Project Report
ATC-260

Multilateration on Mode S and ATCRBS Signals at Atlanta's Hartsfield Airport

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16. Abstract

The ATC community is seeking a way to obtain aircraft ID and improved surveillance on the airport movement area. Surface radars provide good surveillance data, but do not provide ID, may not cover the whole movement area, and suffer from false reflection targets and performance degradations in rain. This report describes an evolutionary technique employing multilateration, TCAS technology, and existing ATCBI transponders to provide the desired surface surveillance information.

Five mutilateration receiver/transmitters (RTs) based on TCAS units, and a central multilateration computer processor were procured and installed on the highest available buildings on the perimeter of the north side of Atlanta's Hartsfield airport. The resulting coverage was such that there was a 93% probability that a multilateration position would be computed on a given Mode S short squitter emitted from a target at a randomly selected position on the movement area. Multilateration was performed on ATCRBS targets using replies elicited by whisper shout methods originally developed for TCAS. Measurements showed that whisper shout was successful in degarbling targets that were in close proximity on the movement area. The probability of obtaining an ATCRBS multilateration position in a given one second interval depended on the number of whisper shout interrogations transmitted. The equipment required over 10 interrogations per target per second to obtain per second multilateration update rates on two typical targets of 58% and 83% respectively. This less than anticipated performance was primarily due to the inefficient whisper shout intgerrogation technique that was used in the tested equipment. This can be corrected in next generation equipment.

The multilateration accuracy was about 20 feet one sigma, as anticipated from theoretical considerations and previous experience with other equipment.

By combining the multilateration data with ASDE data and tracking the results, it would be possible to obtain track reliabilities on the airport surface similar to that obtained elsewhere in the ATC system but at update rates of 1 Hz as required for surface surveillance and control purposes.

The RTs were also capable of receiving Mode S long squitters containing GPS position information. The probability of at least one of the 5RTs receiving a given long squitter was essentially 100% on the movement area.

17. Key Words

multilateration
aircraft surveillance
Mode S
transponder
Automatic Dependent Surveillance
GPS
GPS-Squitter
airport surveillance
ATCRBS
whisper shout

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EXECUTIVE SUMMARY

The ATC community is seeking a way to obtain aircraft ID and improved surveillance on the airport movement area. The present surface detection (ASDE) radar does not provide ID, may not cover the whole movement area, and suffers from false reflection targets and performance degradations in rain. The work reported upon herein describes an evolutionary technique employing multilateration, TCAS technology, and existing ATCBI transponders to provide the desired surface surveillance information.

BACKGROUND

Multilateration using transponder replies has been recognized for over 30 years as having the potential to provide the desired ID and position data. In the 1970's, the Bendix Corporation demonstrated multilateration on ATCRBS replies using expensive steerable beams to elicit replies without synchronous garble. The reply times of arrival were marked and sent to a central computer which determined the aircraft position using calculations similar to those of LORAN and GPS. The system was judged to be too expensive to deploy.

Now, as a consequence of Mode S and TCAS equipment and technology, replies are spontaneously squittered by Mode S transponders, or can be elicited garble-free from ATCRBS transponders by whisper shout. Experiments by Lincoln Laboratory in 1986 at Logan International Airport showed that Mode S and ATCRBS signals can be sent between aircraft on the movement area and receiver/transmitters on the perimeter equipped with simple broad beam antennas. Thus, the replies needed for multilateration currently exist for Mode S targets and are readily obtainable for ATCRBS targets.

A TCAS unit contains all the features necessary to serve as a multilateration receiver except a time of arrival marker similar to that used by Bendix. In the 1990's Cardion Corporation integrated a time of arrival marker and a Collins TCAS unit and demonstrated multilateration on Mode S squitters and replies from modified ATCRBS transponders using four TCAS units, referred to as R/Ts, with omni antennas located on the perimeter of the Atlantic City Airport where the FAA Hughes Technical Center is located. Instead of whisper shout, Cardion's solution to ATCRBS synchronous garble was to modify the transponder with a device that caused the transponder to randomly emit a reply pair, with a spacing of about 175 μs, at an average rate of one Hz.

ATLANTA TEST PROGRAM

In 1995, the FAA tasked Lincoln Laboratory, with the participation of industry, to demonstrate/validate multilateration in the severe multipath and traffic density conditions of Atlanta's Hartsfield Airport. Lincoln Laboratory selected Cardion's equipment for evaluation based on a competitive procurement/rental, and specified that ATCRBS multilateration be performed on replies elicited by whisper shout. Lincoln and Cardion jointly agreed to meet this requirement by sending interrogation pairs for expediency purposes to support the Atlanta test program. It was recognized that this would result in a reduction of the probability of obtaining a position measurement, since a pair of replies was required.

Lincoln Laboratory equipped the five Cardion R/Ts with the same variable wing, broad beam, antennas that Lincoln developed and validated during the ADS-B demonstration at

Logan Airport in 1994. The R/Ts were sited on the highest available perimeter buildings on the north side of Hartsfield in accordance with experience gained during the 1986 measurements and the ADS-B demonstration at Logan Airport. The sites were: Delta hangar, Ford assembly plant, Stouffer's hotel, FAA Regional headquarters, and the north end of Terminal C.

The coverage provided by each of the R/Ts was evaluated by driving a vehicle equipped with a Mode S transponder emitting short and extended squitters on the runways and taxiways. The location of the vehicle was known because the extended squitters contained GPS positions (not differentially corrected). The results showed that each R/T had sufficient range and line of sight to see to the extremes of the movement area. Each also exhibited gaps in the coverage, suspected to be due to multipath. This suspicion was confirmed for one prominent case by an experiment in which RF absorber material was used to block the multipath. The global result is that the probability of making a multilateration position measurement on a given short squitter at a randomly selected position on the movement area is 93.2% (based on at least one perfect squitter, and two or more with 14 or more correct ID bits).

There are several accuracy issues for airport surveillance: bias, standard deviation, and registration with ADSE measurements and airport maps. Theory predicts a multilateration standard deviation of about 10 to 20 feet, and this range of values was observed for targets of opportunity. Position dependent biases were less than 40 feet. No effort was made to compare the registration of multilateration positions with ASDE positions or any maps used by ATC systems. Also, no effort was made to replicate the accuracy measurements previously made by both Cardion and Bendix.

Whisper shout tests were conducted using three simultaneous sequences having S1,P1 spacings of 4, 8, and 16 dB, with step advances of 2, 4, and 8 dB. The sequence was issued every 0.5 seconds, alternating in a round robin fashion amongst the five R/Ts. The degarbling capability of the 4 dB bin width sequence was evaluated for two ATCRBS targets of opportunity taxiing simultaneously and separated by from 500 to 4000 feet, after midnight when the fruit rate was very low. The Mode S functions of the Cardion system were intentionally turned off. The two targets replied on separate interrogations 95% of the time, and the average link margin difference was 8.6 dB. The per second update rates were 83% and 58%. The accuracy was comparable to that observed for squitter multilateration.

Enhancing these ATCRBS update rates, and guaranteeing good performance for more than two targets at a time and in high fruit rates requires developing whisper shout sequences better adapted to the airport environment and developing improved receive/processing equipment and algorithms. In particular, a single interrogation should be used, not the pairs that the current Cardion equipment requires.

The Mode S squitter and ATCRBS multilateration results were very positive and support the conclusion that technology now exists for providing an evolutionary, affordable, solution to the problems of providing ID TAGs on controller ASDE displays, as well as reliable tracks with IDs to drive surface automation systems. Achieving this objective at Atlanta was challenging. Utilization of more ground stations can result in even better performance, but such an enhancement is likely not justifiable on a cost benefit basis, particularly if the data are used with complementary ASDE data which have different dead zones and multipath regions.

CONCLUSION

The tests and analyses reported herein show that affordable technology exists for determining the position and ID of aircraft on the airport surface to accuracies of better than 20 feet using existing ATCBI transponders on aircraft, ground receive equipment derived from TCAS, and multilateration techniques. The resultant data can be used to place aircraft identity TAGS on controller ASDE displays, a challenge which the technical community has been working on for three decades and which has been a high priority of the Air Traffic Control community because of its potential safety benefit. The position and ID data also provide a much needed means for improving ASDE derived track data used to drive automation safety systems such as Airport Movement Area Safety System (AMASS) and Runway Status Lights (RWSL), for supplying surveillance data with aircraft ID to capacity enhancement systems such as Surface Movement Advisor (SMA), and for identifying multipath returns on ASDE radars, which have both capacity and safety implications.

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1. INTRODUCTION

1.1 BACKGROUND

The FAA is responsible for surveillance and separation of controlled aircraft, both in the air and on the movement area of airports equipped with a tower. Airborne surveillance is based on primary radar and either the ATCRBS or Mode S beacon system. Airport surface surveillance is either visual or by the Airport Surface Detection Equipment (ASDE) primary radar. The ASDE radar performance is generally excellent, but may not cover the entire airport surface, may experience false reflection targets, may suffer degraded performance in rain, and does not provide aircraft identity.

There is a need for a beacon surface surveillance system to augment and supplement the ASDE surveillance by filling in coverage holes, helping to reduce false tracks, mitigating bad weather degradation, and providing aircraft identity.

Air traffic control on the airport surface needs higher accuracy than in the air because the aircraft are very close together and undergo large accelerations. The two-way range measurements made by ATCRBS and Mode S beacons are not accurate enough for surface control because of uncertainties in the transponder turnaround time. Multilateration based on accurate time of arrival measurements of transponder replies has the potential to provide the needed accuracy, coverage, and aircraft identity.

1.2 MULTILATERATION

Two-dimensional multilateration is a position measuring method in which the time of arrival differences of a signal emitted by a target in the plane of three receivers are used to form two hyperbolas, the intersection of which determines, in most cases unambiguously, the target position. The emission of the target signal may be spontaneously, or by stimulation by an outside agent. The Bendix Corporation, Lincoln Laboratory, and the Cardion Corporation have all performed work relevant to multilateration on the airport surface during the last 25 years. Bendix demonstrated a narrow beam interrogation multilateration system using ATCRBS transponders in the 1970's. In the 1980's, Lincoln Laboratory demonstrated that Mode S transponder signals emitted by aircraft on the airport surface could be successfully received by omni or broad beam antennas sited on moderately high buildings on the airport perimeter. In the 1990's Cardion Corporation demonstrated multilateration using Mode S and ATCRBS signals at the Atlantic City airport.

1.3 BENDIX – 1970's

The Bendix Corporation in the early 1970's (prior to the development of Mode S) designed, built, and tested an ATCRBS multilateration system on the airport surface at Boston's Logan International Airport. In standard ATCRBS interrogators, interrogations transmitted from a rotating narrow beam elicit responses from all transponders in the beam. When aircraft in the beam are separated in range by less than the distance of an ATCRBS reply length (1.67 nmi), then the replies from different aircraft will overlap in time and potentially garble each other. The Bendix approach to overcome this synchronous garble was to exploit the transponder's suppression feature and suppress all the transponders on the airport surface except those within a region defined by the intersection of two narrow and electronically steerable beams. The technique is described in Reference [1], and illustrated in Figure 1-1. The two antennas received the replies, as did a third station that used a fixed beam broad enough to cover the whole movement area. The times of arrival of the reply were marked at each of the three stations and sent to a central processor where the position was computed. One reason this system was never implemented was that the large aperture antennas with steerable beams were quite expensive.

ATCRBS replies from aircraft on the airport surface would be received with a wide dynamic range of powers by receivers on the perimeter, depending on the ratio of the maximum and minimum ranges of interest. Because of this fact, the method for marking the reply time of arrival must be unaffected by the received amplitude of the reply. For this reason, Bendix used a peak amplitude estimator, illustrated in Figure 1-2, to mark the leading edge of the ATCRBS reply F1 pulse. The Bendix system demonstrated multilateration accuracies of 20 feet or less, which served as an existence proof of accurate multilateration on the airport surface.

1.4 LINCOLN LABORATORY - 1980's

The Bendix system demonstrated that multilateration would work on the airport surface using ATCRBS replies received by two narrow beams and one broad beam. Narrow beams have gain to the target, which improves received signal amplitude, and horizontal multipath is mitigated by the low out of beam gain. As the Mode S and TCAS system developments progressed, there was interest in investigating whether multilateration could be performed on Mode S replies or Mode S squitters using broad beam antennas.

There were several propagation issues to address. The signal may be too weak, or blocked or corrupted by multipath reflections off of buildings, other structures, vehicles or aircraft. Propagation and coverage tests were conducted using two vehicles; one transmitting Mode S discrete interrogations, the other containing a Mode S transponder. It was found that a 27 foot high omni antenna could interrogate, and the Mode S reply could be received, across the movement area except when there was multipath caused by buildings or other objects. The interrogate/receive coverage is shown in Figure 1-3, taken from Reference [2] which describes these tests.

Figure 1-4, taken from the same reference shows an example of a multipath reflection at Logan Airport. The reflected pulse is actually the F1 pulse of an ATCRBS reply that was elicited by an interrogation transmitted by the same 27-foot high omni antenna that was used in the Mode S coverage tests. This demonstrated the viability of performing ATCRBS interrogations on the airport surface.

These results were encouraging and helped lead to later programs in GPS-Squitter on the airport surface, and suggested that Mode S and ATCRBS multilateration using broad beam antennas might be viable on the airport surface.

1.5 CARDION - 1990's

The Cardion Cooperative Area Precision Tracking System (CAPTS) is a multilateration system comprising several receiver/transmitters (R/Ts) based on Collins TCAS II units, a Master Work Station (MWS) to perform computations and display functions, RF modems for communications between the R/Ts and the MWS, and a reference transponder for R/T clock calibrations. A detailed description appears in Section 2. The CAPTS system was demonstrated at the Atlantic City airport. The work is described in References [3] and [4] which indicate that accuracies of 10 feet were obtained.

1.6 ATLANTA MULTILATERATION PROGRAM

The Atlantic City airport at which the CAPTS system was demonstrated has a low traffic density and a benign multipath environment. The low density implies that relatively few ATCRBS and Mode S interfering signals will be present. Atlanta's Hartsfield Airport has a high traffic density, and the north side is surrounded by many buildings and other sources of multipath. In 1995, the FAA tasked Lincoln Laboratory to demonstrate/validate, with the participation of industry, the operational suitability of Mode S and ATCRBS multilateration on the north side of Hartsfield airport. The viewpoint was that "if multilateration would work in Atlanta, then it would work at any U.S. airport". Figure 1-5 shows an aerial photo of the Atlanta Airport. Lincoln Laboratory selected the CAPTS system for this demonstration/validation program after a competitive bid process.

1.7 REPORT OVERVIEW

The suitability of the multilateration concept for the airport surface has been demonstrated at Atlanta's Hartsfield Airport and documented in this report. Section 2 describes the Cardion equipment that was evaluated. Section 3 describes the coverage provided by multilateration receivers sited at Delta's hangar, the Ford assembly plant, the Stouffer's hotel, the FAA Regional headquarters, and Terminal C. Section 4 describes the accuracy of Mode S and ATCRBS multilateration position measurements. Section 5 describes the whisper shout techniques that were developed to provide surveillance on ATCRBS transponders. The summary and recommendations for future work appear in Section 6.

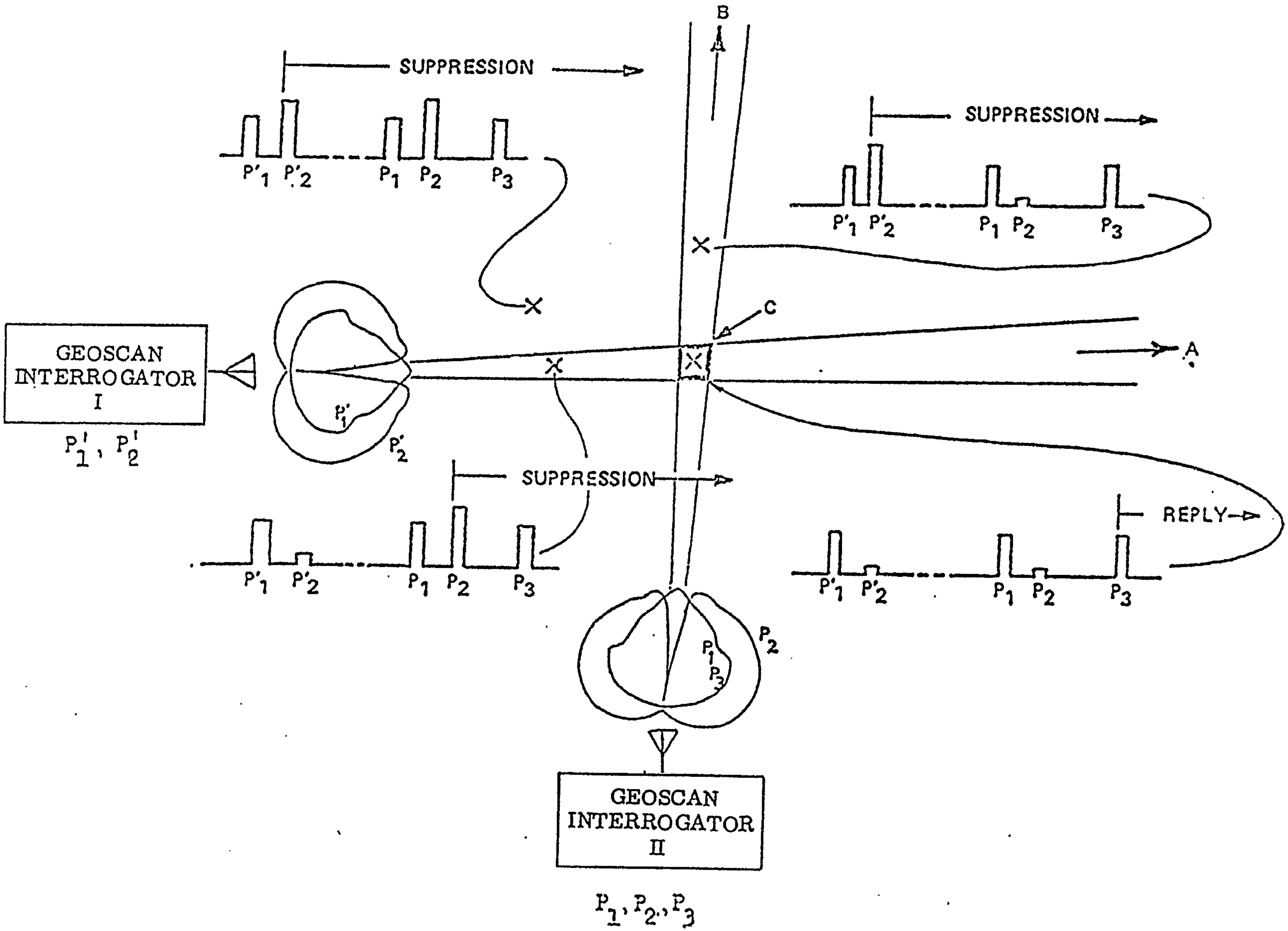


Figure 1-1. Bendix Geoscan interrogation.

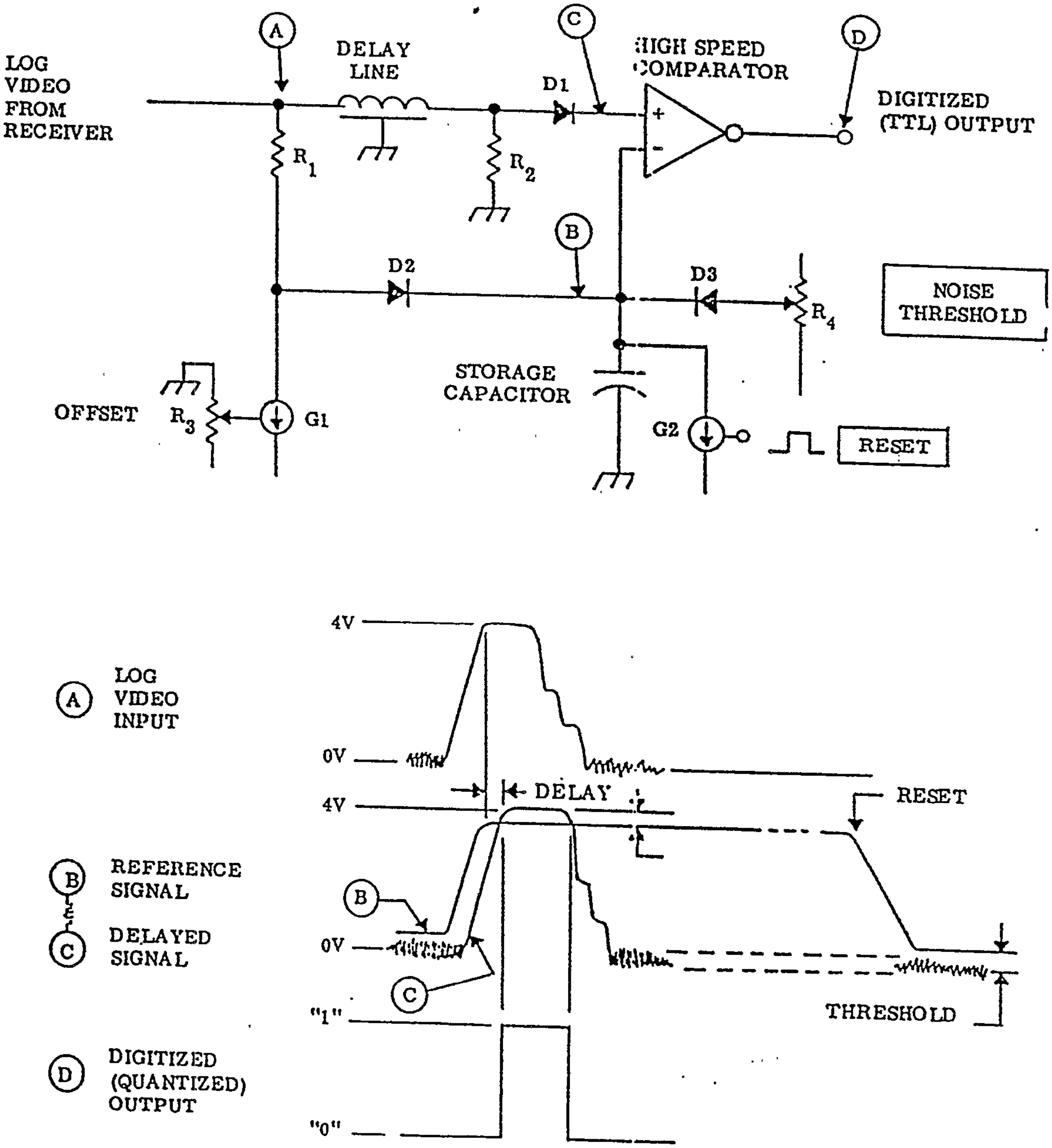
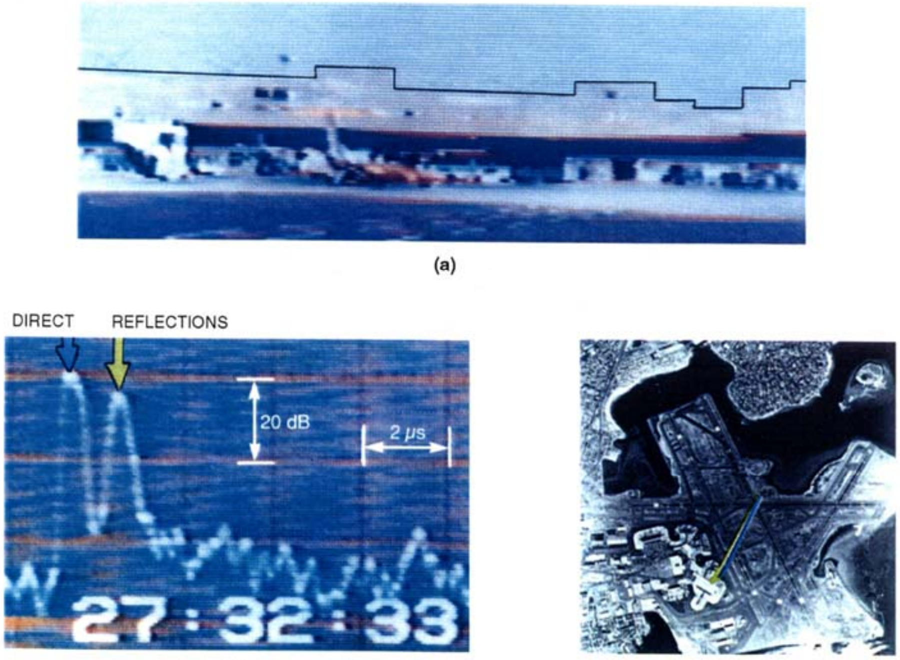


Figure 1-2. Peak amplitude estimation (from Bendix Corporation).

Figure 1-3. Mode S Link Reliability at Logan Airport in 1987



(a)

(b)

(c)

Figure 1-4. A Multipath Reflection at Logan Airport

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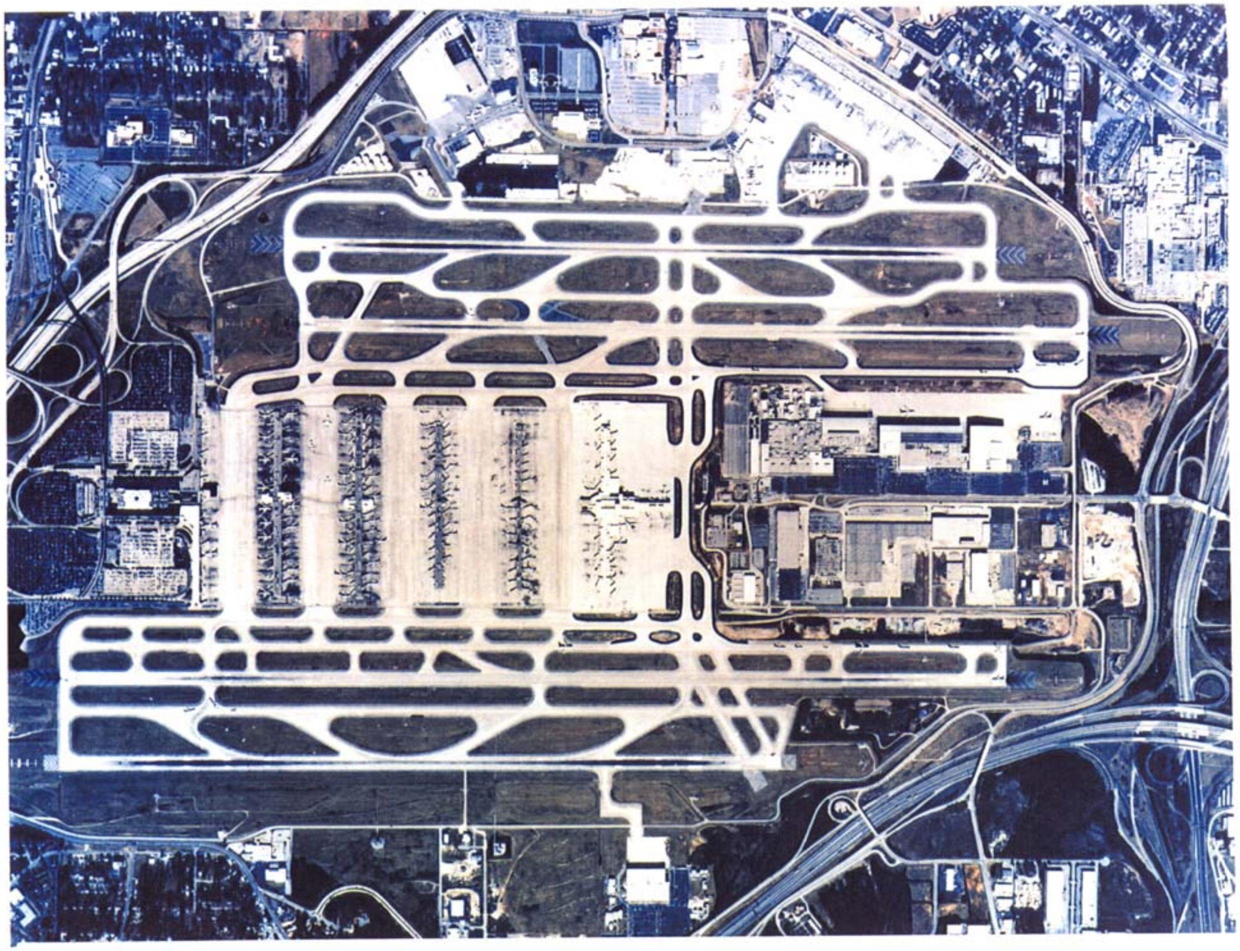


Figure 1-5. Aerial photograph of Hartsfield Airport, Atlanta, Georgia.

2. CARDION CAPTS SYSTEM

2.1 DESCRIPTION OF CAPTS

The Cardion CAPTS equipment used for the multilateration evaluation comprised 5 receiver/transmitter (R/T) units, a master work station (MWS) interfaced to the R/Ts via spread spectrum RF modems, a reference transponder (Mode S aircraft transponder), and a differential GPS system leased from Rockwell Collins.

The R/Ts, built by Cardion, comprised a modified Rockwell Collins TCAS unit, a Rockwell Collins ATCRBS decoder; a Cardion time of arrival (TOA) measurement system containing a 100 MHz clock which functioned on each and every 1090 MHz pulse; and a 68020 microprocessor, which was interfaced to the TCAS unit, the TOA unit, and the RF modem. The initial CAPTS equipment was designed for civil and military applications where the objective was to determine the position of an aircraft by multilaterating on special reply pairs which were stimulated from an ATCRBS transponder by an onboard squitter package. The squitter package stimulated a pair of Mode A transmissions with an inter-reply spacing of about 175 µs, at an average rate of one Hz. The R/Ts continuously listened for ATCRBS replies (which would include fruit from transponders in the air and on the airport surface). The R/T sorted through all these replies looking for pairs with the squitter package spacing. Time-of-arrival information on these reply pairs was then sent to the MWS where multilateration positions were calculated, tracked and displayed. In order to keep the cost of the R/Ts down, Cardion did not employ Cesium or Rubidium clocks; instead, a reference transponder at a known location emitted reply pairs, and their observed times of arrival at the R/Ts were used by the MWS to align the R/T clocks. The MWS was a 486 PC running DOS.

The CAPTS system was then augmented with a Mode S capability to support testing at Atlantic City under a CRDA that Cardion had with the FAA. The augmentation involved adding a TCAS processor subsystem for performing Mode S detection (ATCRBS detection was accomplished by a dedicated Rockwell Collins detector external to TCAS which allowed simultaneous processing of Mode S and ATCRBS replies) and for transmitting Mode S data link messages containing differential GPS corrections and other information to Mode S equipped aircraft or surface vehicles. The TCAS receiver processed short and extended squitter and other data link messages from Mode S transponders. This version of CAPTS was tested at Atlantic City to demonstrate multilateration on short squitter, multilateration on paired ATCRBS replies, Mode S extended squitter for ADS B, Mode S data link for differential correction, and Mode S data link for other information interchange.

The CAPTS equipment was augmented with a whisper shout capability to support the Lincoln Laboratory testing. The first change involved adding a P4 pulse to Mode A transmissions; this pulse tells Mode S transponders that the interrogation is from a TCAS unit, and Mode S transponders should not reply with an ATCRBS reply. TCAS normally uses P4 with a Mode C transmission and this feature was retained. Second, Lincoln and Cardion jointly decided to retain the CAPTS paired ATCRBS interrogation/reply mode to support whisper shout testing; this does not imply this mode is recommended or mandatory for an operational system. In fact, Lincoln Laboratory strongly recommends that it not be employed in an operational system; a single Mode A interrogation should be employed at each whisper shout level, and the R/Ts should each only listen for a time after the interrogation corresponding to the maximum range of surface aircraft from the R/T, typically less than 30 µs, during which time an average of much less than one fruit would be received at typical fruit rates of several thousand per second.

The current pair-wise interrogation implementation has a great disadvantage in that a multilateration position measurement needs two successful interrogations by the interrogating R/T, and two successful reply detections by at least 3 R/Ts.

The present CAPTS architecture does not have a provision for R/Ts to have knowledge in terms of their local clock of the transmit times of other R/Ts or for the R/T to execute commands at specific times. This precludes sending to the MWS only those replies received from aircraft within a few miles of the R/T; e.g., on the airport surface. Thus the R/Ts must process replies over a much larger time window thereby increasing the loading on the R/Ts, RF modems, and the MWS.

The final change proposed by Lincoln Laboratory was that transmitting R/Ts were to send the MWS the time stamp of transmit times to support an evaluation of the use of two-way range data in the position calculation, but this change was not completed.

The resultant modified CAPTS system was installed at Atlanta Hartsfield Airport. Testing uncovered problems in both the hardware and software associated with the higher fruit rates in Atlanta than had been experienced at Atlantic City. The tests also uncovered areas where changes would improve performance, particularly in coping with multipath-induced errors in received messages. Many, but not all, problems were addressed and/or resolved. A partial listing of problems and changes is discussed in Appendix A. The purpose of this critique is to aid contractors in building equipment with both improved performance and lower cost. Lincoln Laboratory believes that the tests clearly indicate that multilateration technology can be obtained commercially; all that needs to be done is to properly integrate, code and package the components.

2.2 DISPLAY

The Cardion MWS drives a CRT display that contains an outline of the airport surface, including all the runways, taxiways, ramps, terminals, and other buildings and features. The display can show raw target position measurements and the smoothed positions. A history trail of several seconds can be displayed.

2.3 MODEMS

Spread spectrum radio modems were used to send data and system commands between the R/Ts and the MWS. These modems operated at about 900 MHz, and at a 9600 bps data rate. There was a Yagi antenna at each R/T aimed toward the MWS collection of Yagi's, one for each R/T and aimed at the associated R/T. Some care had to be exercised to choose modem channel and modulation code to prevent what appeared to be mutual interference at the common cluster of antennas at the MWS end of the links located on the 12th floor of the control tower. Radio links are not recommended for operational installations.

2.4 ANTENNAS

The antennas used at Atlanta were variable wing vertically polarized antennas about 2 feet in height and 1 foot in width. Once set to a gven pattern, the antenna patterns are fixed. The gain patterns are shown in Figures 2-1 and 2-2. They provide several dB of front to back gain ratio, which is useful in giving an advantage to the direct signal from targets on the airport surface, and putting any multipath reflections that may emanate from reflectors off the airport surface behind the antenna at a disadvantage. In other words, these antennas, if placed on the perimeter, can improve the average Signal-to-Multipath ratio.

2.5 SUMMARY SYSTEM ASSESSMENT

The CAPTS system proved adequate to support the evaluation contained in the body of this report. Ideally, the NDI equipment that was used in previous testing at Atlantic City should have worked upon installation and the test program should have occupied 3 months. However, problems attributable to multipath and fruit were uncovered which necessitated numerous fixes. Cardion corrected the problem which stretched out the system evaluation activity. The net result was a good understanding and good software to perform short squitter multilateration and extended squitter processing. The demonstration whisper shout hardware and software were at a much lower maturity level. Some additional testing of whisper shout is desirable to provide the knowledge base to architect and build a second generation system appropriate for production and operational application. We recommend that (1) the multilateration hardware be further developed and made operationally robust; and (2) that some additional testing in other high fruit environments be performed, particularly with whisper shout. The ID and track data which such a system is capable of providing should provide the basis for achieving both capacity and safety benefits on the airport surface.

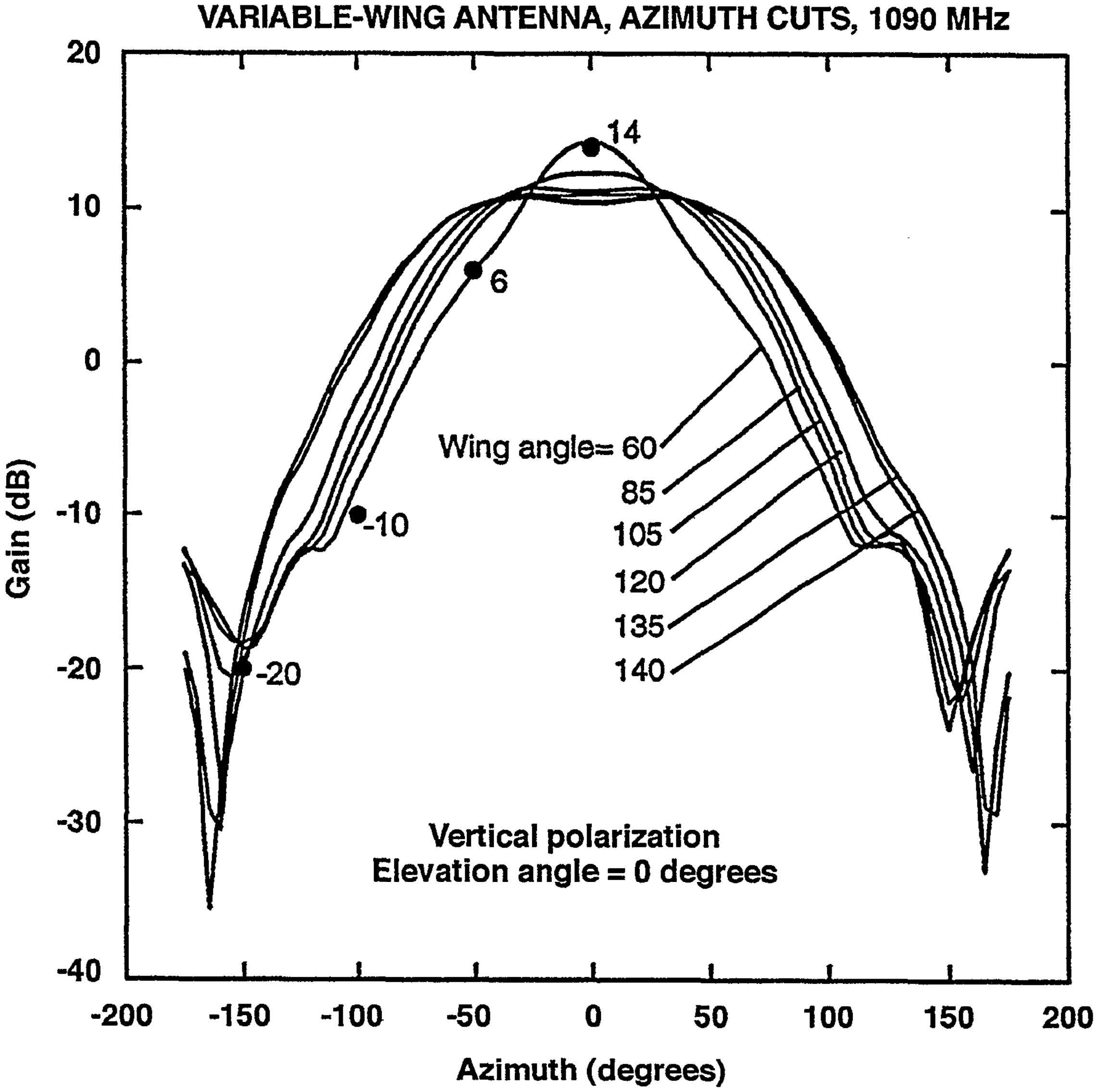


Figure 2-1. *Variable-wing antenna, azimuth cuts.*

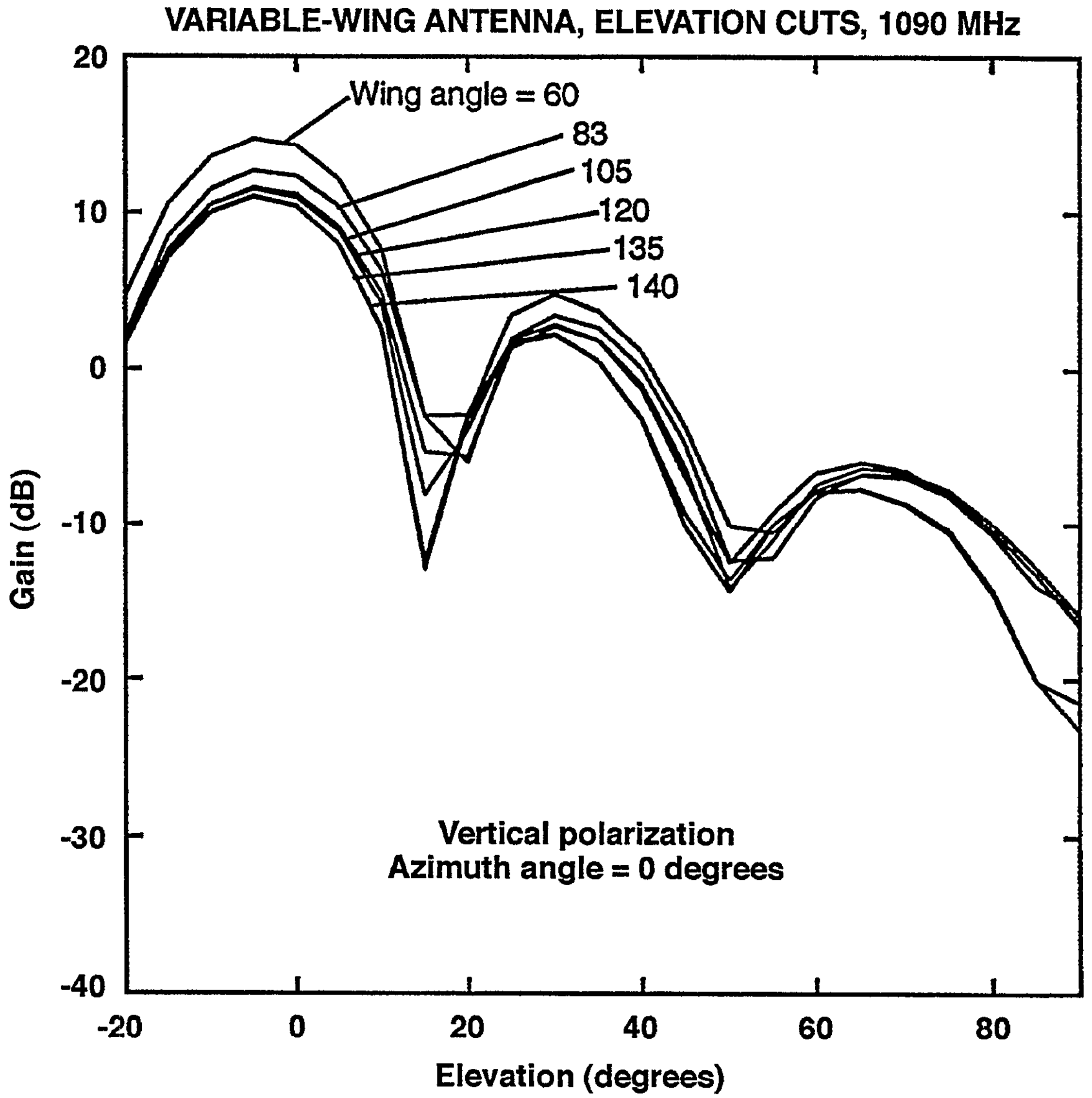


Figure 2-2. Variable-wing antenna, elevation cuts.

