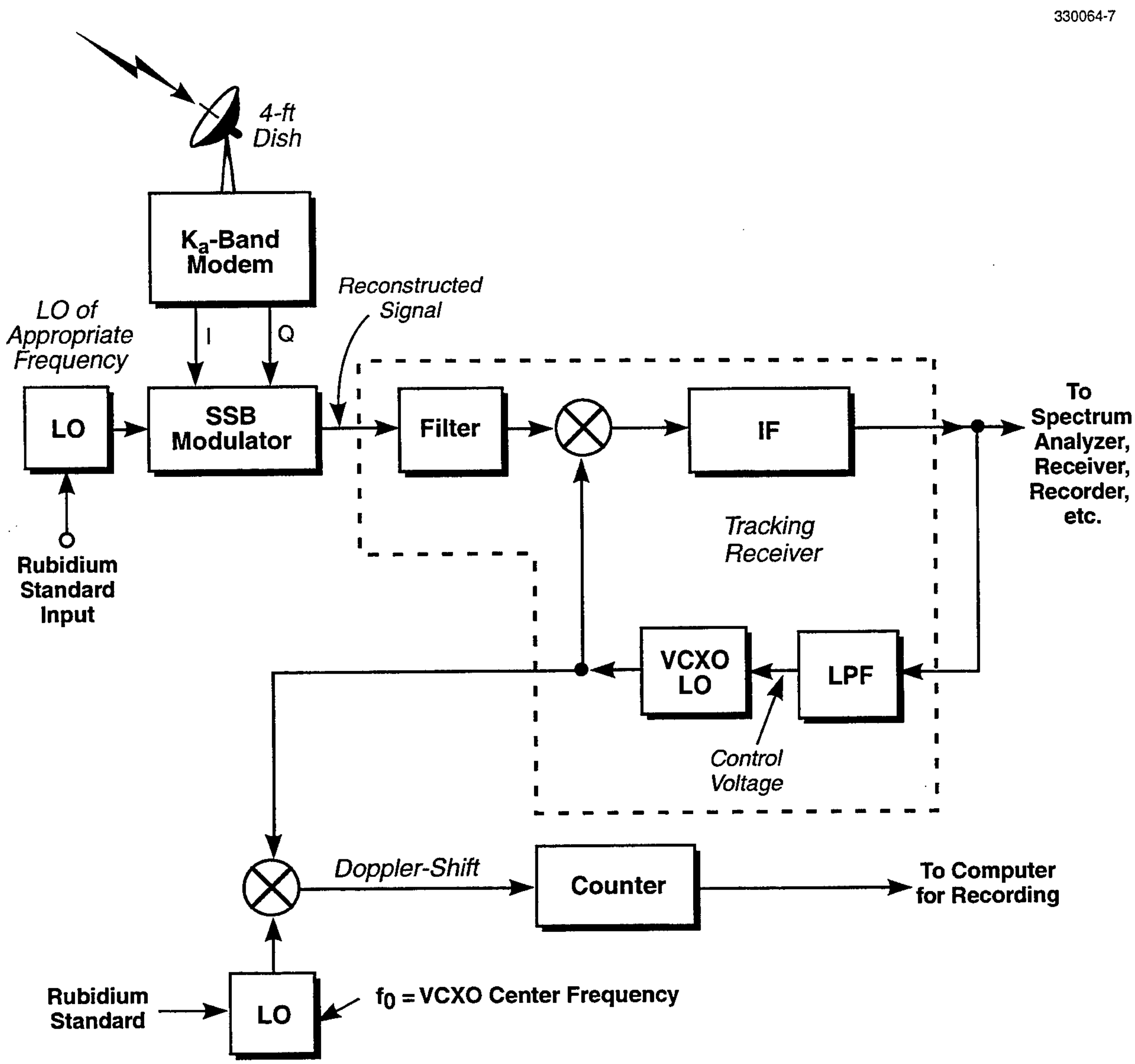


Figure 7. Ground-based hardware for RFI-source location.

This (LO plus Doppler shift) frequency signal is then mixed with an appropriate LO signal and the Doppler shift, by itself, is then available to be counted and recorded on magnetic tape for later processing.

The sign of the Doppler shift is based on the phase-angle relationship of I and Q as shown in Figure 8. By assigning each quadrant to one of the four possible states of I and Q, and given a one-bit change in an I or Q value, the sign can be determined by comparing the previous sample with the present sample. Each quadrant change is counted by an up-down counter over a one-s interval to obtain an accurate measure of the Doppler shift. Because each of the four quandrant transitions can be counted, the system resolution is 1/4 Hz.

There are some restrictions on the measurement technique and its accuracy. Although the satellite can handle several types of modulation, the limiter in the satellite IF section precludes the reconstruction of AM signals. The Doppler shift could still be measured, however.

As previously mentioned, what has been referred to as Doppler shift is really Doppler shift plus transmitter, satellite, and receiver frequency offsets. Frequency offsets are introduced in the satellite due to the fact that the uplink synthesizer is tunable in only ~195-Hz-spaced center frequencies. The LES-8/9 satellites and LL ground hardware contain highly accurate frequency standards with excellent long and shortterm stabilities* which introduce only very small frequency errors. Since the satellite and ground frequency errors are known to be small, the recorded frequency offset is almost entirely due to Doppler-shift plus satellite synthesizer error, plus RFI transmitter carrier-frequency change. At this point, two assumptions are made about the transmitter site –

(1) It is either stationary on the Earth's surface or moving at a rate relative to the satellite which generates a Doppler shift much less than that associated with a stationary site relative to the satellite.

(2) The transmitter carrier frequency is not being purposely changed.**

With these assumptions and enough data over a sufficient period of time, the post-processing program can extract the pur Doppler shift from the recorded data.

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*Satellites ≈ $5{:}10^{10}$/month
Terminals ≈ $1{:}10^{11}$/month (K_a-band)

From LL TR698, p.1, for the satellite-borne oscillators, the short-term stability is "better" ("less") than $6{:}10^{9}$ per 100 μs. Long-term drift is less than $1{:}10^{11}$/day.

**A transmitter could change its carrier frequency systematically such that the Doppler-shift profile would make the transmitter appear to be located elsewhere.

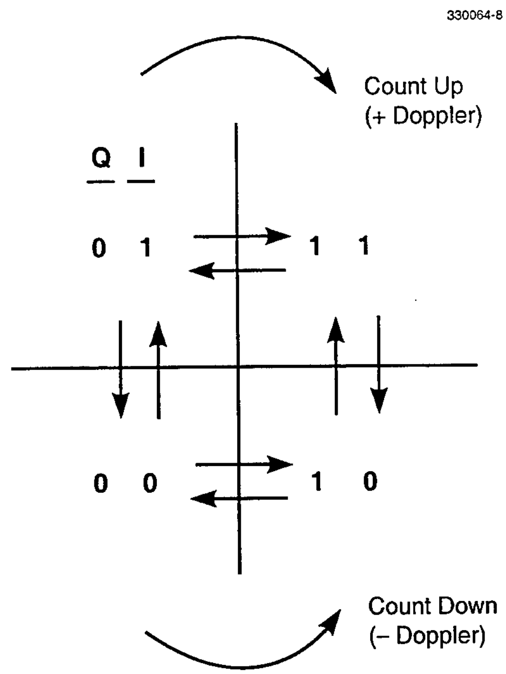

Figure 8. Relationship between I and Q states and Doppler-shift sign.

