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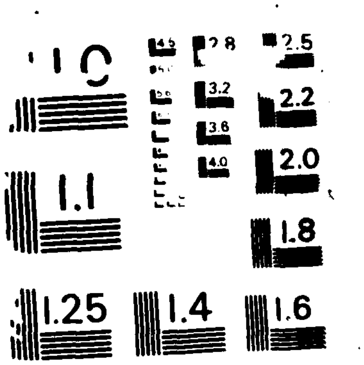

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HIGH RESOLUTION HF TIME OF ARRIVAL MEASUREMENTS (1981-1985)

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ABSTRACT

Between 1981 and 1985, absolute time of arrival (TOA) measurements were made on HF skywave time standard signals at different frequencies. 113 path-months of TOA data were collected over a one hop path between Ft. Collins CO. and San Diego, CA. In addition, 15 path-months of data were collected between Ft. Collins and Oahu, HI. and 12 path-months were gathered on signals between Tokyo, Japan and Oahu. The data shows a higher degree of ionospheric movement than was expected. It also shows a higher degree of stratification within layers than can normally be explained with simple, single layer ionospheric assumptions.

INTRODUCTION

In late 1980 questions arose concerning whether the ionosphere was sufficiently stable to allow precisely measured time of arrival of skywave signals to be used for geolocation in the high frequency (HF) band between 2 and 32 MHz. The chief limitation in the accuracy of this type of system is the amount of uncertainty in the ionospheric height estimation and its temporal stability. Traditional ionospheric research sources did not address the issuein sufficient detail and time resolution to be of any assistance. In order to understand the exact nature of the ionospheric uncertainties and to quantify their extent, experimentation was proposed to sense the variation in the refraction height of the ionosphere as it relates to the time of arrival of the HF signal. The objective of this work was to determine the range of environmentally induced errors in a skywave Time Difference of Arrival (TDOA) measurement, thereby bounding the ultimate geolocation accuracy one could expect from this technique.

The first experimental measurement system, as described by LaBahn (1982), started operation in early 1981. This effort involved establishing a continuous absolute Time of Arrival (TOA) experiment over the one-hop mid-latitude path between San Diego, California and Fort Collins, Colorado. The system was fully digital and stabilized with a cesium beam standard. This work was supplemented with vertical incidence sounder data at both ends of the path, a collateral Doppler sensing system, and coincident satellite solar data. A fully annotated database was prepared and is maintained by the Naval Ocean Systems Center.

In 1983 the Kenwood R1000 receiver was replaced with a newer R2000 which was microprocessor controlled. This allowed the receiver to now sequentially sample four frequencies at 1-second intervals. Because each frequency refracts from a different ionospheric height, the resulting data represent an almost (within 4 seconds) simultaneous look at different levels in the ionosphere. These multifrequency measurements were started in 1983 and have continued through 1986. The data have produced startling results when compared to traditional concepts of how the ionospheric medium behaves.

In late 1983, a longer range adjunct was conceived to address issues concerning TOA signals that transit distances of greater than 4000 Km. Dubbed the Long Baseline Time of Arrival (LBTOA) experiment, a sensor was placed in Hawaii that simultaneously measured time standard signals from Fort Collins, Colorado (WWV) and Tokyo, Japan (JJY). Although somewhat more ambitious than the original TOA sensor, the LBTOA was constructed and deployed in October 1983 (Rose 1984).

From their inception, both TOA sensor experiments were fully digital, facilitating processing and analysis. Concurrent to the development of the TOA and LBTOA sensors, a significant effort was directed toward the computer processing of the data. This has led to an extensive data reduction capability. Every time standard "TIC" pulse is fully retained along with (1) time (UT); (2) frequency; (3) signal strength; and (4) frequency shift (Doppler) data. These data have been stored on magnetic tape since the project inception and now represent a sizable bank of information.

HF absolute TOA measurements assume that the precise time the signal is transmitted is known. The use of WWV and JJY pulses make TOA practical. The only required assumption is that the pulse is exactly transmitted at 00:00 seconds. Experience shows the U.S. Time Standard Station at Fort Collins, Colorado (WWV) and the Japanese Time Standard Station in Tokyo (JJY) are diligent in meeting this stability requirement. This being the case, TOA measurements are a straightforward process when the entire experiment is locked to a Cesium Beam Standard. In addition, each stations TIC pulse is slightly different. WWV is a five-cycle pulse, WWVH (Hawaii) is six cycles, whereas JJY is eight cycles. In addition to normal pulse detection schemes that use leading/falling edges of the pulse, recognition processors are used to identify the right signal for detection.