3. COVERAGE

3.1 SITE SELECTION CONSIDERATIONS

Selection of R/T antenna sites must take into consideration path-loss attenuation due to range and vertical lobing; blockage by buildings, aircraft and vehicles; multipath off buildings, aircraft and vehicles; and Geometric Dilution of Precision (GDOP). In the 1980's, Lincoln Laboratory made some measurements at Logan International Airport that established some general principles of site selection. The application of these principles to the ADS-B demonstration at Logan Airport resulted in excellent coverage of the movement area. The same principles were applied in the Atlanta multilateration program.

An R/T antenna somewhere on the airport receives a direct signal from the transponder and a ground reflection signal of a strength proportional to the reflectivity of the ground near the reflection point. These two signals may add constructively or destructively, depending on the path length differences and the phase shift associated with the ground bounce. In the limit of either the transmitting or receiving antenna (or both) being at zero height above the ground, then the direct and reflected path lengths are the same, and if the ground reflection coefficient is exactly -1, then the two signals are equal in amplitude and opposite in phase so that they cancel each other out. The following expression for the net received power is an approximation that holds when the sum of the antenna heights is much less than the range between the antennas. Note the expression shows that antenna height is advantageous.

$$P_r \cong \frac{P_t}{4\pi R^2}\,\frac{G_t}{1}\,\frac{G_r\lambda^2}{4\pi}\,\frac{(2\pi/\lambda)^2(2h_t h_r)^2}{R^2}$$

Where:

P_t, P_r = Transmitted and received power

G_t, G_r = Transmit and receive antenna Gains

h_t, h_r = Transmit and receive antenna heights

R = Range

In a similar fashion, an R/T antenna may, in addition to the direct signal, receive a signal reflected off a building. Suppose the aircraft, R/T, and building formed an equilateral triangle 2000 feet on a side. The direct signal path length from the aircraft to the R/T is 2000 feet. The reflected signal path length from the aircraft to the building to the R/T is 4000 feet. Since the speed of propagation is about 1000 feet per μs, the reflection would be received 4 μs after the direct signal. If the building is large and very reflective, such as smooth concrete or corrugated steel, then the reflected received power can be comparable to the directly received power even though it travels twice as far. This is because the aircraft antenna may have higher gain in the direction of the building than in the direction of the R/T. Therefore, the reflection of a Mode S or ATCRBS transmission squitter can garble the direct signal, causing corruption of the data bits, or making the preamble impossible to detect. However, the leading edge of the first preamble pulse is generally clean and it should be used for time of arrival measurements.

R/T antenna height helps mitigate building reflections. Imagine an R/T antenna at eye height located on the perimeter vehicle road near the 30-foot high Airborne Express facility, which is the small rectangle at x=0.25 nmi, y = 0.73 nmi in the Figure 3-1. If an observer at the

R/T antenna were looking toward that building and the building were faced with a mirror, then the observer would see in the mirror the reflection of aircraft on the taxiways and runways behind him. If the R/T antenna were omnidirectional, it would receive reflections of ATCRBS replies or Mode S squitters by the same mechanism. If, however, the observer and R/T antenna were 100 feet high, then as the observer looked down at the mirrored face of the building, all he would see is the parking area in front, not any aircraft on the runways. Similarly, the antenna would not receive any squitter reflections from the building.

Perimeter sites are better than sites in the middle of the movement area for several reasons. There are height restrictions in the middle. A site in the middle may see multipath off all the perimeter buildings, whereas a perimeter site would not see multipath from perimeter buildings to either side.

As will be seen in the discussion of Geometric Dilution of Precision (GDOP), obtuse or acute triangles are to be avoided. Triangles that have similar side lengths are preferred. GDOP is better in the middle of the triangle, and poor at the vertices and the extensions of the sides. Ambiguous solutions arise near the vertices and between the extensions of the sides. Therefore, on GDOP considerations, it is not generally useful to place sites in the middle of the coverage area.

In summary, R/T antenna height is desirable, perimeter sites are preferred, and by putting the antennas on buildings, that building is eliminated as a reflection source for that antenna.

The siting process generally proceeds as follows. Make as the first selection the building that is some combination of the highest, has the largest surface, is on the perimeter, and has an unobstructed view of most or all of the desired coverage area. The choice of the second and third sites takes into account to some extent the total number of R/Ts that will be available. For this program, 5 R/Ts were available. For GDOP considerations, the selection of the 4 remaining sites took into account the same factors as the first site, but with the additional considerations that they should be spread more or less uniformly around the perimeter, and compensate for coverage deficiencies of the other sites.

Early in the program, a trip was made to Atlanta to find sites that were both effective and for which arrangements to use it could be made. On this basis, the roof of the Stouffer's hotel seemed to be the best site. Permission to use this site was obtained. It has an excellent unobstructed view of the whole movement area and is high. The second site to be selected was the Delta hangars. They were chosen because they are high and themselves are large reflectors. They also have a fairly unobstructed view of the movement area. Three more sites needed to be selected. Because Stouffers was in the middle of the north side, and Delta was at one end of the south side, it seemed reasonable to pair the Delta location with a second R/T in the vicinity of Terminal C, and to give Stouffer's an east and west neighbor. In this way, the coverage of the lengths of the runways would be more or less uniform.

Therefore, the northern end of Terminal C was chosen as a site. In the northwest corner, the highest opportunity was the FAA Regional headquarters building, and access and permission were obtained from the owner (the FAA leases the building). In the northeast corner, the only available location was the Ford Motor Company plant, even though it was not very high and had some obstruction by foliage. These five sites provided good GDOP, balanced coverage, and mitigated two very large reflectors (Stouffers and the Delta hangars).

3.2 COVERAGE MEASUREMENTS

Coverage measurements were conducted using the Lincoln Laboratory Surface Surveillance Vehicle (SSV). It was equipped with a Mode S transponder that emitted extended squitters that contained GPS derived (not differentially corrected) latitude and longitude. These extended squitters were emitted for the sole purpose of knowing where the SSV was during its travels around the runways and taxiways of the north side of the Atlanta airport. The transponder also emitted short squitters. The reliability of reception of these squitters by each R/T as a function of the SSV position was evaluated. The results are shown in Figures 3-1 to 3-10. In these figures, each dot represents a squitter reception when the SSV was at that position. The position was obtained from extended squitters containing raw GPS positions. Because the positions were not differentially corrected, there are discontinuities and biases due to satellite changes and Selective Availability (SA), respectively. Each of the R/Ts was able to see to the far distant points with usable reliability. That is to say, no R/T lacked the margin to see large areas of the airport surface. The coverage of R/Ts 1 and 2 (Ford and Stouffers) were degraded in the region that would correspond to multipath corruption by reflections of the Delta hangar. The best per squitter performance averaged over the surface was 84.6% for Terminal C and extended squitters in which the 24 bit Mode S ID was correct to within 7 bits. The worst performance was 61.8% for Ford and extended squitters having all 112 bits correctly decoded. The detailed results are given in the Tables 3.1 and 3.2.

Table 3-1. Coverage (ID within 7 bits)

R/T	Short Squitter Reliability (>=14 ID bits)	Extended Squitter Reliability (>=14 ID bits)
0- Delta	75.0	81.8
1 - Ford	75.0	79.1
2 - Stouffers	80.1	80.1
3 - FAA Region	79.0	78.2
4 - Terminal C	83.1	84.6
Average Reliability	78.44	80.76

Table 3-2. Coverage (Correct Message)

R/T	Short Squitter Reliability (Correct Message)	Extended Squitter Reliability (Correct Message)
0-- Delta	63.2	62.4
1 - Ford	62.7	61.8
2-- Stouffers	68.1	67.8
3 - FAA Region	69.3	68.1
4-- Terminal C	70.4	69.2
Average Reliability	66.74	65.86

Notice that the extended squitters were slightly more reliable than the short. This might be explained by the fact that the DF codes for short and extended squitters are 1011 and 1001, respectively. The PPM demodulator of the TCAS unit that the R/T is based on may have a slight asymmetry, which in noisy conditions or multipath conditions has a bias toward decoding 0's. Thus, the DF code richer in 0s would be recognized more reliably.

The May 19 coverage test data was also analyzed to determine the reliability of being able to compute a 2D position on the airport. The criteria was that at least 3 R/Ts received the squitter, and at least one of the R/Ts received all the message bits correctly (in particular, the ID to enable correlation with already-formed tracks), while the others received the ID correctly within 7 bits. The results were that a position could be computed for 93.2% of the squitters, as shown in Figure 3-11. This is quite consistent with what would be expected if the squitter reception process were not a function of position on the airport surface, and the requirement for at least one squitter being high confidence were dropped. In that scenario, the average short squitter reliability of the above table (78.44%) would result in a probability of getting at least three squitters of 93%. If all were required to be high confidence, then the reliability value 66.74% would give a probability of position of 80%. This shows the advantage of not requiring perfect receptions. In the limit of this point of view, the detection of preambles only would be beneficial to the reliability. In this case, correlation would be exclusively by time. There would probably be little occurrence of miscorrelations, i.e., associating squitter receptions from different squitters, because the Mode S rate is so low that receptions received within a time window related to the longest leg of the triangle would rarely include more than one squitter. Numerically, a 10,000-foot R/T separation would result in a window of 10 µs. If the squitter rate were Poisson at 2000 per second, then the probability of receiving 2 squitters in a 20 µs window would be less than 5%.

3.3 MULTIPATH REGIONS

Figure 3-12 shows the multipath regions that simple geometric considerations would predict for the effects of the Delta hangar on the R/Ts and Ford and Stouffers. The coverage Figures 3-1 to 3-10 show a qualitative agreement. Also, see Section 5.3.12.

3.4 CALIBRATION SITE SELECTION

The selection of a site for the calibration source was accomplished so that all sites could get a good view of the calibration source. The obvious choice was on the west end of the top of Stouffer's since it seemed to be visible from all the sites, yet was not too close to the Stouffer's R/T on the east end. However, experimental observations indicated that the Ford R/T had trouble receiving the ID of the extended squitter correctly, due to multipath reflections off the Delta hangar. This was overcome in two ways. First, the calibration correlation algorithm was modified to only require the ID to be correct within 7 bits. Also, in light of the hypothesis that the R/T may have a bias toward decoding 0s as opposed to 1s, an ID rich in 0's was selected, mainly 808080 in Hex.

3.5 COVERAGE SUMMARY

In summary, coverage is optimized by selecting as sites the tops of tall buildings uniformly spaced around the perimeter of the airport, and using antennas that project gain onto the surface. Using these criteria, 5 sites were selected that gave a 93.2% probability of obtaining a multilateration position measurement with one or more perfect Mode S IDs on a given short squitter emitted from a randomly selected position on the airport movement area.

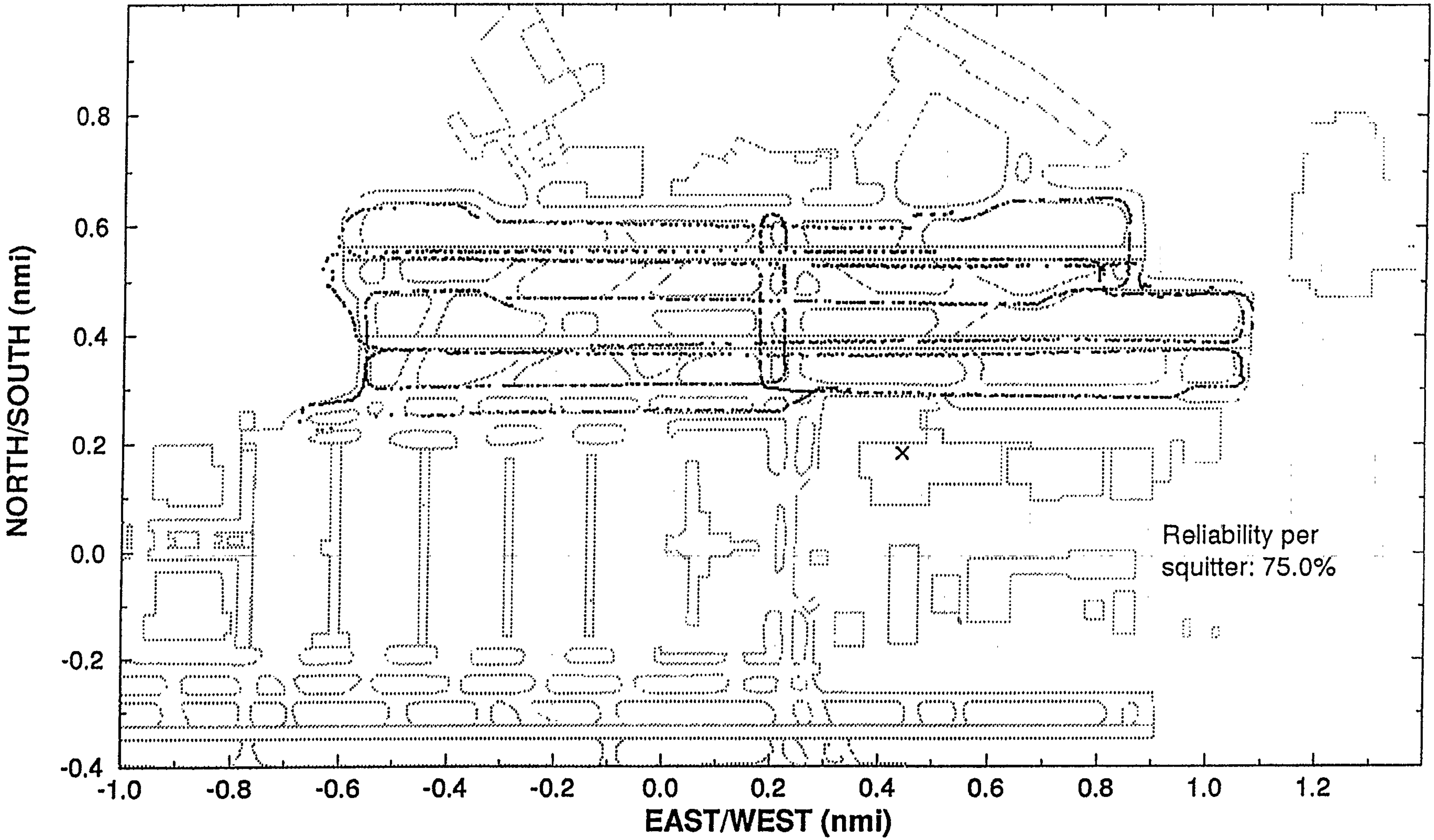


Figure 3-1. Delta short squitter coverage (ID within 7 bits) from SSV. Positions are GPS-derived, but are not differentially corrected.

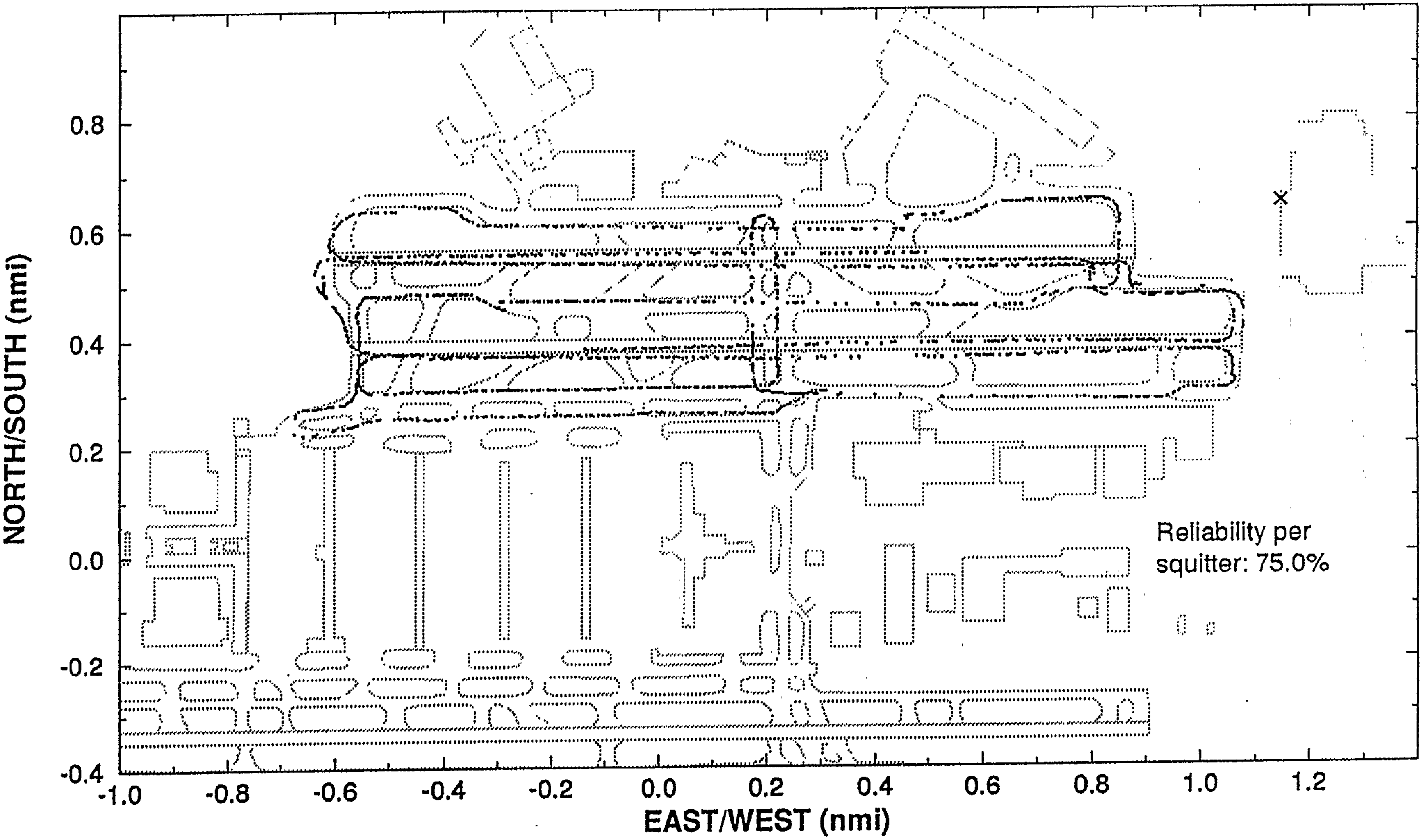


Figure 3-2. Ford short squitter coverage (ID within 7 bits) from SSV. Positions are GPS-derived, but are not differentially corrected.

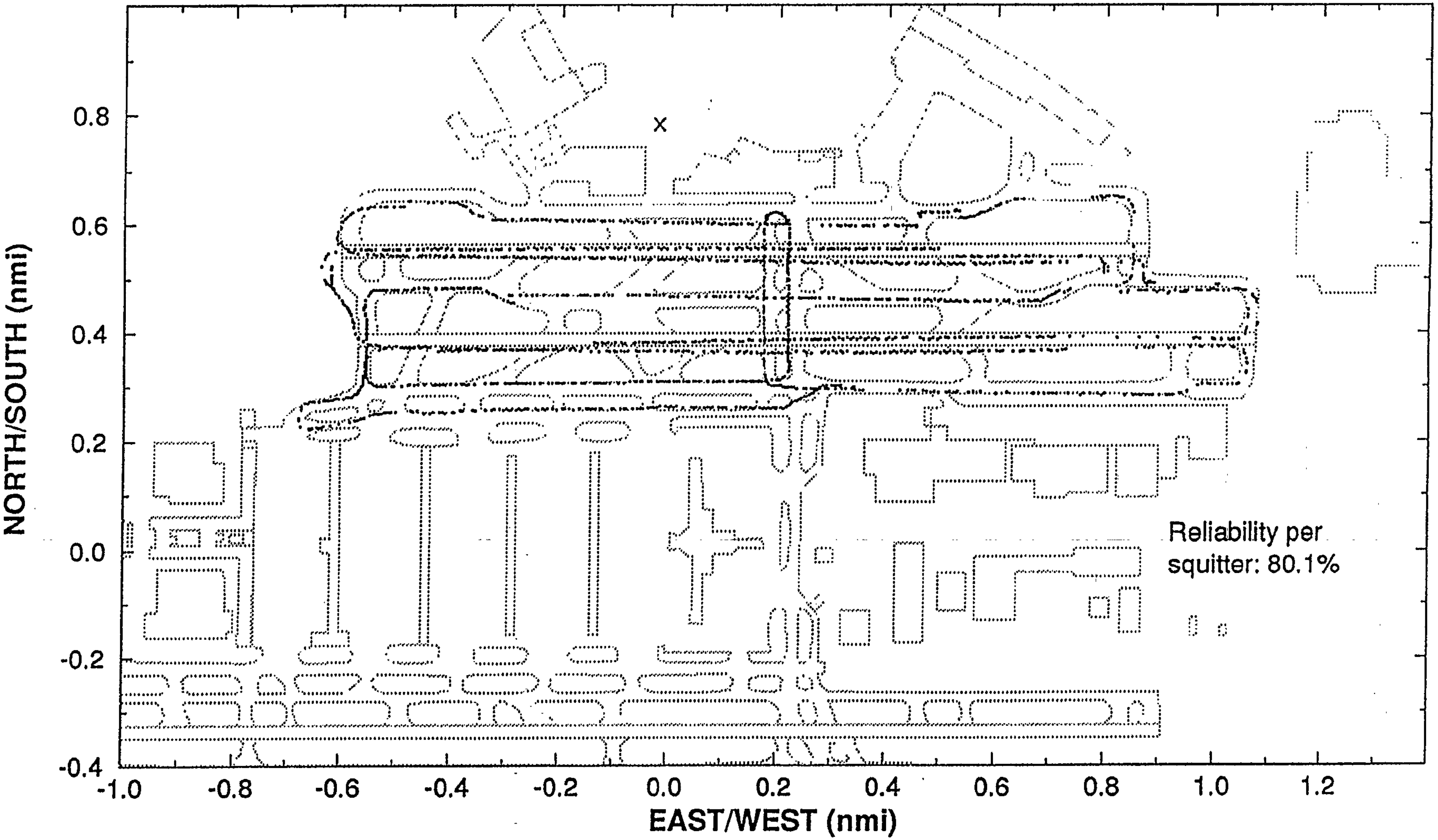


Figure 3-3. Stouffers short squitter coverage (ID within 7 bits) from SSV. Positions are GPS-derived, but are not differentially corrected.

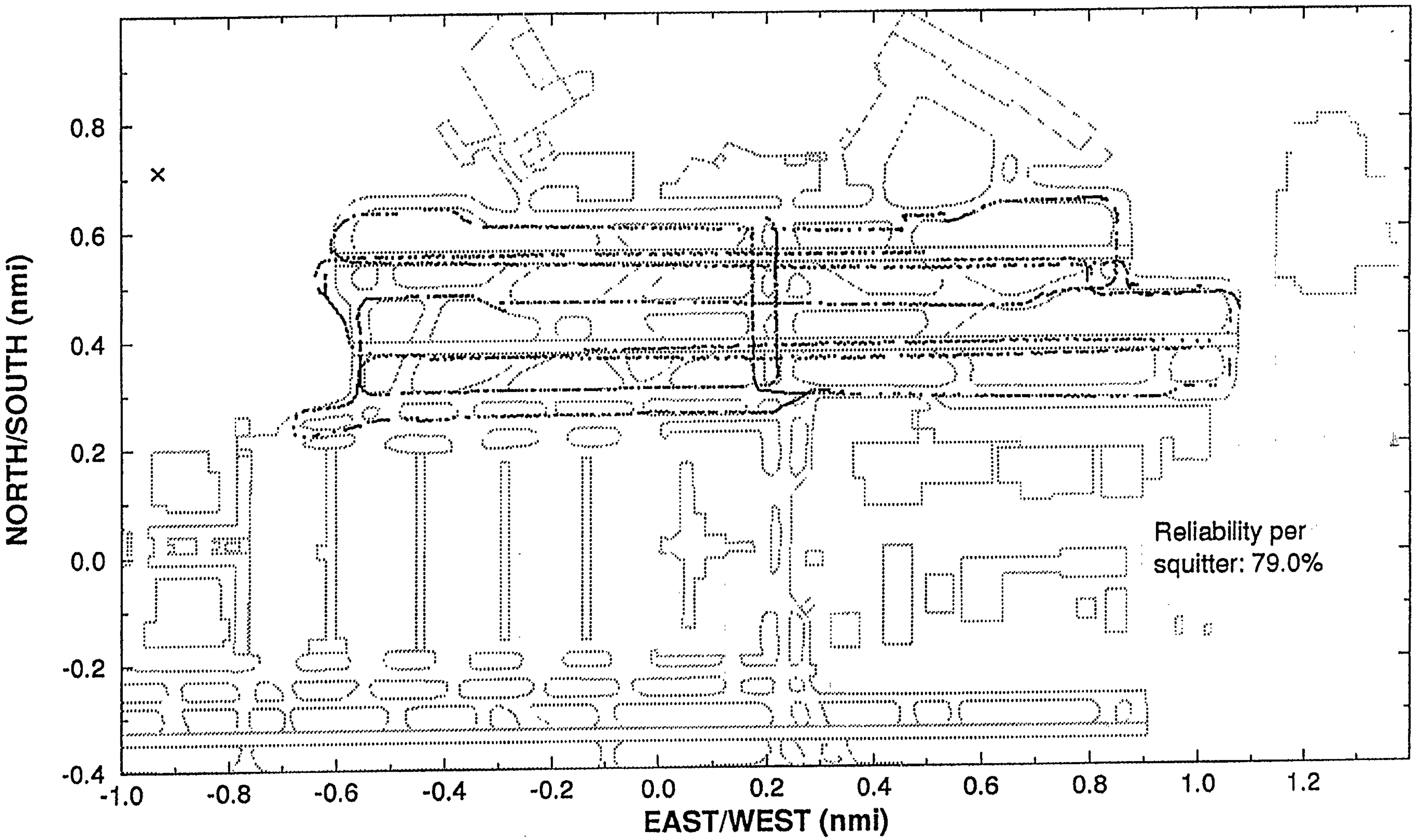


Figure 3-4. Region short squitter coverage (ID within 7 bits) from SSV. Positions are GPS-derived, but are not differentially corrected.

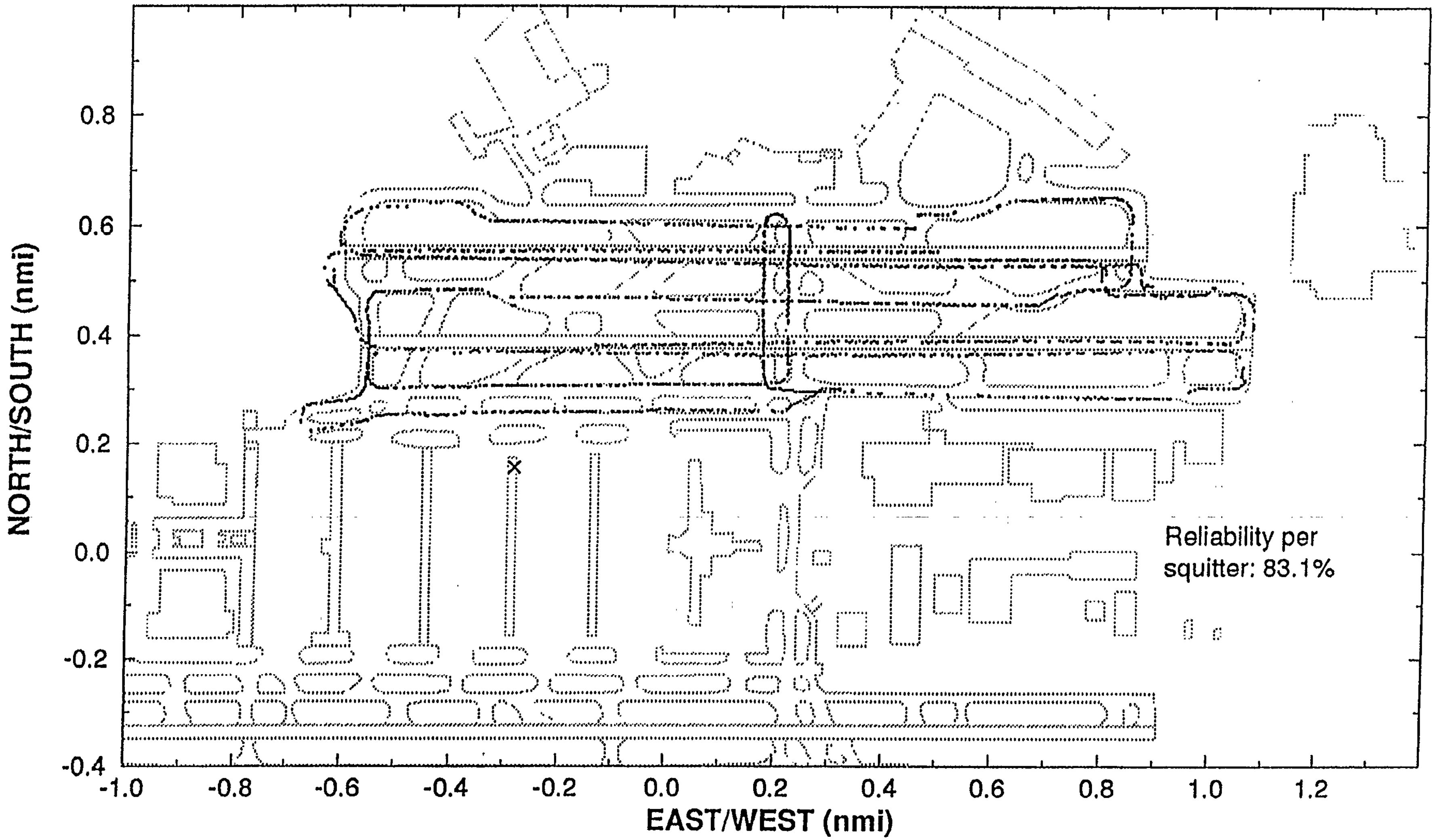


Figure 3-5. Terminal C short squitter coverage (ID within 7 bits) from SSV. Positions are GPS-derived, but are not differentially corrected.

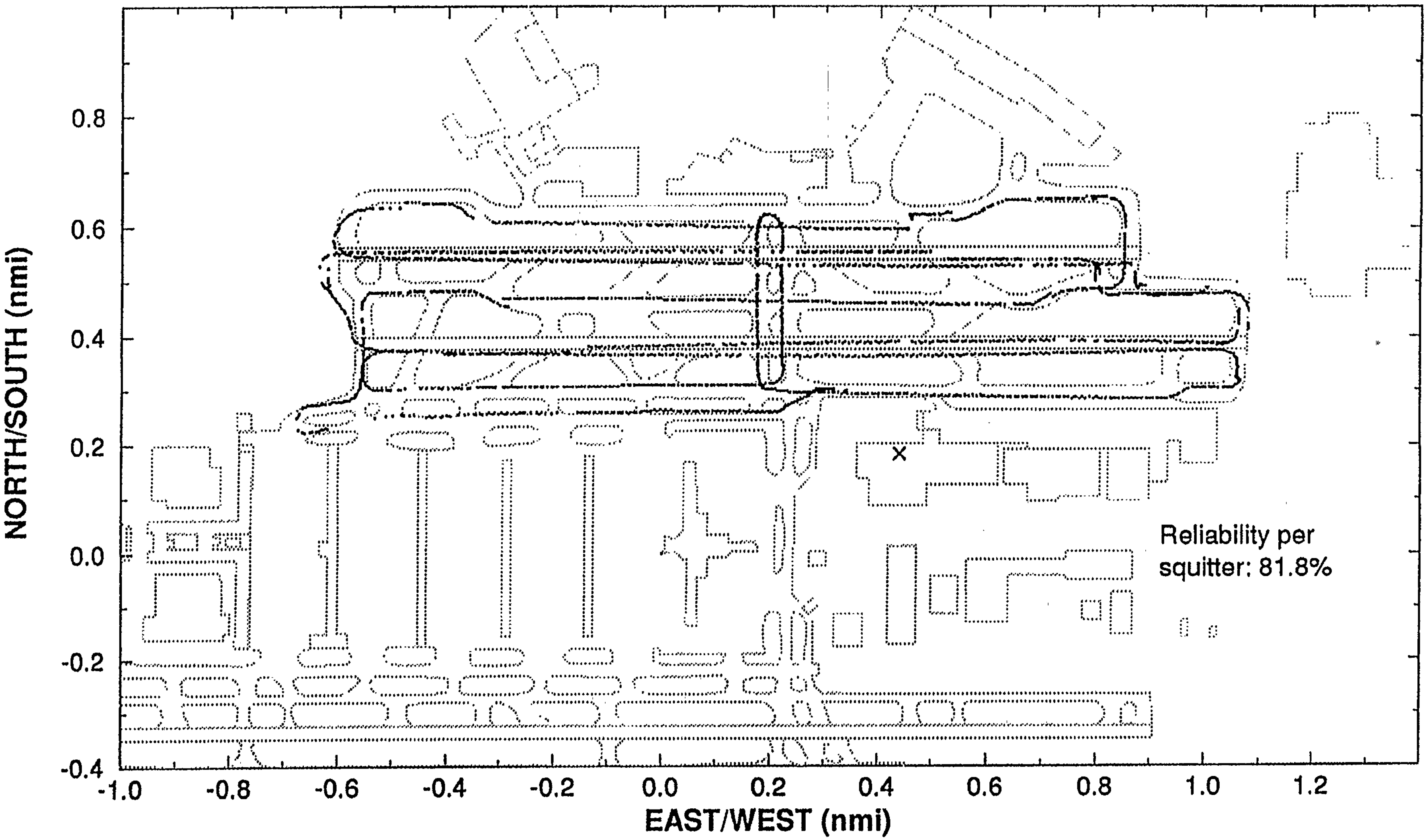


Figure 3-6. Delta long squitter coverage (ID within 7 bits) from SSV. Positions are GPS-derived, but are not differentially corrected.

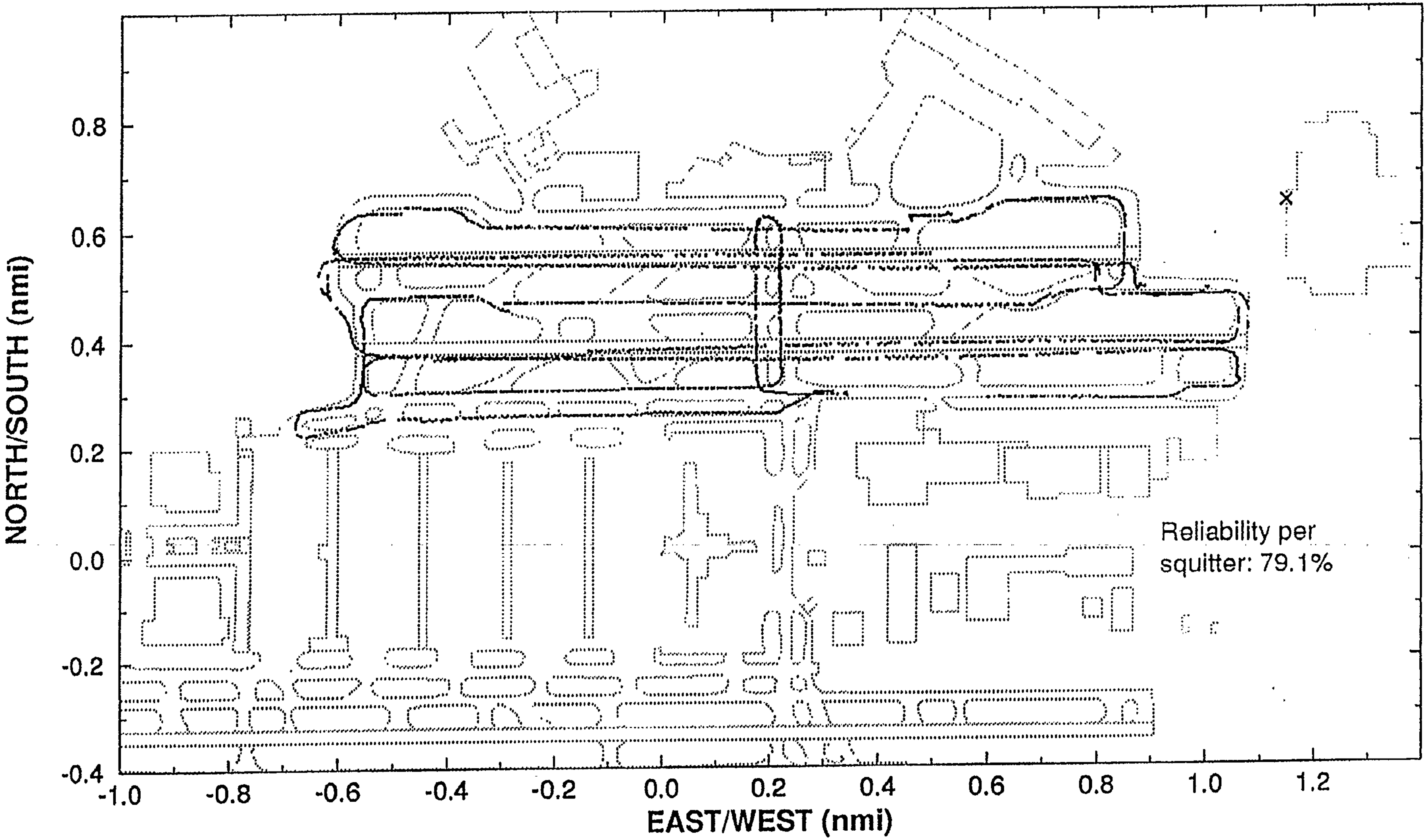


Figure 3-7. Ford long squitter coverage (ID within 7 bits) from SSV. Positions are GPS-derived, but are not differentially corrected.

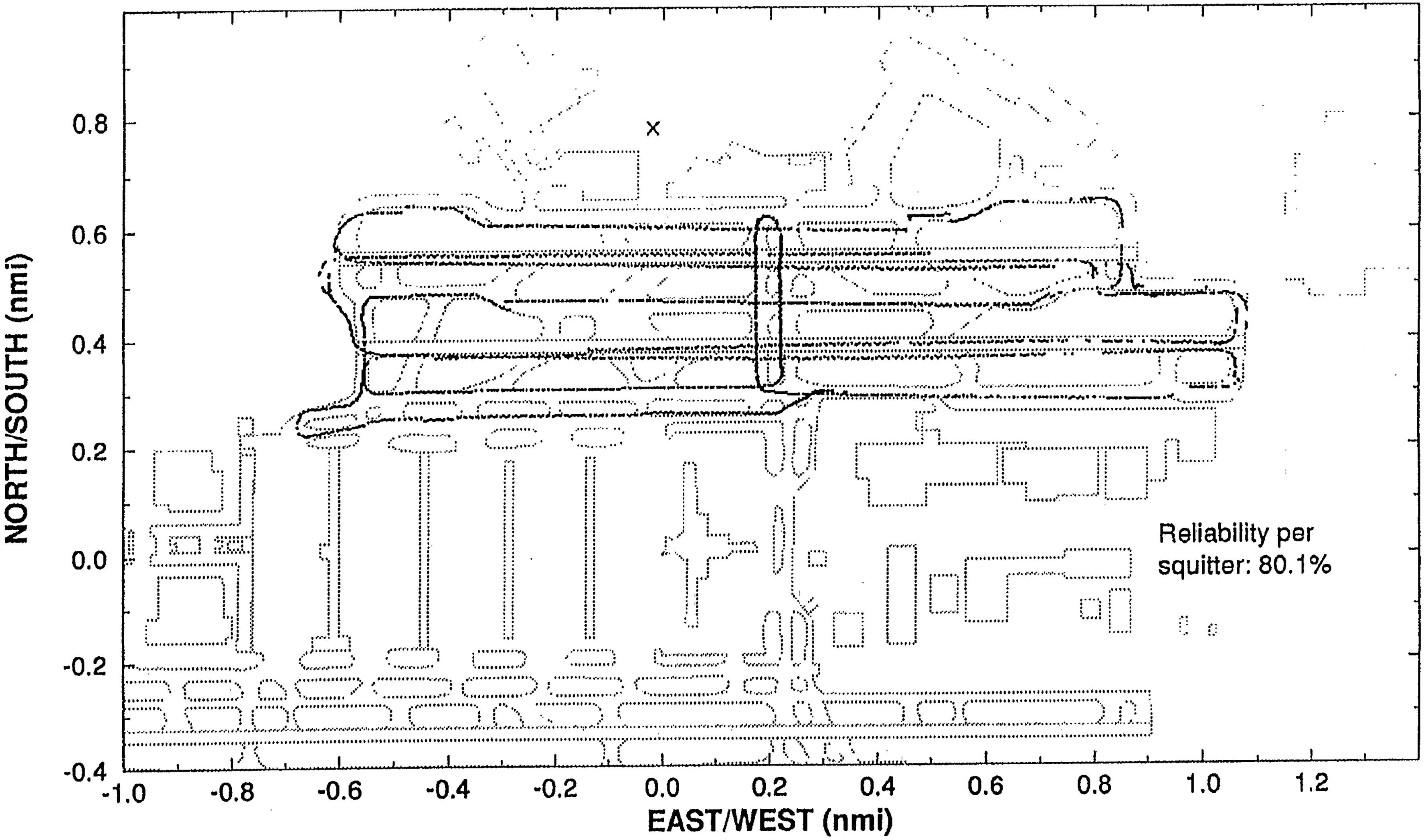


Figure 3-8. Stouffers long squitter coverage (ID within 7 bits) from SSV. Positions are GPS-derived, but are not differentially corrected.