3. POST-PROCESSING OF DATA

After the RFI data is recorded on magnetic tape, its post-processing is done by computer programs written for use in the LES-8/9 program, which have been modified to do the required data reduction. The ideal situation would be to record data over a 24-hour interval, but because of time constraints, availability of manpower, schedules, and the RFI transmission periods, this is not always possible. The accuracy of the site prediction is a strong function of the stability of the RFI transmitter's carrier frequency and the amount of data recorded. The recording need not be continuous over a single time period, but may be segments of a few hours each over several days.

The previously described ground hardware puts the raw data on magnetic tape. Figure 9 shows the processing procedure in flow-chart form. The tape is first pre-processed to eliminate any large erroneous data points and to smooth the remaining data. If necessary, the data can be smoothed by hand and entered manually into the program. The ground system records one-way Doppler shift in Hz, but the Planetary Ephemeris Program (PEP), the program which estimates the location of the transmitter site, requires two-way Doppler-shift data. The pre-processing also does this conversion and outputs two-way Doppler-shift data for use by PEP.

The pre-processed data is next written on a disk file and printed to allow visual inspection. This step is taken to insure that the data is within reasonable limits and that the hardware and recording equipment were functioning properly. Data intervals in which known hardware and recording errors occurred are edited from the file, and the remaining data is put through a plotting program that plots data vs time.

The data plots are then used as a guide to determine an initial estimate of the RFI-source locations. Every point within the satellite viewing area has a unique Doppler-shift signature which is more or less sinusoidal in nature. Knowing the orbit of the satellite and its sub-satellite longitude and latitude, the viewing area can be divided into a number of regions (Figure 10). Each region has a different characteristic curve, which varies slightly depending on the actual site longitude and latitude. By studying these basic curves and comparing them with the RFI Doppler-shift data for variations in amplitude and times of zero-frequency crossing, the region in which the RFI site most likely exists can be inferred, and a point can be chosen as an initial estimate. This initial point, along with the recorded data and an initial value for the RFI frequency (derived from an algorithm using calculations of known LES-8/9 values and various test-equipment values), are all inputted to PEP. A (geocentric) spherical-coordinate system relative to the center of the mass of the Earth is used by PEP, with parameters of radius in kilometers, west longitude in degrees, and north latitude in degrees. Initially, the radius is held constant and the program solves for longitude, latitude of the transmitting site, and center frequency.

The accuracy of the initial site estimate which must be provided can be enhanced if a point or points of zero frequency on the Doppler-shift curve can be determined. These points correspond to zero Doppler shift between the LES-8/9 satellites and the transmitting site. Since this can only occur when the satellite is moving perpendicular to its line-of-sight to the transmitting site, a locus can be drawn on a map of the Earth's surface (with a satellite ground track superimposed) giving a reasonable estimate of

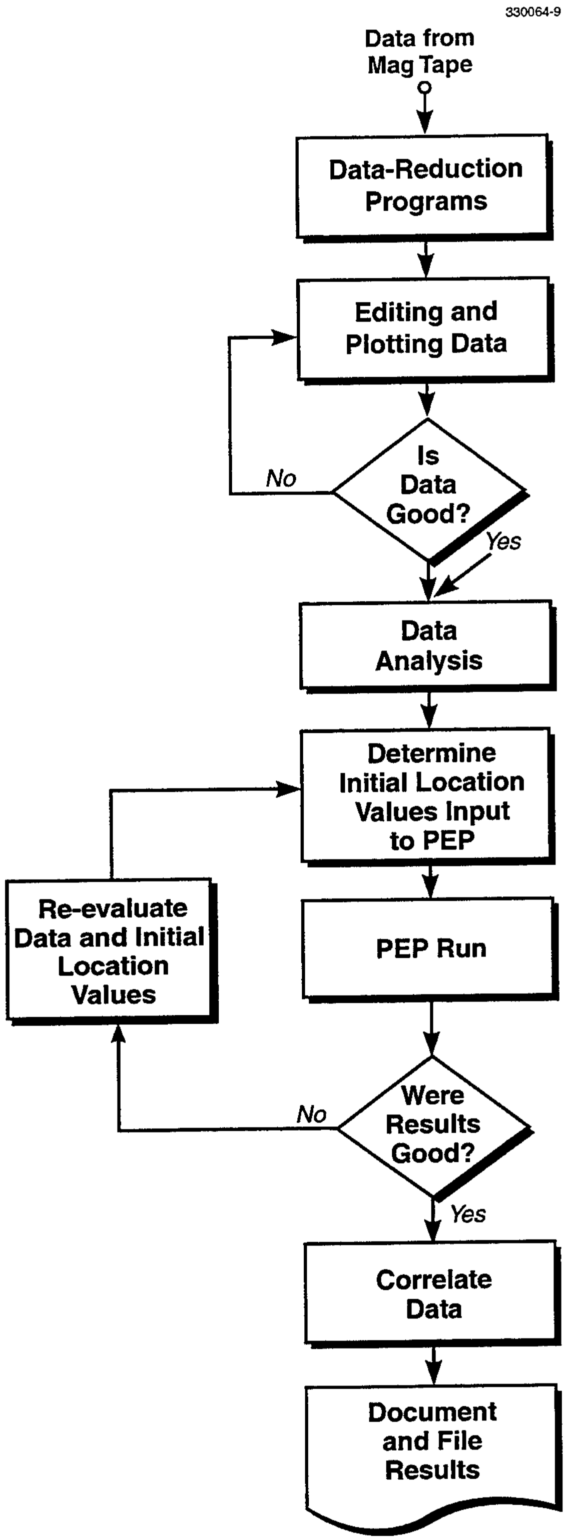

Figure 9. Post-processing flow chart.