Because of the bizarre nature of the initial results obtained in 1981 and 1982, questions arose as to systematic error and stability of the original TOA system and the subsequent LBTOA hardware. To resolve these issues, care was exercised to identify, resolve, or mitigate error sources. A complete description of the TOA calibration was given by LaBahn (1982). It should suffice for this paper to assure the reader that the ionospheric variations shown in the illustrations are real.

The overall TOA database was collected during the decline of solar cycle 21. This cycle peaked in late 1979-early 1980 with a smoothed sunspot number (SSN) of 165. By March 1981, when the TOA experimentation started, the SSN was 145. By October 1983, when the LBTOA was started, the SSN had dropped to 68. It was apparent at the time, that the JJY signal had degraded significantly whencompared to hearability tests conducted a year earlier. When the experimentation was terminated in 1986 the SSN was below 30 with conditions near solar minimum. Therefore it is expected that solar cycle variations can be observed in the database.

Initially, this entire effort was started to develop statistically significant numbers on expected ionospheric uncertainty. This has been accomplished to a degree sufficient to allow HF geolocation system designers to determine the ionospheric constraints on the time-sensitive systems. However, it turned out that the TOA and LBTOA systems were highly sensitiv: ionospheric sensors. A new degree of temporal resolution is achieved when the medium is probed at 1-second intervals. Analysts have had the opportunity to try different time integration intervals to achieve the highest resolution in sensing ionospheric variations. The best results came from a 2-minute integration time which seemed to provide an ionospheric "focal point" allowing detailed viewing of both the slowly varying and rapidly varying components of movement.

From this work emerges a picture of ionospheric movement that is very nontraditional. Investigators have had difficulty reconciling the TOA data with traditional methods of typifying the ionospheric medium. The ionosphere moves much more than originally thought, is more layered than is traditionally assumed, and has a very short temporal correlation period. Analysis of the TOA data has generally generated more questions than have been answered.

DESCRIPTION OF THE ONE-HOP TIME OF ARRIVAL (TOA) DATA

These data consist of measurements of absolute propagation time over a 1394 km path for HF radio signals between 2.5 and 20 MHz. The signals originated from the National Bureau of Standards Time Standard Station (WWV) at Fort Collins, Colorado and were received at the Naval Ocean Systems Center, San Diego.

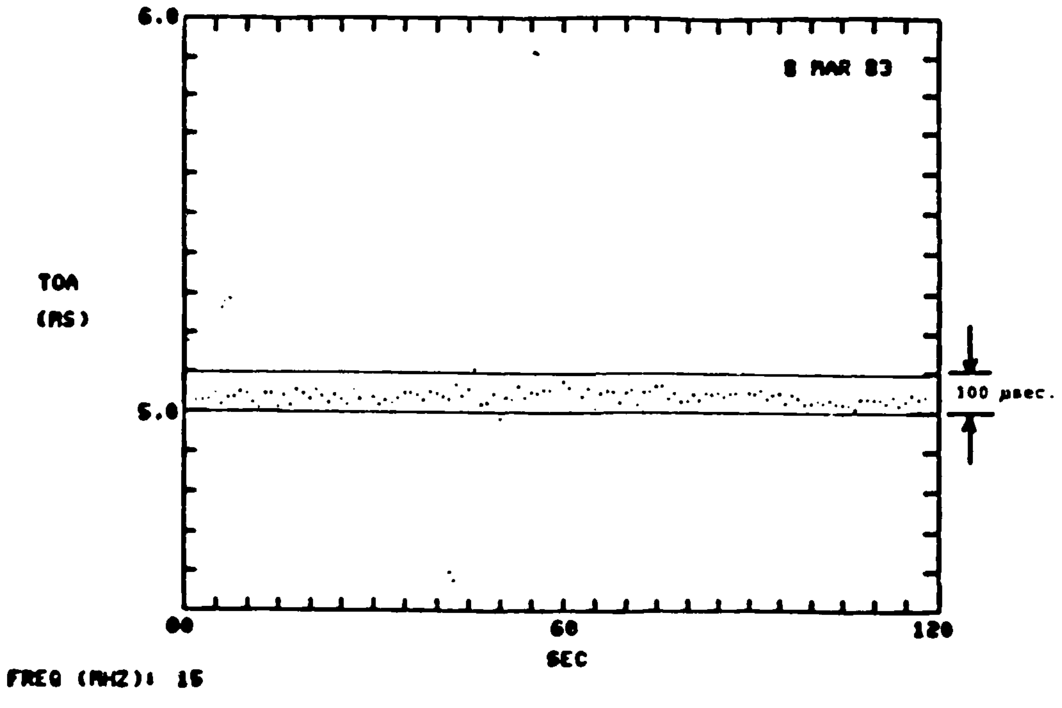
The basis for the measurements are the once a second (1/sec) "TIC" pulses present on the transmissions. These TICs correspond to 5 cycles of a 1-KHz tone which are accurately controlled by a primary frequency standard. A primary frequency standard is also maintained at the receiving site and the experimental procedure consists of determining the TOA of these pulses with respect to the local absolute second.