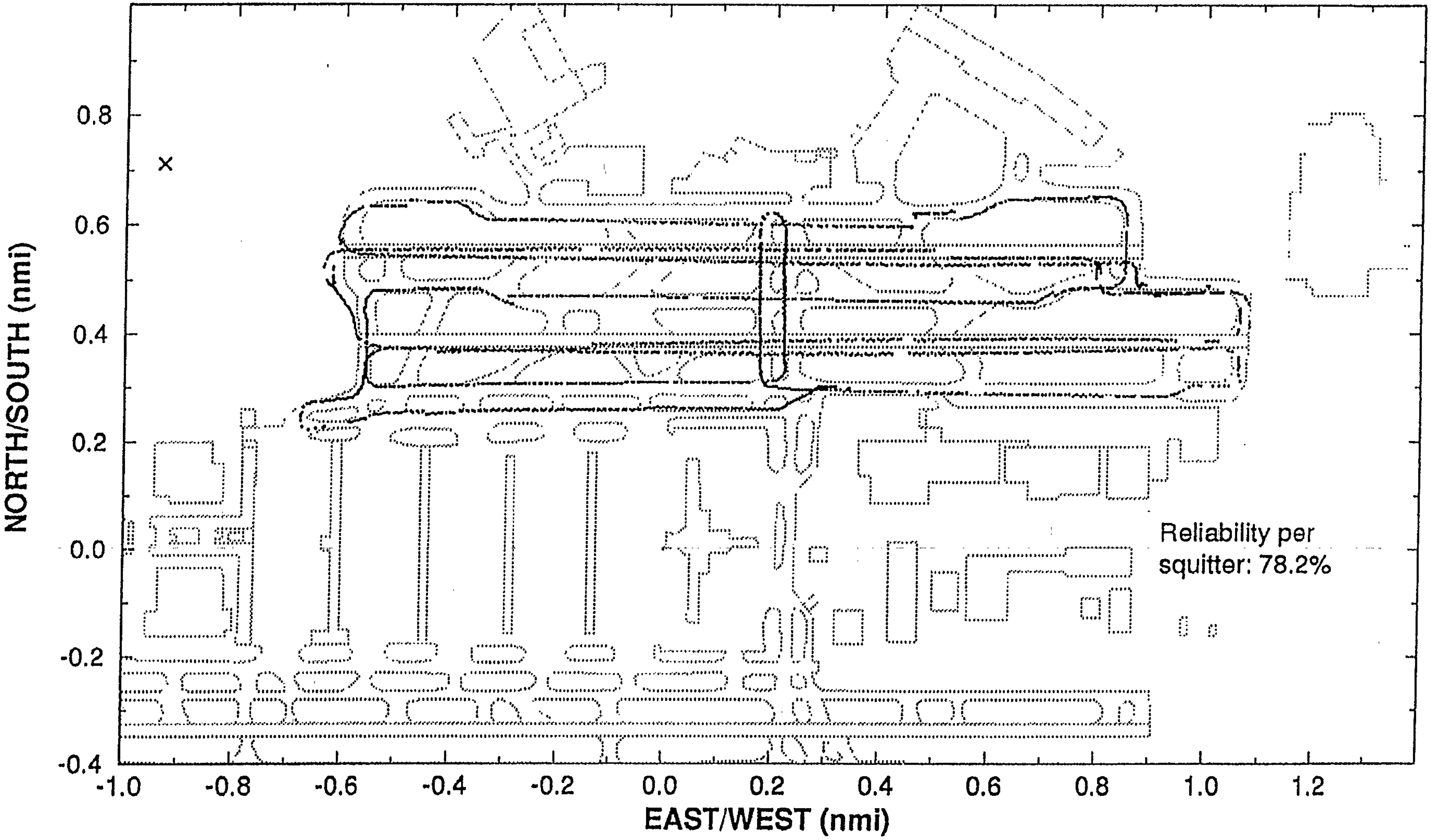


Figure 3-9. Region long squitter coverage (ID within 7 bits) from SSV. Positions are GPS-derived, but are not differentially corrected.

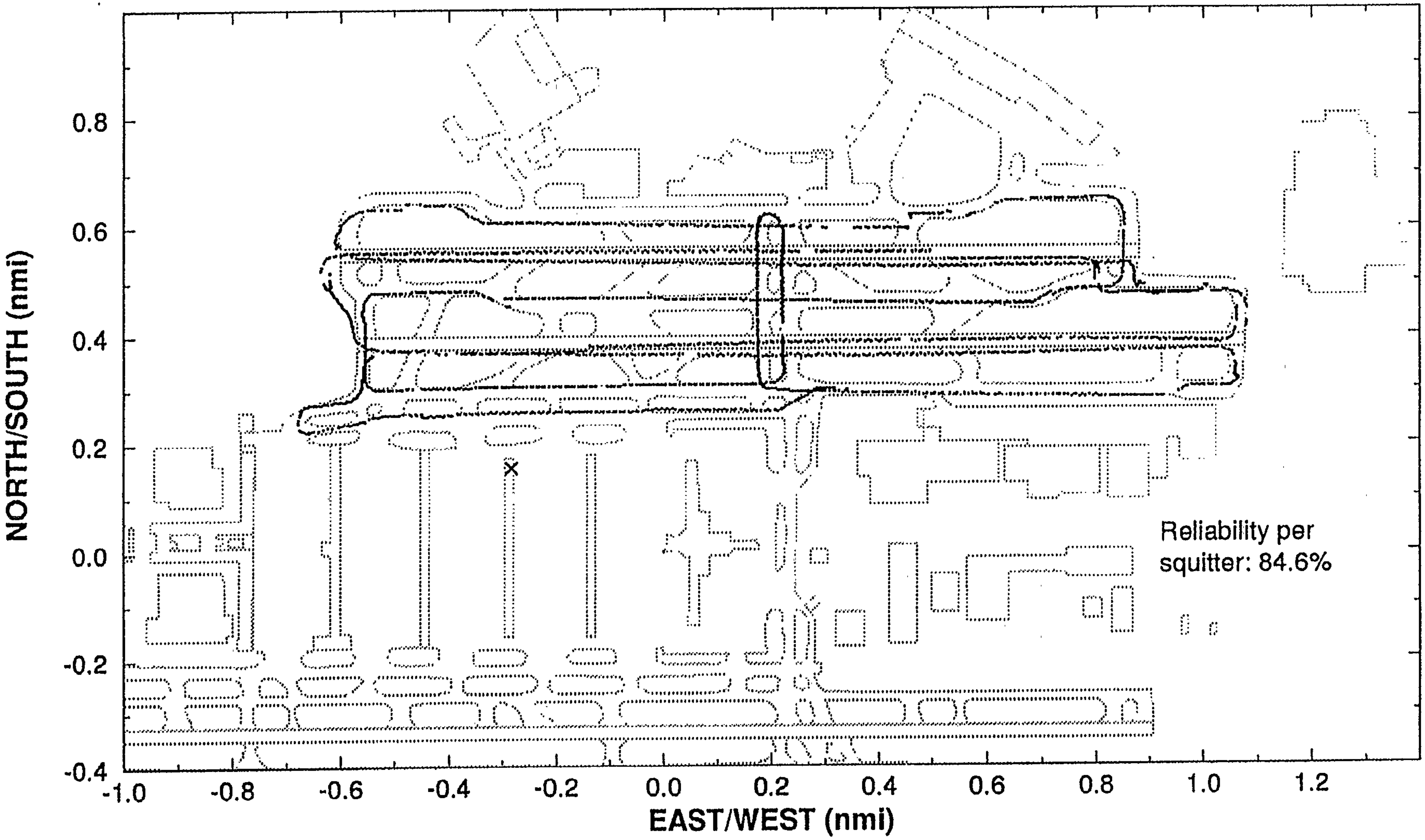


Figure 3-10. Terminal C long squitter coverage (ID within 7 bits) from SSV. Positions are GPS-derived, but are not differentially corrected.

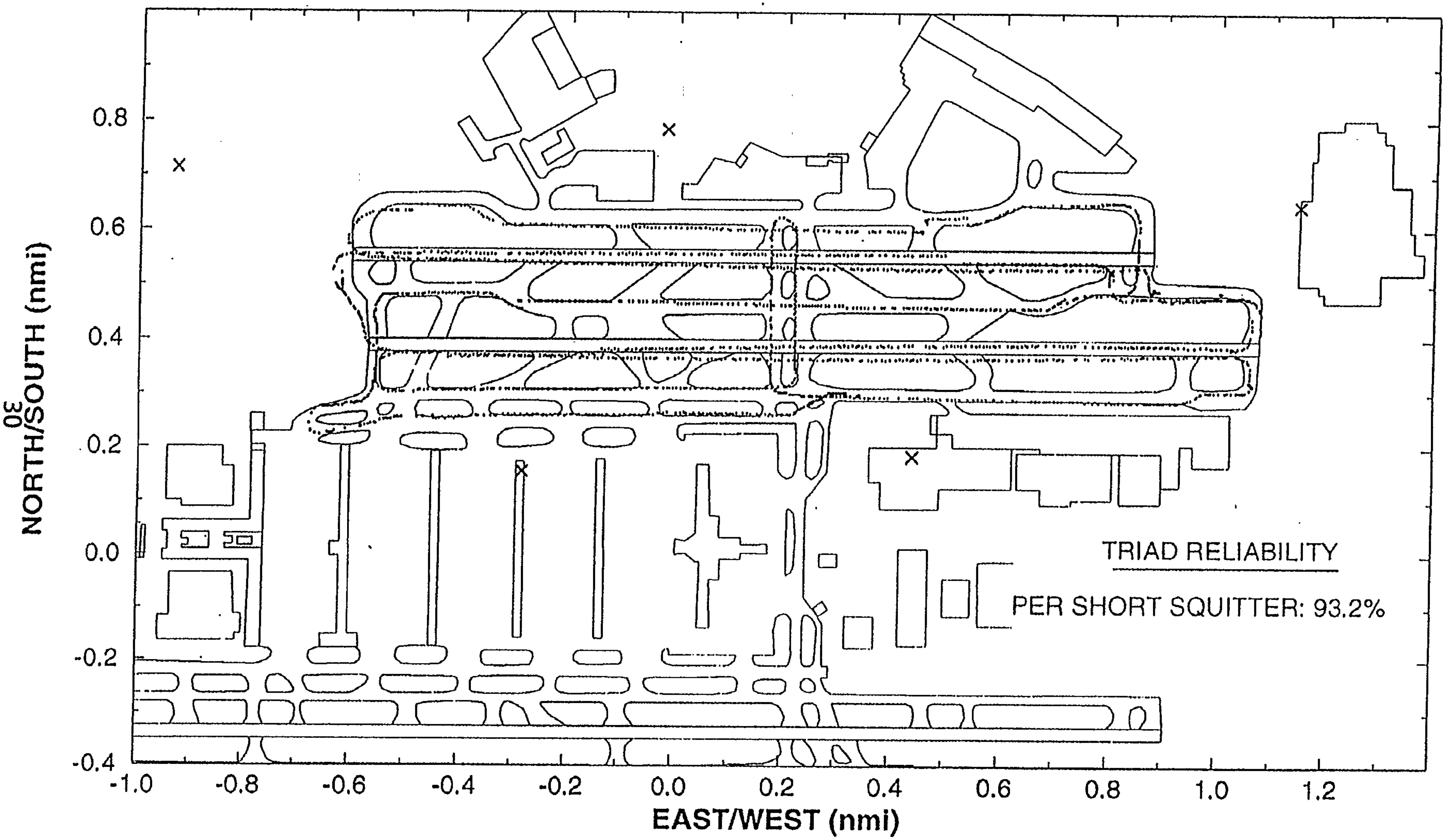


Figure 3-11. Multilateration short squitter coverage (1 squitter with correct ID and 2 or more with ID within 7 bits) from SSV. Positions are GPS-derived, but are not differentially corrected.

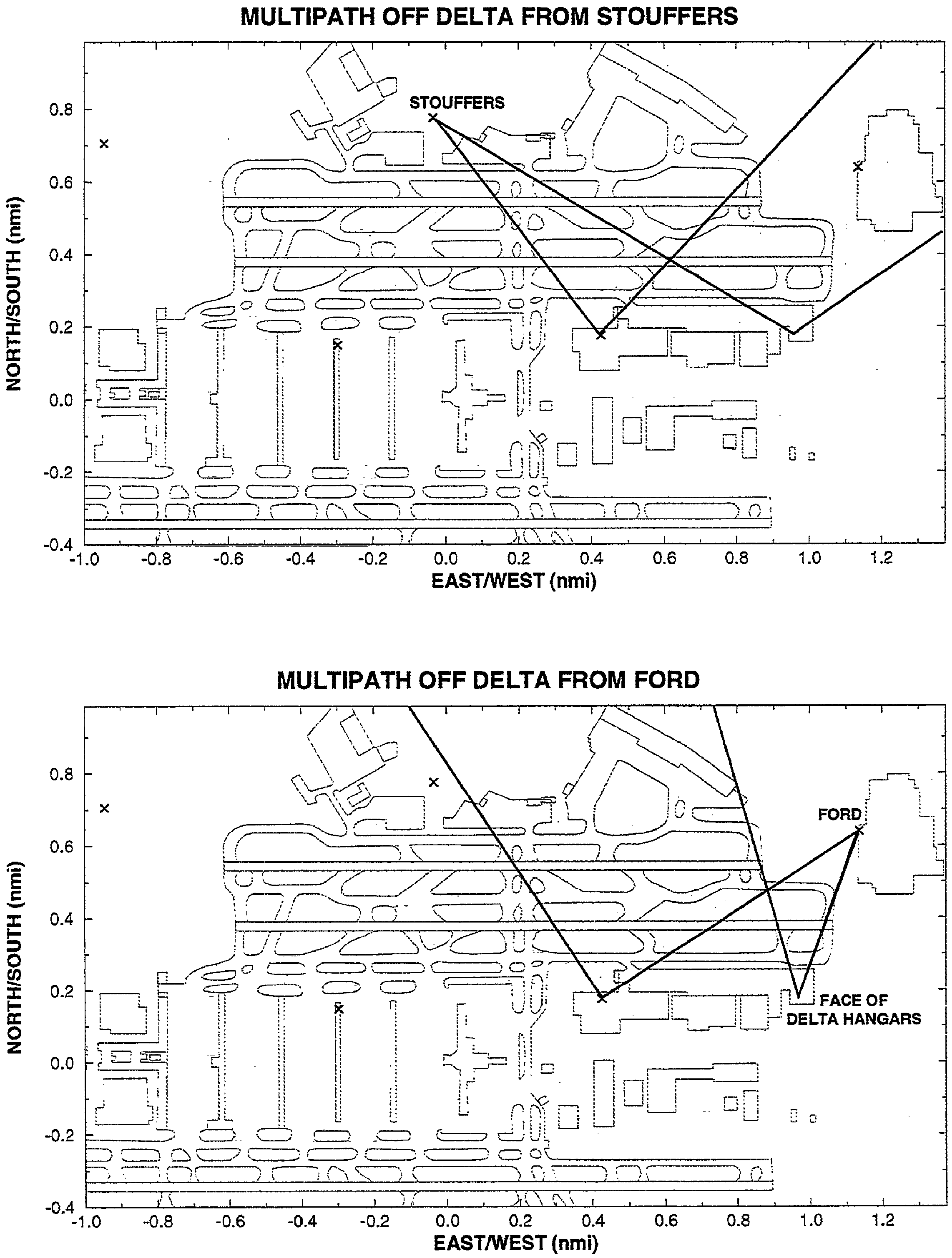


Figure 3-12. Multipath zones due to reflections from Delta hangars; top as seen from Stouffers, bottom as seen from Ford.

4. ACCURACY

4.1 THEORETICAL CONSIDERATIONS

The Bendix Corporation made a theoretical analysis of the accuracy of multilateration on the airport surface and reported the results in Reference [1].

The accuracy of multilateration depends on the following factors:

Pulse rise time

Signal-to-Noise Ratio (SNR)

Pulse Leading Edge detector

Clock quantization

Survey accuracy of receivers and calibration source.

Geometric Dilution of Precision

Multipath corruption

Clock Calibration errors

The effects of pulse rise time and signal-to-noise ratio are given as:

$$\sigma_N = \frac{\text{Rise Time}}{\sqrt{2\,\text{SNR}}}$$

Assuming the weakest reception has a SNR of 20 dB, and the rise time is 100 ns, then the sigma TOA would be 7 ns. Cardion laboratory measurements reported in Reference [3] indicated a sigma of 6 ns for strong signals and a worst case of 16 ns for weak signals. However, there was also a +/- 40 ns signal strength dependent bias in the first generation equipment, most of which was removed in the equipment used in the Atlantic City and Atlanta tests. The TOA accuracy of the second generation equipment used in the Atlanta tests was evaluated using whisper shout data to be less than 10 feet (i.e., one clock count) except for R/T 3, as reported in Section 4.5.5.

Appendix B shows that GDOP is less than 2 in most cases if the preferred R/Ts receive the reply. The GDOP factor must be applied to the TOA measurements, and also to the survey errors, which are assumed to be less than 3 feet. If the R/T clocks have a low rate of frequency drift and the MWS calibration algorithm uses a sufficient amount of smoothing, then the calibration errors should be essentially zero. Finally, if there is no multipath or fruit corruption of the leading edge of the first pulse in the reply, then the accuracy budget would be as in Table 4.1.

Table 4-1. Accuracy Budget

Item	Value
Rise Time and SNR	7 ft
Clock Quantization	3 ft
Multipath and Fruit	0 ft
Calibration	0 ft
Survey Error	3 ft
Net Per TOA (RSS)	8.2 ft
GDOP Multiplier	2
Net Error Sigma	16.4 ft

This predicted value agrees with the Bendix experience at Logan, and the Cardion experience at Atlantic City. Also, this type of accuracy is comparable to or exceeds that obtainable from an ASDE so that association of primary and beacon data should be straightforward.

4.2 POSITION SOLUTION

In the idealized case of three receiving sites and the unknown target lying in a plane, the three times of arrival may be pairwise subtracted to produce three differences. Only two of the differences are independent. The third difference is computable from the other two, so adds no new information. The two differences are sufficient to solve for the two unknowns, the x and y position of the emitting target. Geometrically, each of the differences corresponds to a hyperbola, and the intersection of the two hyperbolas is the position of the target. The position solution is not always unique. Figure 4-1 shows an example of ambiguous solutions. Note that it does not make any difference which two time of arrival differences are used, the solutions are the same. Qualitatively, the ambiguous regions are at the vertices, and between the extensions of the sides, as indicated in Figure 4-2.

Several algebraic solutions have been discovered by various investigators. In one of them, the three time of arrival differences are used to compute a straight line in the plane of the receivers and target. This straight line is then intersected with any one of the hyperbolas. Since the hyperbola is a quadratic, there will be two solutions. If the straight line intersects each leg of the hyperbola once, then the correct solution is the one for which the hyperbola leg agrees with the sign of the time of arrival difference. If the straight line intersects one leg twice, then the correct solution cannot be distinguished from the incorrect one.

There a number of cases for which solution methods have been developed; the 2-dimensional case with all receivers and the target in the same plane; the case where the altitudes of the R/Ts and the target are known; the 3-dimensional case where the presence of arrival times from 4 receivers allows a 3-dimensional position solution. Also, there would exist methods for making use of more than the minimum number of time of arrival measurement, in a least squares type of calculation. The Cardion MWS uses several methods, the details of which are proprietary.

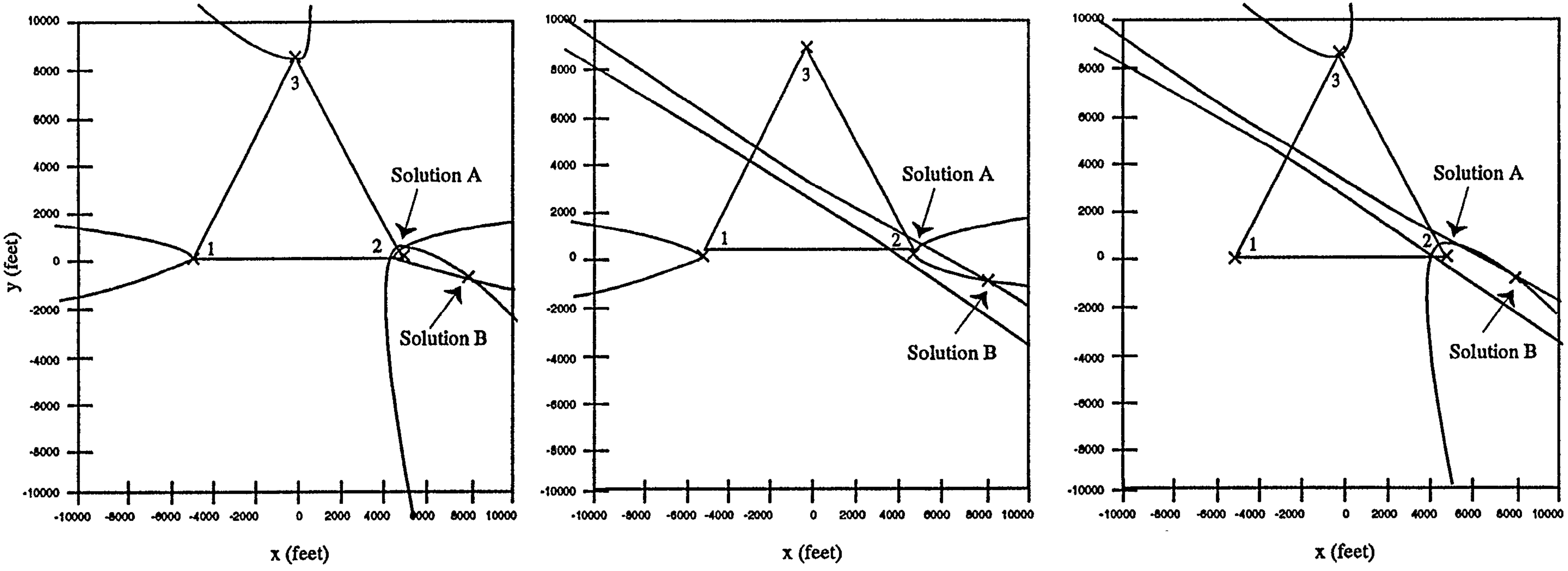
4.3 GDOP

Geometric Dilution of Precision (GDOP) is the factor by which the inaccuracies of the time of arrival measurements are magnified by the geometry of the multilateration solution. GDOP is a function of the shape of the triangle that is formed by the 3 R/Ts whose times of arrival are used to compute the multilateration position. In order to enable the MWS to choose the best set of 3 R/Ts (when more than 3 make a time of arrival measurement) GDOP must be evaluated over the whole coverage area for each of the ten possible R/T triangles. (There are 10 ways to choose 3 R/Ts from a set of 5.) Appendix B shows the 10 GDOP evaluations. Figure 4-3 is a map of the north side of the Atlanta airport showing the minimum GDOP and which R/T triad provides it.

The total area that each R/T site contributes in the minimum-GDOP sense is given in the "GDOP Area" row of Table 4-2. Stouffer's participates the most, and the FAA Regional building the least. The next row in the table shows the short squitter probability of detection average over the whole surface when the ID is correctly decoded within 7 bits, from Table 3-1. (The probability of detection in the region for which the R/T is a minimum-GDOP contributor would be expected to be higher than the value in the Table.) The product of the probability of detection and the area is a rough measure of the relative effectiveness of the R/Ts. Stouffers, with a product of 24.0 is the most effective R/T, while the FAA Regional building is the least. However, it should not be forgotten that the overall reliability and accuracy depends strongly on the presence of 5 R/Ts.

Table 4-2. Relative R/T Effectiveness

Triangle	Delta	Ford	Stouffer	Region	Term C
1	X	X	X		
2	X	X		X	
3 (Never a first GDOP choice)	X	X			X
4 (Never a first GDOP choice)	X		X	X	
5	X		X		X
7 (Never a first GDOP choice)	X			X	X
7 (Never a first GDOP choice)		X	X	X	
8		X	X		X
9		X		X	X
10			X	X	X
GDOP Area (Fraction)	.18	.21	.30	.12	.19
Squitter Detection (%)	75.0	75.0	80.1	79.0	83.1
Product	13.5	15.8	24.0	9.5	15.8

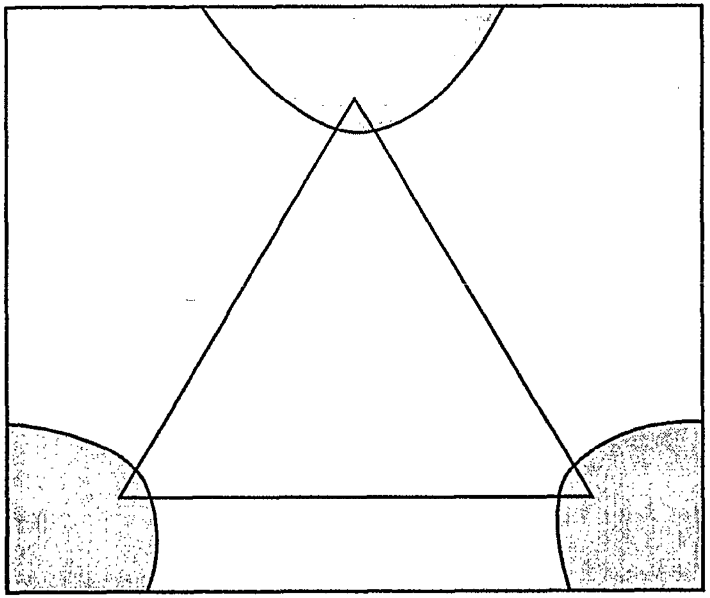


a. Based on hyperbolas 1-2 and 2-3

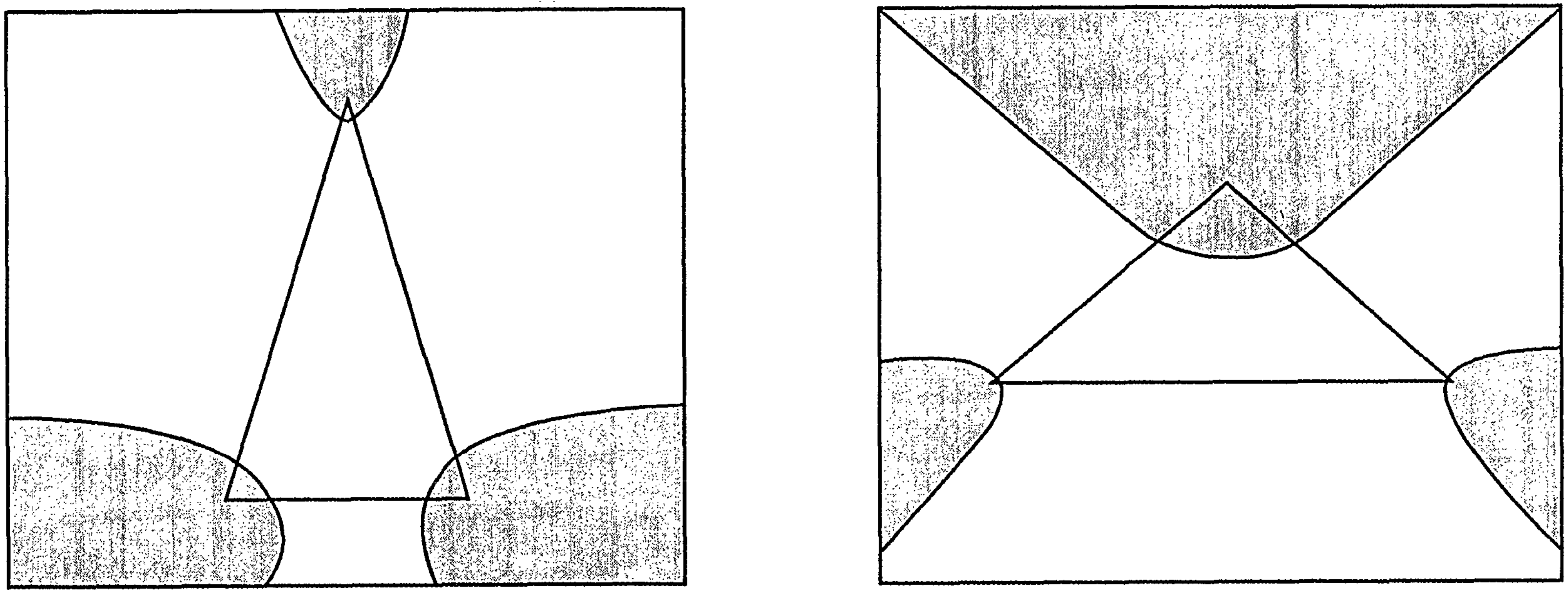
ba. Based on hyperbolas 1-2 and 1-3

c. Based on hyperbolas 1-3 and 2-3

Figure 4-1. Examples of ambiguous multilateration solutions.



a. Equilateral, Sides One Unit Long



b. Isosceles Variation

c. Isosceles Variation

Figure 4-2. Regions of ambiguous multilateration solutions.

4.4 SITE SURVEYS

To perform multilateration computations, the positions of the R/Ts need to be accurately surveyed. The accuracy of the surveys to determine their locations has an impact on the multilateration accuracy similar to timing errors, and is also magnified according to the GDOP. Survey errors should be kept to less than 3 feet. Note that it is particularly important to get the relative site locations accurately, so that the triangle shapes are accurate. A translation of all the receivers would simply move the target positions by the amount of the bias. While a 15-foot bias may not degrade the surveillance applications, a 15-foot shape error magnified by an unfavorable GDOP would produce large position errors. The R/T locations for the tracks reported on in this report are given in the Tables 4-3, 4-4, and 4-5, relative to the airport reference point. The x,y values in each of the tables were computed by various methods from a single set of GPS surveyed latitudes and longitudes.

Table 4-3 was used to generate the tracks of the test vehicle reported in Section 4.5.3 and Appendix C. The values were provided by Cardion using the U.S. Army Engineer Topographic Labs CORPSCON Program, but using an input for the eastern side of Georgia, whereas Atlanta is on the western side.

Table 4-3. Survey Conversion Used for 18 May 1995 Data

R/T	x (feet)	y (feet)	z (feet)
Delta	3171.7	1140.8	1045.0
Ford	7088.3	3769.6	1050.0
Stouffers	131.8	4853.3	1150.0
FAA Region	-5424.3	4761.2	1070.0
Terminal C	-1685.9	1067.6	1138.0
Reference Transponder	-133.9	4853.5	1150.0

Table 4-4 was used by the Cardion MWS to generate the 14 June 1995 Mode S short squitter target of opportunity tracks reported in Section 4.5.4. The values were computed by the U.S. Army program, but this time using an input for the western side of Georgia.

Table 4-4. Survey Conversion Used for 14 June 1995 Data

R/T	x (feet)	y (feet)	z (feet)
Delta	3149.86	1201.34	1045.0
Ford	7010.34	3903.99	1050.0
Stouffers	37.86	4852.38	1150.0
FAA Region	-5512.4	4652.8	1070.0
Terminal C	-1705.7	1034.4	1138.0
Reference Transponder	-227.6	4847.6	1150.0

Table 4-5 is the final set of surveys and was used by the Cardion MWS to generate the May 1996 ATCRBS targets of opportunity tracks reported in Section 5.3.6. The values were generated by an algorithm developed by Lincoln Laboratory and described in Reference [5].

Table 4-5. Final Survey Conversion

R/T	x (feet)	y (feet)	z (feet)
Delta	3147.3	1209.4	1045.0
Ford	7001.5	3922.2	1050.0
Stouffers	25.6	4853.1	1150.0
FAA Region	-5524.9	4639.6	1070.0
Terminal C	-1708.6	1030.2	1138.0
Reference Transponder	-227.1	4847.7	1150.0

The process of obtaining the x,y,z positions of the R/T with respect to the airport reference point (or with respect to the airport map on which the positions are to be displayed) may benefit from further development. A comparison of Tables 4-4 and 4-3 show discrepancies of several feet due solely to the method used to convert the GPS surveyed latitudes and longitudes to x,y values. An alternative approach would be to use laser range finders and theodolites to establish the triangle shapes.

4.5 ACCURACY EVALUATION

4.5.1 Historical

The Bendix Corporation evaluated the accuracy as described in Reference [1] and found a sigma position of less than 20 feet. Similarly, Cardion and the Hughes Technical Center evaluated accuracy at 10 feet using a laser tracker. Since the major objective of this effort was to evaluate the impact of multipath and fruit, no theodolite or laser tracker measurements were made in Atlanta.

4.5.2 Overview

This section describes three different accuracy assessments. The first is on 18 May 1995 for CAPTS raw squitter TOA's from the SSV test vehicle traversing the movement area, but for which the multilateration processing was performed by Lincoln Laboratory. Secondly, for several Mode S short squitter targets of opportunity in real time by the CAPTS system as it existed on 14 June 1995. Finally, multiple replies elicited by whisper shout interrogations were used to measure the raw R/T TOA accuracy.

4.5.3 SSV Test Vehicle – 18 May 1995

This section describes an investigation performed by Lincoln Laboratory early in the Atlanta tests using the raw squitter TOA data recorded by the MWS for the SSV vehicle and calibration transponder on 18 May 1995. The purpose is to illustrate some of the aspects of multilateration, in particular, the effects of survey errors, GDOP, and calibration. The data are useful because the SSV was careful to travel on the exact center line of the runways and taxiways. Lincoln Laboratory performed this work on a SUN workstation in Lexington because Cardion did not provide a method to replay the raw TOA data through variations on their algorithms in the MWS.

In the Cardion MWS during 1995, the calibration replies from the reference transponder were not smoothed to explicitly determine the frequency differences amongst the 5 R/Ts 100 MHz oscillators These oscillators are used to mark the time of arrival. First generation triad selection, multilateration, and tracking algorithms were installed. Lincoln Laboratory felt that the tracks were not representative of the "potential of the technology". Therefore, both Lincoln and Cardion explored algorithm enhancements.

The results of the Lincoln investigation are given in Appendix C. In summary, a sigma of less than 10 feet was achieved. Intertriad biases were observed, as well as a consistent mis-registration, particularly in the form of a rotation, with respect to the airport map. These tracks were formed using the original R/T site locations in Table 4-3 provided by Cardion. The results stimulated further investigations into survey conversion and CAPTS algorithms. The biases and rotation were greatly reduced by the recalculations of the surveys described in the previous section.

4.5.4 Targets of Opportunity – 14 June 1995

Figure 4-4 shows the superimposed position measurements made by the CAPTS on 14 June 1995 for several targets of opportunity landing on runway 8L and taxiing to the gate areas, and several targets taxiing into position and taking off on runway 8R.

The tire marks visible on aerial photos indicate that touchdowns are typically at about x = -0.3 in the figure. The runways are 150 feet wide. Consider that there are three phases to the landing process: the overflight prior to touchdown, touchdown and deceleration, and preparation for turnoff. During the overflight the north/south component of the position measurements are centered on the runway, and have a spread that is approximately half the runway width. i.e., 75 feet. This would indicate unbiased measurements with a standard deviation of about 22 feet. During touchdown and deceleration there may be a slight bias of approximately one third of the runway width, or 40 feet to the south. In the third phase, the tracks are about centered on the runway, and show a spread of about 60% of the runway or about 90 feet. The spread may be partly due to the pilot "setting up" for the turn off onto the taxiway.

For takeoffs, the measurements of targets that taxi northward onto the runway and make a right turn to the takeoff hold point are all within the pavement boundaries. During the acceleration to takeoff speed, the measurements move to the right until x = -0.3 then move back to the center for liftoff. The reason is unknown. The spread is less than half the runway width during the period when the target is still in contact with the runway. At about x = 0.0 the spread begins to grow, reaching a full runway width around x = 0.6. This may be because the various aircraft are in the air, and no longer directly over the runway center line.

The targets are rotationally registered with the map much better than for the 18 May data, as would be expected by the fact that the survey values were recalculated as in Table 4-4. But, the registration is not perfect, especially during the U turn in front of the Delta hangars. Lincoln believes that techniques can be developed to remove intertriad biases and mis-registrations with maps (and other sensors such as ASDE). Nevertheless, the 14 June tracks represent a great improvement over the performance of the CAPTS during the early phases of the Atlanta tests and on 18 May 1995.

4.5.5 Time of Arrival Accuracy

Section 5 will describe the whisper shout aspect of CAPTS and multilateration. Some additional work with whisper shout replies was done to evaluate TOA accuracy, and the results are described here. Whisper shout can provide a means to evaluate accuracy at a fixed target position for slow moving targets, so that the sigmas of the TOAs can be studied in detail. This is because a whisper shout sequence, with many interrogations in a short period of time, provides several time of arrival differences for each pair of R/Ts. This evaluation is independent of target motion (the taxiing target is essentially stationary for the 52 ms the interrogations spanned and the 100 MHz oscillator drifts are small in that time).

Tables 4-6 and 4-7 were computed from R/T receptions during 10 transmissions of the whisper shout sequence described in Section 5. There were 6 cases for Target 6130 at 6 positions taxiing down runway 26R during the late night, and 4 cases for Target 2761 rolling down 8R. Since the taxiing targets were essentially stationary during the 52 ms that the 26 long whisper shout sequence took, the pairwise time of arrival differences represent just the effects of the TOA marking function, the clock quantization, signal to noise, oscillator frequency differences integrated over 52 ms, and any possible corruption of the leading edge by multipath. (The data were taken late at night when the fruit rate would have been negligible.) In each of the cases, all 5 R/Ts received the emitted ATCRBS reply. There were either 4, 5, or 6, replies emitted during each whisper shout sequence.

The pairwise sigmas, labeled 0-1 to 3-4, and in units of clock counts, and averaged over all the 10 cases, appear in Table 4-6. They range from 0.7 to 2.5 counts. These values were used to estimate the TOA sigmas for each of the R/Ts. These values are in Table 4-7. The average for all the cases are 0.9, 0.8, 0.9, 1.9, and 0.8 for the R/Ts 0, 1, 2, 3, and 4, respectively.

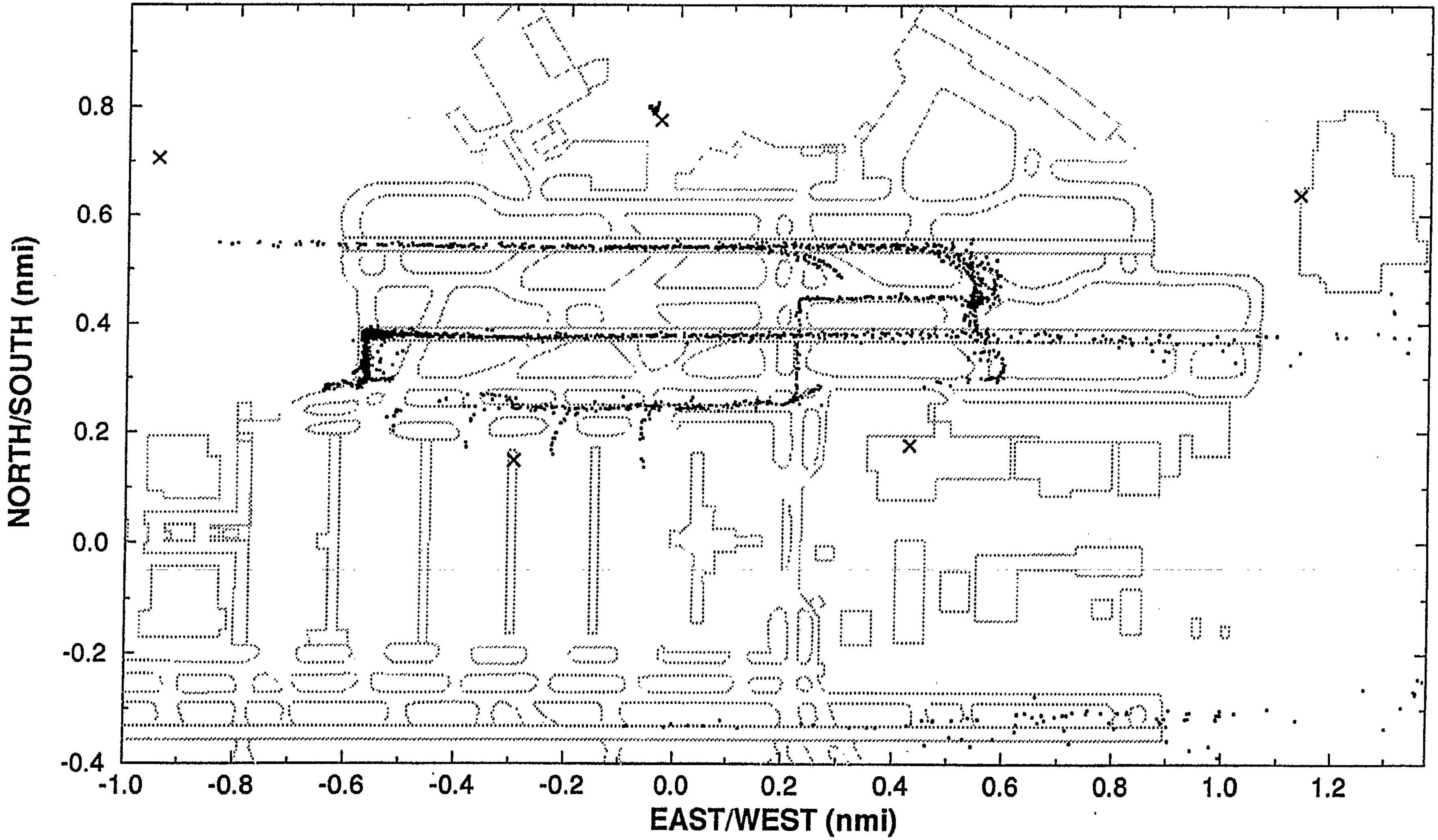


Figure 4-3. MWS target of opportunity short squitter multilateration, using survey latitudes and longitude converted to x,y by Lincoln Laboratory.