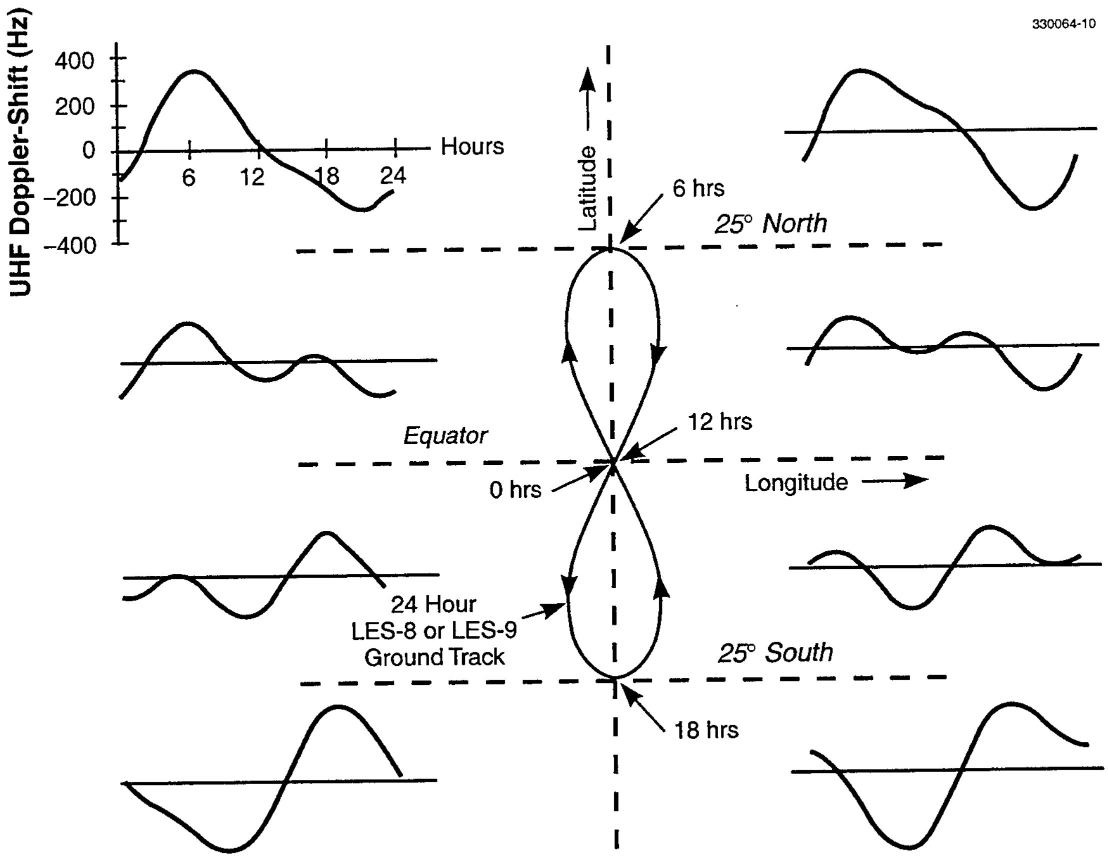

Figure 10. Characteristic Doppler-shfit curves for eight regions in the area of satellite coverage.

the curve along which the site must lie. If two such zero-slope points are known, two loci can be drawn, and the intersection would represent an estimate of the site location. This procedure has limited absolute accuracy. Any combination of zero Doppler-shift points, whether recorded within one 24-hour period or over a longer period (even the same point one or more days apart), can be used.

Recalling that the term Doppler shift as used in this document actually represents a frequency change due to many factors, the processing requires extraction of the pure Doppler shift from the recorded data. Since a maximum Doppler-shift value exists in the UHF domain, based on comparison of recorded data with characteristic curves as in Figure 10, the data can be adjusted by a fixed frequency offset to insure that the maximum excursions fall within the known maximum range. If sufficient data is recorded to determine a zero-frequency crossing point, fixed frequency biases can be reduced since the offset is known. This, however, is generally not the case and a judgment must be made.

If a slow RFI-transmitter oscillator-frequency drift exists, as is likely, the problem becomes slightly more complex. One of three methods can be employed to help solve this problem. The simplest procedure is to record data on two or more successive days over the same time interval. If no drift existed, the data should be identical (with a 4-min earlier day-to-day time correction due to the LES-8/9 satellite orbits); thus any difference is due to the drift of the transmitter oscillator. Once the drift rate has been determined, this information can be entered into the PEP processing.

The second method to determine the drift rate involves first obtaining program convergence with a fixed frequency offset and then attributing some portion of the resultant difference between predicted and observed frequencies to RFI-transmitter oscillator drift. With this drift-rate estimate, another computer run of the data can be made with this information as an additional program input. This process can continue iteratively until as tight a convergence as desired is obtained.

If data exists over several days, a third solution involves ignoring the entire issue of drift rate as a PEP input since the program will do a least-squares-fit on the data and will effectively eliminate the drift rate.

PEP was originally designed to process observations of the Sun, Moon, planets and interplanetary spacecraft (Reference 2). Modifications were made at Lincoln Laboratory so that PEP can handle Earth satellites. This large, complex program ran on the Laboratory's IBM-370/168 system. A primary use of PEP at Lincoln has been to generate sets of accurate orbital elements for LES-8/9 satellites for a considerable time into the future.

It is beyond the scope of this document to give a complete understanding of the PEP computer program; for such an explanation, the reader is referred to Reference 2. In general terms, however, a typical PEP computer run attempts to determine satellite orbital elements (semi-major axis, eccentricity, inclination, ascending node, argument of perigee, and mean anomaly) based on observations of the satellite from Earth. With the LES-8/9 satellites and ground-based hardware, the observation data, recorded on magnetic tape, can include (1) range information which is based on the time delay of a signal transmitted up to the satellite and back down, with the satellite and ground-terminal induced time delays removed; (2) differential range based on integrated coherent Doppler shift, from which Doppler shift can be derived by taking the derivative of the integrated coherent Doppler shift; and (3) azimuth and elevation angle to the satellite. Not all these quantities can be recorded simultaneously; ranging and differential ranging based on coherent Doppler shift are mutually exclusive. Time and weather conditions (temperature, pressure, relative humidity, and index of refraction*) are also recorded on the tape. The data is then pre-processed to correct for anomalies and biases prior to being input to PEP along with initial estimates of the satellite's orbital elements. Based on the recorded data, the program performs iterative calculations to determine orbital elements which best fit the data. The process continues until specified convergence criteria are met. The final orbital elements can then be used as an ephemeris data base from which future predictions of range, azimuth, elevation angle, and range rate (or Doppler shift) can be derived for any given site coordinates to some reasonable accuracy.

The orbit-fitting process involves taking initial satellite conditions, along with real-time satellite tracking data from a known site, and implementing the above process, resulting in adjusted initial conditions and a refined orbit. In processing RFI-source data, instead of solving in essence for a new orbit, a known orbit is used and the interactive process solves for the site coordinates. If the error bars associated with the results are not acceptable, further refining of the data and/or introducing a better initial site estimate may be necessary. The PEP output yields a set of site coordinates which best fit the data presented to the computers, but the accuracy of the results is highly dependent on the quality and quantity of data.

Based on insight from looking at many Doppler-shift plots (as in Figure 10) and after processing much data, it would appear that the behavior of the peaks of the Doppler-shift curves is strongly associated with the latitude of the transmitting site while the times of the zero-frequency crossings of the curves are associated with its longitude. Thus, in taking the RFI data, these are the most important parts to record as they best "nail down" the Doppler-shift curve. Without knowledge of these sections of the complete 24-hour curve, PEP has more freedom to fit the recorded pieces to an arbitrary curve and thus the final site coordinates have larger errors associated with them.

*These quantitites are usually set to nominal default values, but can be used if the orbit-fit precision requires.

4. RESULTS

In September 1977 and again in April 1978, to check out the hardware and software previously described to locate a transmitter source, a CW tone was transmitted from Lincoln Laboratory to LES-9 and was recorded and processed. Figure 11 shows the actual (calculated) Doppler-shift curve for Lincoln Laboratory on the day of the test and the measured data. The location technique was shown to work, with the result that with only three hours of data, the transmitter site was predicted to within ~0.01° latitude and 0.05° longitude (see Figure 12). More data over a longer time period would have yielded even better accuracy. This was a best-results test in that both the transmitted uplink signal and the local-oscillator signals in the satellite and terminal receiver were derived from very stable (independent, of course) frequency standards.