Primary detection of the 1/sec TIC is done first by recording the time in microseconds after the second cycle occurs in the AM detected signal. These were accumulated ,along with the time of day information, on magnetic tape. To minimize extraneous data, the received signals are windowed about the expected propagation time (4 to 12 milliseconds).

A threshold is used in the peak detection system so that only signals above a certain level will be detected. This eliminates low level noise. However, the system is still subject to high level noise. To reduce this problem, time averaging was used. The times when peaks were detected were accumulated over 2-minute periods. This creates enhancements in reoccurring events while random noise generally presents a low level background. The averaged data were then processed by searching for peak accumulations which matched the signature of the transmitted TIC. Figure 1 has been included to show what makes up a typical 2-minute TOA sample. This is a relatively stable example of 15-MHz signals and it should be noted that the second-to-second "wander" is contained within a 100-microsecond window. While this may seem trivial, it should be kept in mind that a 10-microsecond error equates to an approximate 1.5-nmi range error in geolocation systems. Figure 1 implies that in a 2-minute period, the uncertainty in the emitter location due to ionospheric movement is between 10-15 nautical miles. If the observed period is expanded to a 24-minute interval, we can see the impact of sampling at 1-second intervals. Figure 2 shows a plot of all the 15-MHz TIC pulses received during a 24-minute interval. This "scatter-gram" shows the best-case (least) variability to be about 25 microseconds, the nominal value to be about 50 microseconds with excursions approaching 100 microseconds.

Figure 3 shows an example of a 24-hour plot of TOA recorded at each of the four frequencies sampled. Each small dot is a two minute average, as described earlier. The important feature to note in Figure 3 is how each frequency (or more correctly the ionospheric control points) seem to vary almost independently of each other. The TOA's of approximately 4.7 milliseconds are E-region modes. The TOA's above 5.0 milliseconds are signals via the F-region.

Figure 1. 120 Seconds of Time of Arrival Data From WWV
(Each Dot is the TOA of an Individual TIC Pulse)



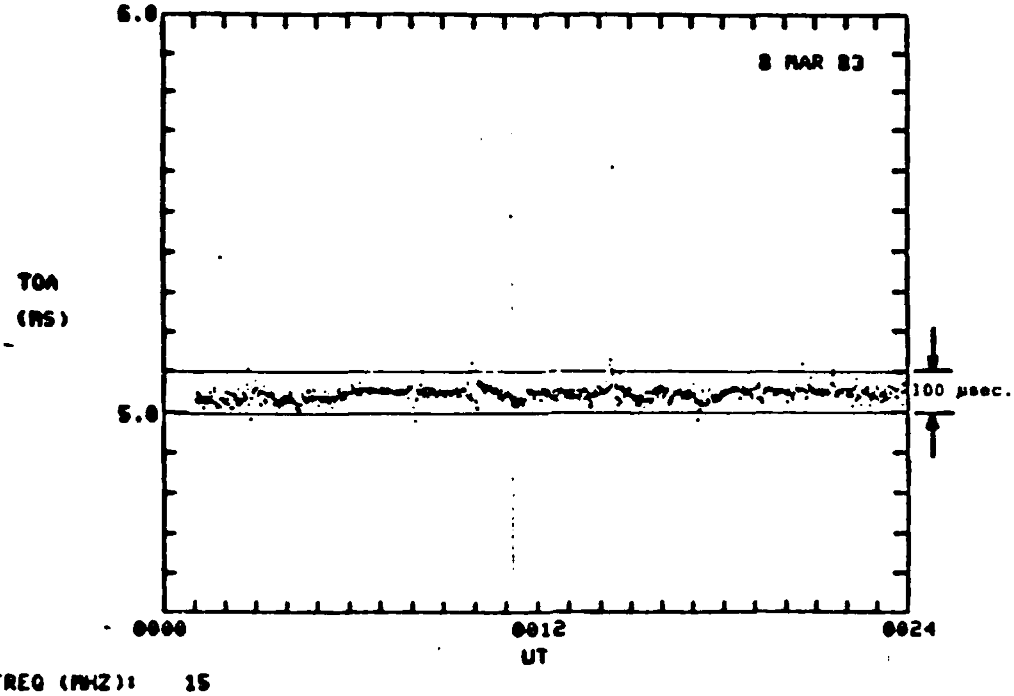


Figure 2. 24 Minutes of TOA Data (WWV to San Diego)