These data indicate that, at least for the central region of the airport, R/Ts Delta, Ford, Stouffers, and Terminal C have a sigma of less than one count (10 ns). If the calibration process were to model the oscillator frequency differences, and average the offsets over 10 seconds, then the calibration error would be small. Therefore, a reasonable expectation of accuracy would be 10 feet times a GDOP of 2, resulting in 20 feet. Note that for unknown reasons, the Region R/T had twice as much error in time of arrival measurements.

It is important to note that these were small general aviation ATCRBS targets, with possibly lower antennas than Mode S squittering targets, and therefore with less signal-to-noise ratio. Also, as discussed in Section 5, the R/Ts had attenuators with values ranging from 4 to 16 dB in the cable leading to the antenna. This further reduced the available signal to noise ratio. Ideally these attenuators, which were part of the whisper shout adaptation, would only be in the transmit path, so as to not degrade the TOA accuracies during reply reception.

Table 4-6. Pairwise R/T TOA Sigmas

R/T Pair	0-1	0-2	0-3	0-4	1-2	1-3	1-4	2-3	2-4	3-4
Sigma (Counts)	0.7	0.7	2.3	1.2	1.0	2.1	1.3	2.5	1.4	2.0

Table 4-7. Single R/T TOA Sigmas

R/T	Sigma (Counts)
0 - Delta	0.9
1 - Ford	0.8
2 - Stouffers	0.9
3 - FAA Region	1.9
4 - Terminal C	0.8

In conclusion, the observed TOA accuracies are similar to what was measured on the bench by Cardion.

4.5.6 Triad Selection

Whenever more than three times of arrival are available for a position computation, there arises the question of which three should be used to compute the position, or whether an averaging technique and more replies should be used, e.g., a Kalman filter. In the case of choosing to use only 3, GDOP and possibly other considerations can be used to select the three. The Cardion MWS uses a Receiver Selection Table to determine which three to use. During the time that the 14 June 1995 data were output by the Cardion system, there was no algorithm in effect to use more than 3 positions. The basis for developing the Receiver Selection Table is proprietary to Cardion.

4.5.7 Accuracy Summary

In summary, multilateration accuracy on Mode S squitters and ATCRBS whisper shout replies has been observed to have a sigma of less than 20 feet, and any position dependent biases can likely be removed by better surveys and algorithm enhancements.

5. WHISPER SHOUT

5.1 BACKGROUND AND THEORY

Whisper shout was developed for TCAS surveillance of ATCRBS targets to prevent synchronous garble of targets at nearly the same range from the TCAS aircraft. It works by utilizing the sidelobe suppression function of ATCRBS transponders, in which the transponder will go into suppression whenever it sees a pulse pair separated by 2 µs, in which the second pulse is higher than the first pulse. The nominal suppression period is 35 µs. Each P1 P3 pair of interrogation pulses in a whisper shout interrogation (except the lowest power one) is preceded by an S1 pulse that is 2 µs earlier than the P1 and lower in power, for example by 4 dB. The P1 P3 powers in the sequence increase, for example by 2 dB, for each interrogation. A typical target will not see any of the three pulses from the early low power interrogations as they all are below its Minimum Threshold Level (MTL). Then it will see the P1 and P3 but not the lower S1, and so will reply. On succeeding higher powered interrogations, it will see all three, in particular the S1 followed 2 µs later by the higher P1, and so will suppress. In general, because of variations in transponder MTLs, and antenna gains, two aircraft at the same range will not reply to the same interrogation within the sequence. Thus, synchronous garble will be prevented.

5.2 APPLICATION TO AIRPORT SURFACE

Two important changes have taken place since the Bendix experiments of the 1970s which make the task of tracking ATCRBS equipped aircraft easier on the airport surface. First, TCAS whisper shout technology exists for partitioning replies of surrounding aircraft and thereby reducing garble. Second, most aircraft at major U.S. airports are TCAS-II (and thereby Mode S) equipped; therefore the system must only handle a handful of surface aircraft at any time. However, it is important to note that it must also cope with airborne aircraft which can be problematic because of the way in which ambiguous multilateration solutions for distant aircraft often map back onto the airport surface

The objective of the present evaluation was to see if TCAS technology could be adapted to the surface to cope with the residual ATCRBS transponders. First, it was recognized that the standard TCAS waveform of Mode C interrogations with P4 pulses would cause report-to-target correlation problems because the Mode C altitude of most surface aircraft is similar. Therefore Mode A interrogations must be used with an appended P4 pulse to preclude Mode S transponders from replying. Second, the aircraft are generally much closer to the interrogator on the surface than in the air so the interrogation levels need to be adjusted lower. Finally, multipath is present and its effect on reply efficiency was a concern since whisper shout interrogations take place near MTL.

5.3 WHISPER SHOUT EVALUATION

5.3.1 Objectives and Obstacles

The objective of the Atlanta whisper shout tests was to determine if the technique could be made to work for aircraft on the surface. Ideally, we would have tried Mode A interrogations with P4 pulses initially and then explored augmenting this sequence with a few Mode C interrogations to aid in editing out airborne tracks either associated with overflights or ambiguous solutions associated with more distant aircraft. Unfortunately, implementing such a capability within CAPTS in a timely and reliable manner was judged to be intractable. Therefore, Lincoln and Cardion jointly agreed to employ a paired interrogation approach and use much of the CAPTS R/T and MWS software.

Equipment changes were made to allow the TCAS units to transmit paired Mode A and C interrogations with or without P4 at programmed power levels from the R/Ts on a round robin or other basis; i.e., each R/T completes its sequence and then the next R/T does the same. The pair spacing had to exceed the ATCRBS transponder spec on turn around time and suppression; thus the CAPTS number of 175 µs was used. The MWS software needed to be modified to cluster receptions of the same reply since ATCRBS transponders may reply to one, two, or three consecutive interrogation power levels depending on their characteristics and the design of the whisper shout sequence.

Initial testing at Atlanta yielded very discouraging results; a very low probability of receiving paired replies from any and all R/Ts. However, there were also brief periods late at night when sporadic tracks were output from the system. Some evaluators thought the problems were caused by multipath, fruit, excessive interrogation power and/or suppression by the airport beacon interrogator.

Problem identification and correction were both difficult. First, the R/Ts provide almost no visibility as to the internal data processing; only the output to the MWS was readily available and as discussed in Appendix A, the MSBs of the TOA data were not updated in a timely manner. Second, the MWS recording uses two different conventions for ATCRBS code such that visually identifying reply pairs of interest is difficult.

The test program involved hardwiring transponders to R/Ts, instrumenting R/Ts with PCs and examining the output data in fine detail The conclusion was that there were several problems in the system; the most severe was that R/Ts were not able to perform their defruiting functions in the presence of the Atlanta fruit environment. Details of this problem are contained in Appendix A. A consequence of the problem was that the likelihood of getting a reply pair degraded with both fruit and with the number of interrogations which preceded those which elicited a reply pair. Therefore best performance was obtained at night with a sparse whisper shout sequence. The second problem was that 50% of the time the TOA data from an R/T did not increase monotonically with time. At this point, Lincoln called a halt to the test program and requested a walk through of the R/T code.

Some of the problems uncovered in the walk through are described in Appendix A. The conclusion was that a total fix required a different code structure, more efficient code and a faster microprocessor. The contractor set upon making the code more efficient but retaining the same structure and microprocessor. A firm date was established for the completion of testing. After several debug trials, the system was declared ready. The schedule then allowed for half a day of testing; the results are reported in the remainder of this section. It is important to note, however, that the testers did not have complete confidence in the integrity of the system and one important feature of the R/T software had been discarded in the quest for speed. It dealt with enhancing the code bit quality (accuracy) of weak ATCRBS replies. Normally, this would not have been a concern because whisper shout adjusts transmit power to interrogate near threshold, but replies should be well above threshold. However, some attenuation had been placed in R/T antenna cables common to both interrogate and reply such that replies were nearer to threshold than necessary.

The whisper shout tests were conducted on the day that the Cardion R/Ts were modified for the last time. Funding, the Olympics, and other schedule problems precluded extending the tests.

5.3.2 Interrogation Waveform

The interrogation method employs an interrogation pair; a Mode A followed 175 µs later by a Mode C. This method is a holdover from the original CAPTS concept in which the ATCRBS transponder was modified to spontaneously emit replies. It would have been very difficult to process all received replies, because the fruit rate is very high, and every fruit would have to have a position computed from it. The method used involved defruiting at the R/T. The R/T only passes along the reply pairs with the correct spacing to the MWS.

The R/Ts have to listen for much longer that the range extent of the airport, because they don't know exactly when the interrogating R/T will interrogate. A preferred way to operate is to only send a single interrogation, not a pair, and to listen only as long as corresponds to the maximum range of interest, which in the case of on the airport surface is only 2 nmi, i.e., 24 µs. Even at a fruit rate of 20000 fps, 24 µs would result in only .49 fruit per listening window. The fruit rate on the airport would be expected to be lower because of line of sight and blockage considerations to the airborne fruit producers.

A consequence of using the paired approach is that the probability of receiving a reply for multilateration processing is lower than necessary, i.e., if the probability of receiving a single reply is 0.9, the pair probability is degraded to 0.81, and 0.5 is degraded to 0.25, etc. Note that interrogation efficiency is definitely an issue, since with whisper shout, interrogations take place near transponder threshold.

5.3.3 ATCRBS Mode A Codes

The R/Ts and MWS use several representations of the ATCRBS Mode A codes.

a. The normal octal ABCD format used by pilots and controllers. This format was used by the CAPTS display.

b. An octal version, but in the bit order of transmission. (The transmission order is: F1 C1 A1 C2 A2 C4 A4 X B1 D1 B2 D2 B4 D4 F2).

c. The decimal representation of b. above.

For the two targets of opportunity observed during the whisper shout evaluation the codes are as follows:

Table 5-1. ATCRBS Code Representations

Target	Octal: ABCD Order	Octal: Transmit Order	Decimal: Transmit Order
First	5250	6310	3272
Second	7145	2761	1521

Analysts examining the data (and report readers) have to cope with all of the above variations. It is helpful to note that all the code representations for the first target are even and are odd for the second target.

5.3.4 Attenuations

A whisper shout sequence has a maximum and minimum interrogation power. If the maximum is needed for all candidate targets, then no partitioning will occur. At the other extreme, if all targets reply to the lowest power interrogation, then again no partitioning will occur. In other words, the dynamic range of the whisper shout sequence must match the statistical dynamic range of the interrogation margins to the targets of interest. This range is dependent upon both position on the airport surface and aircraft type. General Aviation aircraft with bottom antennas may require a much higher level interrogation than air carrier aircraft with top mounted antennas.

The dynamic range of a whisper shout interrogation sequence can be adjusted by inserting a fixed attenuator between the R/T and the variable wing antenna, preferably in the transmit path only. In these tests the attenuator was placed in the cable, and so affected both transmit and receive paths. A set of experiments was conducted with the SSV test target, equipped with an ATCRBS transponder to determine the attenuator values to use for each of the five RTs. The SSV was positioned at each of the four corners of the north side of the Atlanta airport, and interrogated by a whisper shout sequence in a round robin fashion by the five RTs. The particular whisper shout level within the sequence that the transponder replied to was used to determine the margin. Attenuators were then chosen so that the transponder would reply to about the middle of the sequence averaged over the four SSV locations. The resulting attenuator values are given in Table 5-2.

Table 5-2. Fixed Attenuations for Whisper Shout

RT Site	Attenuation (dB)
Delta	10
Ford	6
Stouffers	16
Region	4
Terminal C	10

5.3.5 Whisper Shout Sequence

Data were taken in the late evening and early morning. The MWS had provision for 26 whisper shout interrogations. The R/Ts and MWS data recording did not provide an explicit data field associated with each reply pair to indicate which interrogation produced the reply. Instead, there was an intent that the time of whisper shout interrogation, in TOA clock time, would be sent from the R/T to the MWS for every 5th whisper shout interrogation. This information plus the known spacing between interrogations, as defined by the TCAS hardware, and equal to 2 ms, would allow a determination of which replies were elicited by which interrogations. Unfortunately, the lack of a long RTR word length made such association by time difficult. This is because the RTR was only 16 bits long and at 100 MHz it rolled over every 655.36 μs. In principle, the R/T 68020 computer would count the rollovers in a 16 bit memory location, which would be appended to the RTR 16 bit word. However, the 68020 computer could be quite late in responding to the interrupt, and so the 32 bit word could be off by several (or even many) multiples of 65536. Consequently, it was known that this method would not be completely accurate.

Initially, it was decided to try at least two whisper shout sequences: a sequence with 24 steps and 2 dB bin widths, and one with 12 steps and 4 dB widths. The preferred way to experiment with whisper shout sequences is to send each sequence and record the replies for subsequent playback analysis. During playback, the performance of each sequence can be evaluated, and the optimal sequence identified for operational use. This method compares sequences for the same conditions and same targets, and is the method used to develop the sequences for TCAS I and TCAS II. Qualitative examination of tracks on the MWS display indicated that tracking was not as reliable as desired, and seemed to be better with wider bin widths. Also, the MWS software whisper shout menu provided only 26 interrogation possibilities. So the following whisper shout sequence was adopted for the final whisper shout test and evaluation. Three sequences, plus some buffer interrogations, were fit into the 26 available levels, as shown in Figure 5.1.

a. A sequence 12 long with 2 dB steps and 4 dB bin widths[i]

b. A sequence 6 long with 4 dB steps and 8 dB bin widths

c. A sequence 3 long with 8 dB steps and 16 dB bin widths

d. Two "buffer" interrogations with S1 greater than P1, intended to elicit no replies, and aid in the later identification of which replies came from which whisper shout interrogations.

e. An intended additional three buffer interrogations, but which were incorrectly entered and so had maximum P1 attenuation but no S1.

This sequence was transmitted by the Delta R/T, then 0.5 seconds later by the Ford R/T and so on in a round robin fashion. Thus, there are two scan rates: (1) the 2 Hz (0.5-sec period) "corporate" rate in which no distinction is made as to which R/T interrogates, and (2) the 0.4 Hz (2.5-sec period) rate associated with a particular R/T.

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[i] The bin width is defined as the difference between the S1 amplitude and the P1 amplitude.

5.3.6 Targets of Opportunity

There were two targets of opportunity during the late night data-taking session. Both taxiied out from the General Aviation base, onto runway 8L/26R and taxiied west for takeoff on 8R. As such, their paths were in the central region of the airport, and they were both in that region simultaneously. The position solutions computed using a 2-dimensional method are shown in Figure 5-2. Figure 5-3 shows the position solutions for Target 5250, and Figure 5-4 for Target 7145. The position solutions were analyzed for a 100-second period (from 360 seconds to 460 seconds) to determine the update rate (blip scan ratio), which is defined as the probability of getting a position measurement on a scan, where a scan is defined as the transmission of the full 26 level whisper shout sequence described in Section 5.3.5. The overall MWS surveillance scan rate was 2 Hz, in a round robin fashion amongst the 5 R/Ts. There were 200 scans, 40 per R/T, with an individual R/T scan period of 2.5 seconds. The x,y positions for this 100 second period are shown in Figure 5-5. Figure 5-6 shows the y positions vs time. Target 5250 has a constant y, and Target 7145 starts at y=0.48 nmi and ends at 0.38 nmi. There are 20 surveillance scans per 10 seconds time division. It can be seen in Figure 5-6 that some scans have more than 1 position update, while some have no updates. The plot is known to represent 367 positions, but, there are only 330 "dots" because some positions are plotted on top of each other. Target 5250 has at least one position on 123 scans, for a blip scan ratio of 124/200 = 62%. One scan has 5 positions and 7 scans have 4 positions. Target 7145 has at least one position on 78 scans, for a blip scan ratio of 39%. Three scans have 4 positions, and none have 5. Appendix D shows similar plots, one for each R/T showing the positions generated when that R/T was the interrogator. The results are in Table 5-3. Assuming that the differences in R/T interrogation efficiency are due to site differences and not R/T performance differences, these data suggest that multilateration system performance may benefit from using the R/T sites that interrogate with high efficiency more often, and de-emphasizing the interrogation rates from R/T sites with lower efficiencies. For example, Table 5-3 shows the blip scan ratio that would result from interrogating only from Stouffers, Region, and Terminal C.

Table 5-3. Blip Scan Ratios for Individual R/Ts

RT Site	Blip-Scan Ratio (5250)	Blip-Scan Ratio (7145)	Blip-Scan Ratio Average
Delta	22/40 = .55	8/40 = .20	.38
Ford	14/40 = .35	10/40 = .25	.30
Stouffers	32/40 = .80	18/40 = .45	.63
Region	26/40 = .65	26/40 = .65	.65
Terminal C	30/40 = .75	16/40 = .40	.58
Average of All RTs	.62	.39	.51
Average of Stouffers, Region, Terminal C	.73	.50	.61

With respect to accuracy, the spread of the y measurements is about 60 feet peak to peak, corresponding to a sigma of about 17 feet. Figure 5-7 shows the same y measurements as Figure 5-6 for Target 5250 (except for a few seconds while it was moving in y) and a subset selected as follows. The purpose is to illustrate the improvements that can be obtained by using target of opportunity data to infer the raw performance of the multilateration system, and use the information to refine the outputs to the user. A determination was made using the data that the target was on a known runway and would be expected to be traveling straight. The raw measurements were divided into those made on the odd scans and the even scans. The sigma of the odd scan measurements was evaluated for each RT triad, as shown in Table 5-4. There is a wide variation in the accuracy of the triads. The table shows the GDOP factor associated with the triads, and it can be seen that GDOP does account for the accuracy variations.

Table 5-4. Sigma y, odd scans, for Triads

Triad	Sigma y (ft) (odd scans)	GDOP
024	10.4	1.2
234	11.7	2.9
134	15.0	1.7
124	16.4	1.2
034	21.7	1.9
023	25.5	1.6
123	26.6	1.8
012 013 014	(Insufficient data)	2.4 2.1 2.3

On the even scans, the Table was used to select the measurement made using the triad with the lowest sigma. Two scans were discarded because the measurement was more than 50 feet from a sliding prediction. The resulting measurements are shown in Figure 5-7 by the solid line, labeled LL TSM (Triad Selection Method). The accuracy was substantially improved by this method. The raw even scan measurements had a sigma of 16.8 feet, and the selected measurements had a sigma of 8.6 feet.

5.3.7 Replies per Sequence and Link Margin

Because the update rates for Targets 5250 and 7145 were so low, a detailed analysis was made of the CAPTS reply data and the position data (which indicated which triad was used to compute the position). The reply data were processed by hand with spread sheet and graphical techniques for a 100-second period in order to determine which R/T interrogated, which whisper shout interrogations elicited replies, and which R/Ts received the replies. The spread sheet and graphical technique was necessary because:

1. The most significant half of the recorded times for the reference calibration transponder receptions was missing.

2. The recorded interrogation times were inaccurate by random amounts, and also by integer multiples of 655.36 microsec.
3. The interrogation times were missing from the recording 80% of the time.

Of particular interest is the number of replies per whisper shout sequence. This was evaluated for the 4 dB wide sequence, which in theory should elicit 2 replies per sequence. Figure 5-8 shows the number of replies per sequence for Target 6310 for each R/T for the 100 second period. (Note from Table 5-1 that Target 6310 is track 5250, and Target 2761 is track 7145.) Figure 5-9 shows the results for Target 2761. Target 6310 (5250) was seen quite well by Stouffers, reasonably well by the Region and Terminal C, and less well be Ford and Delta. Target 2761 (7145) was seen less well by the Region and Terminal C, and poorly by Stouffers, Ford and Delta.

The uplink interrogation margin can be estimated by observing at which level in the whisper shout sequence the target replied. If it is the highest power whisper shout interrogation that elicits the replies, then the margin is practically 0; otherwise the target would have replied to a lower power interrogation in the sequence. If it replies to the lowest power interrogation in the sequence, then the margin is at least 24 dB; otherwise it would have required a higher power interrogation.

The margins for Target 6310 (5250) are shown in Figure 5-10. For the R/Ts at Terminal C, the Region, and Stouffers, they were always above 10 dB, while they were less than 10 dB for Ford. The Delta margin ranged from 3 to 17 dB. The R/Ts with higher margin had more replies per sequence. Similarly, in the case of Target 2761 (7145), Figure 5-11, the margins were better for the R/Ts that had more replies per sequence. Naturally, no margin can be computed if there are no replies, which is the case initially for R/Ts Stouffers Ford, and Delta. But, note that when these R/Ts begin to get replies from Target 2761, the margins are very low and grow thereafter.

We conclude that too much attenuation was likely used in the R/Ts for the whisper shout tests. The attenuations would have been better selected from target of opportunity data on the airport, instead of the SSV on the perimeter service road, especially since most ATCRBS targets have bottom mounted antennas only a few feet off the ground, while the SSV antenna on the top of the vehicle was about 12 feet high.

5.3.8 Degarbling Performance

The degarbling effectiveness of whisper shout depends on the degree to which nearby targets reply to different whisper shout levels. This was evaluated for the 4 dB and 8 dB bin sequences. The 4 dB results for R/T 3 interrogating during the 100-second analysis period are shown in Figure 5-12. The open circles represent receptions by R/T 3 of replies with the Mode A code 6310, where the time axis indicates the scan, and the y axis the whisper shout level. The per scan interrogation efficiency is 0.60 (or better, since there may have some scans in which replies were emitted, but none were received with perfect code bits). There were an average of 1.5 replies received on scans for which at least 1 R/T received a reply with perfect code. (If no R/T received a reply with perfect code, then the most likely explanation is that no replies were emitted due to interrogation failures.) The number of replies per scan varied from 1 to 3, which is consistent with TCAS whisper shout operational experience. The solid triangles are for Target 2761, which had slightly lower interrogation efficiency and replies per scan values. The degarbling performance is indicated by the fact that the targets reply to different levels in most cases. To see this better, a smooth dashed curve is drawn through the 6310 data and a solid smooth curve through the 2761 data. The spread of the data about the smooth curves is consistent with TCAS experience. During the 100 seconds, Target 6310 moves steadily toward R/T 3, and the trend of the dashed curve indicates that less power is needed as the target gets closer, as would be expected. Figure 5-13 shows the results for the 8 dB bin width sequence. It has many features in common with Figure 5-12, as would be expected. However, it is interesting that the interrogation efficiencies and replies per sequence are better for this wider sequence. This phenomenon, which may be due to the paired interrogation technique, deserves further investigation.

There will be operational cases where targets are not successfully partitioned into different whisper shout levels by a particular R/T. But perhaps a different R/T will partition effectively. This is illustrated by Figure 5-14, where the smooth curves indicate that R/T 4 sees a large margin difference between the two targets in the period 360 to 410 when R/T 3 had a small difference. Then, in the period 410 to 460, the situation is reversed, and R/T 3 sees the larger margin difference. A simplified analysis shows that R/T diversity can be very effective.

Let:

W = the number of whisper shout levels in the sequence
T = the number of targets
R = the number of R/Ts

Then the probability that a given target is ungarbled at at least one of the R/Ts, assuming independence amongst the R/Ts is:

$$p_{ungarbled\ at\ K\ RTs} = 1 - \left\{ 1 - \left[\frac{(W-1)}{W} \right]^{T-1} \right\}^{R}$$

If a whisper shout sequence had 12 levels (W = 12) and there were 5 R/Ts (R = 5) and 10 targets (T = 10) then the probability of a given target being the only one to reply to at least one of the 50 interrogation would be 91.4%.

5.3.9 Interrogate and Receive Efficiencies

The R/T interrogation and reply processing performance was analyzed for the Targets 6310 and 2761 during the 100 second data interval. The results are in the tables below. Table 5-5. shows which whisper shout levels elicited replies from Target 6310 during 100 seconds while the target traveled about one half mile. Delta and Ford (0 and 1) required high powered interrogations. Stouffers needed only low powered interrogations, and the Region and Terminal C required low to moderate power. (Recall that fixed attenuations of 10, 6, 16, 4, and 10 were inserted in the antenna cables of the R/Ts 0-4, respectively.)

Table 5-5. Replies vs Whisper Shout Level (4 dB Bins, Target 6310)

	Replies Received with Code=6310				
	Interrogating R/T				
WS Level	0 (10 dB)	1 (6 dB)	2 (16 dB)	3 (4 dB)	4 (10 dB)
1 (Lower Power)	0	0	32	9	0
2	0	0	72	17	4
3	0	0	8	9	6
4	2	0	3	7	9
5	4	0	2	22	27
6	3	0	0	8	17
7	4	1	0	3	9
8	2	7	0	0	5
9	2	8	0	4	1
10	17	6	0	4	0
11	14	4	0	0	0
12 (High Power)	2	13	0	0	0
Sum	50	39	117	83	78

Table 5-6 shows the replies with code 6310 according to which R/T interrogated and which R/T received the reply. The diagonal elements (in bold type) indicate the respective per scan round reliability. For example, Delta (R/T 0) received 10 replies with code 6310 during the 38 scans on which it sent out a whisper shout sequence, for a per scan round reliability of 10/38 = 0.26. The per interrogation round reliability would be calculated as about half the per scan value, because on each scan, the whisper shout sequence has 12 interrogations, 4 dB between the S1 and P1 powers, and with 2 dB increases in the P1 power. Since the bins have 2 dB of overlap, there are two interrogation opportunities per sequence (except an the highest level when there is only one, see Figure 5-1). Note that this approach underestimates the round reliability, because it only includes replies that were received with perfect code. The column summations show the effectiveness of each R/T at receiving replies. For example, Stouffers (R/T 2) receives 112 replies during the 190 scans (from interrogations from all R/Ts), while Ford (R/T 1) receives only 30. (Again, note that the table only includes perfect code replies.) The row summations indicate interrogation effectiveness. For example, 117 replies are received (by all R/Ts) when Stouffers interrogates, while only 39 are received when Ford interrogates.

Table 5-6. Interrogations vs Replies (4 dB Bins, Target 6310)

	Receiving R/T							
Interrogating R/T	0	1	2	3	4	Sum	Number of Scans	Replies per Scan
0	**10**	4	15	14	7	50	38	1.32
1	4	**5**	10	8	12	39	38	1.03
2	25	8	**34**	31	19	117	38	3.08
3	15	8	24	**24**	12	83	38	2.18
4	15	5	29	16	**13**	78	38	2.05
Sum	69	30	112	93	63	367	190	1.93

Table 5-7 summarizes the interrogation and receive efficiencies, and the per scan round reliability of each R/T. The per scan interrogation efficiency is computed as the number of scans transmitted by the R/T (38 in each case) minus the number of scans for which no R/T received a perfect reply, divided by 38. The receive efficiency is the number of replies received over all 190 scans (column sums in Table 5-6) divided by 115 (i.e., 190 minus the number of scans for which no R/T received a perfect reply, the sum of the first row, 75). The per scan round reliability is the diagonal elements in Table 5-6 divided by 38.

Table 5-7. Summary Performance (4 dB Bins, Target 6310)

Performance (T=6310, WS=4dB)	R/T 0	R/T 1	R/T 2	R/T 3	R/T 4	Sum
Number of Scans with no reply	20	22	3	14	16	75
Per Scan Interrogation Efficiency	.47	.42	.92	.63	.58	
Receive Efficiency	.60	.26	.97	.81	.55	
Per Scan Round Reliability	.26	.13	.89	.63	.34	

Tables 5-8 and 5-9 and 5-10 give the results for Target 2761.

Table 5-8. Replies vs Whisper Shout Level (4 dB Bins, Target 2761)

	Replies Received with Code=2761				
	Interrogating R/T				
WS Level	0 (10 dB)	1 (6 dB)	2 (16 dB)	3 (4 dB)	4 (10 dB)
1 (Lower Power)	0	0	1	0	0
2	0	0	0	5	0
3	3	0	0	11	0
4	0	0	0	3	4
5	0	0	0	8	0
6	0	0	0	1	1
7	0	0	5	7	0
8	4	0	0	7	0
9	0	1	0	3	0
10	0	0	1	0	14
11	0	0	3	9	3
12 (High Power)	0	1	4	3	6
Sum	7	2	14	57	28

Table 5-9. Interrogations vs Replies (4 dB Bins, Target 2761)

	Receiving R/T							
Interrogating R/T	0	1	2	3	4	Sum	Number of Scans	Replies per Scan
0	2	1	2	0	2	7	31	.23
1	0	0	0	0	2	2	31	.06
2	2	3	3	4	2	14	31	.45
3	5	12	13	17	10	57	30	1.90
4	2	7	11	3	5	28	31	.90
Sum	11	23	29	24	21	108	154	.70

Table 5-10. Summary Performance (4 dB Bins, Target 2761)

Performance (T=2761, WS=4dB)	R/T 0	R/T 1	R/T 2	R/T 3	R/T 4
Number of Scans with no reply	29	29	25	16	21
Per Scan Interrogation Efficiency	.06	.06	.19	.47	.32
Receive Efficiency	.32	.68	.85	.71	.62
Per Scan Round Reliability	.06	.00	.10	.57	.16

The low per scan round reliabilities for Target 2761 are probably due to interrogation difficulties related to the low margins shown in Figure 5-11. Note that the receive efficiencies are comparable to those for Target 6310.

5.3.10 Code Bit Errors

The performances in Tables 5-5 to 5-10 only include replies with perfectly decoded Mode A codes. The analysis was repeated 4 additional times allowing for code bits errors as described below:

Case -2:	This case allowed up to two conversions of 0's to 1's.
Case -1:	This case allowed a single conversion of a 0 to a 1.
Case 0:	(This is the case of perfect code, i.e., no bit errors)
Case +1:	This case allowed a single conversion of a 1 to a 0.
Case +2:	This case allowed up to two conversions of 1's to 0's.

The conversions from 0's to 1's (inserted code bits) correspond to a hypothesis that the conversions were due to garble arising from fruit or a reply from the other target on the same interrogation, or else by multipath. The conversions of 1's to 0's (dropped code bits) correspond to a hypothesis of low margin or sub-optimal code bit declaration hardware in the reply decoders. (The reply decoding enhancement feature in the R/Ts units was disabled during these tests, so code bit detection was not as sensitive as the F1, F2 bracket pulse detection.) Figures 5-15 a and b show the changes in replies received per sequence by the interrogating R/T for the 5 cases, for Targets 6310 (3272) and 2761 (1521).

For Target 3272, R/T 2 seems to drop code bits, but not suffer from garbling. Note that Stouffers interrogates 3272 with low whisper shout power, indicating plenty of uplink margin, even with the use of the 16 dB fixed attenuator in the antenna cable. Perhaps if the attenuator were only in the transmit path the code reliability would be improved. The excellent height of Stouffers may explain the low incidence to conversions from 0's to 1's. R/T 4 seems to suffer from garbling.

For Target 1521, the performance is much worse than for 3272, and is not as much improved by allowing for code bit errors. R/Ts 0, 1, and 2 (Delta, Ford, and Stouffers) show little or no improvement when code bit errors are allowed. This suggests that it is the interrogation link that is failing. Interrogations might fail because of low power or because of a

P1 pulse multipath reflection that arrives 2 μs later and causes suppression. The fact that Stouffers interrogates the other target with the lowest power whisper shout levels, coupled with the fact that both targets are in the center of the airport surface where the multipath would be similar, suggests that 1521 may not be interrogated because of low margin, perhaps because it is a small aircraft with a very low bottom mounted antenna.

5.3.11 Example Scan

An example scan was analyzed in detail, at 386.160 seconds, with the results shown in Figure 5-16a. The horizontal axis is whisper shout level. Levels 1 to 12 are the 4 dB bin sequence, 15 to 20 are the 8 dB bin width sequence, and 23 to 25 are the 16 dB bin width sequence. The vertical axis is the sum of the ranges from the interrogating R/T (the Region) to the target and from the target to the receiving R/T. (The axis is actually time, i.e., the sum range divided by the speed of light, and in units of tens of ns. The transponder turnaround times of Targets 6130 and 2761 were estimated using the tracks formed by the MWS, and subtracted out.) The MWS tracks were used to predict the sum ranges (converted to time as described), which are indicated for Target 2761 by the 5 right-facing arrows with open heads tipped by filled squares. The R/T associated with the prediction is indicated by the number (0 to 4) at the arrow heads. Each received reply is indicated by the symbols described below:

a. A filled triangle is a reply having code 6310.

b. A filled square is a reply having code 2761.

c. An open circle is a reply having a code other than 6310 or 2761.

For example, on whisper shout level 25, indicated by the vertical down-facing open headed arrow, there were 4 reply receptions. Three are shown with filled squares, indicating code 2761. These three were received at times very close to the predicted times for Target 2761 at R/Ts 1, 2, and 3, as indicated by the fact that the filled squares lie on the horizontal arrows labeled 1, 2, and 3. Obviously, the whisper shout level 25 interrogation successfully interrogated 2761, and R/Ts 1, 2, and 3 received the reply with perfect code. A reply was also received having a code other than 6310 or 2761, indicated by the open circle on the vertical arrow. The data tag indicates that it was received by R/T 4, and had a code of 0221. Since this reply was received at the time predicted for a reply emitted by Target 2761, as indicated by the fact that it lies on the horizontal arrow labeled R/T 4, then it is quite certain that this reception arises from the same reply that is responsible for the 3 previously mentioned receptions at R/Ts 1,2, and 3 with code 2761. The code of 0221 differs from the true code of 2761 by having 4 dropped bits. Since apparently no other target replied to the level 25 interrogations, these dropped bits must be due to multipath, low signal, or deficiencies in the R/T code detection function. Experience has shown that multipath is more likely to cause the insertion of extra code bits into the reply received on the direct path, rather than cancellation of real bits. Although a reply correlation algorithm that uses only code would group the three 2761 receptions for computing a multilateration position, the triad 1,2,3 may not have a favorable GDOP. A reply correlation algorithm that used predicted times of arrival would find the R/T 4 reception, and a triad including R/T 4 could result in a more accurate position. Or, perhaps the position computation could be improved by using all 4 times of arrival.

Note that on interrogation level 24, 4 replies were received, none of which had codes of 6310 or 2761, but all of which were received near the times predicted for Target 2761. Figure 5-16a does not include data tags showing the codes or receiving R/T for these 4 receptions, but Figure 5-16b does, and they show that the receptions are from the appropriate R/Ts. The reception at R/T 1 does not agree well with the prediction for unknown reasons. The recorded data shows that it is 12 counts late, corresponding to 120 µs.)

Figure 5-16b contains horizontal left-facing filled head arrows indicating the predicted times of arrival for replies from Target 6310. On whisper shout level 5, the Region R/T elicited a reply from Target 6310, and that reply was received by R/Ts 2, 0, 1, and 3 at approximately the predicted times and with the correct code. There was also a reception by R/T 4 having code 6310, but it was received at about 1300 counts, which is about 350 (3500 ns, 3.5 µs) counts later than the predicted count of 950, presumably due to multipath. (Referring ahead to Section 5.3.12, Figure 5-17, this reception arose from multipath off the Stouffers building.) Vertical up arrows with filled heads are used to associate replies from Target 6310. The .OUT file includes a multilateration position based on the replies from R/Ts 0, 2, and 3. Target 6310 also replied to whisper shout levels 6, 17 and 23. Positions were computed on levels 6 and 17 using R/Ts 0, 2, and 3. No position was computed on level 23. The open circles indicate that a reply from R/T 4 was available with code 4010 on level 17. Also, on level 23, 5 replies were received: 2 with correct code from R/Ts 2 and 3, and 2 with code 6110 from R/Ts 0 and 4, all four at the predicted times. These replies could have been used to compute positions. The fifth reply had code 0310, and was presumably another instance of multipath received at R/T 4, as had occurred on level 6.

Figure 5-16b also shows the partitioning performance of whisper shout. The 4 dB bin width sequence (levels 1 to 12) resulted in one interrogation on which only Target 6310 replied, and one interrogation in which (undesirably) both targets replied. The 8 dB bin width sequence (levels 15 to 20) and the 16 dB bin width sequence (levels 23 to 25) resulted in partitioning. The results for Target 6310 are summarized in Table 5-11, and the positions that were computed by the MWS are in Table 5-12.

Table 5-11. Summary of Example Scan, Target 6310

	Interrogations (WS Levels)	Direct Receptions from Target 6310	Direct Receptions with wrong code	Multipath Receptions code, delay (counts)
0 - Delta	NA	4	6110	
1 - Ford	NA	1	-	
2 - Stouffers	NA	4	-	
3 - Region	5,6,17,23	4	-	
4 - Terminal C	NA	2	4010 6110	6310, 350 6130, 350 0310, 350
Total	4	15	3	3

Table 5-12. Positions for 6310 on Example Scan

6310 Positions	East/West (ft)	North/South (ft)
W/S Level 5	732.9	2696.6
W/S Level 6	752.3	2692.6
W/S Level 17	756.0	2705.6

Turning attention to Target 2761, replies were elicited on levels 6, 18, 24 and 25, with the replies summarized below. The .OUT file indicates that the MWS did not make any position computations. However, the figure suggests that positions could have been computed on whisper shout levels 6, 24, if the reply correlation algorithm used time of arrival rather than code. Figure 5-16b shows that 3 replies with perfect code were received on level 25. The MWS uses the times that the MWS receives replies over the RF radio links during the reply correlation process. The replies from level 25 were received at the MWS at 386215 ms, 386267, 386308, and 386267 for R/Ts 1,2,3, and 4. The spread of 93 ms, which is due to delays in the radio links, may have exceeded a parameter setting in the correlation algorithm. Finally, a hyperbolic line of position could have been computed on level 18, and used to make a hybrid update/coast of the target.

Table 5-13. **Summary of Example Scan, Target 2761**

	Interrogations (WS Levels)	Direct Receptions from Target 2761	Direct Receptions with wrong code	Multipath Receptions code, delay (counts)
0 - Delta		0		
1 - Ford		3	2521 0300	
2 - Stouffers		4	0300 0300	
3 - Region	6, 18, 24, 25	4	3767 3722	0561, 400
4 - Terminal C		2	0221 0221	
Total		13	8	1

In summary, each target replied on 4 of 6 possible interrogations. Target 6310 had slightly more reliable bracket detection and much more reliable code pulse detection. Both targets experienced multipath, and it was consistent for Target 6310. The MWS outputs positions for each interrogation, rather than on a per scan basis. The MWS apparently cannot compute positions in some cases where there are apparently enough replies with the correct code and/or replies that are received at times that could have been predicted from prior track history; i.e., the MWS does not seem to make enough use of reply correlation based on time of arrival. Section 5.3.15 will estimate the improvement that could be made.

5.3.12 Multipath

The reply data were searched by hand to find cases where a given R/T received two reply receptions from the same target (based on them having the same or nearly the same codes) on a particular interrogation. An ellipse was formed having foci at the location of the receiving R/T and at the known target location, and with a string length equal to the foci separation plus the delay between the two receptions. If the second reply were caused by a multipath reflection, then the reflector would lie on, and tangent to, the ellipse. Figure 5-17 shows the ellipses for four such cases, one for each R/T except Stouffers. When the figure is overlayed with an aerial photo of the airport, it is clear that the reflectors are the buildings indicated in the figure and labeled as "Eastern Hangar", "Stouffers", "Airborne Express", and "Delta Hangar". These results suggest that the multilateration system could be provided with algorithms to automatically recognize multipath replies and deduce the general location of the reflectors. A table of reflectors could be maintained that would assist in rejecting multipath receptions, not only of ATCRBS replies, but possibly of Mode S squitters. This would reduce reply correlation processing and the false track rate.