In September 1977, additional source-location experience was obtained by tracking a UHF signal in the uplink frequency band to which LES-9 could tune. The signal was recorded (Figure 13) for approximately nine hours (over three days during the same time period) with the results indicating the transmitter site to be located at 100.29° west longitude and 26.23° north latitude. It was later verified that a site transmitting at the frequency in question was indeed located at 99.17° west longitude and 26.06° north latitude, near Los Guerra, Mexico. Figure 14 gives a tabulation and comparison of the results, while Figure 15 shows the reconstructed CW signal which was tracked.

A third test was conducted in November 1977, with a transmission from the TROC site at Brandywine, Maryland. Figure 16 shows the actual Doppler-shift curve for the TROC site and the measured data. With the five hours of data, the site was located to within ~1.63° in latitude and ~2.46° in longitude (see Figure 17). Figure 18 shows the reconstructed (a) binary frequency-shift-keyed (BFSK) signal and the (b) CW tone transmitted by the TROC site during the test.

The RFI at 303.5 MHz which originally prompted this entire source-location effort comes and goes. Many hours of data were recorded, but there were only three time intervals during the day when the signal appeared somewhat periodically. The signal had a large oscillator drift of approximately 100 Hz of sinusoidal frequency variation (period ~90 minutes) riding on the Doppler-shift curve (see Figure 19). Initial speculation was that the oscillation might be caused by a transmitter in an airplane making large, slow orbits; but the numbers did not fit the hypothesis well. The current guess is that the oscillation simply represents the cycling of a temperature-control element in the transmitter's frequency source. This would indicate a frequency source with a stability of about 3 parts in 10^7 which is sufficient for many practical applications.

After processing the data as recorded and also after much pre-processing and smoothing, PEP would choose a site location, but with large error bars around it. All attempts to tighten the final answer failed to pinpoint a single location, which forced a highly conservative estimate of the transmitter site to be given as an area 60° west longitude to 76° west longitude by 12° south latitude to 15° south latitude (see Figure 20). Some time later it was learned that a communications network existed in Peru (area unspecified) using a frequency of 303.5 MHz.

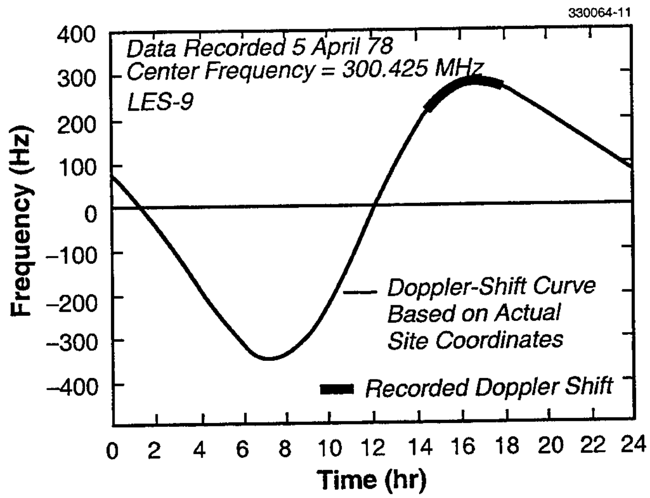

Figure 11. Lincoln Laboratory Doppler-shift curve.

330064-12

	Latitude North (deg)	Longitude West (deg)
Survey Data (Geocentric)	42.27	71.27
Measured* (Geocentric)	42.28	71.32
∣ Error ∣	~0.01	~0.05

*Based on 3 hours of tracking data on a stable CW signal at high (S/N).

Figure 12. Location of Lincoln Laboratory.

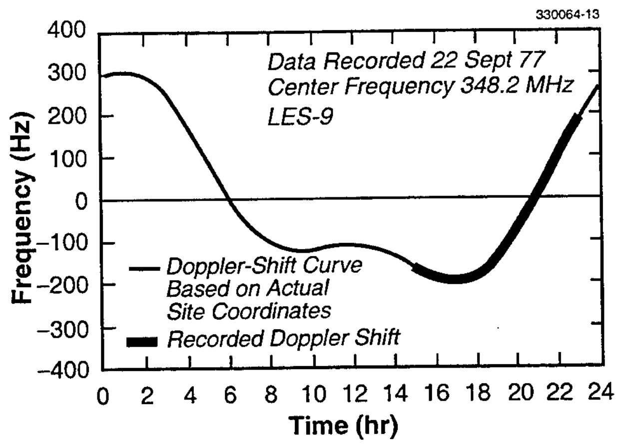

Figure 13. Mexico-site Doppler-shift curve.

330064-14

	Latitude North (deg)	Longitude West (deg)
Actual Coordinates (Geocentric)	26.06	99.17
Measured (Geocentric)	26.23	100.29
|Error|	~0.17	~1.12

Figure 14. Location of Mexico site.

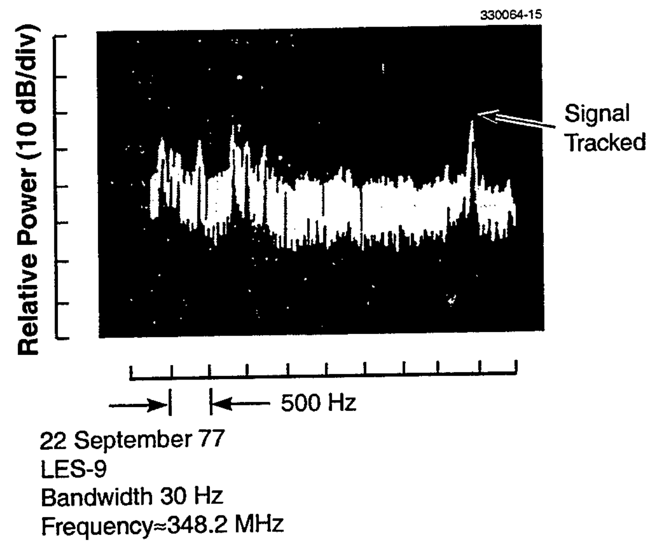

Figure 15. Reconstructed Mexico-site transmission.

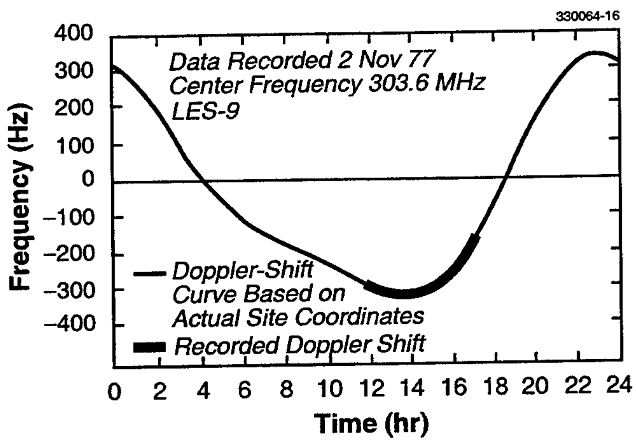

Figure 16. TROC, Brandywine, Maryland, Doppler-shift curve.

330064-17

	Latitude North (deg)	Longitude West (deg)
Actual Coordinates (Geocentric)	**38.49**	**76.84**
Measured (Geocentric)	**36.86**	**100.29**
|Error|	**~1.63**	**~2.46**

Figure 17. Location of TROC, Brandywine.