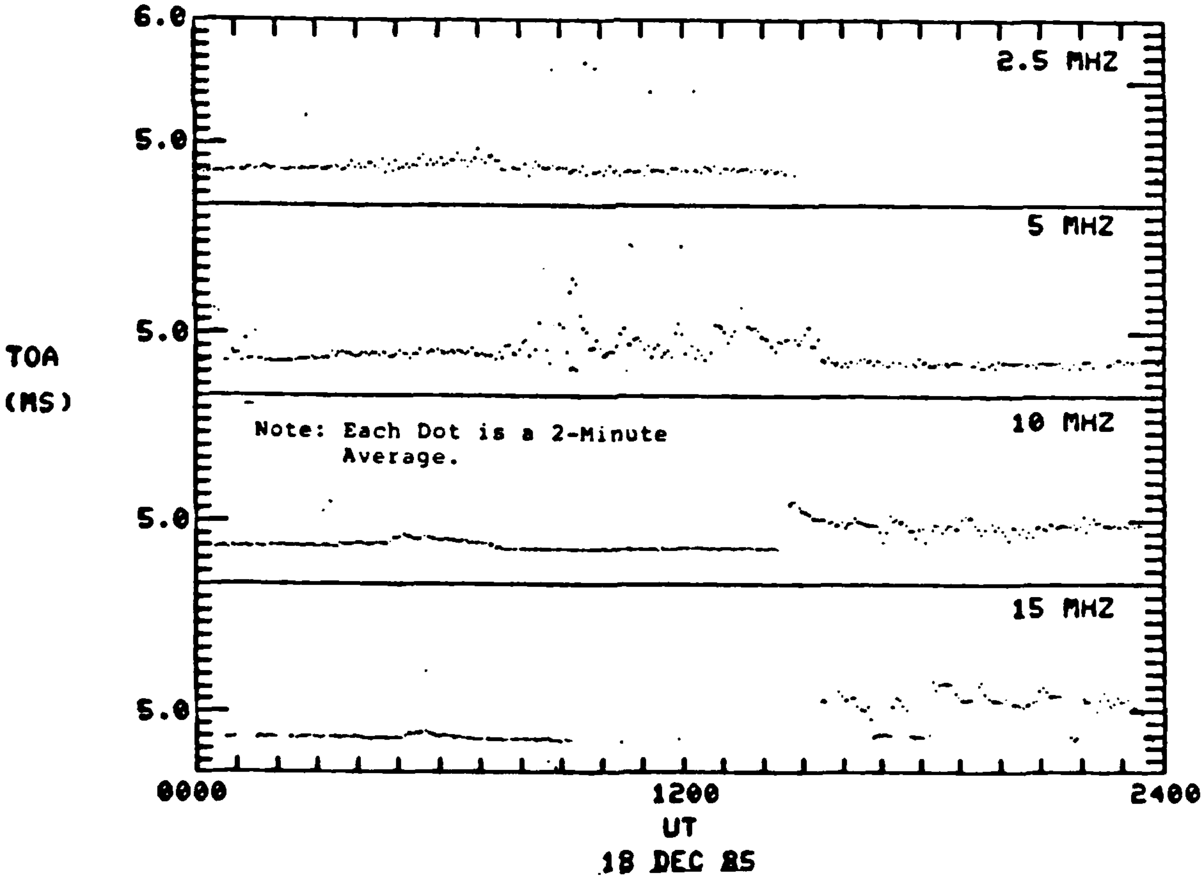


Figure 3. Multifrequency TOA Data for 24 Hours (WWV to San Diego)

Figure 3 shows data from a single day. Another method to view the data is to lump together the data for a 30-day period for each hour and develop a population distribution for each hour. Then the TOA characteristics for each day can be typified for that month. Each hourly average represents 54,000 TIC pulse samples. When this population distribution is plotted isometrically as a function of TOA and time of day, certain features appear. Figure 4 illustrates how this population might appear. Each peak in occurrence represents a different propagation mode or a permutation of that mode. The actual uncertainty is represented by the width of this population distribution at some variance about the mean. Figures 5(a), 5(b), 5(c), and 5(d) show examples of these monthly TOA distributions for the month of December 1985 at 2.5, 5.0, 10.0, and 15.0 MHz. The difference in TOA variability between E and F region is seen by the spread of the population distribution. The E-region provides a stable, predictable medium while the F-region (figure 5(c) between 16UT an 24UT) TOA's are spread over 100 microseconds. Each of these figures represent a "path-month" of data. 113 path-months of data have been derived (Rose,1986) from this experiment since it was started in May 1981. Complete tabular statistics for each hour, for both E and F-regions, were also developed.