5.3.13 Correlation by Time Differences of Arrival

The purpose of reply correlation in multilateration is to determine which reply receptions at the R/Ts arise from a particular reply emission by a target. If a group of receptions, one from each R/T, lie within a time window less than the dimensions of the R/T array, and all have identical 4096 codes, and it is assumed that ATC assigns unique 4096 codes, then the receptions must arise from a single reply emission by the target. The pairwise time of arrival differences can be used to compute a multilateration position. If, in such a window, there is more than one reception by one or more R/Ts, and if the codes do not have any patterns of consistency, then identifying receptions that arise from the same reply emission, and correlating them for the purpose of forming DTOA's would be difficult. Incorrect correlations would lead to multilateration positions that are phantoms, that is, do not correspond to real targets. One way to prevent such phantoms is to require code agreement. But, requiring code agreement will reduce the number of position measurements, due to the code errors that are anticipated due to garbling from multipath and fruit, and dropped bits when the reply amplitude is near the R/T detection threshold. Although it may be prudent to only initiate tracks using position measurements computed from replies that have perfect code agreement, it may be unnecessarily strict to require perfect code agreement to update existing tracks. A more effective correlation method may be to form all possible DTOA's and use those that lie within small time windows that are predicted from the set of existing tracks. This method is illustrated in Figure 5-18 (a), (b), and (c) for the Targets 6310 and 2761 during the 100 second time interval previously described. Figure 5-18 (a) shows all the DTOA's for R/Ts Stouffers and Terminal C for the 4 dB whisper shout sequence, and when the codes of the receptions that are differenced are both equal to 6310 (symbols "o") or 2761 (symbols "Δ"). The predicted DTOAs are shown as the solid lines, and were made from the existing tracks. The DTOAs that lie near the predictions are sparse. (The DTOAs do not lie precisely on the prediction solid lines because the predictions were made by a polynomial over the whole 100 seconds, for convenience. In practice, the predictions would be based on a Kalman filter.) There are quite a few "o"s at about 300 counts, corresponding to 3 μs, below the prediction for Target 6310. These are due to multipath receptions at Terminal C. The multipath receptions would have too big of a time of arrival, and so the Stouffers TOA minus the Terminal C TOA would be negatively in error. Referring to Figure 5-17, it can be inferred that this multipath is caused by a reflection off of Stouffers. Figure 5-18 (b) is for the 8 dB bin sequence. As has been observed previously, this sequence performs better than the 4 dB sequence. Figure 5-18 (c) shows all the DTOAs, which were computed without considering the reply codes at all. It is clear that more DTOAs would be available for computing multilateration positions if correlation was by time alone. Note especially the improvement for Target 2671 in the interval 440 to 460 seconds. Similar figures for the other R/T pairs are shown in Appendix E.

5.3.14 Additional ATCRBS Tracks

Two ATCRBS targets were tracked while taking off during a 20 minute day-time data recording session using a whisper shout sequence having 9 dB bin widths, and a 3 dB increase in power for each of 9 steps, shown in Figure 5-19. This sequence gives the transponder 3 opportunities to reply, and was chosen as a compromise between wide bins, several interrogation opportunities per scan, and not so many levels that the R/T and/or MWS would be overloaded during the high traffic and fruit daytime environment. The sequence was transmitted in a round robin fashion amongst the 5 R/Ts at a 2 Hz rate. The 2-dimensional multilateration positions that were generated before liftoff are shown in Figure 5-20. The target having a Mode A code of 6375 took off about one minute into the data taking session from runway 26L. The target having a Mode A code of 4175 took off about 17 minutes into the session from runway 26R.

Figure 5-21 shows the x (East/West) and y (North/South) positions vs time for Target 6375. The grid lines are spaced at 2.5 seconds, representing a complete interrogation cycle amongst the 5 R/Ts. Figure 5-22 shows the y vs time, with symbols indicating which R/T is interrogating, and Figure 5-23 uses symbols to show which triad was used to compute the position. The interrogations were evenly balanced amongst the R/Ts, and triad 0,1,3 (Delta, Ford, Region) was used most often to compute position.

Figures 5-24 and 5-25, show the positions vs time and the interrogating R/Ts for Target 4175. The interrogations are balanced amongst the 5 R/Ts. Triad 0,1,2 (Delta, Ford, Stouffers) was used most often to compute the position.

5.3.15 Summary Whisper Shout

This section shows that whisper shout successfully degarbles ATCRBS targets, and that the multilateration positional accuracy is comparable to that achieved for Mode S targets. However, the update rate for ATCRBS targets was much less than for Mode S, probably for the following reasons:

a. An interrogation is necessary to produce an ATCRBS reply, whereas Mode S squitters do not require an interrogation.

b. The CAPTS used a paired interrogation for ATCRBS, which requires two successful interrogations by the interrogating R/T, and two successful reply detections by each of at least 3 R/Ts before a position can be computed.

c. ATCRBS transponder antennas are bottom mounted whereas Mode S squitters are emitted from the top antenna.

d. The R/Ts did not perform ATCRBS code detection as reliably as possible.

e. The MWS did not make best use of the ATCRBS replies that were emitted by the targets.

A mathematical model was developed in order to use the measured results from Targets 6310 and 2761 to predict the performance for an improved system design. The model of the R/T and MWS processes was verified by comparing its predicted update rates for the two targets with the measured values. The model's predictions were 67% and 33%, respectively, which agreed well with the values observed directly. The model was then applied to an hypothetical multilateration system similar to CAPTS, but with the following differences:

1. It uses a single interrogation instead of the paired interrogation technique.
2. It uses 4 dB whisper shout bins with a step advance of 1 dB, which provides 4 interrogation opportunities per scan.
3. It re-invokes the code enhancement feature of the R/Ts.
4. It performs reply correlation using the sum-range (reply time of arrival minus interrogation time).
5. It tracks the time of arrival differences, so that positions can be computed from composite reception triads.
6. It uses 6 dB less attenuation at Delta, Ford, and Stouffers.

The actual measured reply and receive efficiencies, and the round reliabilities, described previously are for the paired interrogation technique. If the reply correlation were perfect, then the ideal update rate would have been slightly higher than measured, presumably because of less than perfectly efficient reply correlation and position computation algorithms. In the model, the measured interrogation and reply efficiencies, and round reliability values were used to estimate the corresponding values that would result from using a single interrogation. The single interrogation values were then used to estimate the update rate that would result if the reply correlation algorithms and position computation algorithms efficiencies were increased by correlating on time of arrival and tracking the time of arrival differences. A whisper shout sequence with 4 dB bins and a 1 dB step advance was assumed. Also, 6 dB attenuation was assumed to be removed from Delta, Ford, and Stouffers, to increase the interrogation reliability of Target 2761.

The model predicts that the surveillance reliabilities for these two targets would increase from 67% and 33% to 93% and 87%, respectively, as shown in Table 5-14. This would be a significant improvement over the CAPTS system, yet is well within the capabilities of TCAS technology.

In conclusion, the Atlanta whisper shout tests and subsequent analyses demonstrated and validated the viability of using whisper shout on the airport surface, although the particular equipment that was tested did not include all of the necessary hardware and algorithm features. The needed features already exist in similar equipment, or would be straight forward extensions of existing techniques.

Table 5-14. Predicted Performance of Improved System

	Update Rate (Probability of a position measurement for a whisper shout sequence)					
	Target 6310			Target 2671		
	CAPTS Predicted	CAPTS Measured	Improved Predicted	CAPTS Predicted	CAPTS Measured	Improved Predicted
Single interrogation efficiency, 4 dB bins	.61		.61	.37		.47 [3]
Paired interrogation efficiency, 4 dB bins	.37		NA [1]	.14		NA [1]
Interrogation opportunities/sequence	2	2	4 [4]	2		4 [4]
Per scan interrogation efficiency	.61	.60	.98 [1,4]	.26	.22	.92 [1,3,4]
Single reception with perfect code efficiency	.81		.86 [5]	.81		.86 [5]
Paired reception with perfect code efficiency	.66	.64	NA [2]	.66	.64	NA [2]
Round Reliability (perfect code)	.40	.45	.84 [1,2,4,5]	.17	.18	.79 [1,2,3,4,5]
Ideal update rate (4,8,16 dB sequences)	.743		.974	.361		.915
Correlation, Multilateration efficiency	.90		.95 [6]	.90		.95 [6]
Net update rate (%)	.67	.62	**.93**	.33	.39	**.87**
Notes:						
[1]	Eliminate the paired interrogation technique.					
[2]	Eliminate the paired reception requirement.					
[3]	Remove 6 dB of attenuation from Ford, Delta and Stouffers R/Ts. This will only impact 2761, which had low interrogation margin.					
[4]	Use 4 dB bins, but with a step advance of 1 dB instead of 2 dB					
[5]	Re-implement the R/Ts code enhancement feature.					
[6]	Perform reply correlation using time of arrival. Track time of arrival differences.					

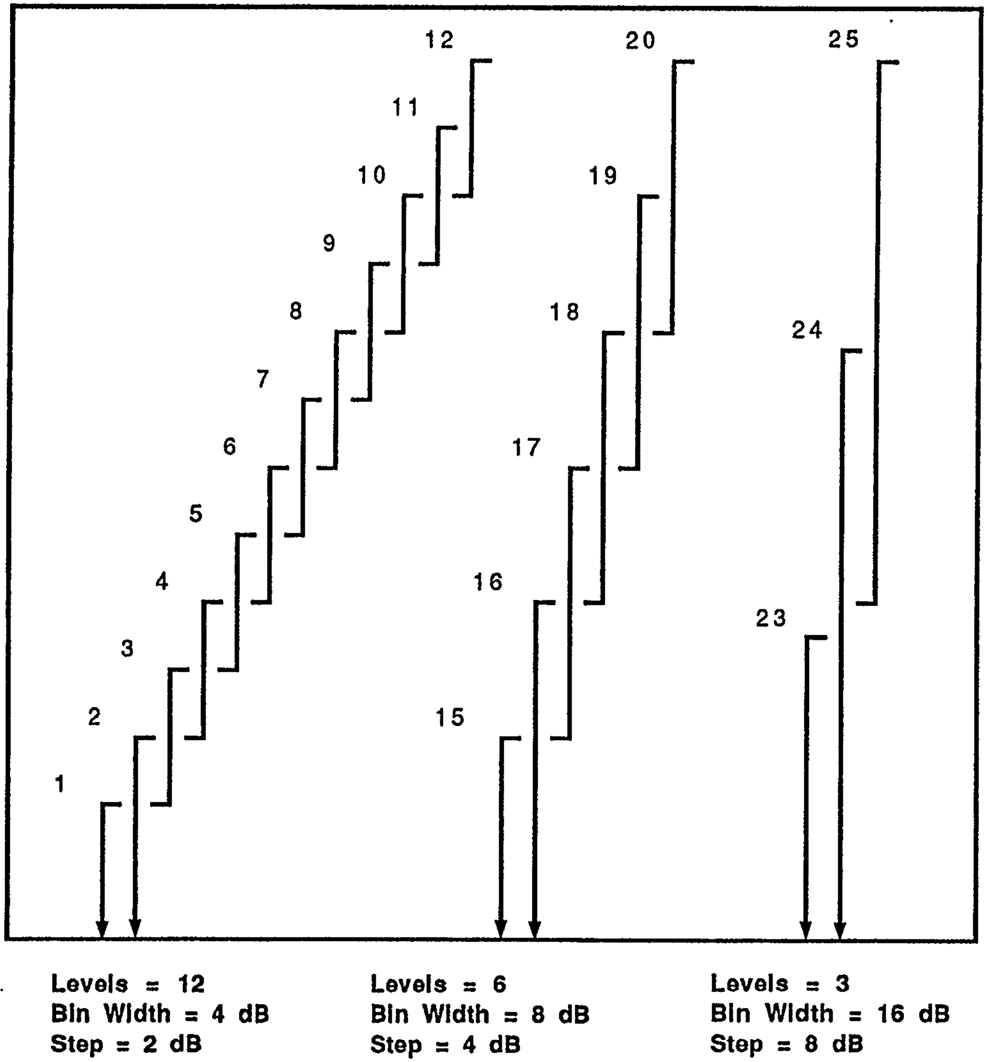


Figure 5-1. Whisper shout sequences (4 dB, 8 dB, 16 dB Bins).

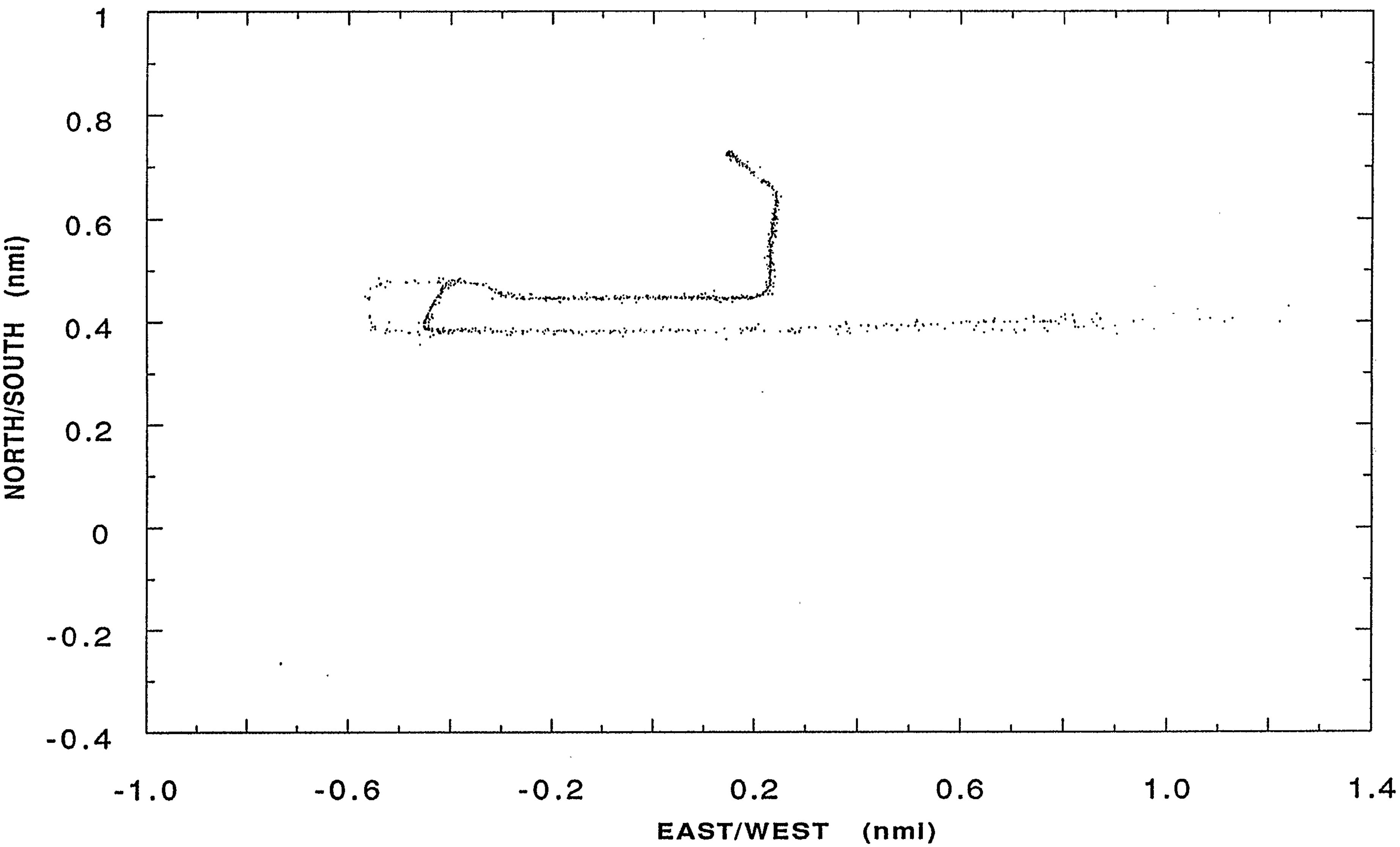


Figure 5-2. All x,y positions for ATCRBS Targets 5250 and 7145.

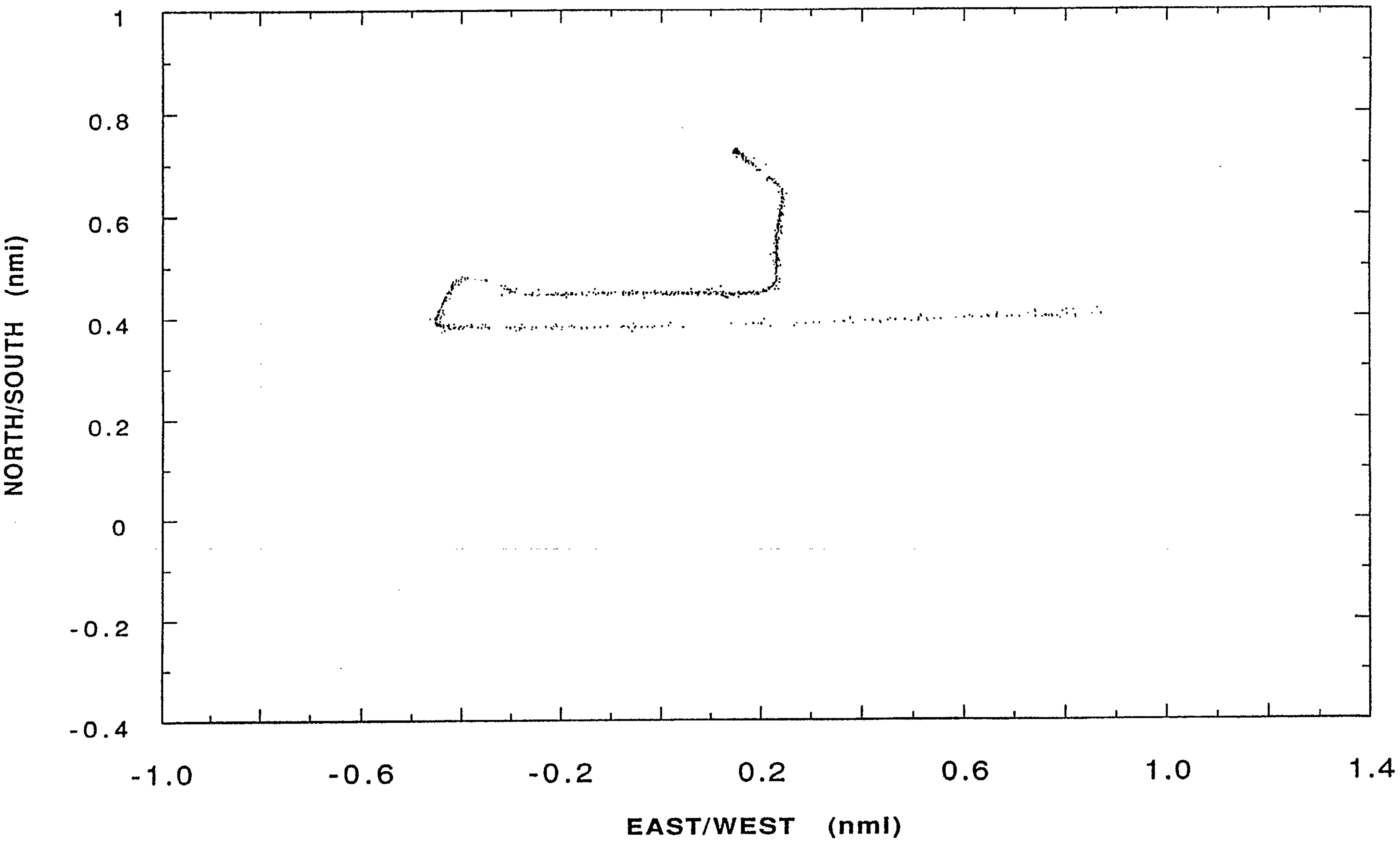


Figure 5-3. All x,y positions for Target 5250.

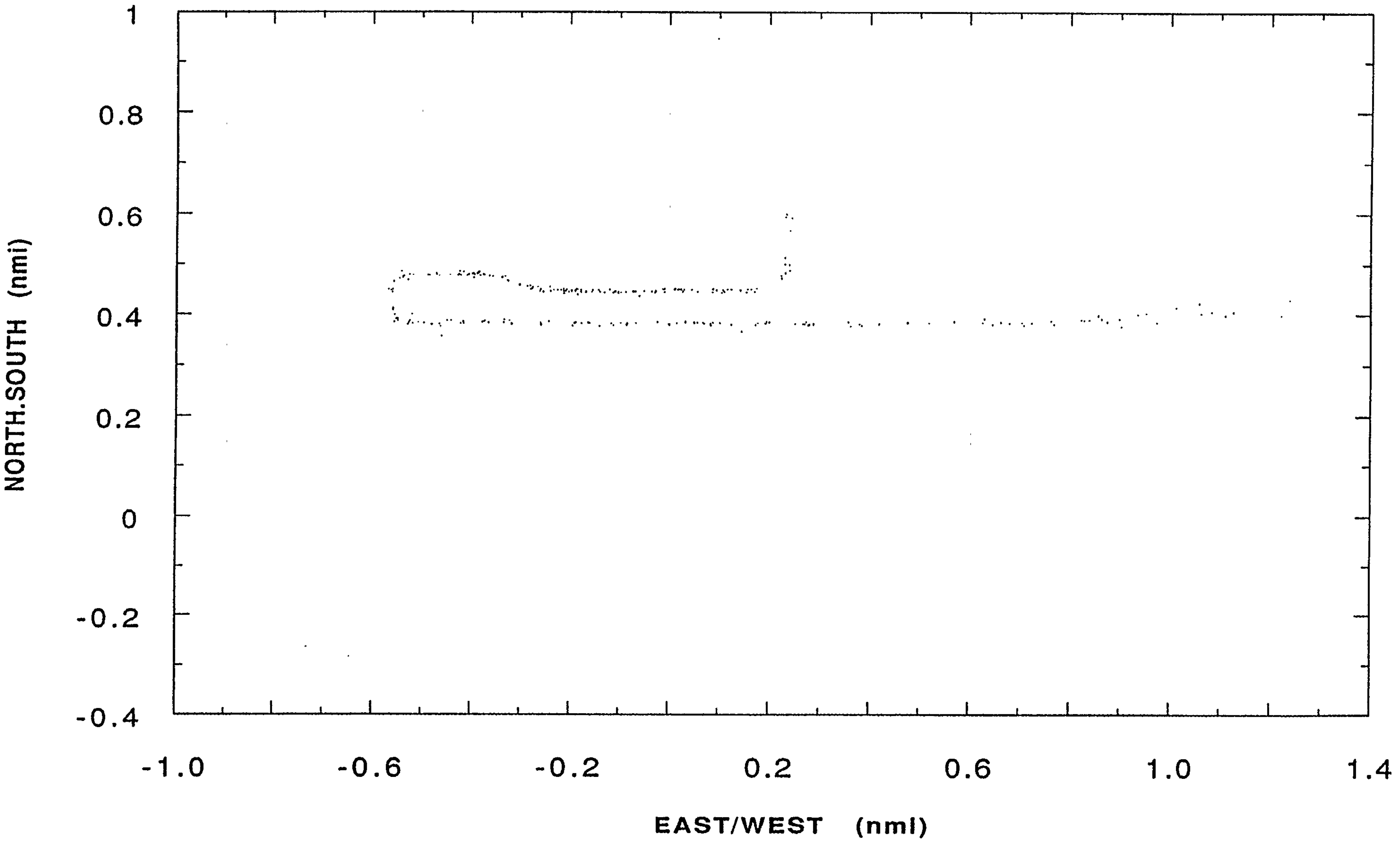


Figure 5-4. All x,y positions for Target 7145.

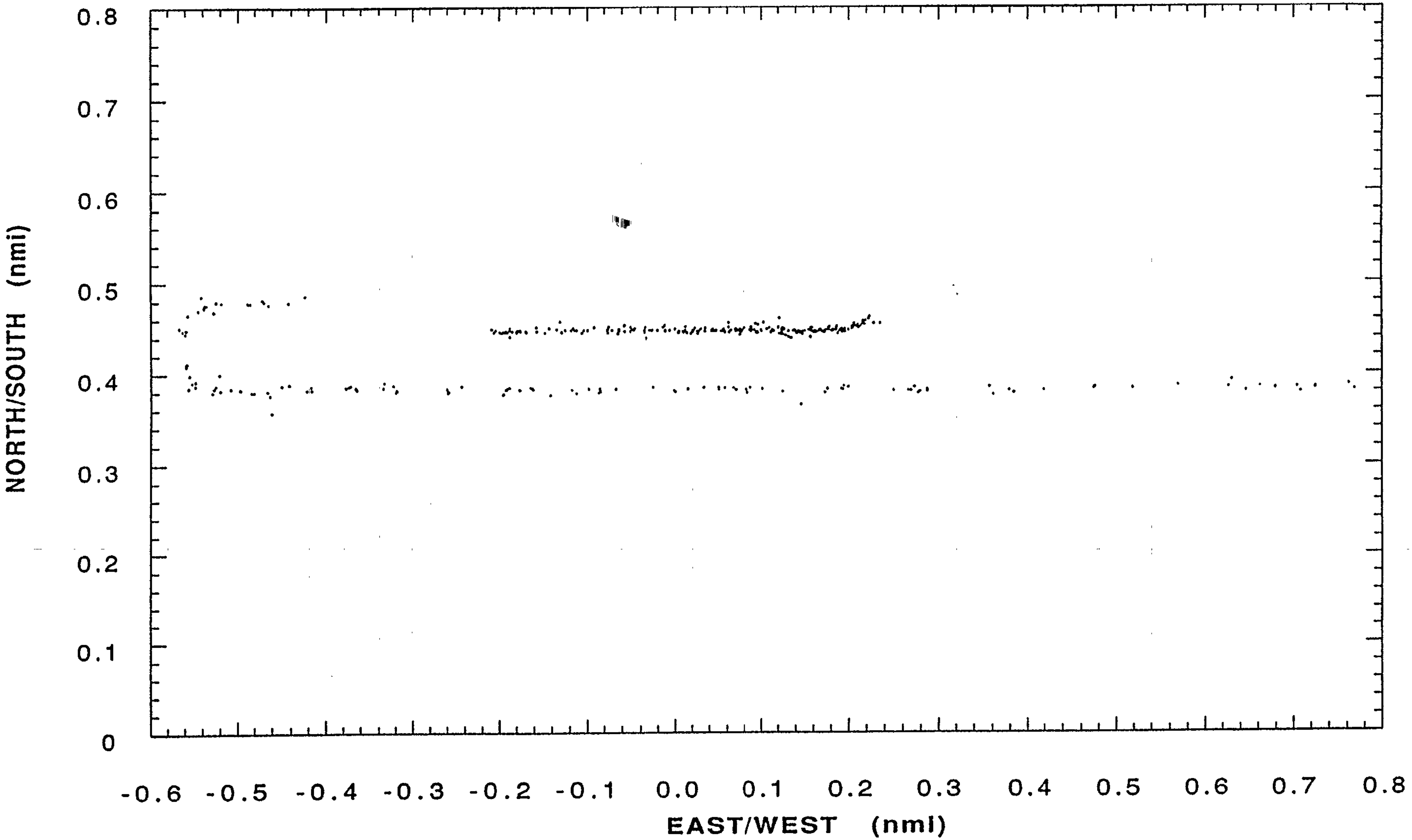


Figure 5-5. One hundred seconds of x,y Positions for Targets 5250 and 7145.

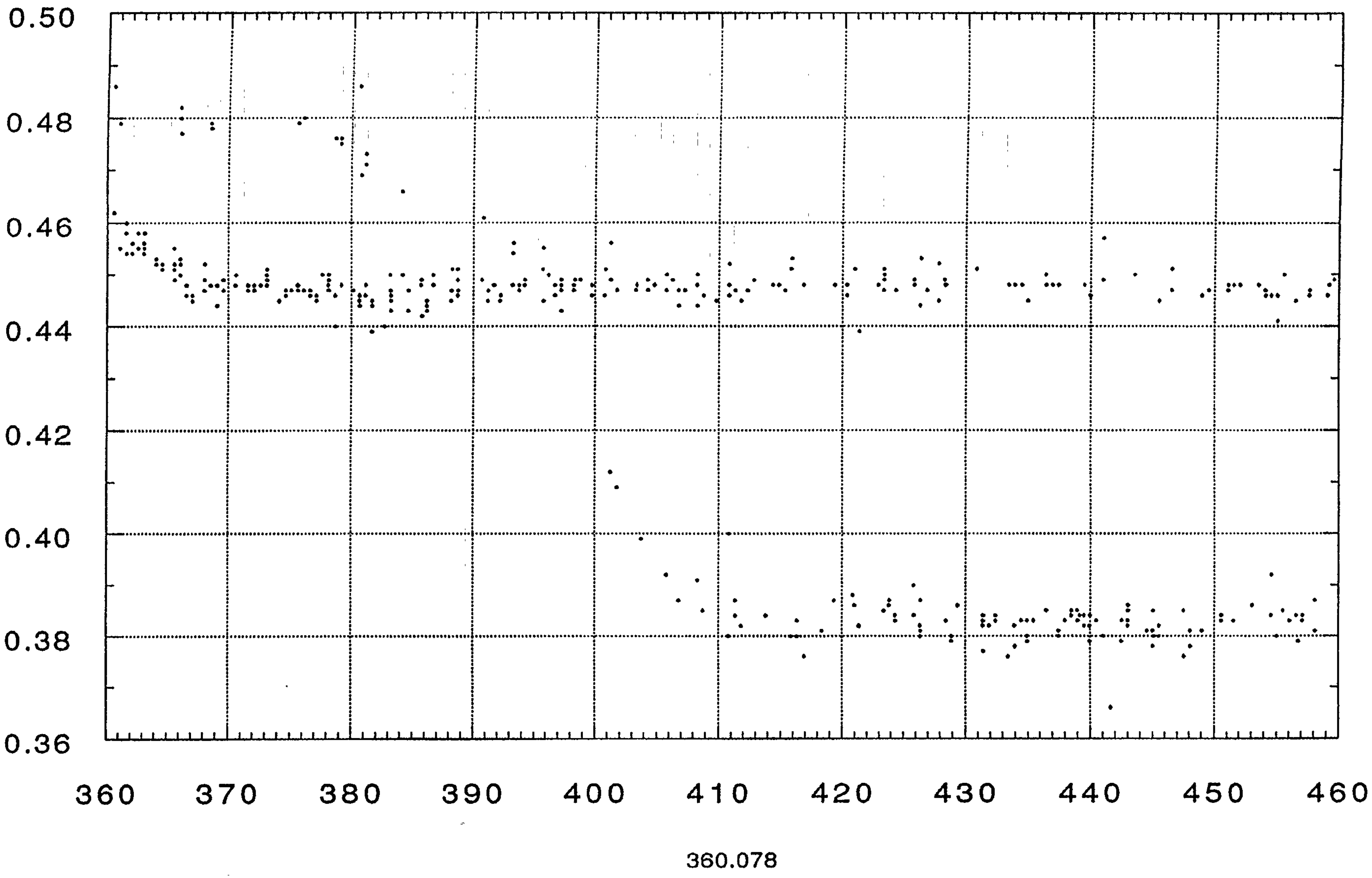


Figure 5-6. One hundred seconds of y Positions vs Time for Targets 5250 and 7145.

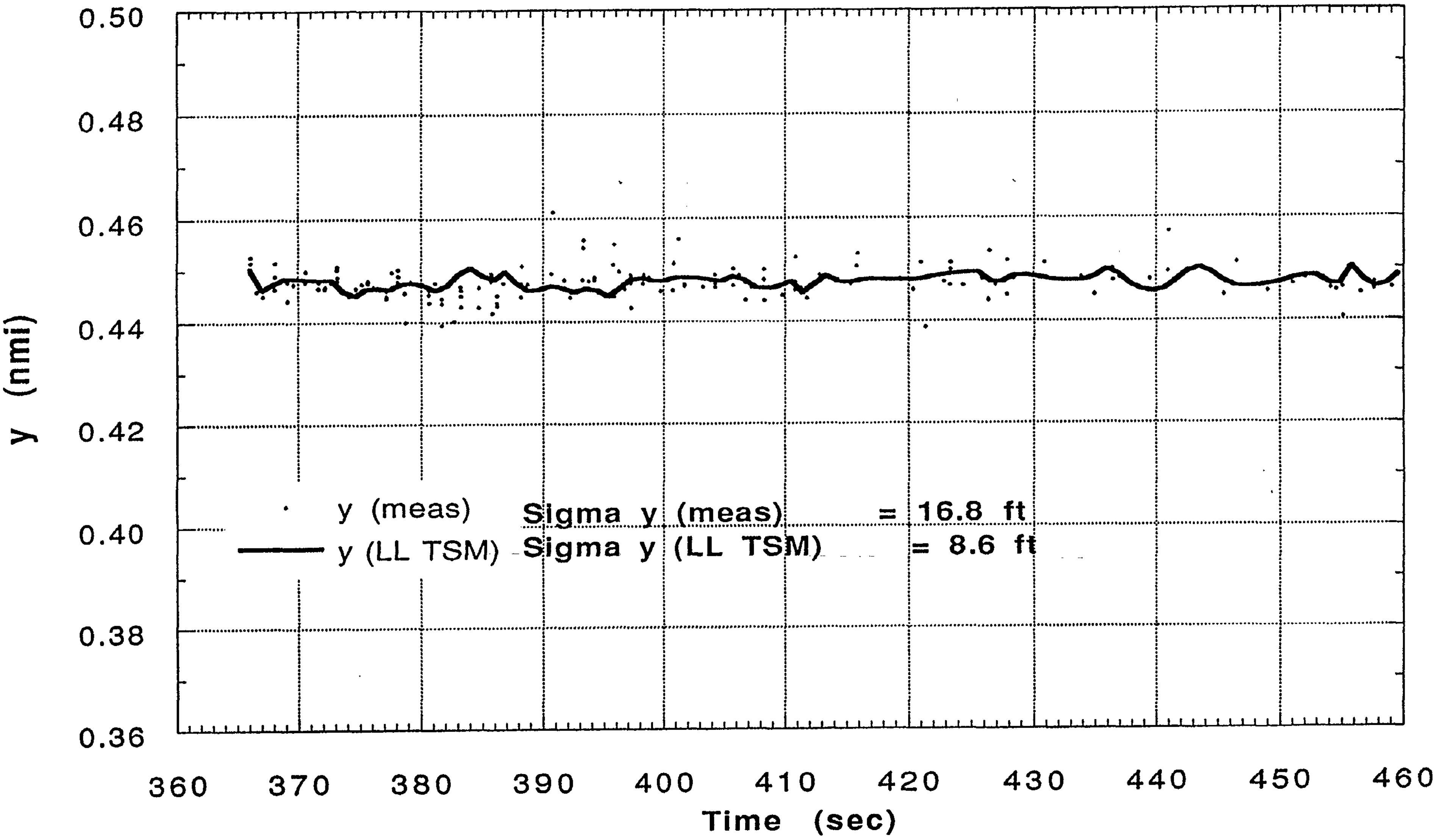
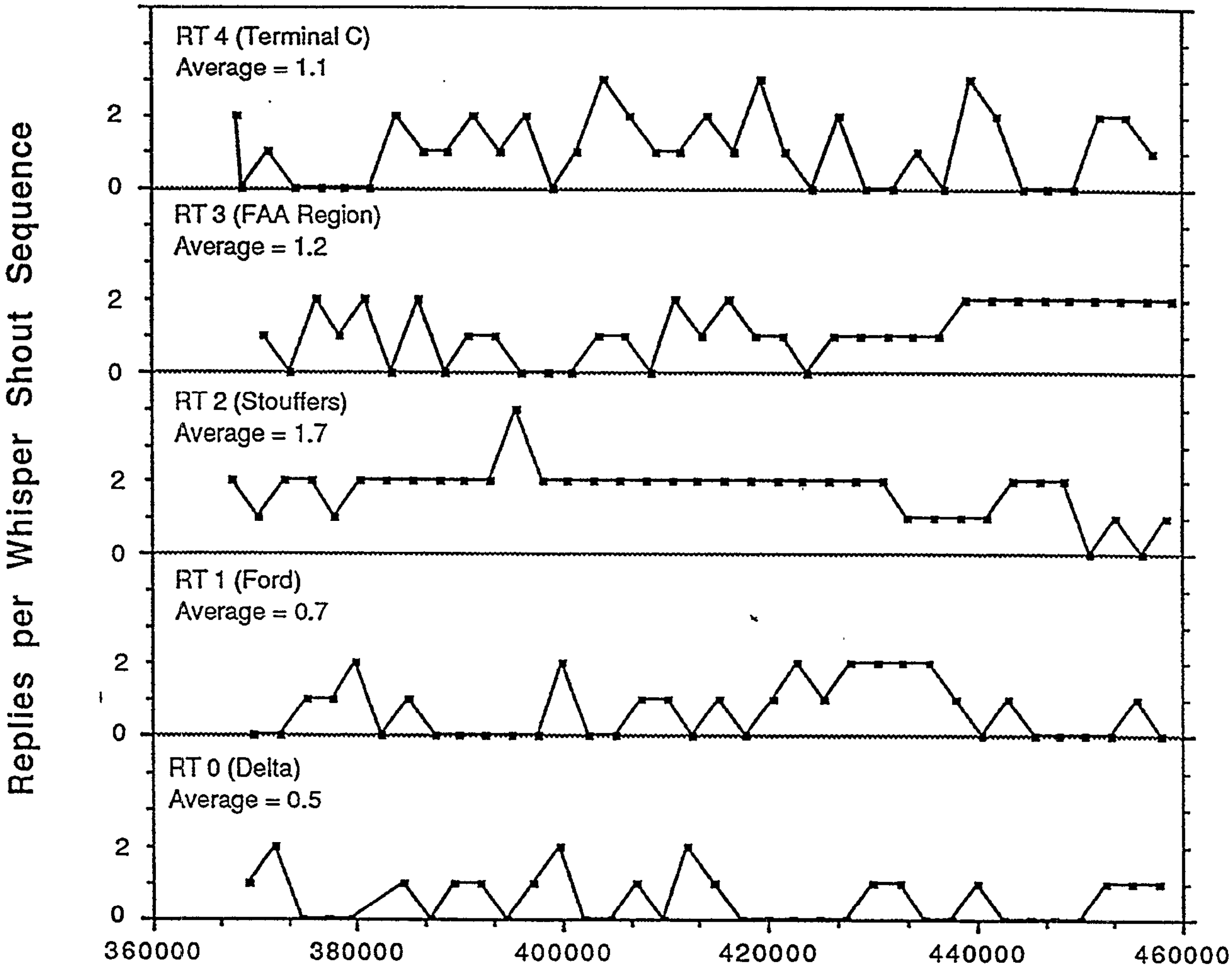


Figure 5-7. One hundred seconds of y Smoothed vs Time for Targets 5250 and 7145.



Replies per Whisper Shout Sequence
(2 dB Step Size, 4 dB Bin Width)
(Target 6310)

Figure 5-8. Replies per whisper shout sequence, 4 dB bins, Target 6310.