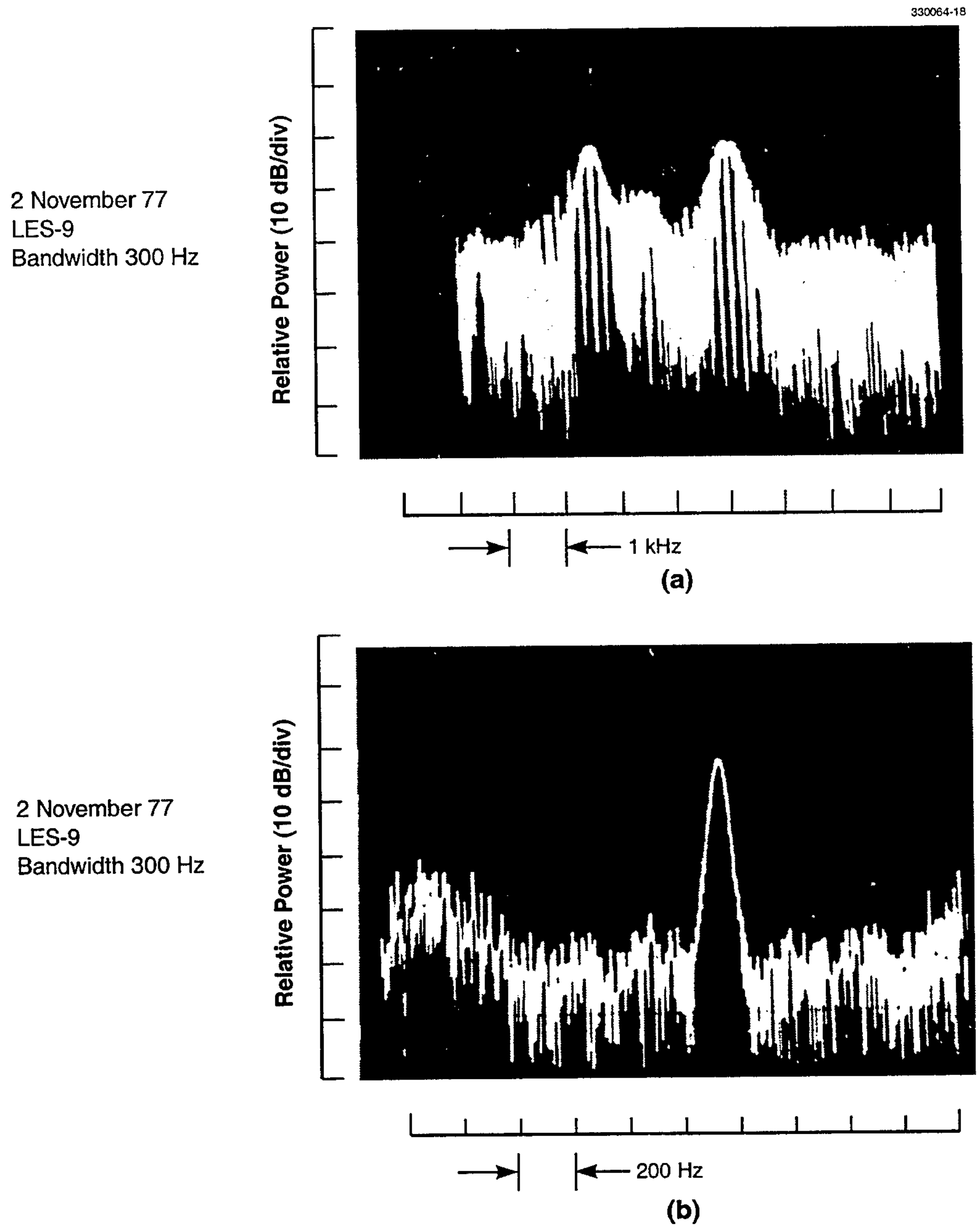

Figure 18. Reconstructed TROC transmissions.

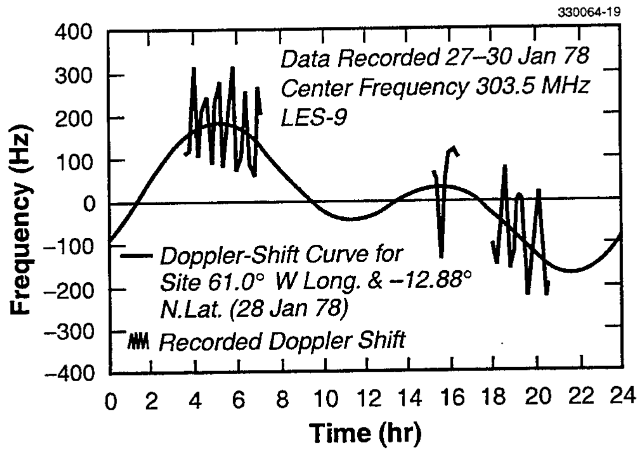

Figure 19. South American Doppler-shift curve.

Figure 20. Speculated location of South American site.

With the equipment assembled for this project, minimum signal levels of +30 dBmW EIRP and +26 dBmW EIRP (satellite sample channel 88 or 8.9-kHz filter respectively) are required for tracking and recording purposes. No precise determination has yet been made as to the quantity and quality of data recorded to achieve location information to a desired accuracy.

5. TERMINATOR-MOTION TECHNIQUES FOR LOCATION OF RFI SOURCES

In conjunction with RFI-source-location work described above, a cooperative test was conducted between an AFCS terminal at Croughton, England, and Lincoln Laboratory. As LES-9 moves in its near-circular, synchronous orbit inclined ~25° to the Earth's equator, the terminator sweeps back and forth over much of the Earth's surface (Figure 21) in a well-determined manner. Subject to several assumptions, it may be possible to infer the location of an uplink transmitting site from the times when LES-9 rises and sets as seen from the site.

The experiment involved Croughton transmitting a UHF CW tone into LES-9 over a 33-hour period while Lincoln Laboratory monitored and recorded the satellite MFSK-channel receiver input power via the telemetry link. The effective rise and set times were then determined from transitions in the post-processed plots of the receiver power (Figure 22). From PEP printouts the satellite positions were determined for these times, which were assumed to coincide with 0° elevation angle from the transmitter to the satellite. A plotting program was then used to overlay the 0°-elevation-angle contours (terminators) on a map. The intersection of the particular rise and set portion of the terminators should be the transmitter location.

One restriction on this location technique lies in the fact that there can exist two places where the rise and set portions of the terminators intersect. Thus, a unique site cannot always be located in this manner, but some further study and thought may lead to the elimination of one. Even if one site cannot be ruled out, with only two sites to start searching, the number of possibilities (corresponding to the entire satellite coverage area) has been greatly narrowed.

In the case of a satellite in low-altitude polar orbit, it appears that some other information is required in order to eliminate one of the two points of terminator intersection. Figure 23 shows how two different transmitting sites, at the same latitude but equally distant in longitude from the sub-satellite ground track, are indistinguishable insofar as the terminator-motion technique is concerned. It is possible that consideration of the effects of the rotation of the Earth under the satellite (implicitly neglected in Figure 23) would make it possible to get a unique solution for the location of the transmitting site. That factor is relied on to resolve a similar east-or-west-of-the-ground-track ambiguity in the TRANSIT navigation system.