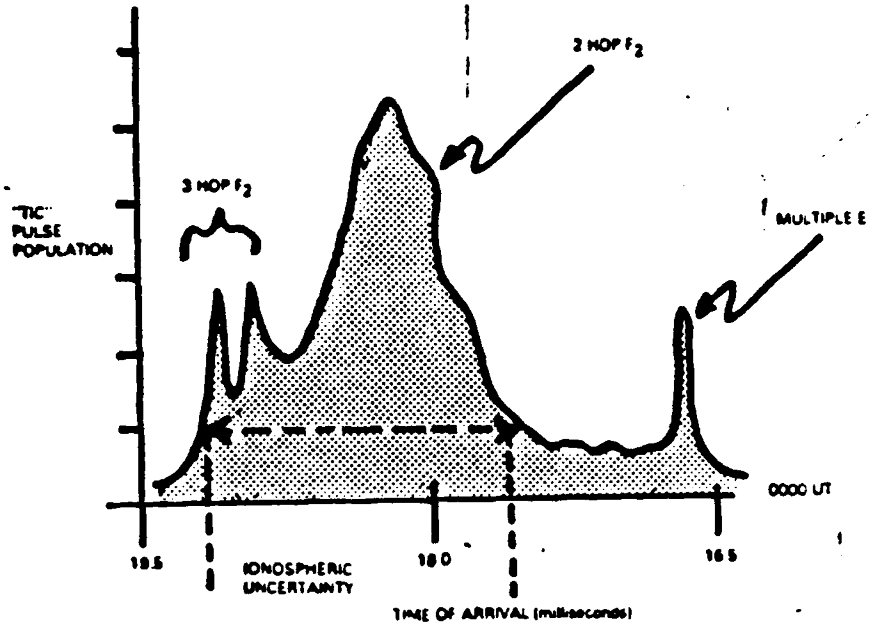


Figure 4. Time of Arrival Population Distribution

DESCRIPTION OF THE LONG BASELINE TIME OF ARRIVAL (LBTOA) DATA

The NOSC Long Baseline Time of Arrival (LBTOA) experiment was installed at the Naval Security Group Activity, Wahiawa, Hawaii on 4 October 1983. This experiment was designed to measure the TIC signals from WWV, Fort Collins, Colorado and JJY Tokyo, Japan.

An extensive hearability study was conducted in November-December 1982. The LBTOA system design was based on these studies. The heart of the sensor hardware was the Kenwood R2000 receiver which was controlled by an 8086 microprocessor. The frequency to be monitored and the exact time window of the signal to be looked at is controlled by this microcomputer. The system is slaved to a cesium beam primary standard.

The LBTOA system used two 16-degree beamwidth sectors formed on the FRD-10A CDAA antenna system. One beam was pointed at WWV and the other at JJY. Experience with this antenna has shown that this configuration provides more than enough rejection to eliminate co-channel interference. For example, both JJY and WWV can be monitored on 15 MHz without the signals interfering with each other.