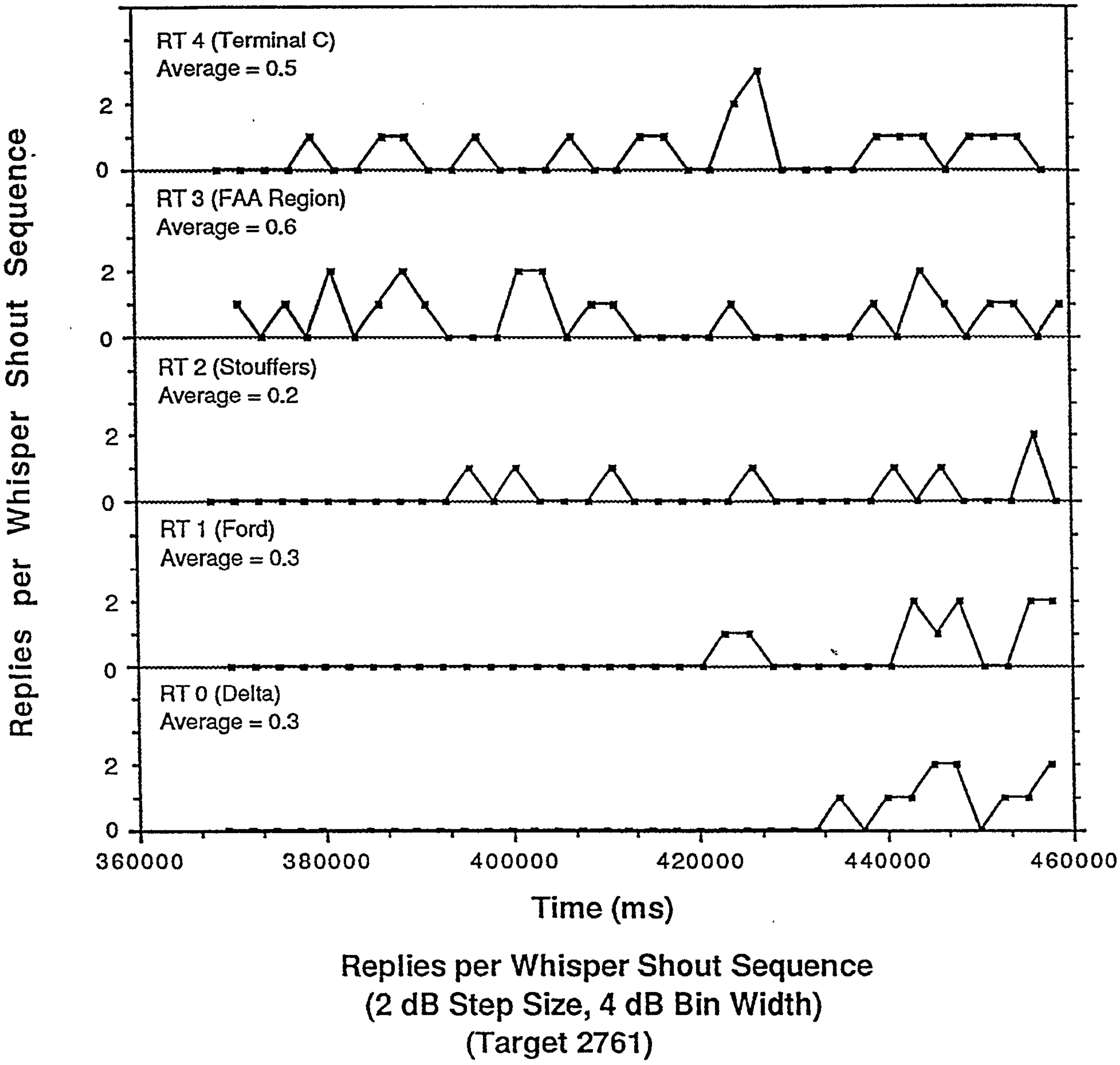
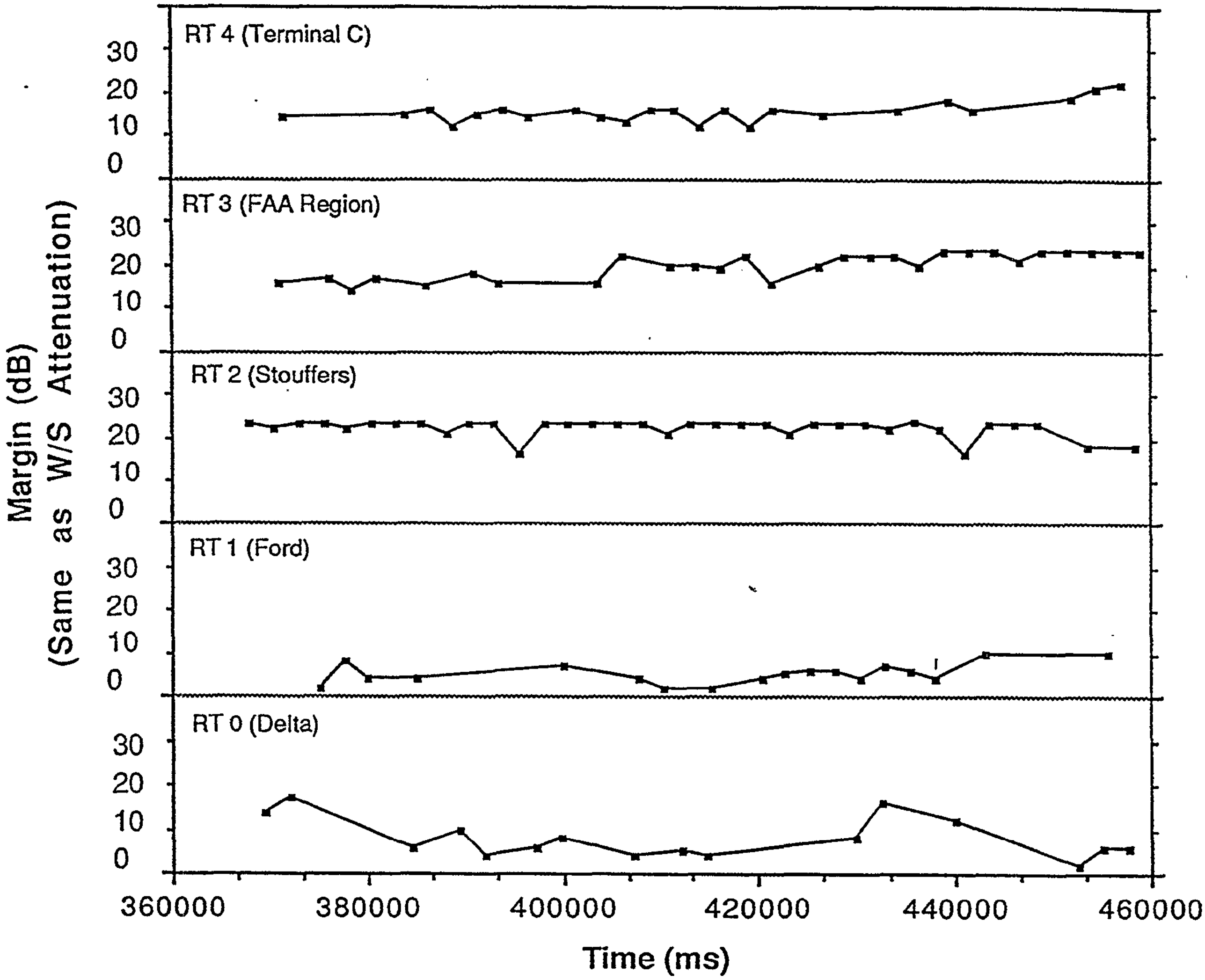


Figure 5-9. Replies per whisper shout sequence, 4 dB bins, Target 2761.



Interrogation Link Margin (6310)

Figure 5-10. Interrogation link margin for Target 6310.

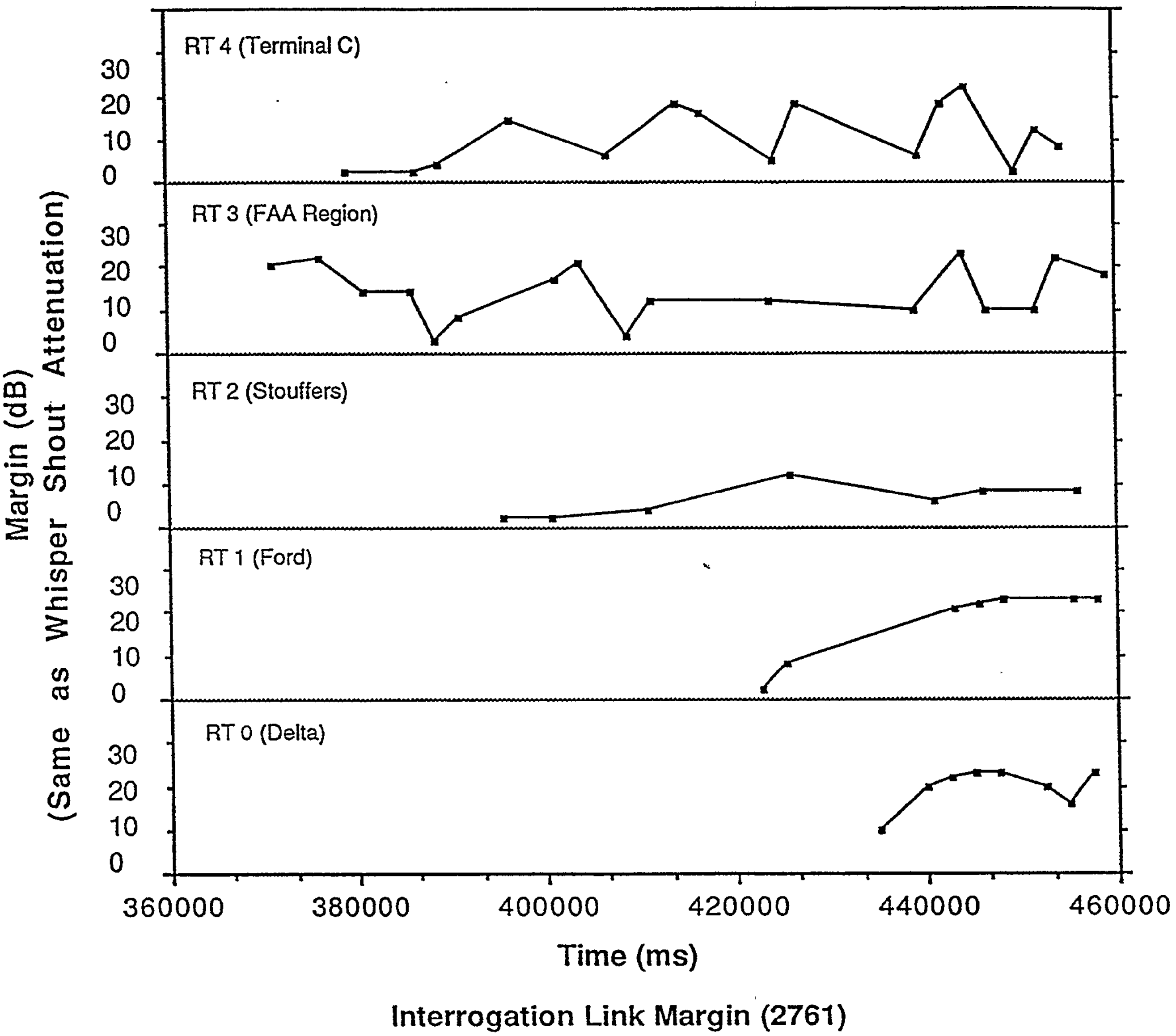
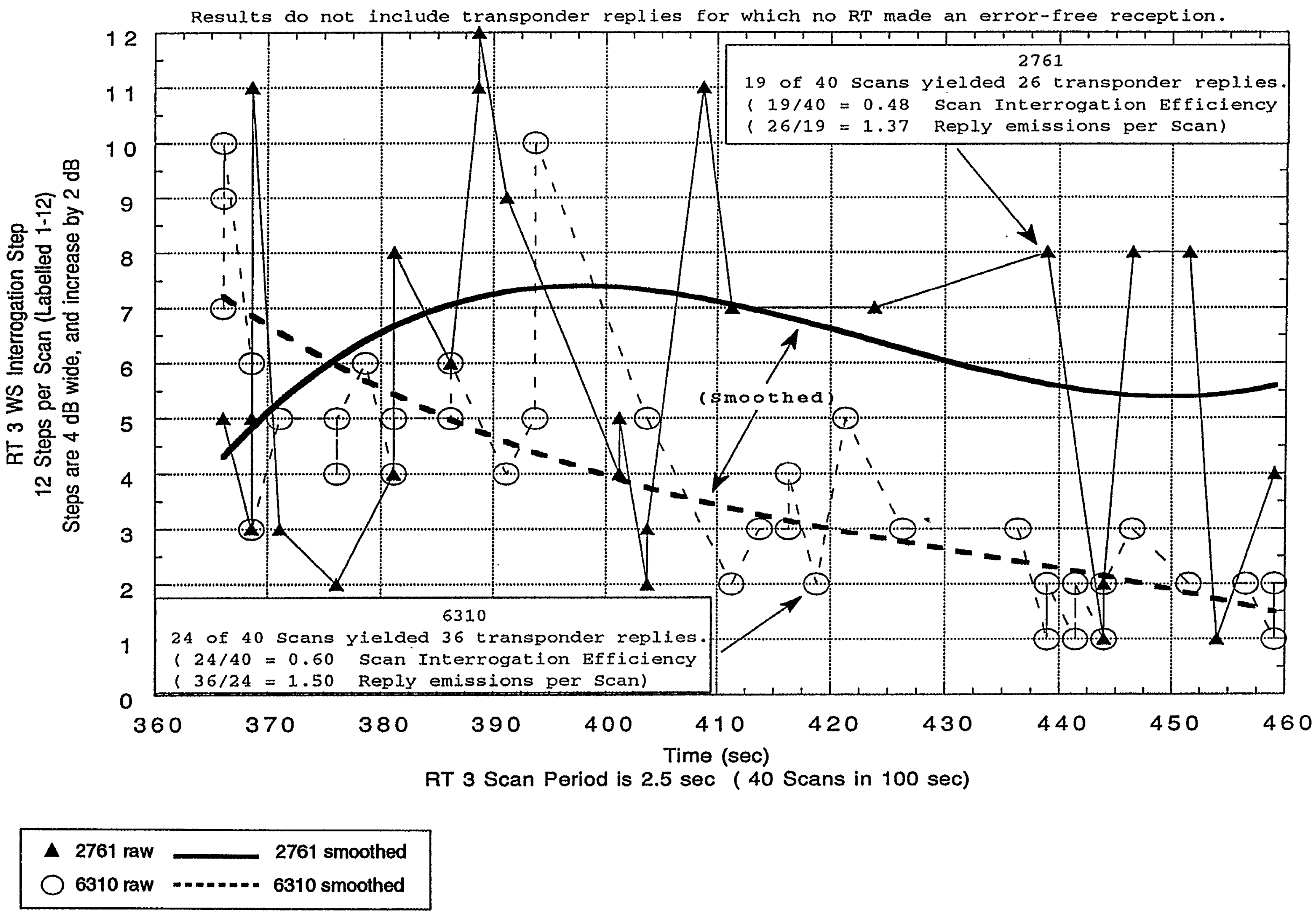


Figure 5-11. Interrogation link margin for Target 2761.



Results do not include transponder replies for which no RT made an error-free reception.

2761
19 of 40 Scans yielded 26 transponder replies.
(19/40 = 0.48 Scan Interrogation Efficiency
(26/19 = 1.37 Reply emissions per Scan)

6310
24 of 40 Scans yielded 36 transponder replies.
(24/40 = 0.60 Scan Interrogation Efficiency
(36/24 = 1.50 Reply emissions per Scan)

Figure 5-12. Partitioning by 4 dB Whisper Shout Sequence, Region RT.

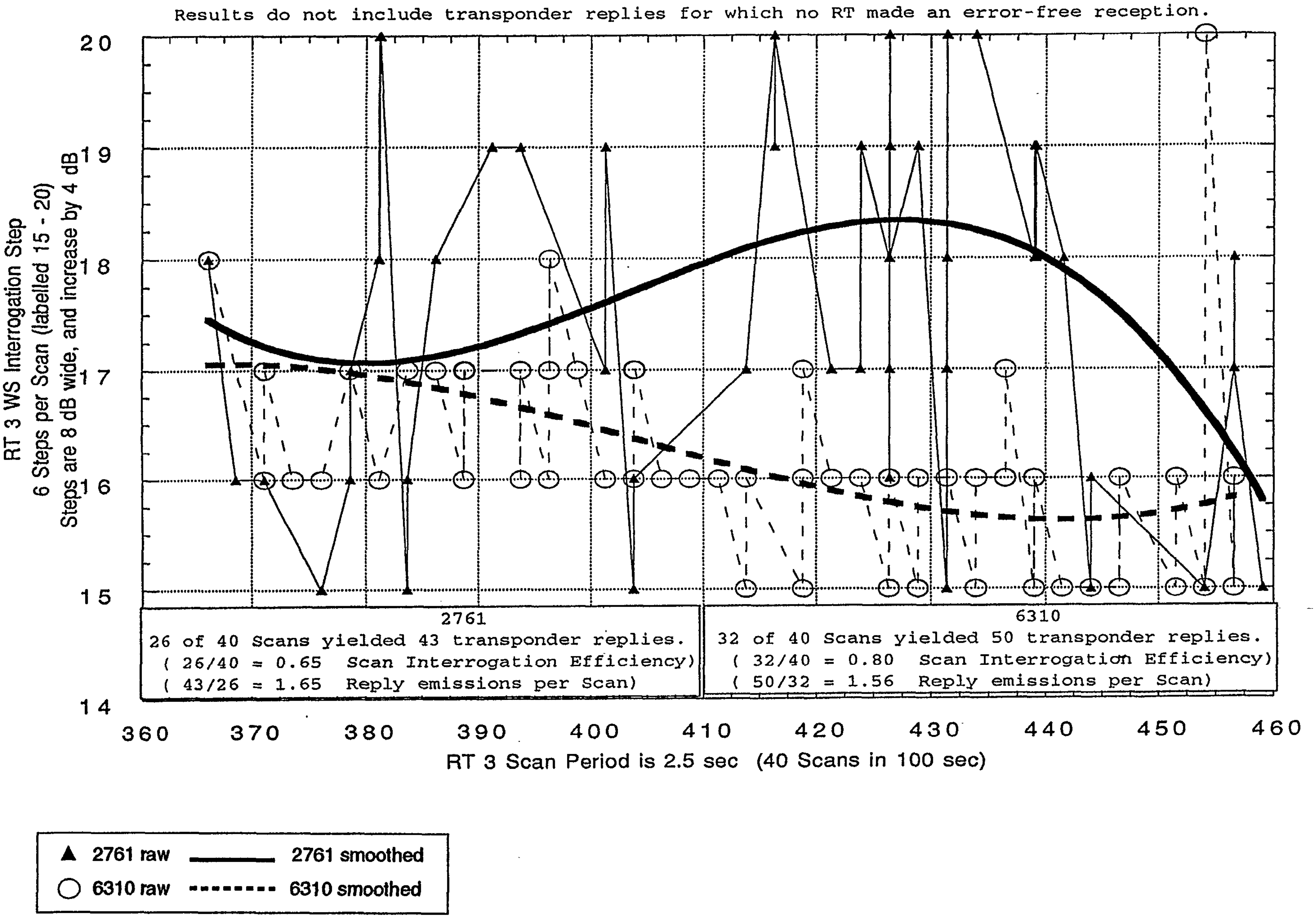


Figure 5-13. Partitioning by 8 dB whisper shout sequence, Region RT.

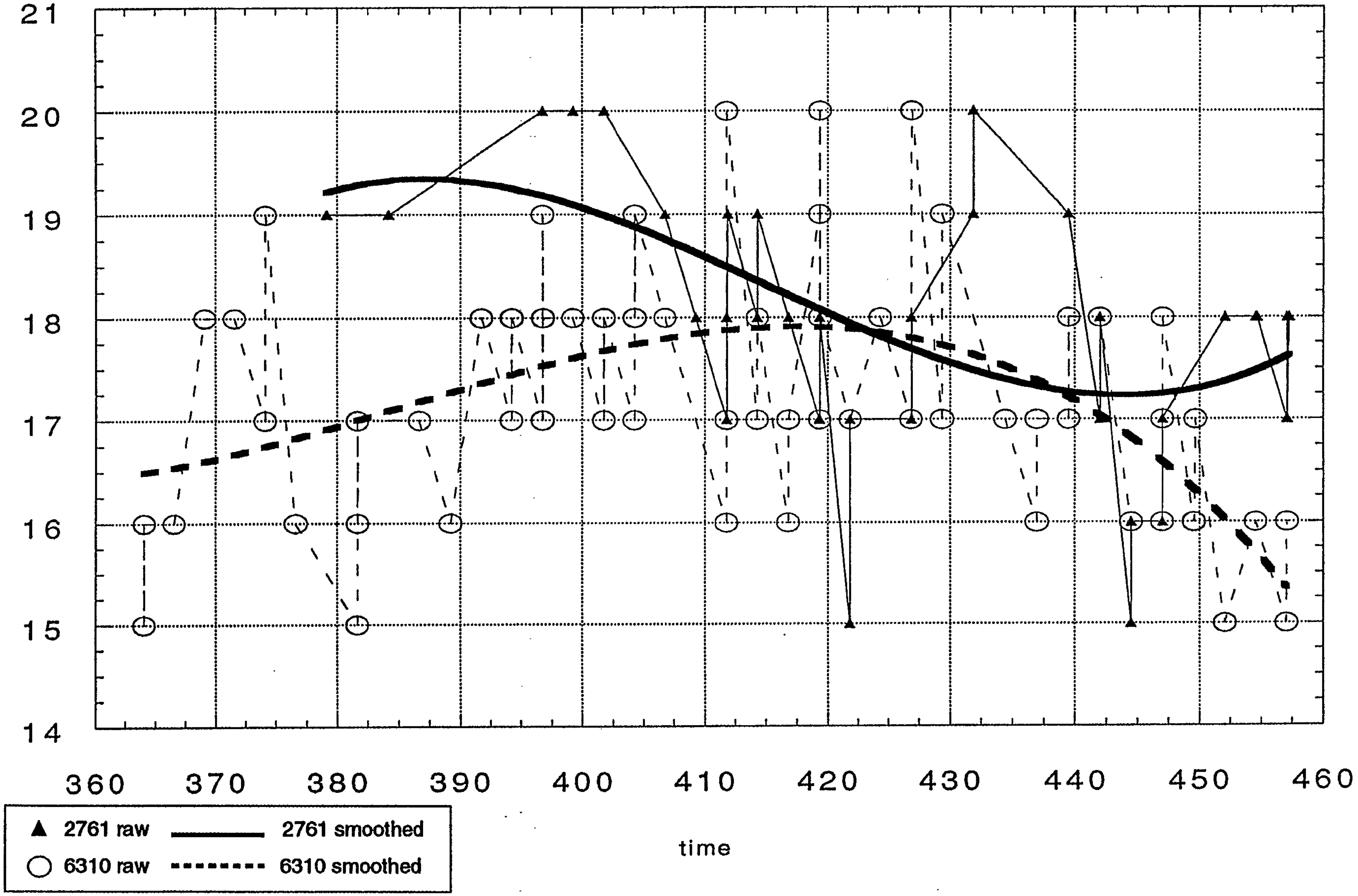


Figure 5-14. Partitioning by 8 dB whisper shout sequence, Terminal C RT.

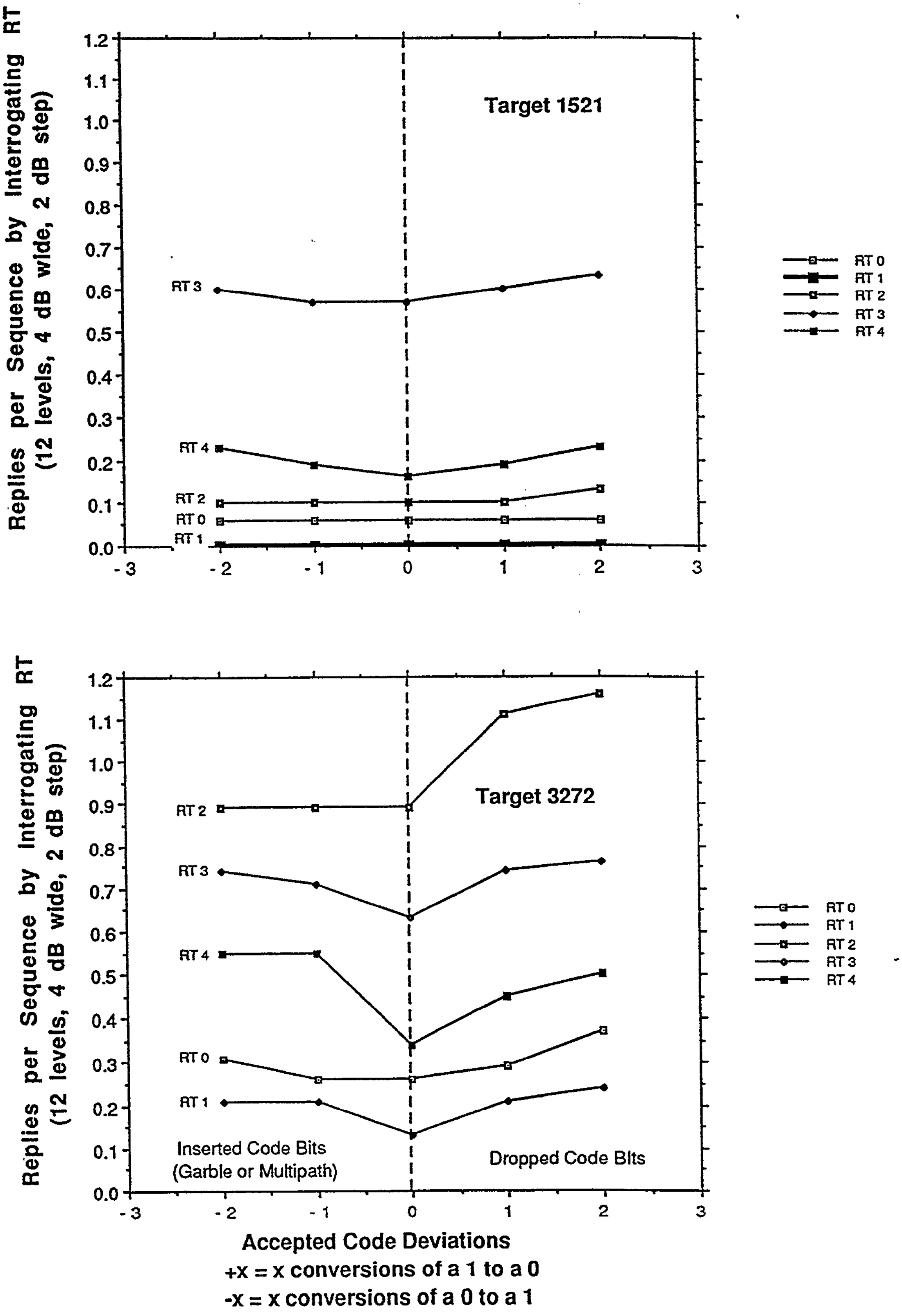


Figure 5-15. Incidence of inserted and dropped bits in reply Mode A codes.

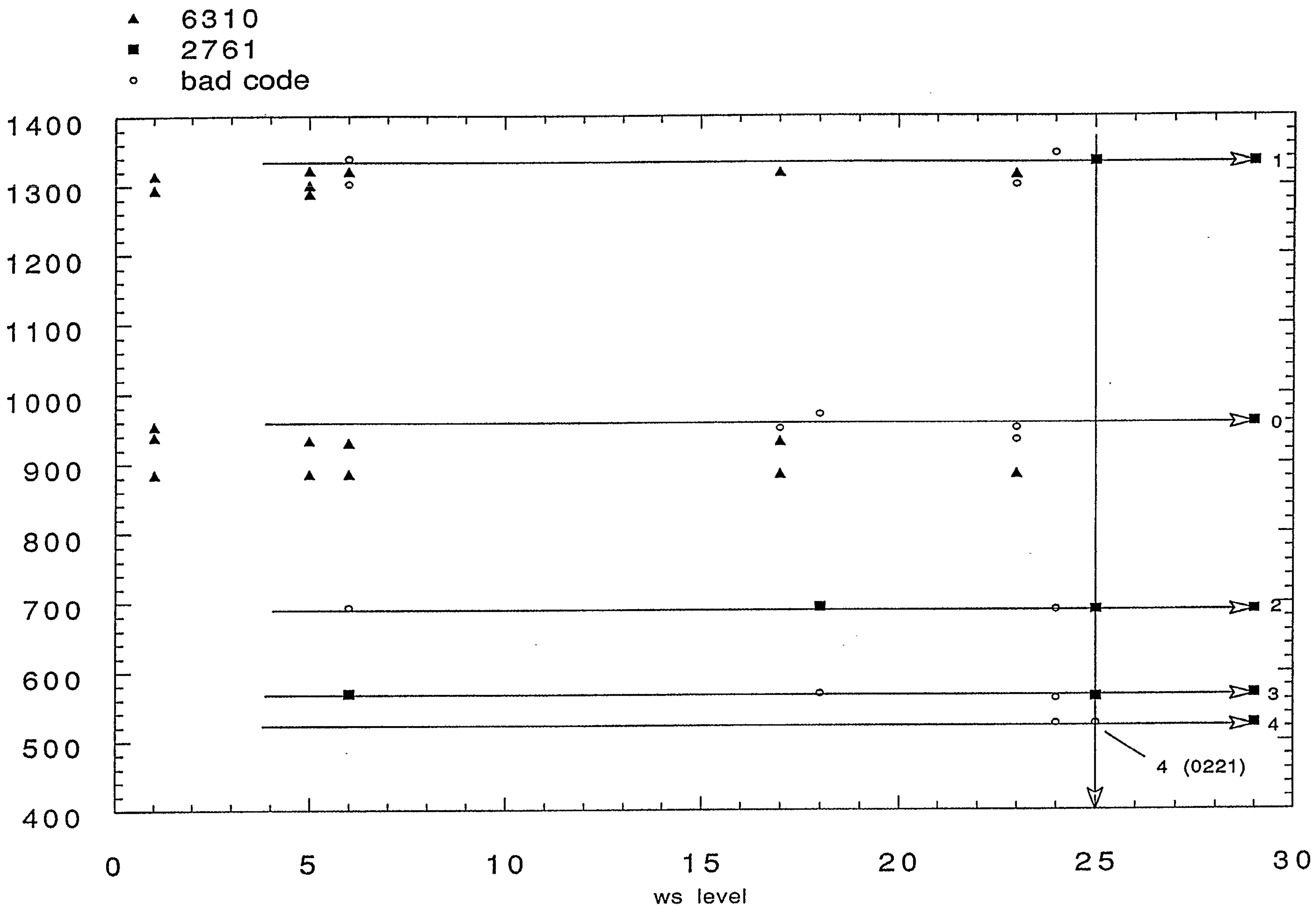


Figure 5-16a. Reply correlations by predicted arrival time on one scan for 3 whisper shout sequences.

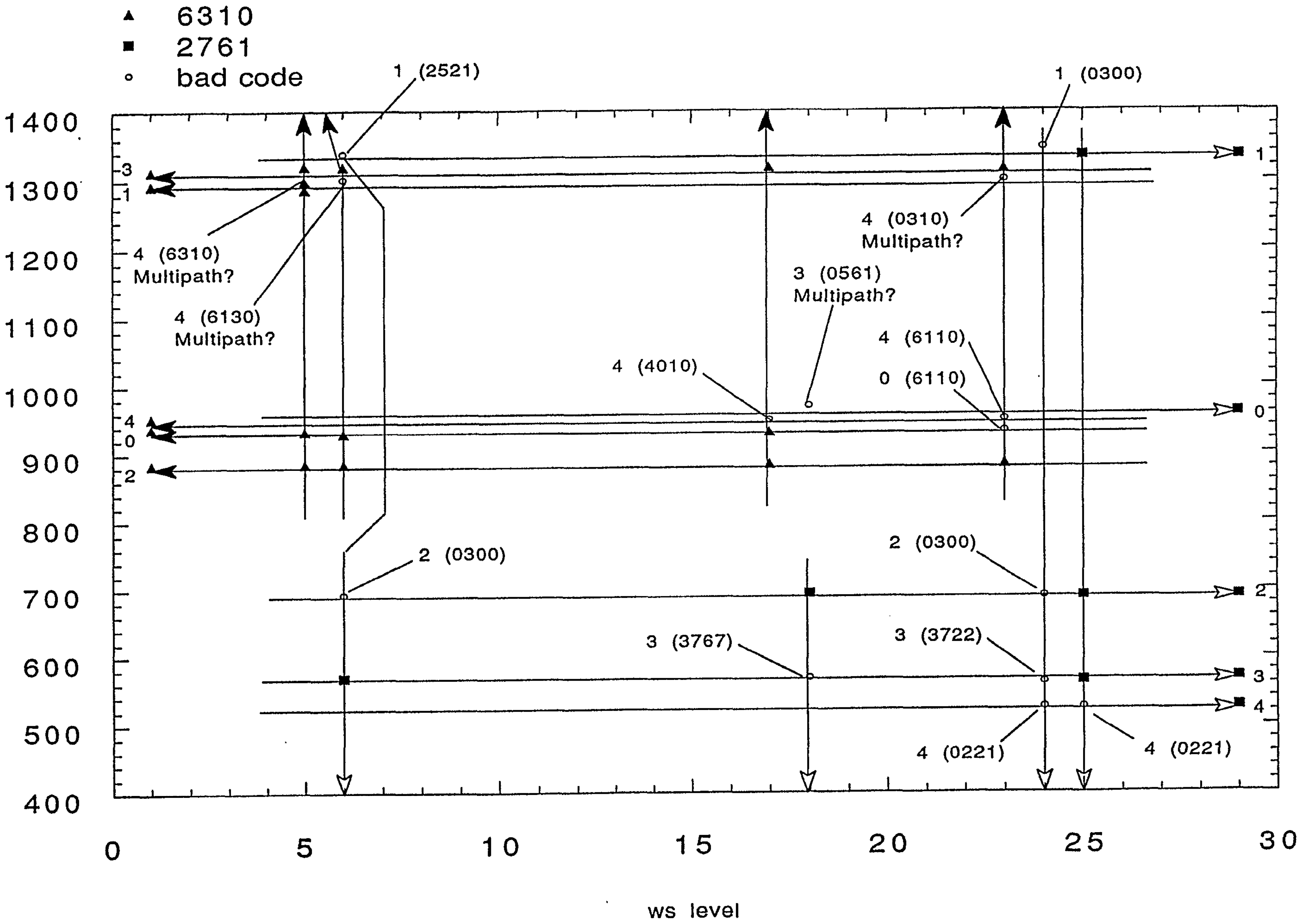


Figure 5-16b. Reply correlations by predicted arrival time on one scan for 3 whisper shout sequences (with additional symbology).

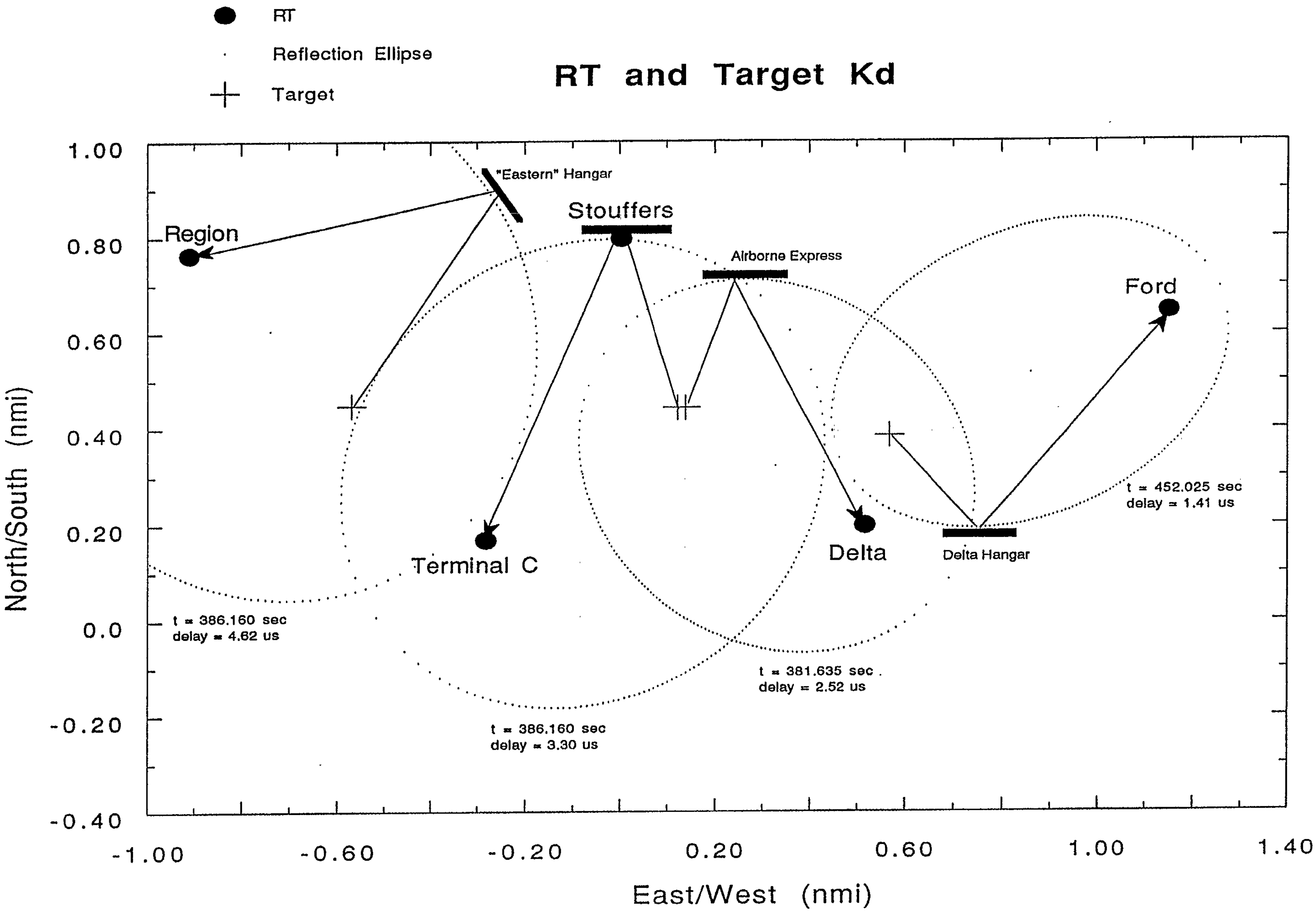


Figure 5-17. Multipath reflectors causing delayed receptions at Delta, Ford, Region, and Terminal C.

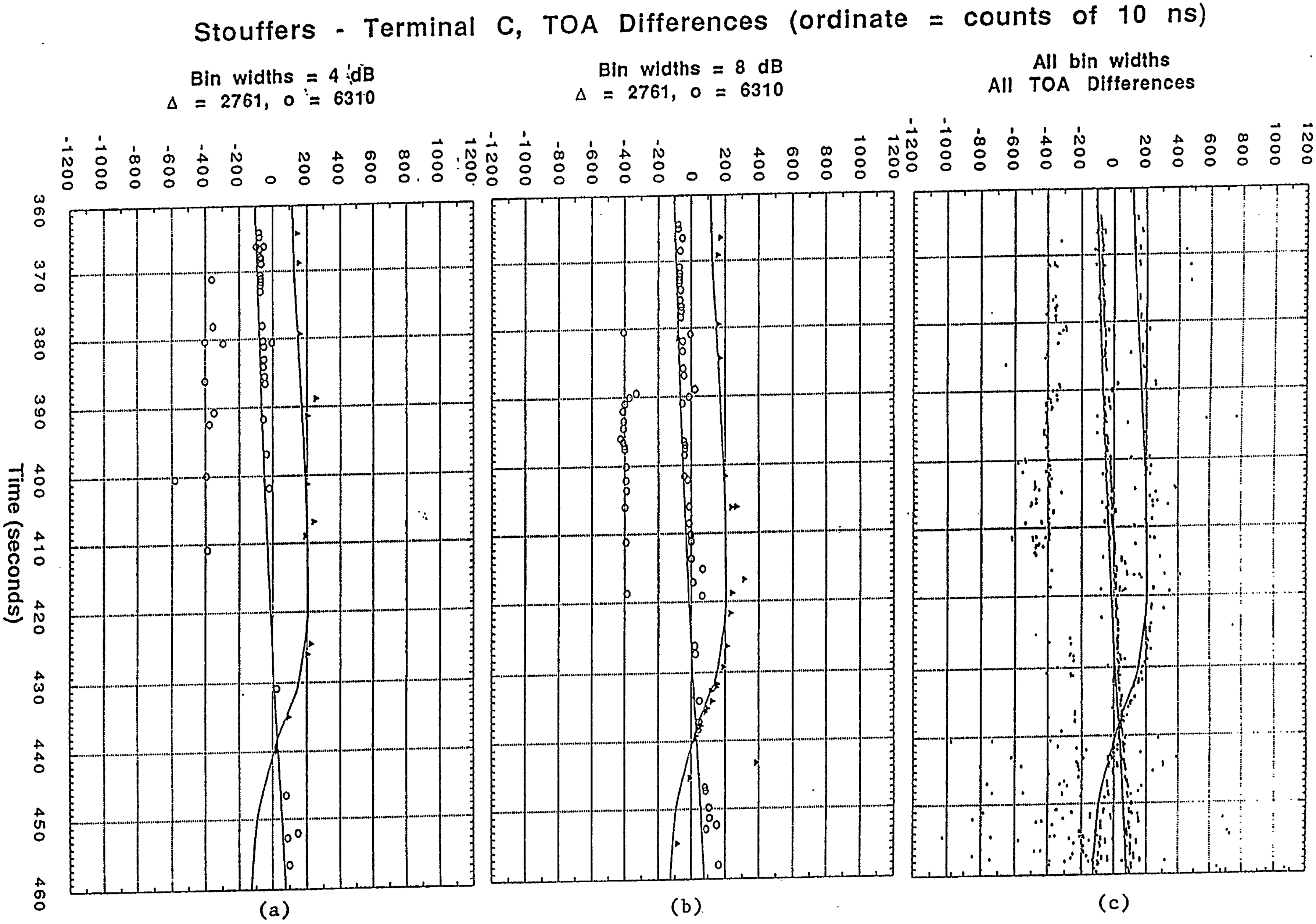


Figure 5-18. Correlation of DTOAs (Stouffers - Terminal C) to predictions.

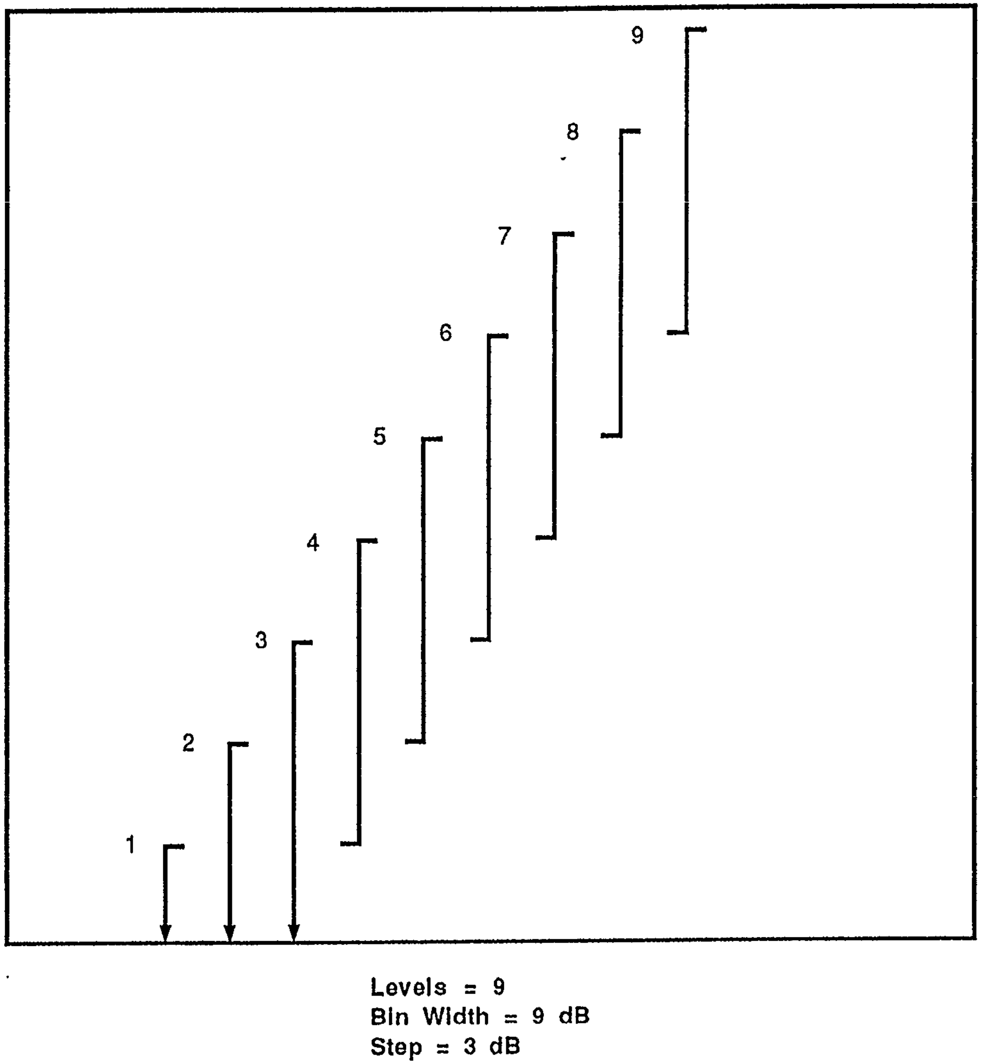


Figure 5-19. Whisper shout sequence (9 dB bins).