In the case of LES-8 or LES-9, which have east/west excursions in the ground tracks of their orbits (Figure 10)*, it appears that one of the two points of terminator intersection can always be eliminated, yielding a unique solution. Figure 24 shows schematically how this is done. Attention is concentrated on the halves of the terminators that correspond to the satellite rising and setting respectively.

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*The figure-8 east/west excursions come about because the Earth is rotating under the satellite, around an axis ~25° away from the perpendicular to the orbit plane.

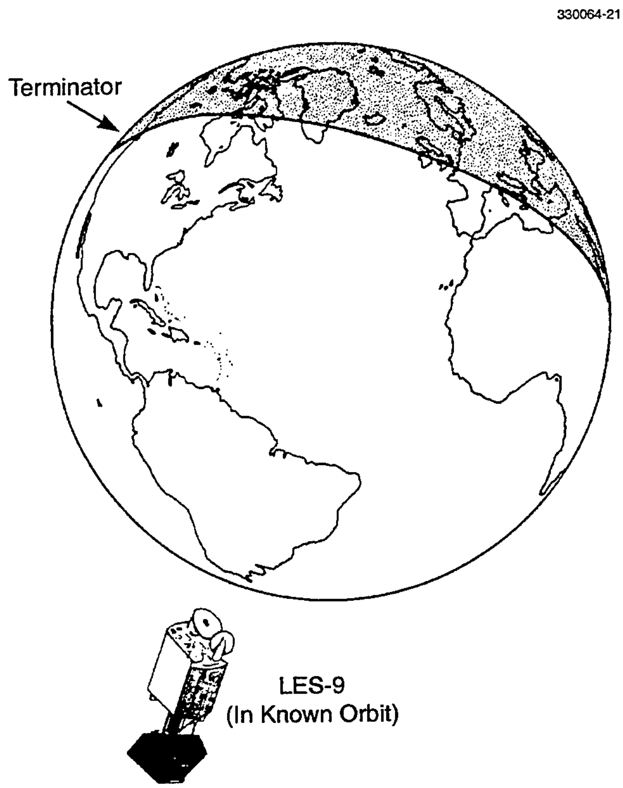

Figure 21. Illumination of the Earth by LES-9 at one point in its orbit.

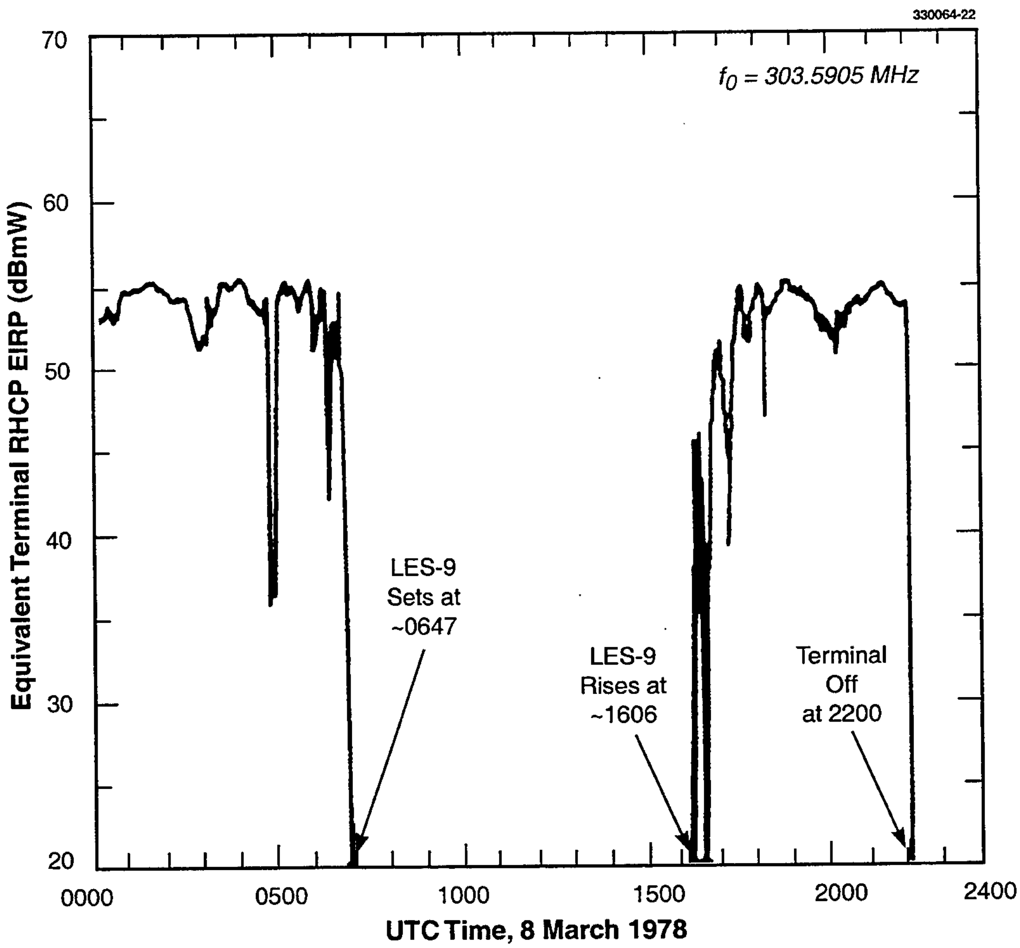

Figure 22. Croughton's CW signal as received by LES-9.