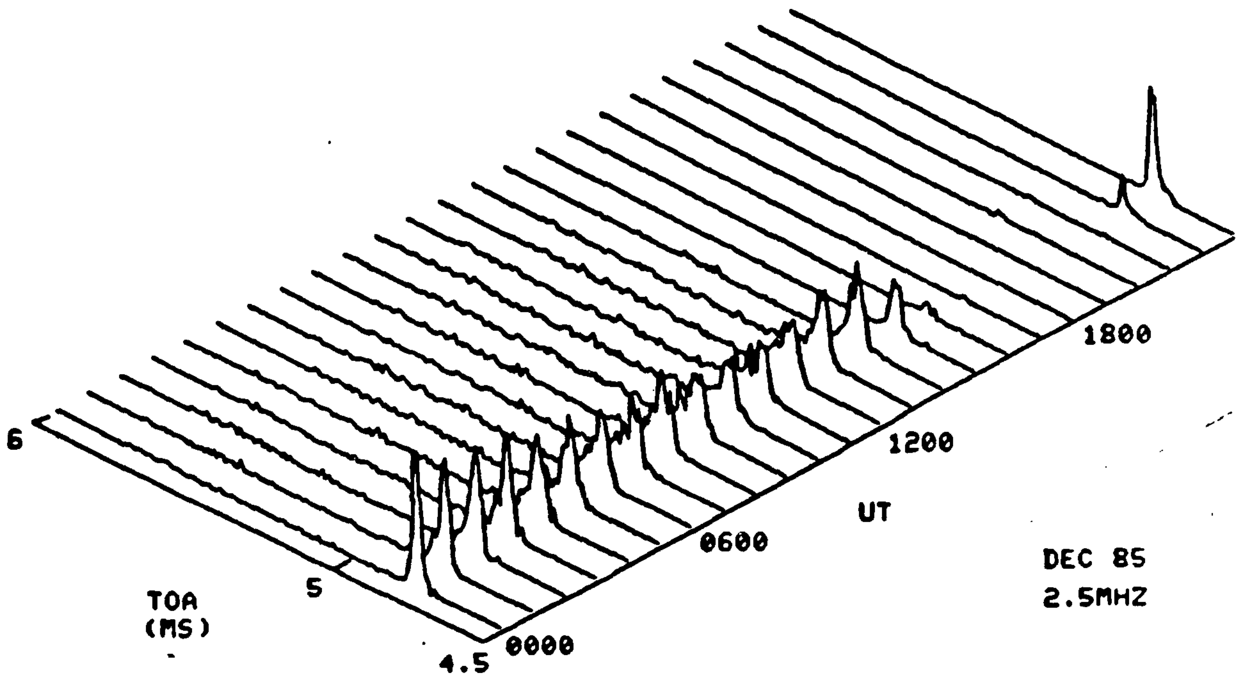


Figure 5 (a) 24-Hour TOA Characteristics for December 1985 - 2.5 MHz. Fort Collins, CO. (WWV) to San Diego, CA.

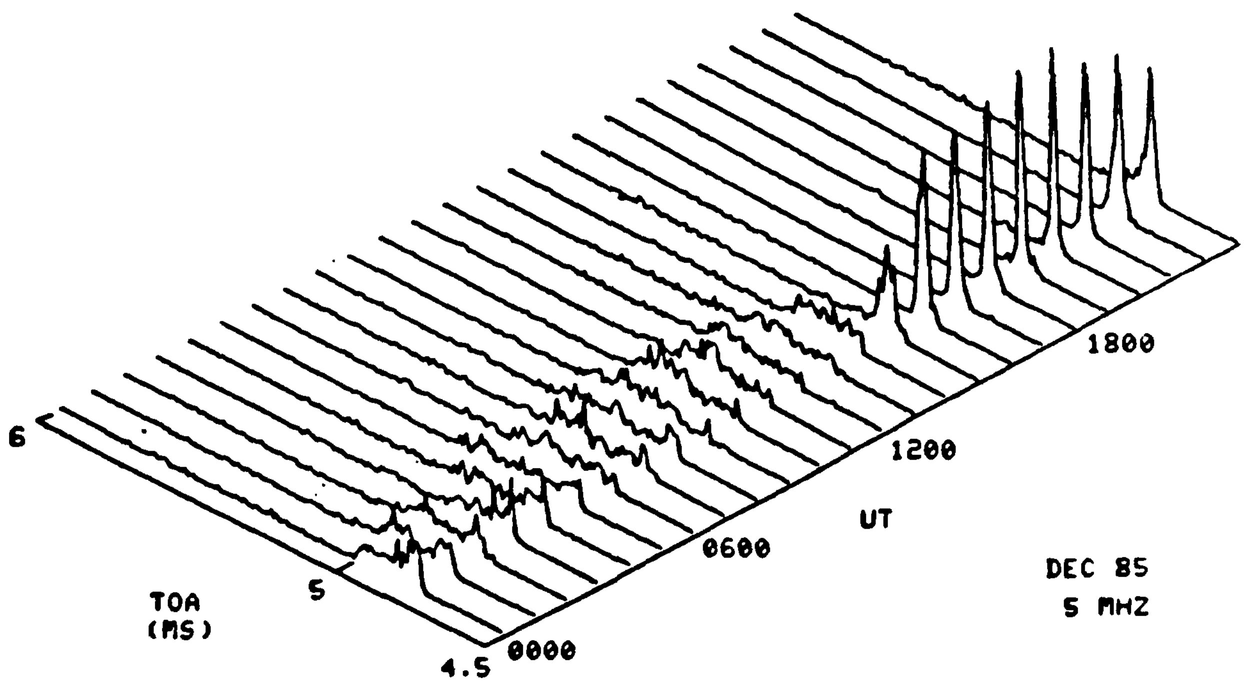


Figure 5 (b) 24-Hour TOA Characteristics for December 1985 - 5.0 MHz. Fort Collins, CO. (WWV) to San Diego, CA.