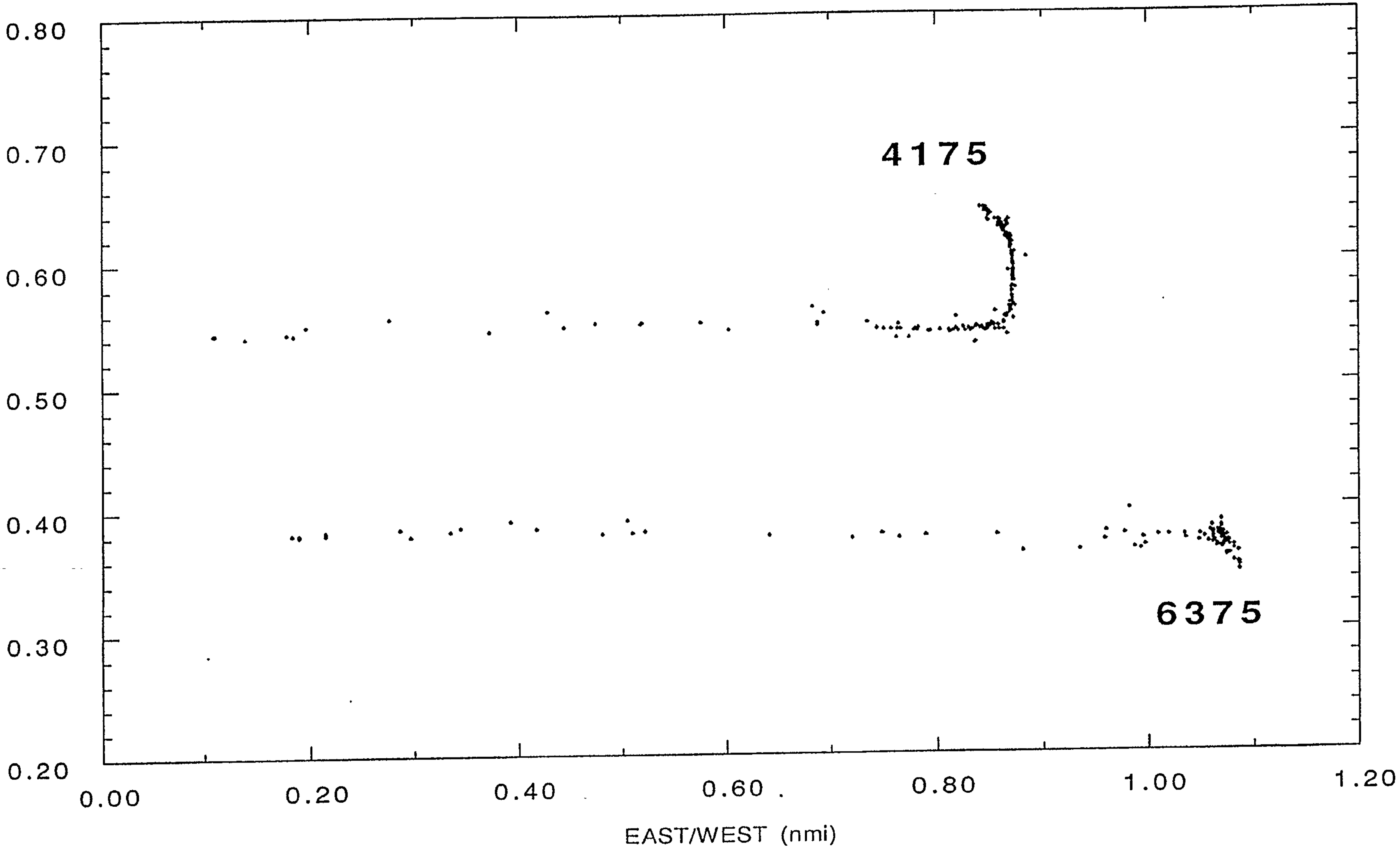


Figure 5-20. All x,y positions for daytime Targets 4175 and 6375.

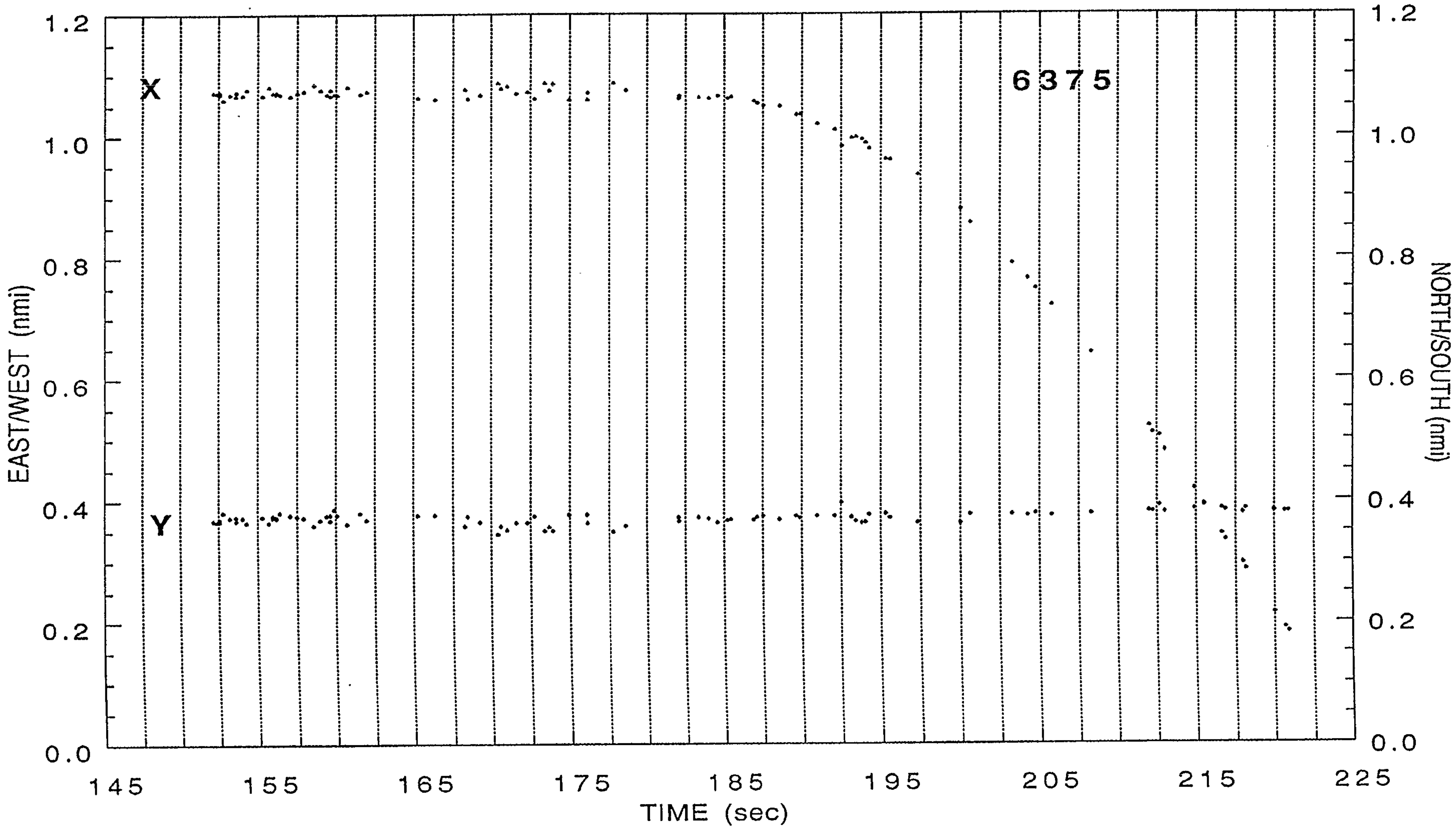


Figure 5-21. Eighty seconds of x,y Positions vs Time for Target 6375.

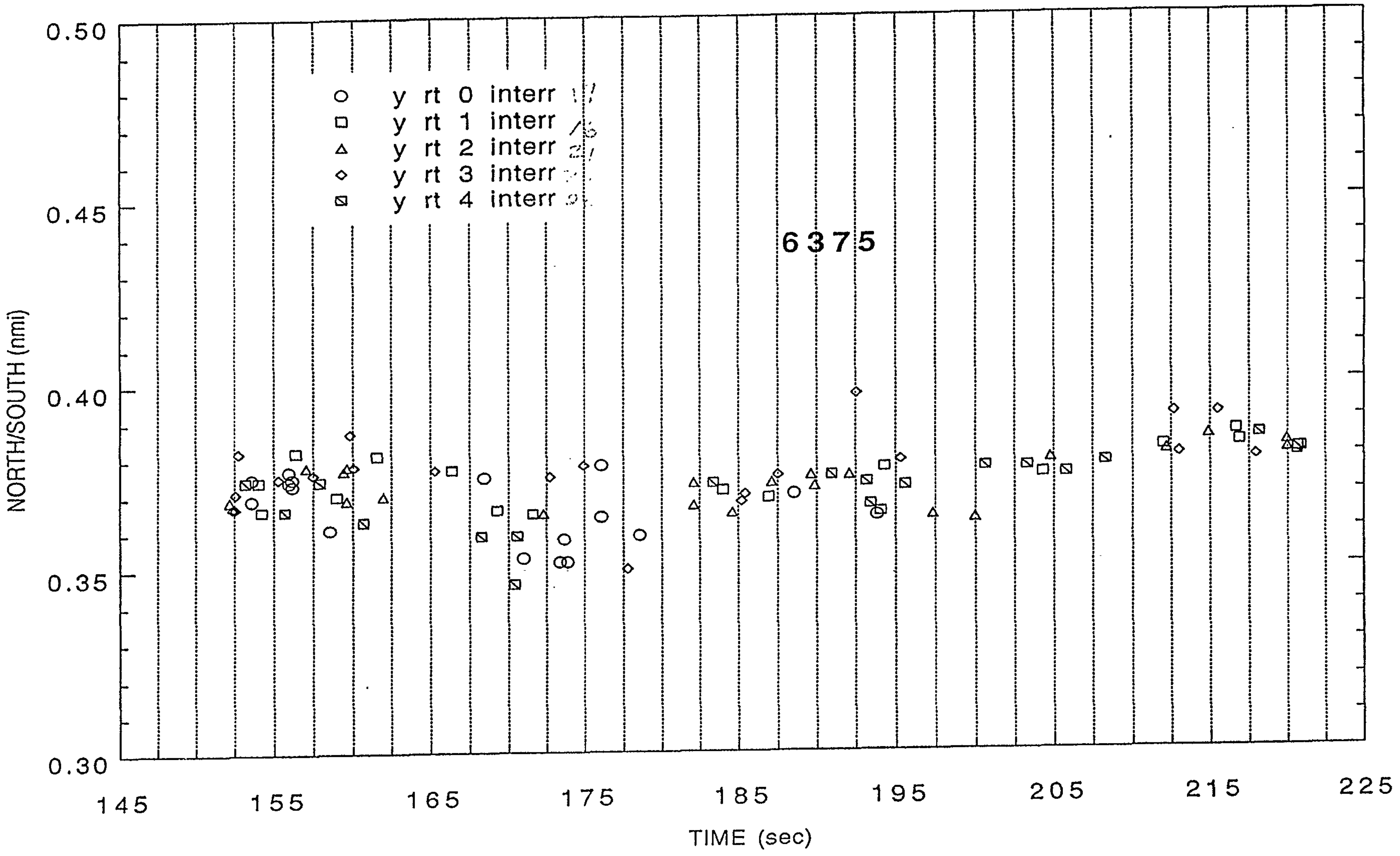


Figure 5-22. Eighty seconds of y Positions vs Time Showing Interrogation RT for Target 6375.

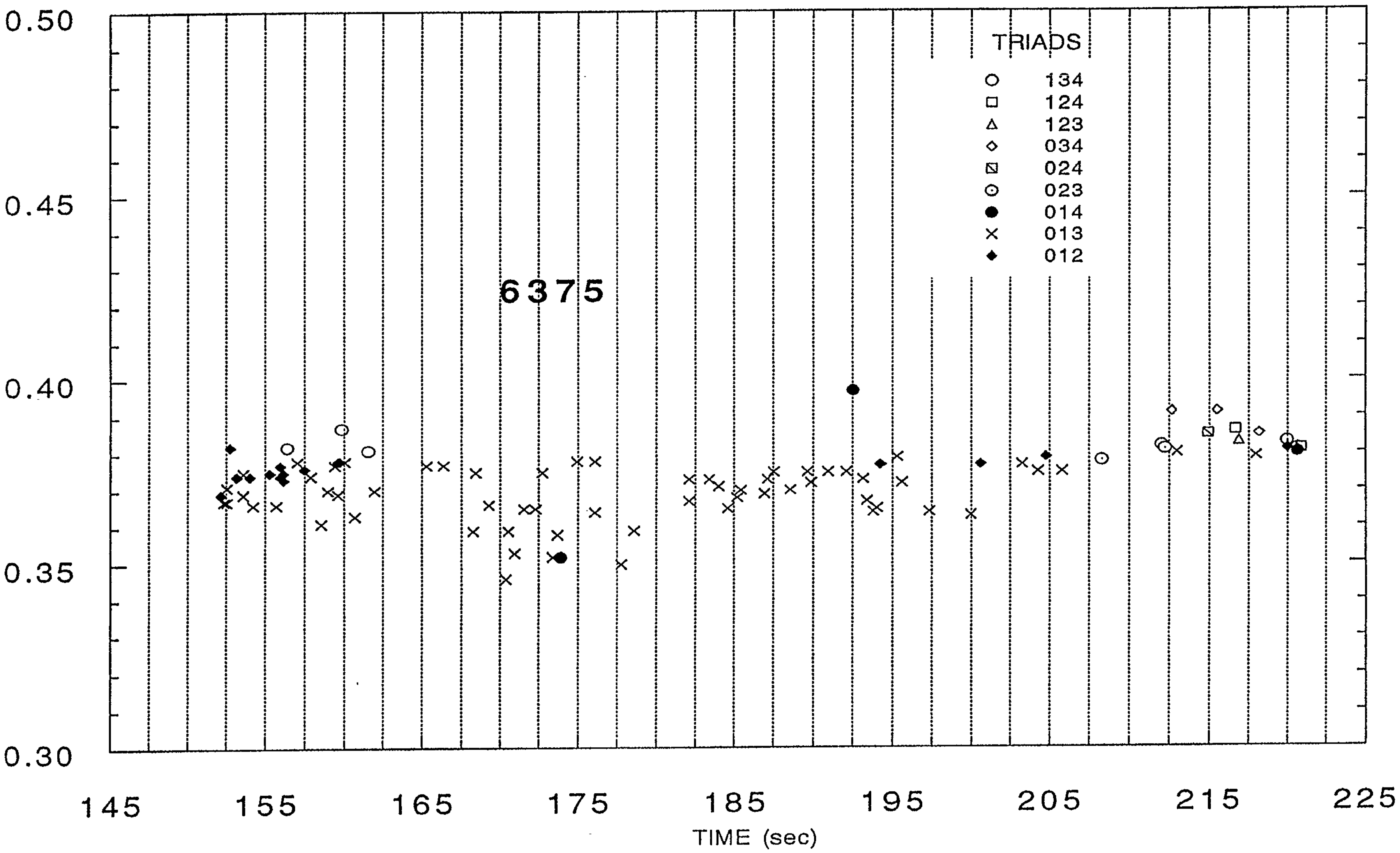


Figure 5-23. Eighty seconds of y Positions vs Time Showing RT Triad for Target 6375.

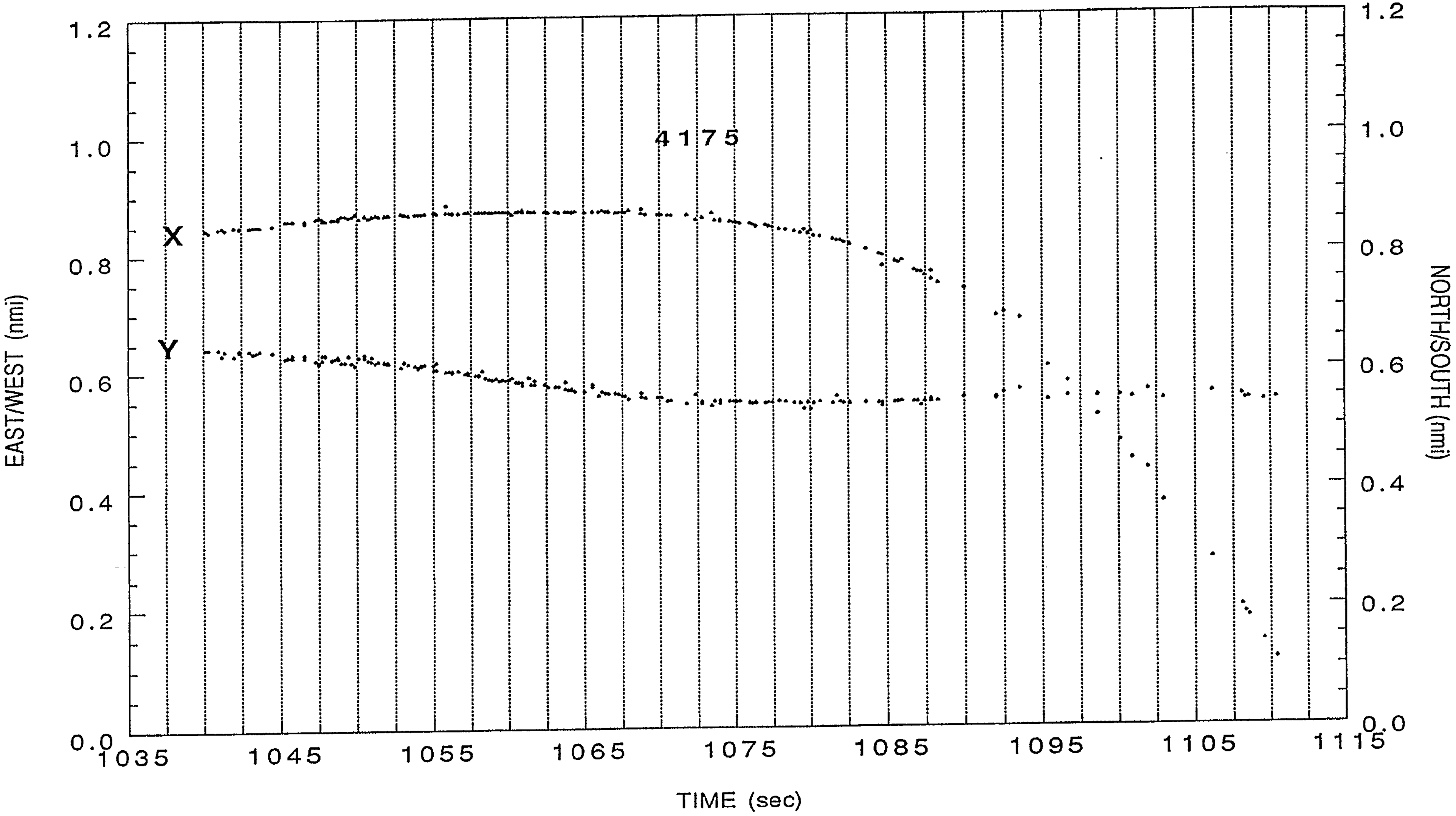


Figure 5-24. Eighty seconds of x,y Positions vs Time for Target 4175.

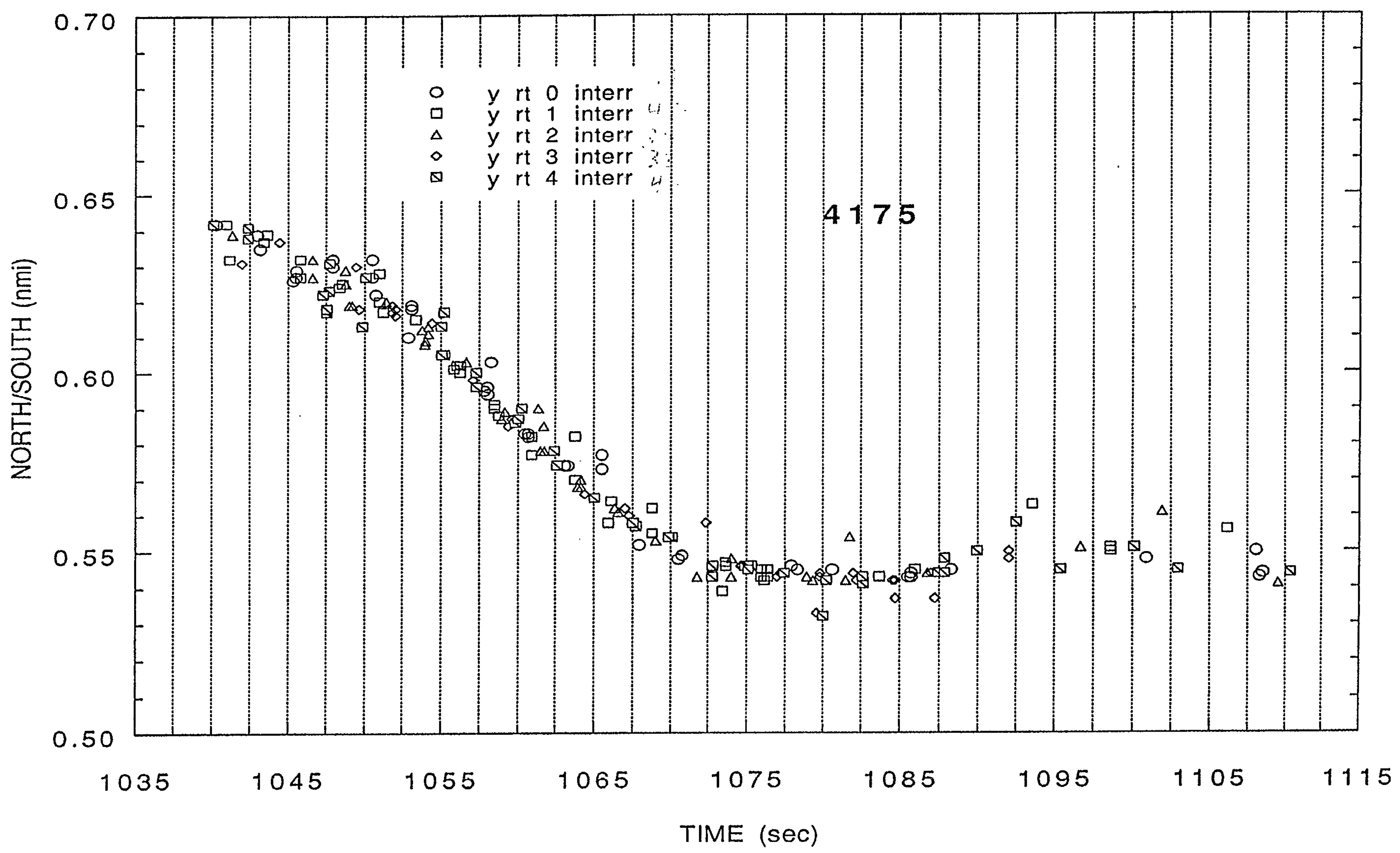


Figure 5-25. Eighty seconds of y Positions vs Time Showing Interrogating RT for Target 4175.

6. SUMMARY AND RECOMMENDATIONS

6.1 SUMMARY

The overall conclusion of this work is that technology for providing ID both on controller displays and on tracks to support surface automation functions is available and does not require any additional aircraft equipage. A multilateration system which functions with ATCRBS transponders, current TCAS/Mode S equipage (which is the dominant equipage at major US airports), and future TCAS extended squitter equipage can be developed today and fielded for operational application at major airports in a few years. The system architecture should differ somewhat from the CAPTS equipment used to support the experiments reported upon in this document to provide improved whisper shout performance.

6.2 RECOMMENDATION FOR ADDITIONAL TESTS

The development/deployment effort for obtaining an operational multilateration system will require additional testing of whisper shout while the development of the operational system is underway. The tests should focus on measuring the probability of interrogating for and receiving single replies instead of reply pairs. Whisper shout sequences should be refined in terms of their bin widths, step advances, and dynamic range. The utility of using range data to improve track update rate and to resolve ambiguous solutions should be investigated. Such testing could be conducted in a 3-month period using CAPTS-like equipment with software and equipment reliability problems corrected and with additional instrumentation and recording on the R/Ts to permit examination of individual reply data. Such instrumentation was used in Atlanta for diagnosing R/T problems. The equipment should include a functioning playback capability so that reply correlation, tracking, calibration, and other algorithms can be refined.

In order for whisper shout to function, ATCRBS transponders must be in the normal operating mode when on the airport surface, not in standby. At present pilots or weight-on-wheels switches place transponders in the standby mode. This was originally mandated to prevent the possibility of mainbeam replies from surface transponders (or sidelobe replies if sidelobe suppression in not fully effective on the surface) from garbling replies from nearby aircraft on approach, landing, missed approach, or takeoff.

The Atlanta experience indicated that the small numbers of ATCRBS transponders that were inadvertently operating on the surface apparently did not cause problems for the controllers, either because the Mode S beacon's sidelobe functions and reply decoding were effective, or because the replies that may have been elicited did not impair the controller's ability to perform their functions. The effect of these inadvertently operating transponders on TCAS has not been fully investigated, but TCAS upgrades to handle surface aircraft without overloading the system are already planned.

Another issue that needs examination is the impact of a handful of active ATCRBS transponders on a major airport when the Mode S SSR beacon interrogator is functioning in Mode S backup mode (sliding window) or when an monopulse Mode S beacon interrogator of the type planned for the ASR-11 is in use. Also, studies of the impact of a similar number of transponders at smaller airports with older beacon interrogators needs to be examined.

6.3 RECOMMENDED ALGORITHMIC ENHANCEMENTS

The testing conducted under this effort indicated a number of areas where the system performance could be improved by algorithm refinements, as described below. In each case, time and equipment problems, and the unavailability of CAPTS algorithms imbedded in a functioning playback facility, precluded such studies during the Atlanta activities.

a. Utilization of replies with bit errors. Multilateration positions can be computed for subsequent tracking without requiring that three R/Ts see the same reply, one decoding the Mode S reply perfectly and the other two decoding the Mode S ID within 7 bits. This is because the raw input to a multilateration computation is actually two time of arrival differences. If time of arrival differences were tracked independently versus time, including a ID constructed from past history for each pair of R/Ts, then a position could be computed from two smoothed and extrapolated differences. Also, a further examination should be conducted on what type of flawed reply was acceptable. Ideally, preambles with no associated data bits would be acceptable. The Atlanta experiment allowed up to 7 Mode S ID bit errors, and up to 3 ATCRBS code bit errors.

b. Bias removal. Lincoln Laboratory studies indicate that accuracy improvements could be obtained by methods to detect and compensate for position dependent biases and possible biases amongst R/T triads. Obviously, one should first work on obtaining excellent survey data on R/T position and height.

c. Other solution methods. Lincoln Laboratory made preliminary investigations of multilateration solution methods that make optimal use of the R/T heights, and target height when it can be observed from Mode S fruit replies or ATCRBS Mode C replies. In addition, methods to form improved position estimates when a reply is seen by more than three R/Ts should be implemented.

d. Clock bias and drift estimation. Lincoln Laboratory studies indicated that accuracy can be enhanced by improved methods using the calibration replies from the reference transponder. The CAPTS 100 MHz oscillators exhibit frequency drifts which could be compensated for more completely than was observed during the Atlanta evaluations.

e. Tracking. Improvements in eliminating outlier and spurious positions are also needed. In this regard, an area where major improvements are necessary is to identify and suppress multilateration positions that are computed as being on the airport surface when the real aircraft position is well away from the airport in distance and altitude. This problem was seen for aircraft taking off; the system tracked them for several miles as they left the airport and then the track would reappear on the surface.

f. Track fusion. The importance of good beacon tracks is lessened when the data are used in conjunction with ASDE derived track data. Here the key issues are to associate the multilateration ID tag with an ASDE track and to fill in ADSE coverage gaps. R/T siting should be such that holes in multilateration do not overlay ASDE coverage gaps. Both systems are susceptible to multipath, but whereas ASDE multipath causes false targets, the primary effect of multilateration multipath is to produce coverage gaps. Occasionally multilateration multipath may cause false positions, but they would not be the same false positions generated by ASDE.

The area of correlating multilateration and ASDE position measurements needs attention for several reasons. First, if the long term mode of operation of the system is to be extended squitter, then one would likely consider deploying a sparse multilateration system with fewer R/Ts and poorer coverage. How good does the coverage need to be if it is complemented with ASDE data? Should R/T siting criterion take into account providing good coverage where ASDE only tracking is known to be problematic; i.e. where aircraft come in close proximity?

g. Adaptive whisper shout sequences. The whisper shout sequences briefly utilized in Atlanta were time invariant and round robin amongst the R/Ts. Overall reply efficiency could likely be improved by sending more interrogations from some R/Ts than others, by selecting the sequence and levels based on the runway configuration in use, and possibly by adapting portions of the sequence to the positions of tracks on the surface; i.e., having a track while scan type of sequence.

h. Use of error correction on Mode S replies. Current generation TCAS equipment does not implement Mode S error correction of the type used in the Mode S ground sensors. Neither do they implement improved error detection developed by Lincoln Laboratory and under consideration for next generation TCAS. These techniques are of most use for coping with overlapped ATCRBS replies, but a brief study of the applicability to multipath induced error should be conducted to determine if it can reduce the number of R/Ts required for either short squitter multilateration or extended squitter.

APPENDIX A - CAPTS ASSESSMENT

A.1 SQUITTER RECEPTION AND BIT ERRORS

Initial CAPTS testing indicated that the severe multipath environment predicted for Atlanta was indeed present and frequently caused bits to be in error in the received messages. It was decided that for multilateration processing of target data and for time processing of reference transponder data, Mode S data with several address bits in error should be allowed. Cardion implemented software to allow messages with up to 7 of the 24 address bits to be in error for replies used to update (not initiate) tracks. They also studied using different numbers of erroneous bits; these results are not reported herein. This feature significantly improved the blip/scan ratio for updating multilateration tracks and tracking time drift using the reference transponder. A similar technique was used for tracking ATCRBS targets using whisper shout.

The Mode S 1090 MHz waveform uses pulse position modulation (PPM) to send bit information. Data from the CAPTS system indicated that "1" bits were more likely to be in error than "0" bits, perhaps due to a bias in the PPM decoding function. This was mitigated for the reference transponder by selecting a Mode S ID rich in "0"s (808080 in hex).

Some experimental data from the CAPTS system appeared to indicate that the probability of receiving a short squitter was less than that of receiving an extended squitter. The differences were small and may be associated with another anomaly uncovered with respect to short squitter transmission rates from Mode S transponders. The Mode S specification states that the average rate of short squitter transmissions should be once per second. Data measured at Atlanta indicated that some transponders squittered at rates which exceed the specification by 10 to 20%. Some tests were conducted on the test transponders used to estimate probability of squitter detection, but they were not exhaustive and some anomalies in transmission rate may have been present which influenced the data. In any event, whether the problem was in the transponder or reply processor, it did not have a significant impact on the results of the testing program.

A.2 TIME OF ARRIVAL MEASUREMENT

The time of arrival measurement technique used in CAPTS was a second generation implementation which measured the time of arrival of the point on the leading edge of a pulse that is 6 dB below the peak of the pulse. This method is insensitive to pulse amplitude, which is desirable, as was recognized by Bendix in their multilateration system in the 1970's. Data on the implementation and performance of the hardware were provided by the contractor's proposal, however, are not included in this report because of its proprietary nature.

The hardware measured the TOA of every 1090 Mhz pulse satisfying a pulse width criteria; this circuitry worked quite well. The dominant cause of TOA errors appeared to be associated with other hardware and software in the system. The first cause of software-induced TOA errors was the clock drift estimation algorithms. The second TOA problem was associated with hardware and software for associating the fine 100 MHz TOA pulse data with the coarse TOA reply data from the ATCRBS and Mode S reply detectors. The first association problem was caused by features of the Collins reply detectors which were not factored into the design of the Cardion equipment. The problem caused the pointer from the coarse TOA data to the fine TOA data to drop a count every time a reply was received. Therefore, in a high fruit environment as in Atlanta, the equipment performed less well than at Atlantic City. The result of the problem was that after several replies were received, fine TOA of the wrong pulse would be associated with the reply from an R/T thus adversely impacting the accuracy of the multilateration position estimate. The body of the report shows track position jumping when an RT TOA slips from the first preamble pulse to the second. The work around to this problem was to frequently reset a clock thereby zeroing the offset. A better fix would be to change the code in a PLD in the Collins hardware.

The TOA course/fine association software had a second problem which was uncovered in whisper shout testing. In the high fruit environment experienced during the daytime at Atlanta, the interrupt driven non reentrant defruiting software discussed in the following section, often ran behind time which allowed the pulse TOA buffer to be overwritten. Thus, data were lost and/or corrupted and initially led some evaluators to an erroneous conclusions as to the viability of whisper shout on the airport surface.

The CAPTS equipment provided 32 bits of 100 MHz TOA data; the 16 LSBs were updated in hardware and were subjected to the reset operation just described. The 16 MSBs were software bits which were updated via an interrupt. Unfortunately, the interrupt had a low priority so the 16 MSBs were not always updated in a timely manner. This deficiency complicated the assessment of whisper shout reply data. Laborious graphically-assisted hand analysis was necessary to determine which replies came from which whisper shout interrogations.

Correlation using only TOA of ATCRBS replies from the R/Ts could probably be performed if 32 bits of 100 MHz TOA's were available, because the ambiguity time (42.9 seconds) is sufficiently large. Such correlation would be quite difficult for the 655.36 μs ambiguity time corresponding to only 16 bits. This is because the ambiguity time is about one third of the approximate 2 ms spacing of whisper shout interrogations. The 655.36 μs ambiguity would also greatly complicate time of arrival correlation of Mode S preamble detections. Time of arrival correlation would be helpful for squitters in which the ID is severely corrupted due to multipath.

A.3 COMMENT ON WHISPER SHOUT

The testing done in Atlanta with CAPTS employed a Mode A/C pair of interrogations at each whisper shout level. As mentioned above this was done for expediency purposes. A consequence of using this approach is that the probability of receiving a reply pair data in the master work station is lower than that of receiving a single reply. The experimental results indicated that the pair blip/scan was lower than anticipated, but still sufficient to support tracking; particularly when replies with a few bits of code error were allowed to update tracks. Insufficient data were acquired and analyzed to enable us to quantify the various mechanisms causing the lower-than-anticipated reply pair probability; e.g., R/T or transponder interrogation failures, transponder reply failures, failures in the reply reception processing (see Section A.4), and failure of the R/T software. Equipment problems, multipath, and fruit all contribute to lowering the reply probability and additional testing with properly functioning equipment should be performed to better understand this issue. These data will enable improved whisper shout sequences to be tailored to the surface. Also, it will provide insight as to the performance to be anticipated when single interrogations are used vs a Mode A/C pair. Note that we recommend

Mode A on the surface whereas TCAS uses Mode C in the air because the altitude data of surface vehicles is quite similar.

A.4 REPLY PROCESSING AND WHISPER SHOUT REPLY DEFRUITING

CAPTS employs Collins ATCRBS and Mode S reply processors. The Mode S processor is integral to the Collins TCAS. Like other manufacturers of TCAS units, the processing identifies bits likely to be in error but does not attempt to correct the errors using the features designed into the waveform and utilized by ground based Mode S sensors.

The ATCRBS processor in the TCAS unit is not used since TCAS runs in either ATCRBS or Mode S mode, but not both simultaneously. Therefore, CAPTS employs an ATCRBS reply processor external to the TCAS unit. Cardion reported that the ATCRBS detector has a feature whereby it performs poorly on weak replies. The problem can be corrected by using "reply enhancement" software. Cardion originally had software to perform this function in the R/Ts; unfortunately, it had to be stripped out to cope with the fruit environment.

The R/Ts perform the defruiting function for whisper shout by looking for a reply pair with the correct spacing. The ATCRBS code and TOA data are then transferred to the MWS. Analysis of early whisper shout data indicated that the system often worked in the evening but almost never worked during the daytime when considerably more ATCRBS and Mode S activity was present at 1090 MHz. The problem was traced down to the inability of the 68020 software to perform the defruit operation in the presence of fruit. It ran behind time such that the fine TOA data in the buffer were overwritten; thus, precise TOA data for a totally different reply were associated with ATCRBS replies which significantly reduced the likelihood of finding reply pairs with the correct time spacing let alone performing multilateration on the resultant data.

On 20 September 1995, whisper shout tests were conducted using an ATCRBS transponder mounted on a van and driven along the north side service road. The vehicle was not tracked reliably. The whisper shout interrogation and reply reception performance is summarized for 200 seconds of data in the Table A-1. In addition, 4 ATCRBS targets of opportunity were tracked and they had per second update rates of .24, .17, .24, and .28. Both Lincoln Laboratory and Cardion agreed that CAPTS whisper shout needed further refinement.

Table A-1. Whisper Shout Efficiencies

Performance per WS Sequence	Delta	Ford	Stouffer	Region	Term.C
Interrogation Efficiency	0.00	0.61	0.65	0.00	0.48
Interrogate/Receive Efficiency (Round Reliability)	0.00	0.39	0.48	0.00	0.18
Receive Efficiency (To replies elicited by other R/Ts)	0.29	0.44	0.36	0.00	0.23

Cardion made CAPTS modifications and testing was resumed on 18 October 1995. Again, whisper shout interrogation and receive efficiencies were agreed by both Cardion and Lincoln Laboratory to be poor.

After more development, tests were conducted on 26 October. Unfortunately, it was quickly revealed that several of the R/Ts did not perform whisper shout at all for 50% of the time (specifically, whenever the MSB of the 32 bit time of arrival clock was 0, which is half the time).

Eventually, CAPTS was announced as being ready for final whisper shout testing the week of 20 to 24 May 1996. During this week, additional problems were discovered and repaired, including a fix to streamline the R/T defruiting software and deleting the code enhancement associated with weak replies along with unnecessary Mode C processing. The positive result is that sufficient data were taken to document that whisper shout clearly works on the airport surface. The downside is that we do not have a clear picture of how well it works since the detector processing was sub par because of the deletion of the code enhancement.

In addition, on 23 May, three versions of the MWS software were under consideration for use during the whisper shout tests: Versions g, h, and i. Version g was the current "baseline" for which the most experience existed. Version h, included a capability to average the TOAs of the four Mode S preamble pulses, "cleaned up" the reference transponder offset calculation, fixed a bug in the ATCRBS cluster algorithm, and intended to fixed a bug in the whisper shout interrogation commands. Unfortunately, the latter fix actually caused interrogations to stop, so both parties agreed that Version h was eliminated as a candidate. Version i fixed the whisper shout interrogation problem with h, and was recommended by Cardion. In the end, data were taken with Versions g and i. The whisper shout evaluation in this report is based on the data taken with Cardion's recommended Version i, in deference to their recommendation. As an additional attempt to give the CAPTS system the best opportunity to demonstrate good performance, data were taken by Lincoln Laboratory between one and two o'clock in the morning, on the last day during which the program could support such tests, so that the interference on the uplink and downlink channels would be minimized. The Mode S operation was also turned off to preclude any possible incompatibilities between ATCRBS and Mode S operation that might inadvertently have been introduced in the brand new Version i. Finally, the whisper shout sequence and update rate were chosen to give CAPTS the greatest possible opportunity to exhibit successful performance.

During the data analysis, it was discovered that Version i did not record the most significant 16 bits of the 32 bit times of arrival for the Mode S squitters emitted by the reference transponder. This problem had never before been observed. Lincoln Laboratory recovered the bits by utilizing a hand chosen set of ATCRBS replies from targets of opportunity for each of 200 whisper shout sequences during 100 seconds of data. Further compounding the whisper shout data analysis was the fact that the recorded reply data did not include a field indicating which whisper shout interrogation within the sequence caused the reply. In principle, the 32 bit time of arrival could be used to compute the level, but this method did not work because the most significant 16 bits are counted in an R/T interrupt routine, which was observed to be as far as 10 interrupts behind, corresponding to over 6 ms, making the computation of whisper shout level very unreliable. To overcome this problem, Lincoln used spread sheet and graphical correlation, by hand, of all 5,200 whisper shout interrogations in a 100-second period of time to determine which replies went with which interrogations.