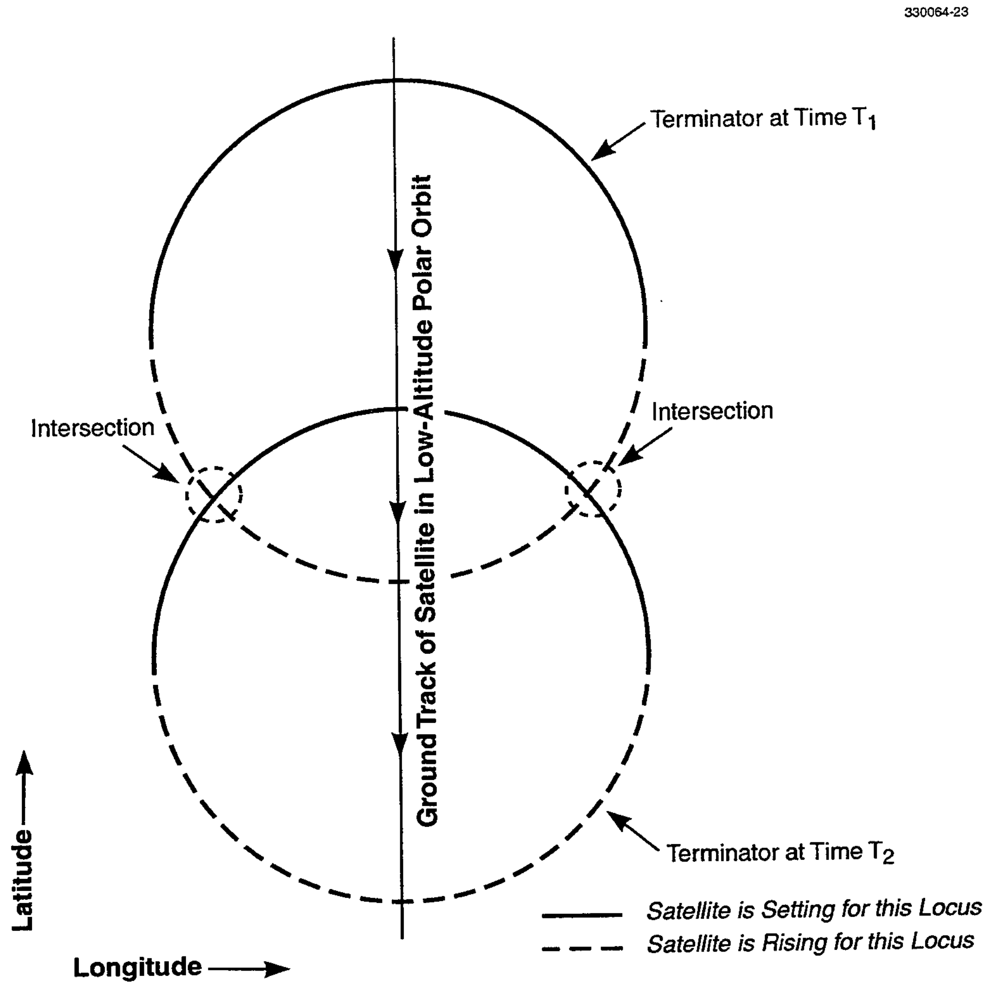

Figure 23. Ambiguous terminator intersections.

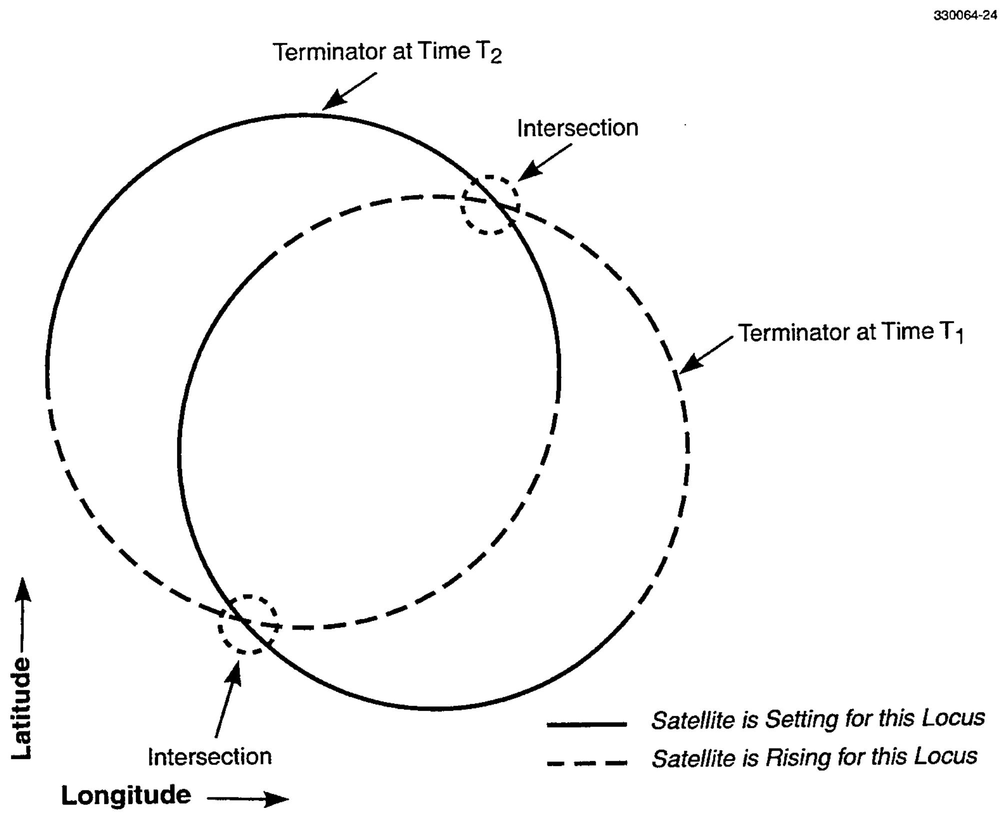

Figure 24. Choosing the unique intersection of the terminators.

Figure 25 shows an expanded view of the area where the rise and set terminators crossed in the Croughton test. Two rises and one set were observed during the test period, making possible two separate determinations of site location. The intersections do not lie quite at the Croughton site, but bracket it. Several factors affected the testing, but the important result is that the intersection of rise and set terminators can be used to determine the approximate location of a transmitting site under favorable circumstances.

A similar experiment was conducted with the SAMSO terminal at Camp Parks, California, but the post-processing of the telemetry showed several irregularities which were sufficient to preclude determining rise and set times.

Here are the assumptions that must be invoked in applying this method of RFI-source location:

(1) The transmitting terminal lies in a region over which the terminator does indeed move. If the satellite never sets or rises in the terminal's sky, the method fails.

(2) The transmitting terminal is ON, at a generally constant level of EIRP (RHCP for LES-8/9), during the times of rise and set. If the terminal is OFF then, no data can be gathered. Furthermore, OFF/ON and ON/OFF transitions might be fallaciously interpreted as rises and sets, leading to meaningless results.

(3) The topography around the transmitting terminal is such that 0° elevation angle does indeed represent the local horizon. A hill along the azimuth from the terminal to the rising or setting satellite could make this assumption untrue, for example. Buildings on site (including other antenna systems) could also interfere with clean, nominal, rises and sets.*

In the case of the Croughton experiment, (2) was assured by the test plan. (1) was a reason for choosing that site. (3) is believed to be true (based on unofficial information) but has not been conclusively verified.

*UHF transmissions are capable of propagation beyhond the geometric horizon.