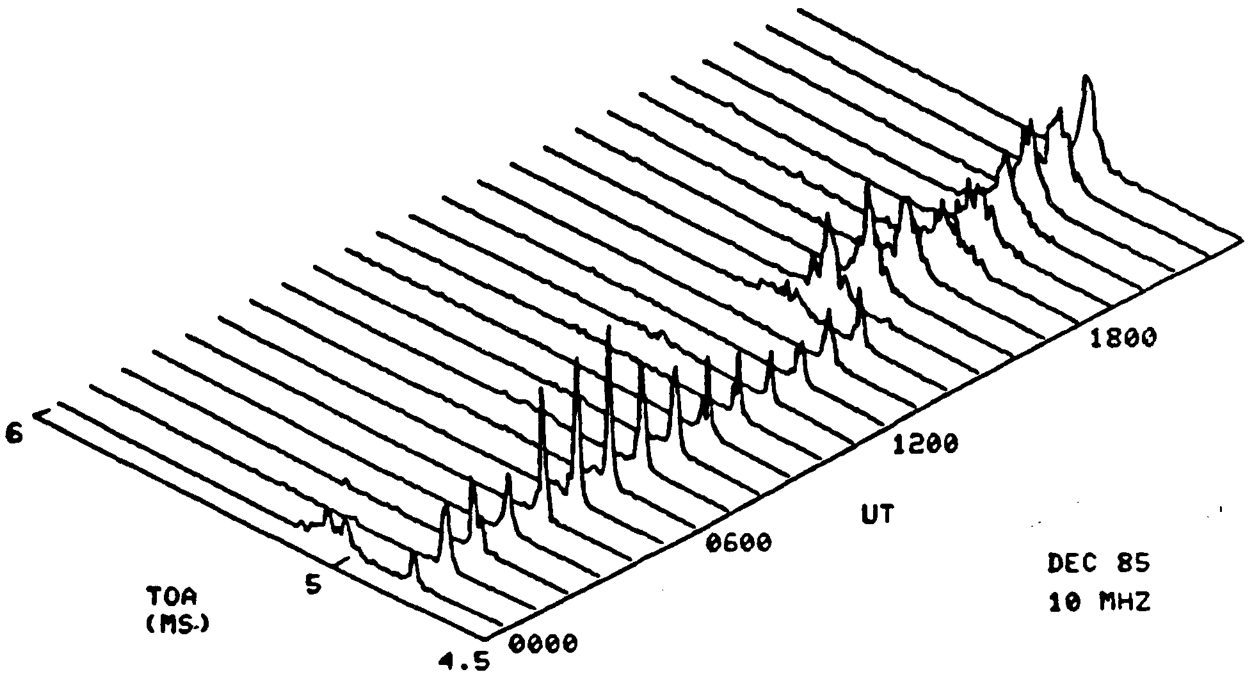


Figure 5 (c) 24-Hour TOA Characteristics for December 1985 - 10.0 MHz.
Fort Collins. CO. (WWV) to San Diego, CA.

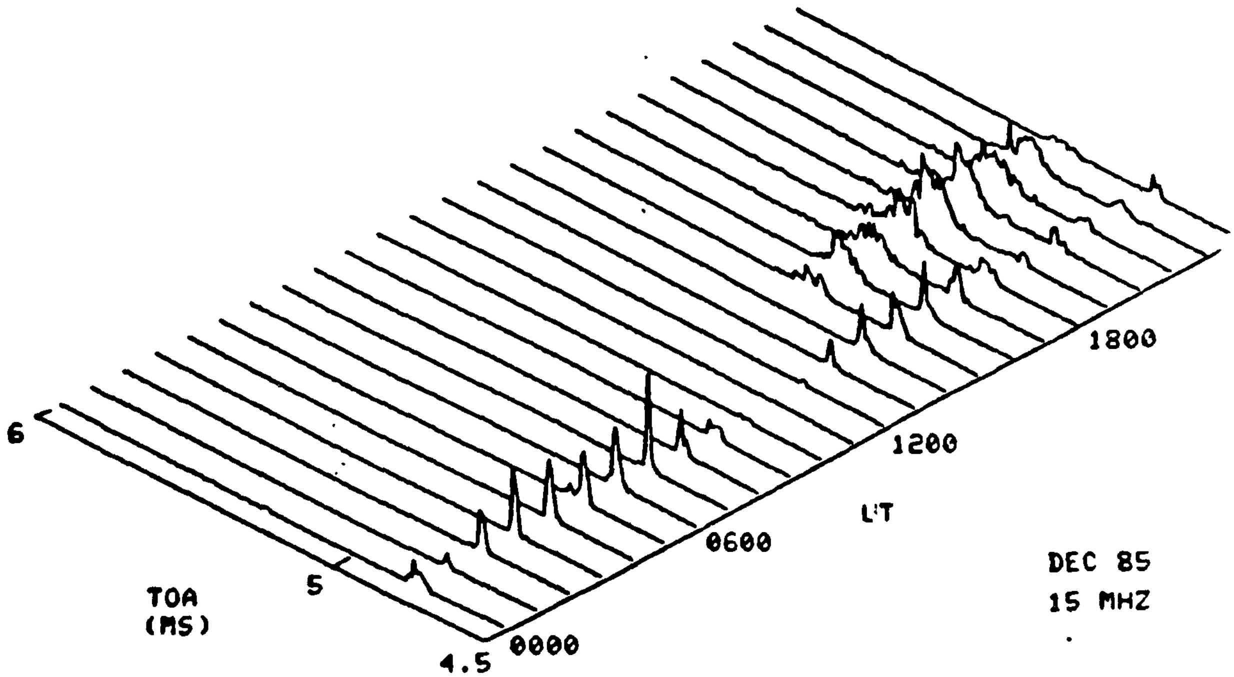


Figure 5 (d) 24-Hour TOA Characteristics for December 1985 - 15.0 MHz.
Fort Collins, CO. (WWV) to San Diego, CA.

The experiment consisted of monitoring first WWV and then JJY in succession each second. The time gates for each channel were opened at preprogrammed times. This allowed the desired signal to be measured and unwanted time standard signals which have different and known TOA's to be rejected. The most troublesome of these were stations in the Soviet Union and on Formosa.

27 path-months of the long baseline data were collected. Figure 6 shows path-month isometric plots for December 1984 for both the WWV and JJY signals. Note the significantly increased spread of the distribution. This experiment has shown that the more times a signal interacts with the ionosphere, the greater the amount of variation in the signal time of arrival. A two-hop mode, typical of the WWV signal, has only two control points which interact with the lower part of the ionosphere. A 3-hop signal, the primary JJY mode, is of steeper incidence, is refracted higher in the ionosphere, and is therefore, subject to a larger number of ionospheric variations. This difference is seen in figure 6. When these data are compared with the 1-hop TOA data, which shows some periods of good stability, it suggests that time sensitive HF geolocation may not be practical beyond 1-hop propagation distances.

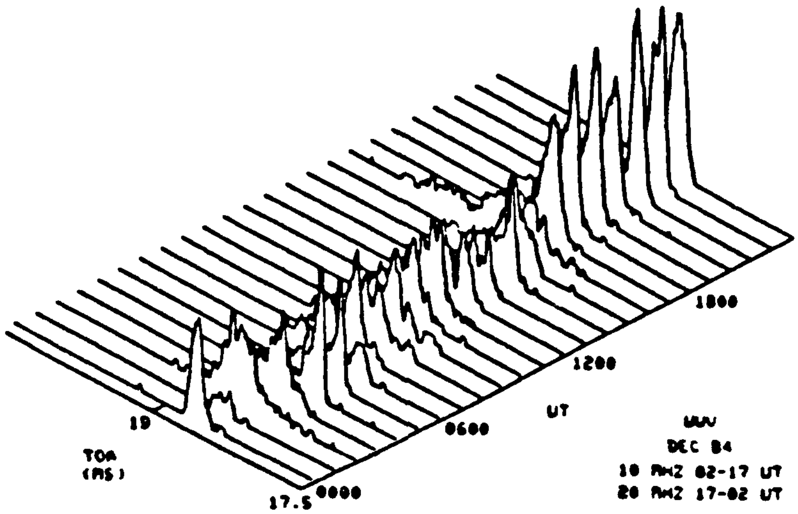


Figure 6 (a) Hourly Long Baseline TOA Averages - December 1984
Fort Collins, CO. (WWV) to Wahiawa, HI.

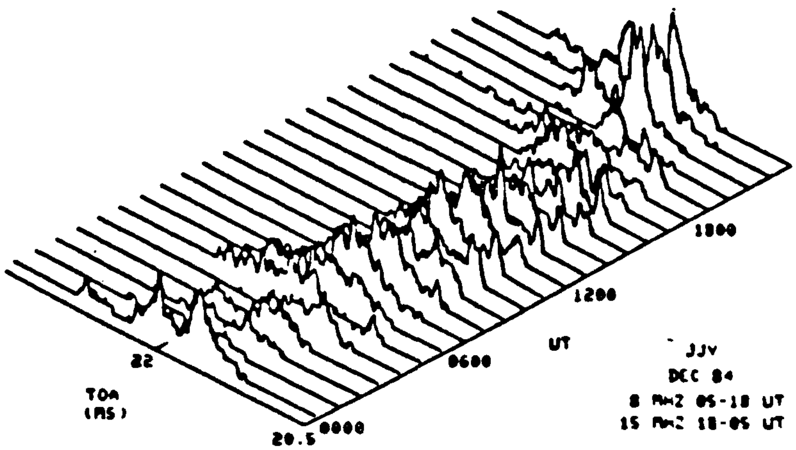


Figure 6 (b) Hourly Long Baseline TOA Averages - December 1984
Tokyo, Japan (JJY) to Wahiawa, HI.

These numbers provide a first estimate of the level of uncertainty introduced into skywave measurements. It indicates that HF TDOA is only realistic at ranges inside one-hop and on frequencies that will sustain only one or two modes of propagation. Further the user must be able to positively identify which mode the TDOA measurement was made on. Finally the lack of spatial correlation in the observed ionospheric variability indicates a redefinition of ionospheric models may be necessary to accurately forecast skywave events for time sensitive HF sensors.

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