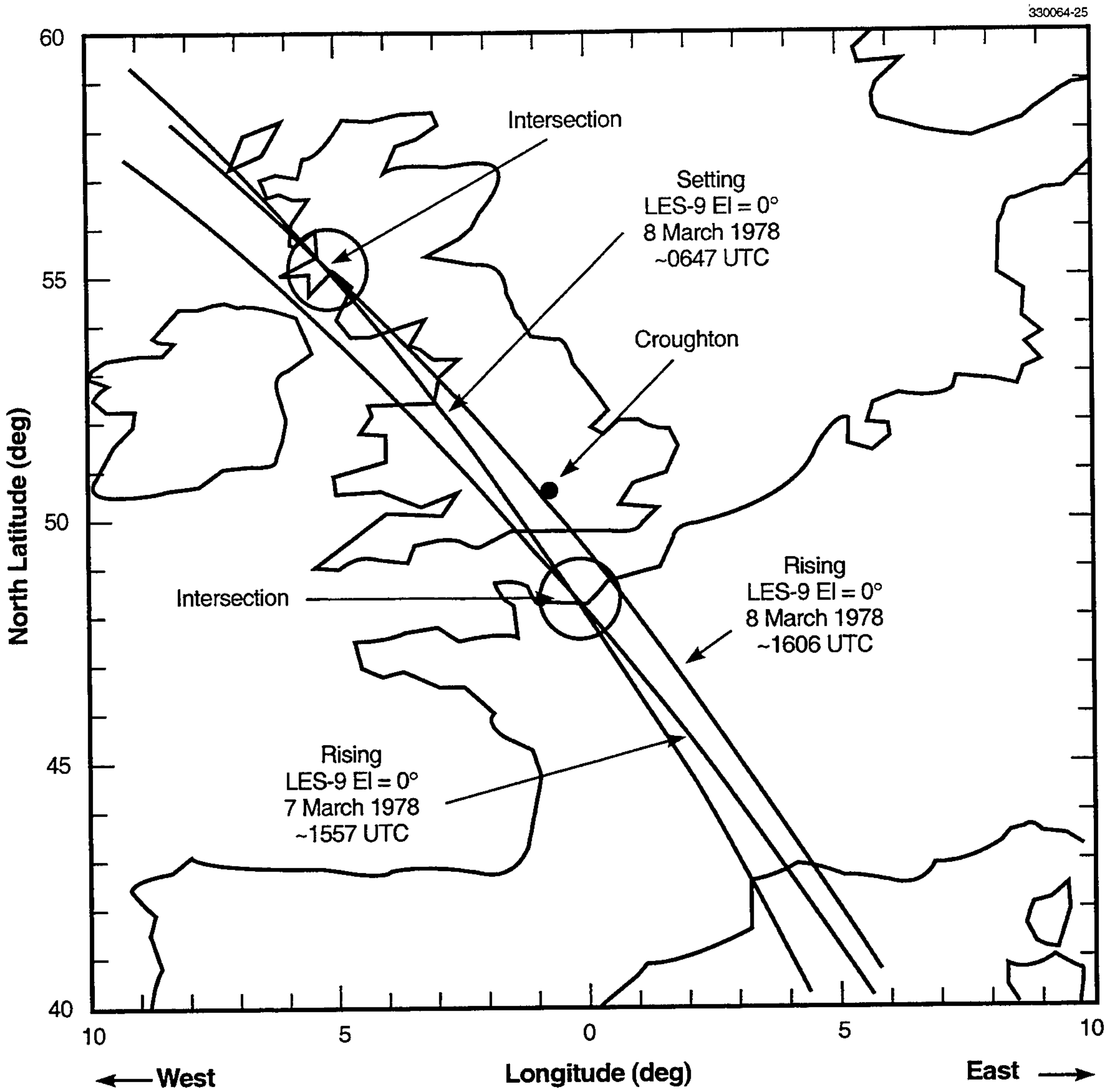

Figure 25. Where is Croughton?

6. OTHER LOCATION TECHNIQUES

Other location methods exist, such as LORAN and TRANSIT, and are well documented in detail in other literature. The LES-8 and -9 satellites could be used to locate a transmitter site by signal-reception differential-time-delay techniques (related to LORAN), provided the signal is being received by both satellites. Again, the theory behind the procedure is documented elsewhere.

In the case of the troublesome RFI at 303.5 MHz in the LES-9 wideband transponder (Section 1), the signal could not be detected by the power-monitoring telemetry point in LES-8's uplink receiver when it was tuned to 303.5 MHz. It was tempting to plot the terrestrial coverage of the two satellites at a particular time when LES-9 heard the RFI but LES-8 did not and to declare that the offending transmitter site must lie in the portion of the LES-9 coverage area that was not being shared with LES-8. However, that would have been leaping to a conclusion. It is possible that the transmitting site lay in the common coverage area of LES-8 and LES-9, but that its EIRP in the direction of LES-8 was so low that the power-monitoring telemetry point could not measure the received uplink signal. That could come about if LES-8 were seen through far-out side-lobes of a directive transmitting antenna, or if terrain features or structures blocked the view to the satellite.

7. CONCLUSIONS

The Doppler-shift technique for the location of a transmitter source as employed by Lincoln Laboratory has been shown to work on several different sites. The method has even been demonstrated when predicting with small amounts of data and also with data having large transmitter-oscillator drift. The prediction can be enhanced by recording the Doppler-shift-curve peaks and zero crossings, but this is largely dependent on the periods when the signal appears in the satellite uplink receiver and the availability of the ground signal-processing and recording equipment. Pre-processing and smoothing of the data is also beneficial in reducing the errors associated with the final site estimate.

The terminator-motion (rise and set) technique of source location has also been demonstrated within the limitations noted in Section 5. The degree of accuracy is dependent on many variables. It is generally much less accurate than the Doppler-shift method.

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1. "Interagency Committee for Search and Rescue, Ad Hoc Working Group Report on Satellites for Distress Alerting and Locating, Final Report," NASA-TM-74770 (October 1976), pp. 3-14, 3-16, 5-1/5-12, F-1/F-14, UNCLASSIFIED.

2. M.E. Ash, "Determination of Earth Satellite Orbits," Technical Note 1972-5, Lincoln Laboratory, MIT (19 April 1972), DDC AD-742301, UNCLASSIFIED.

GLOSSARY

ABNCP	Airborne comand post
AFCS	Air Force Communications Service
AFEWC	Air Force Electronics Warfare Center
AJ	Ani-jam
AM	Amplitude modulation
BFSK	Binary frequency-shift keying
BPF	Bandpass filter
BW	Bandwidth
CW	Continuous wave
dBW	Decible referenced to a watt
DPSK	Differential phase-shift keying
EIRP	Effective isotropically radiated power
ESD	Electronic Systems Division, USAF
f_d	Doppler-shift frequency
f_o	Center frequency
GHz	Gigahertz (10^9 hertz)
Hz	Hertz
IF	Intermediate frequency
I and Q	In-phase and quadrature
k	Kilo (thousand)
K_a-band	Frequencies in the band 36 to 38 GHz (in LES-8/9 usage)
kHz	Kilohertz (10^3 hertz)
kW	Kilowatt (10^3 watts)
ksps	Kilosamples per second
LES-8/9	Lincoln Experimental Satellites 8 and 9
LL	Lincoln Laboratory
LO	Local oscillator
LPF	Low-pass filter
MFSK	Multiple frequency-shift keying
MHz	Megahertz (10^6 hertz)
MIJI	Meaconing/intrusion/jamming/interference
PEP	Planetary ephemeris program

QPSK	Quadrature phase-shift keying
RFI	Radio-frequency interference
RHCP	Right-hand circularly polarized
SAMSO	Space and Missile Systems Organization, USAF
SAR	Search and rescue
SARUS	Search and rescue using satellites
TROC	Tactical Relay Operations Center
UHF	Ultra-high frequency (225 to 400 MHz in military usage)
USAF	United States Air Force
W	Watt

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13. ABSTRACT (*Maximum 200 words*)

A method to determine unknown RFI-transmitter site coordinates based on Doppler-shift measurement using the LES-8 or LES-9 satellites and previously existing pieces of ground hardware and software is described. Test cases were run to evaluate the procedure. Several RFI sources have been located. A description is given of the satellites, ground hardware, and software (as they pertain to the location technique), along with results of the site-location experiments.

A second method of site location, the terminator-motion technique, is presented. It is based on a satellite rising and setting as seen from the unknown RFI-transmitter site. Restrictions on this technique are discussed and results of a test case are presented.

This report was originally Classified. It is being reissued with corrections of a few minor errors and misprints.

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