A.5 COMMUNICATIONS BETWEEN R/Ts AND MWS

Communications between the R/Ts and MWS was accomplished by spread spectrum RF modems provided by the FAA Hughes Technical Center. Although they did cause problems, there were instances where certain R/T problems were wrongly attributed to the modems. Although these modems have much lower life cycle costs than leased lines, we strongly recommend that leased lines be seriously considered in any operational system; particularly since other users of the uncontrolled spectrum will likely appear and disappear over time such that link performance will vary with time.

A.6 SUMMARY R/T ASSESSMENT

With the exception of the RF modems, the individual R/T components generally worked fine. Most problems were associated with inadequate integration of the components, expedient packaging, loose interconnect cables and pollen in the air filters. Thus we strongly recommend that any operational system employ second generation R/Ts. Such units should overcome the integration problems associated with TOA pulse dropping and code enhancement. Furthermore, such systems should employ faster microprocessors capable of keeping up with the fruit rate and capable of providing accurate TOA MSBs.

The RF interconnect of the upgraded R/Ts should allow external attenuators to be placed in the transmit path alone. For the Atlanta tests, an attenuator was placed in the common receive transmit path; also the controlled attenuator in the TCAS unit was employed.

Finally, Lincoln Laboratory recommends that the overall architecture of the combined R/T and MWS system be changed such that R/Ts may be issued commands to be performed at specific times using their internal clock. This will permit whisper shout to employ single Mode A interrogations at each interrogation level vs the paired approach used for expediency purposes.

A.7 SUMMARY MWS ASSESSMENT

The MWS was a 486 PC running DOS and proprietary CAPTS software. We did not have insight as to all of the algorithmic details throughout the software evolution, but did identify areas where improvements appeared desirable. The first area involves the algorithms used for tracking R/T clock drift based on processing replies from the reference transponder. Second, the clustering algorithms should be improved and techniques should be developed to remove triad biases. Next, the use of whisper shout range data in addition to TOA should be explored. Finally, the need for algorithms to cope with the unreliable time data should be overtaken by the architectural change discussed in the previous section.

The original CAPTS multilateration algorithm was an iterative 2D approach instead of a closed solution. We briefly explored alternative closed form solutions and 2 1/2 D approaches to cope with the disparate heights of the R/T antennas and portions of the runways at Atlanta. Some additional work in this area appears desirable.

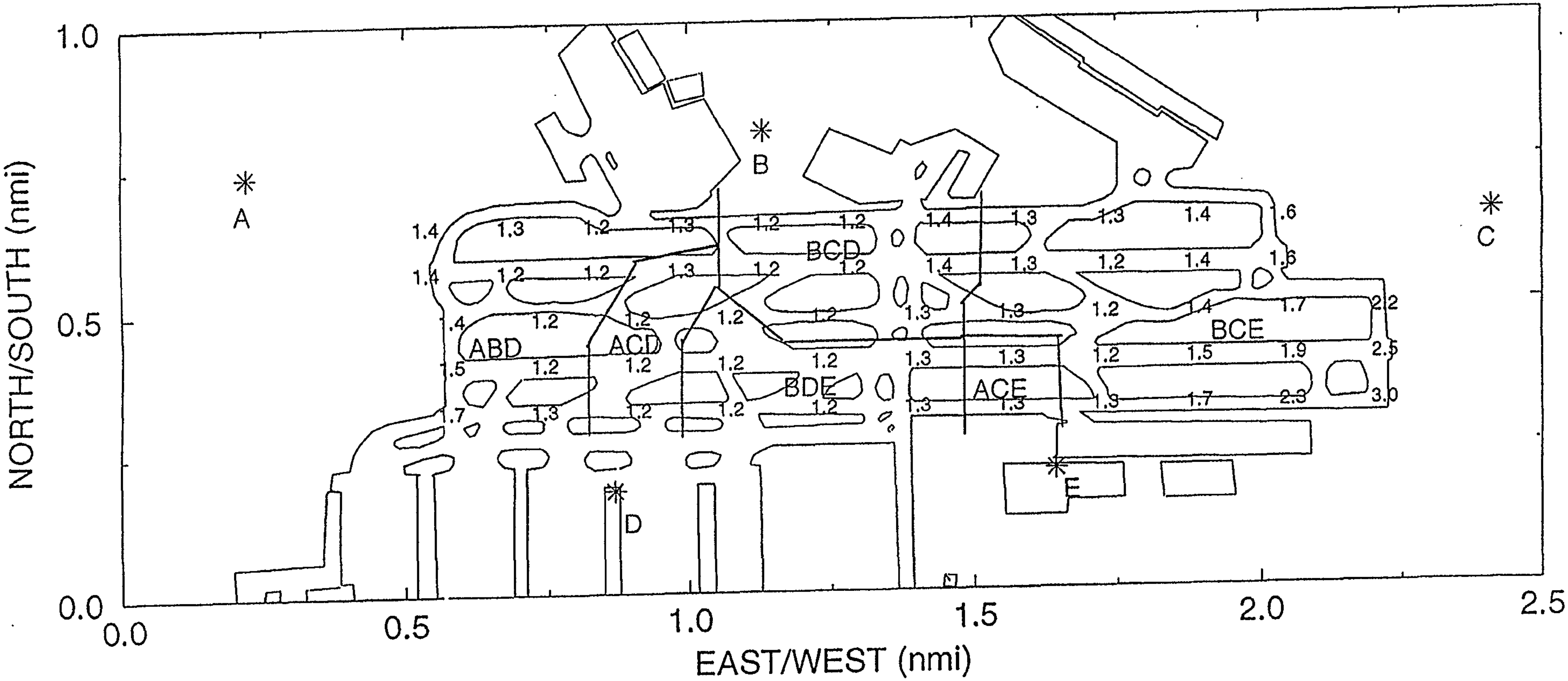
Multipath reply degradation led to the utilization of replies with errors in updating tracks. Additional work is desirable to determine how much error to allow; ideally only TOA on some replies is necessary to update a track. Cardion has performed some proprietary work in this area.

Tracking algorithms were continually changing throughout the course of the evaluation. Additional improvements appear to be realizable and techniques should be developed which utilize both more than 3 replies and fewer than 3 to update tracks. Algorithms to reduce possible inter-triad biases should be developed.

Finally, the MWS data recording software has some features which are extremely user unfriendly and should be changed to protect the sanity of the users. In particular, some uniformity of convention should be adopted regarding formats for ATCRBS replies. This problem coupled with the unreliable TOA MSB data from the R/Ts and overwriting of TOA data in the R/Ts greatly complicated the assessment of whisper shout performance.

APPENDIX B – GDOP

GDOP was evaluated on the north side of the Atlanta airport for the 5 R/T sites. Since there are five sites, there are ten possible triangles that could be used to compute the target position (assuming each site provided a TOA measurement). These results are shown in Figures B-1 to B-10. In general, triangles that have angles that are neither excessively obtuse nor acute have GDOPs of less than two in the central region. The GDOP slightly outside the triangle, in the direction along the perpendicular bisector of a side, can be reasonably well behaved. If 3D multilateration is implemented, then 3D GDOP will need to be evaluated. GDOP should be between 1 to 3 for acceptable performance.



A = Region
B = Stouffers
C = Ford
D = Terminal C
E = Delta

Figure B-1. Minimum GDOPs and associated RT triads.

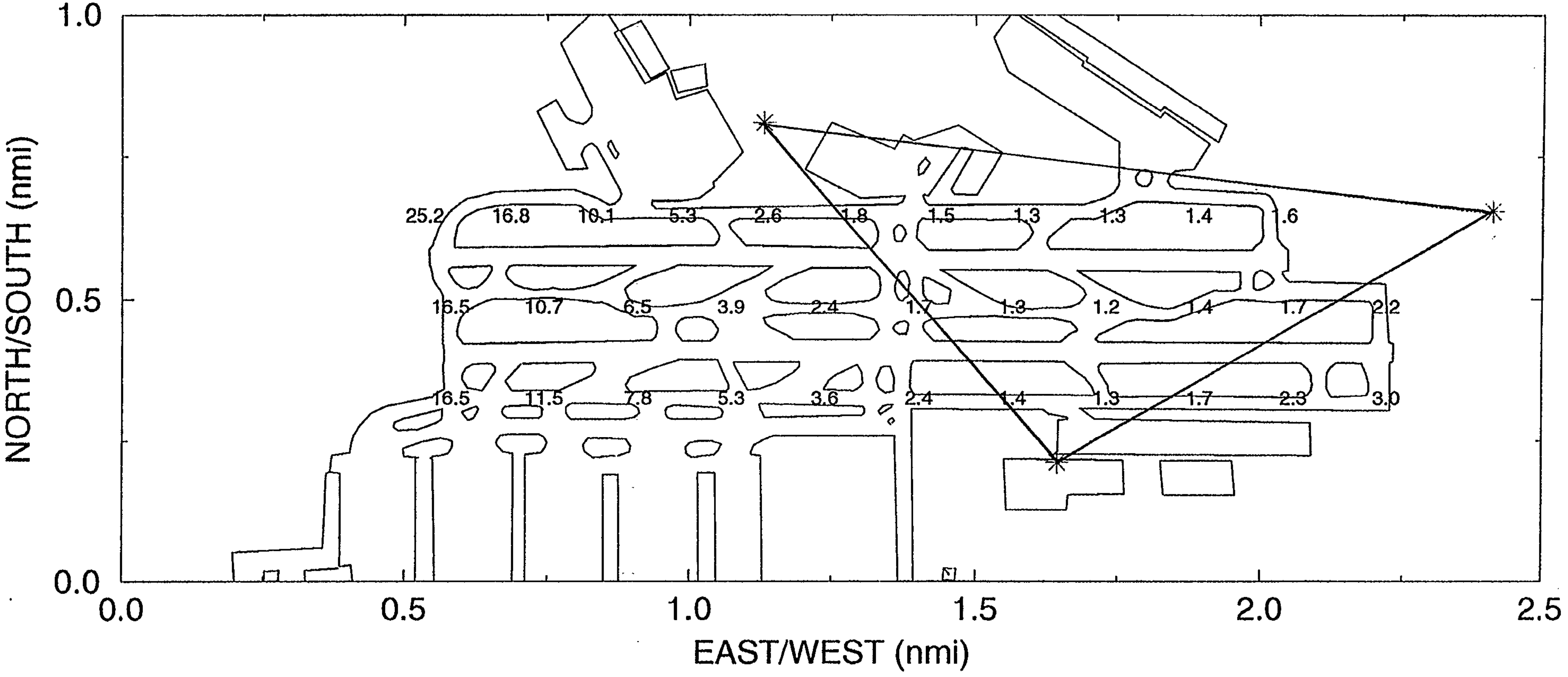


Figure B-2. GDOP for Delta, Ford, and Stouffers.

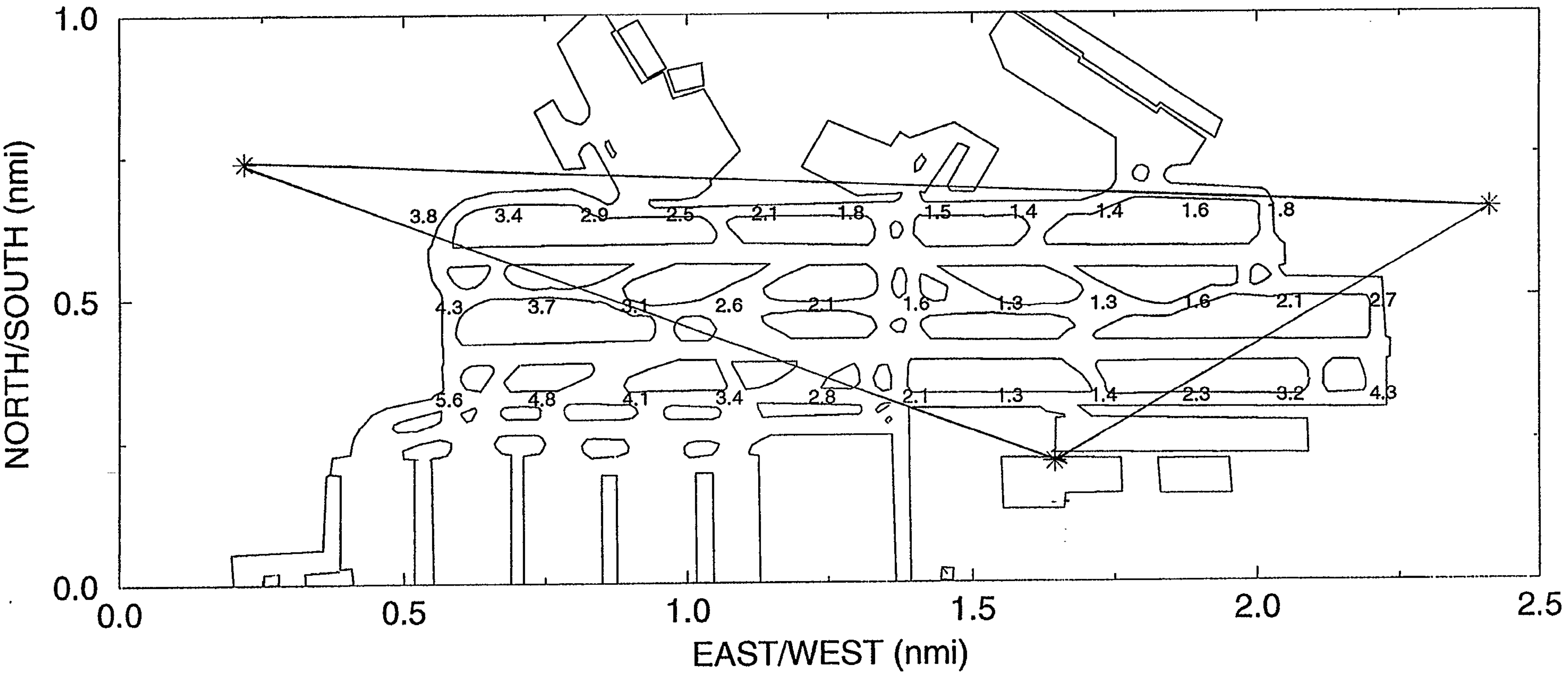


Figure B-3. GDOP for Delta, Ford, and Region.

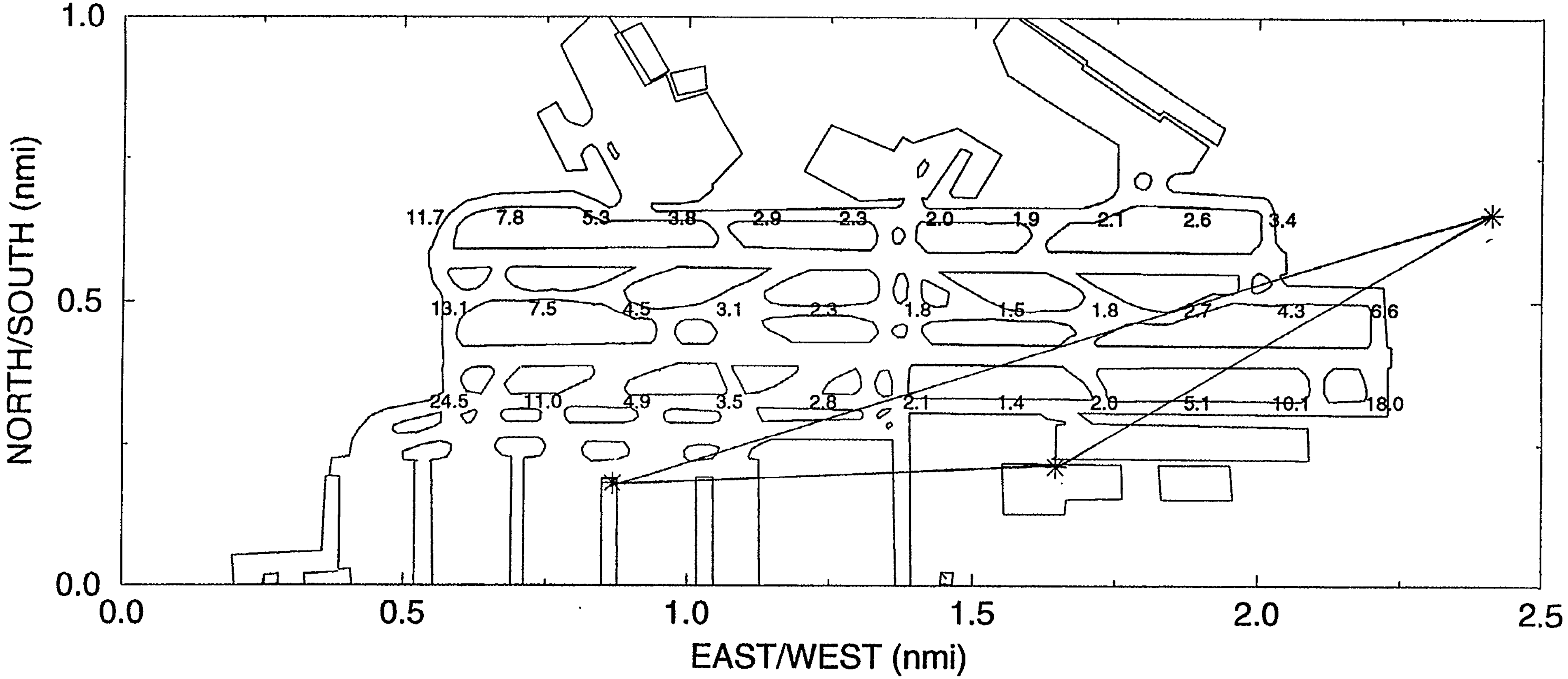


Figure B-4. GDOP for Delta, Ford, and Terminal C.

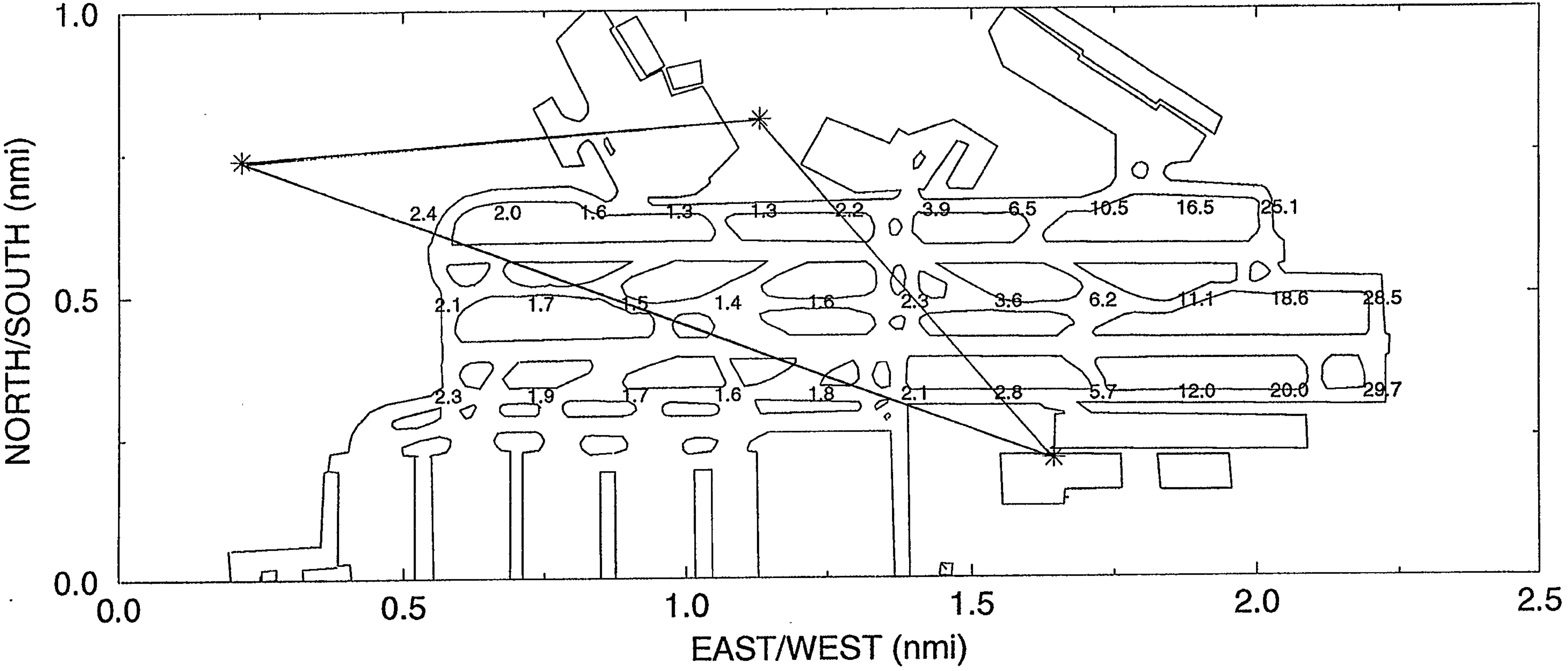


Figure B-5. GDOP for Delta, Stouffers, and Region.

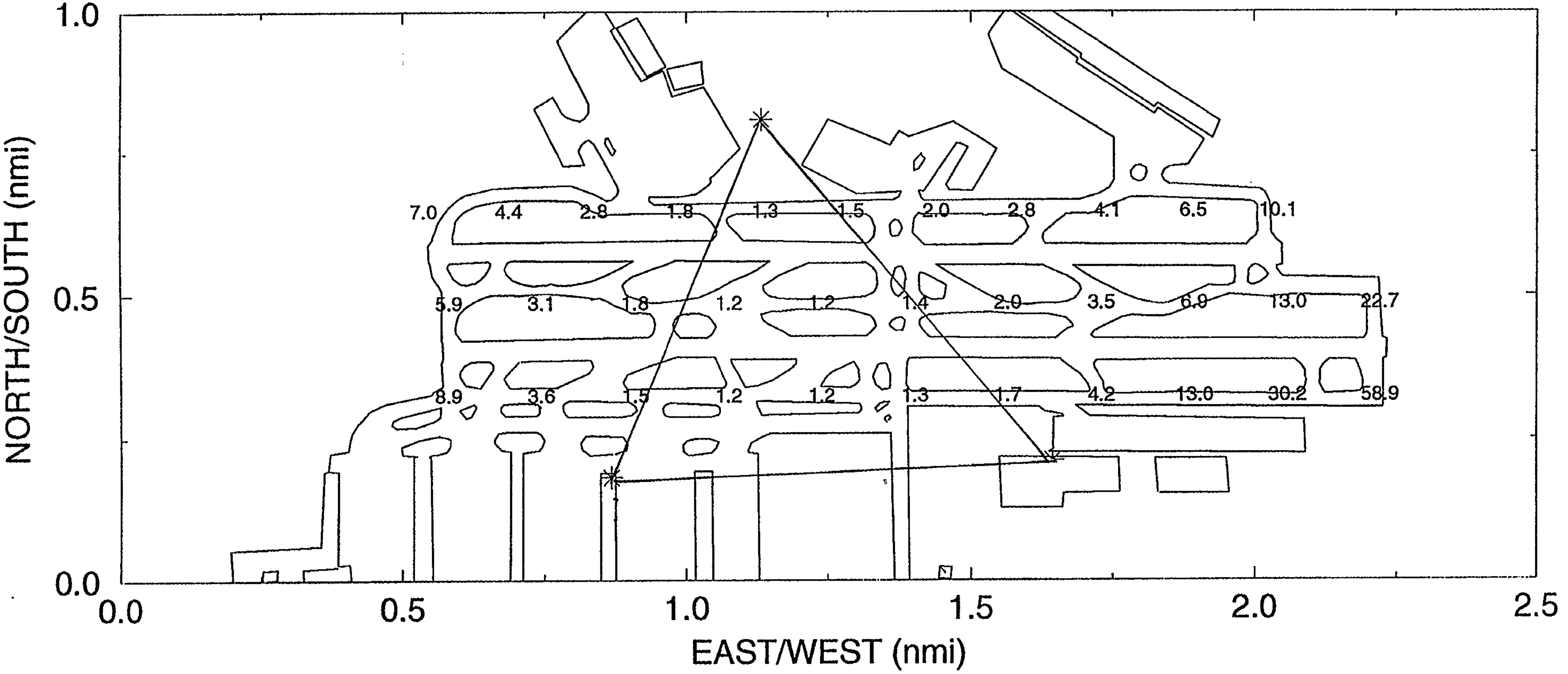


Figure B-6. GDOP for Delta, Stouffers, and Terminal C.

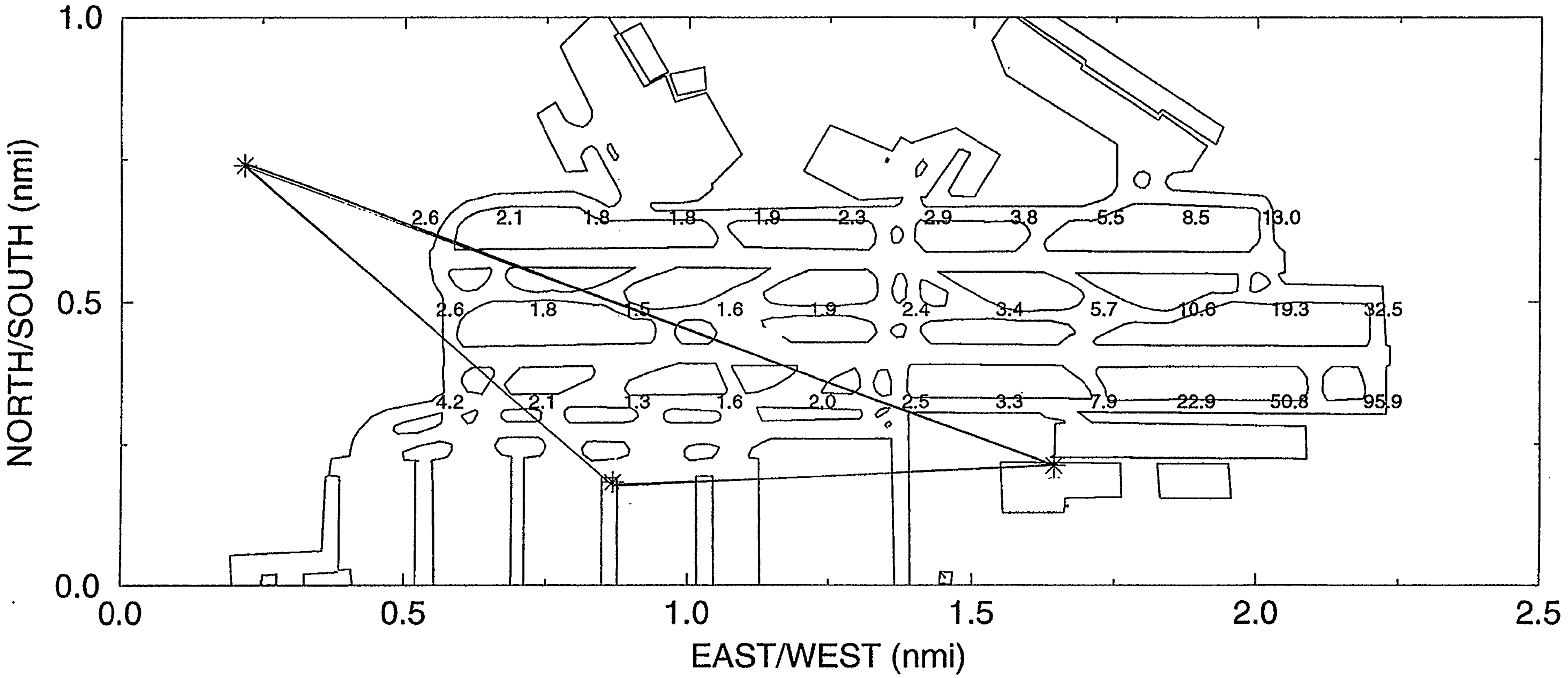


Figure B-7. GDOP for Delta, Region, and Terminal C.

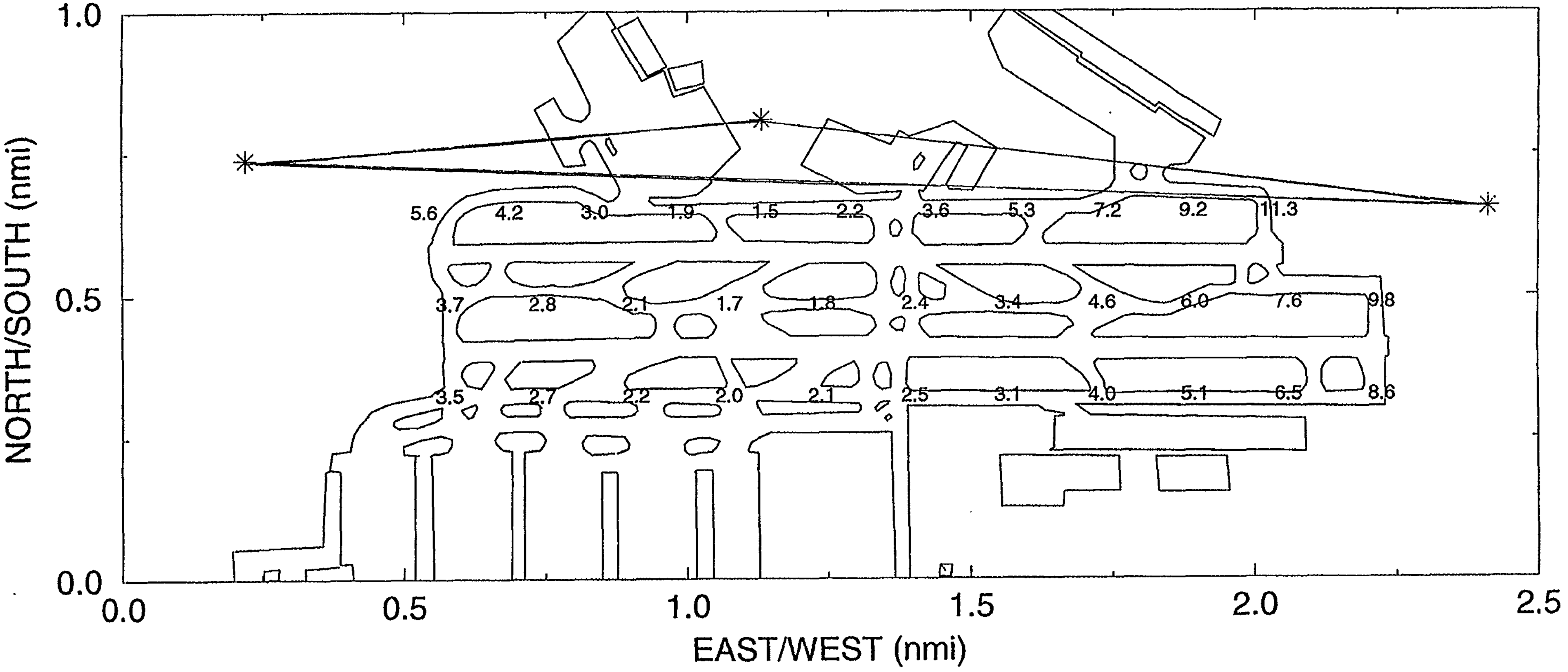


Figure B-8. GDOP for Ford, Stouffers, and Region.

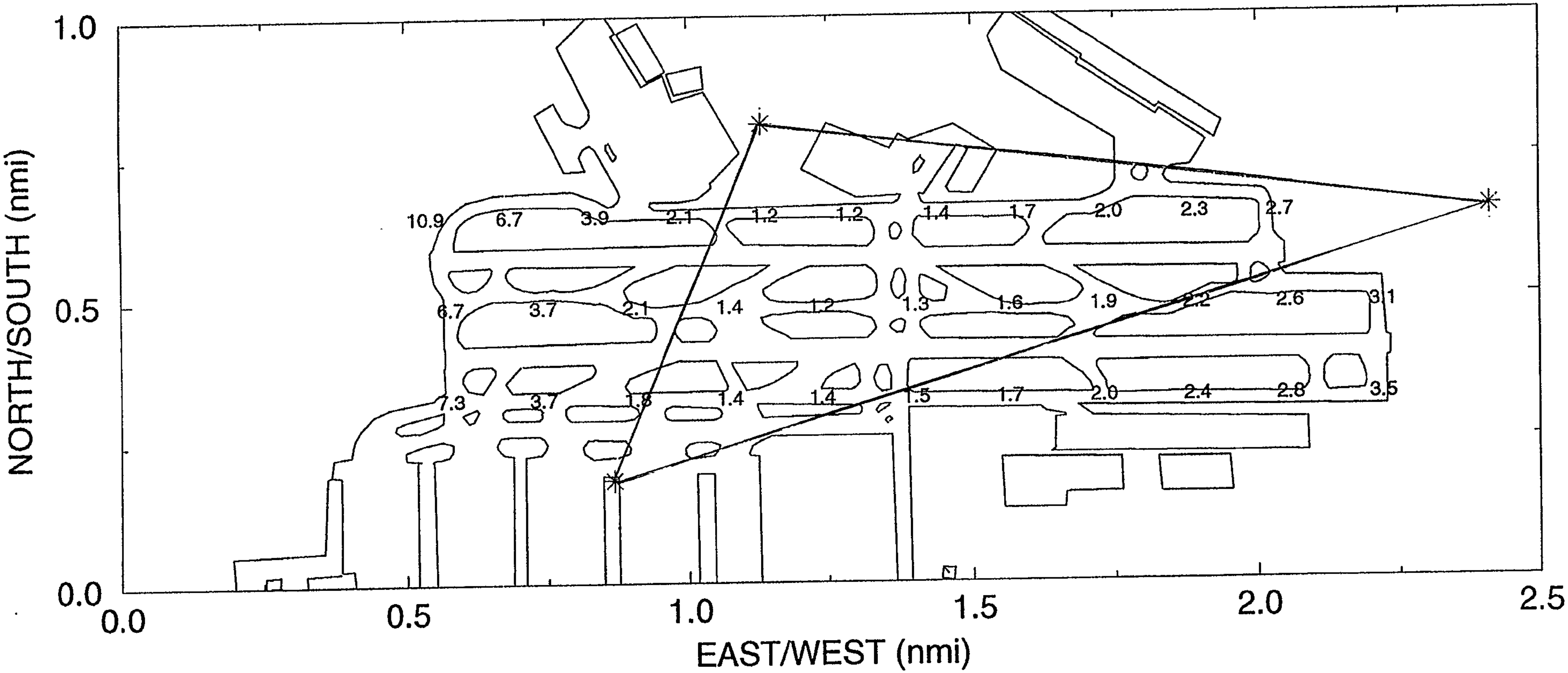


Figure B-9. GDOP for Ford, Stouffers, and Terminal C.

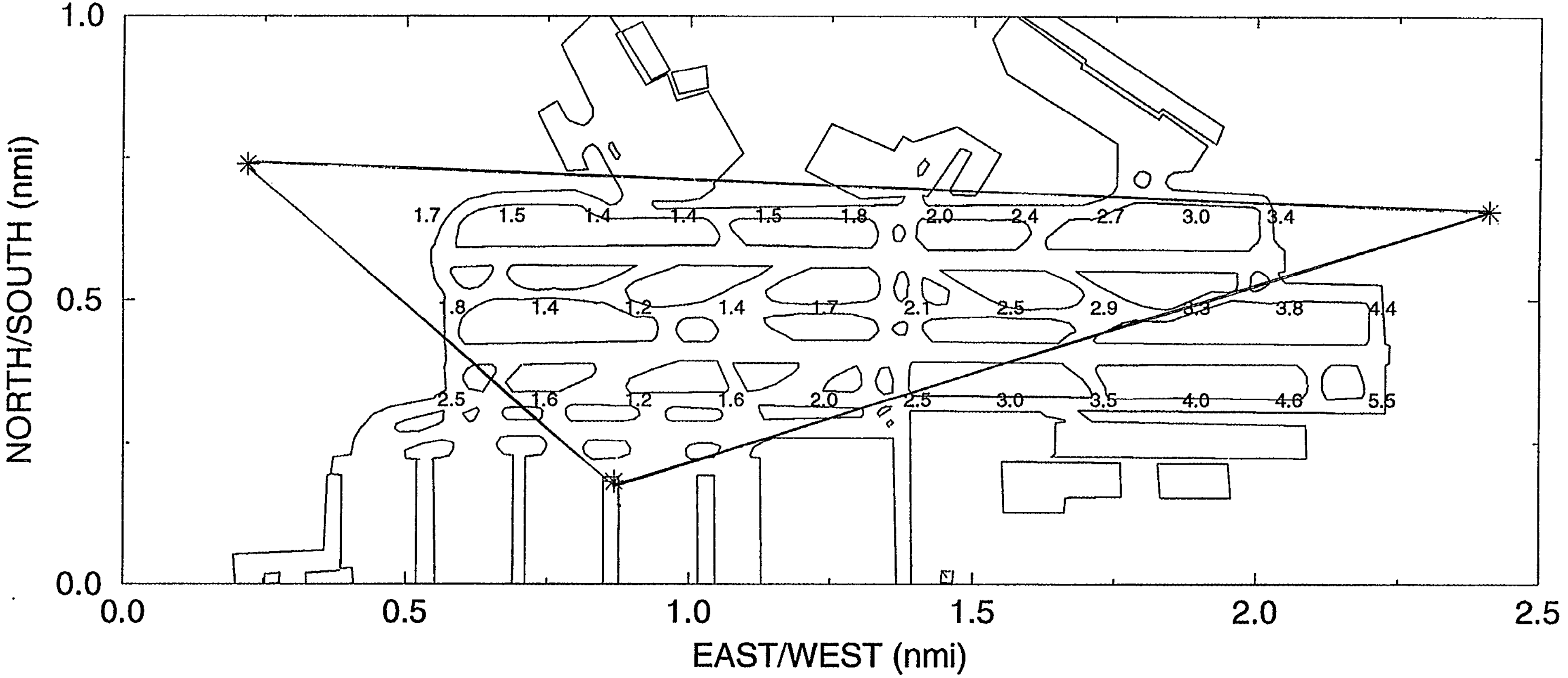


Figure B-10. GDOP for Ford, Region, and Terminal C.

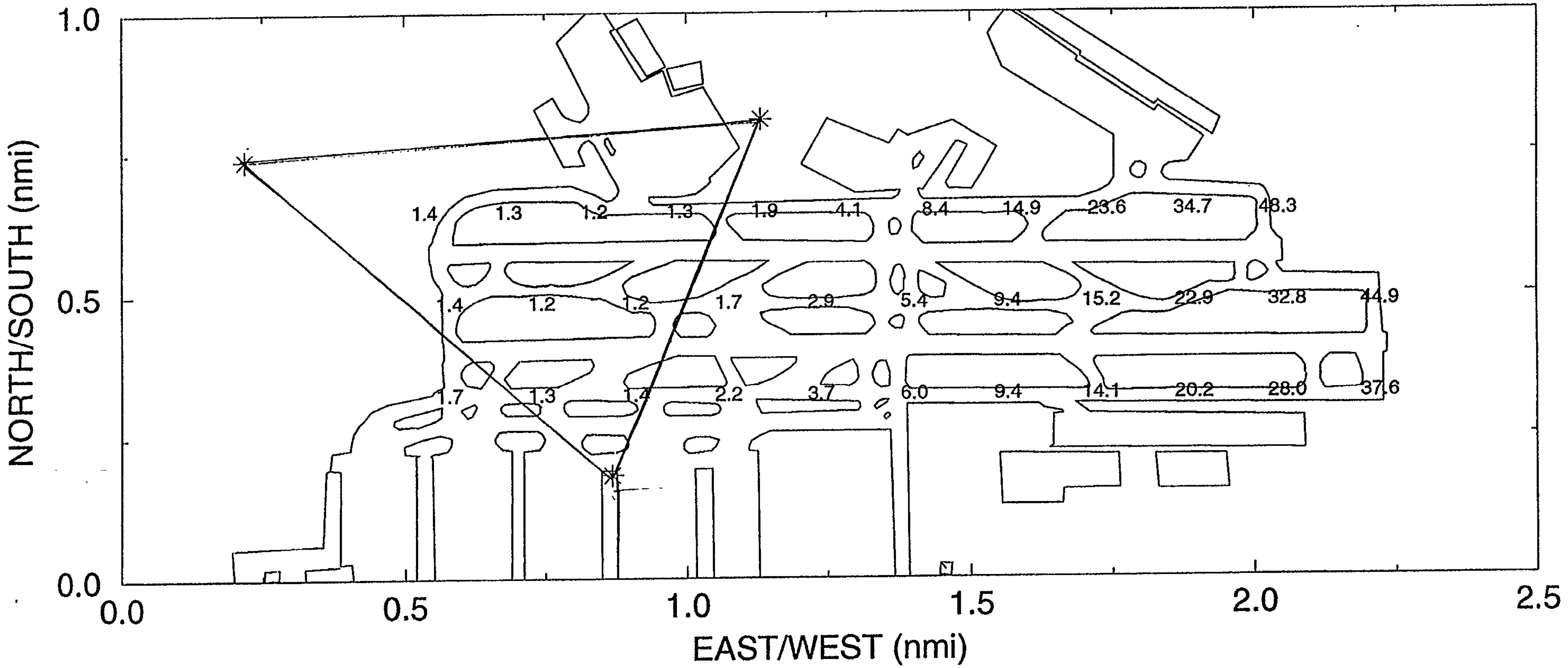


Figure B-11. GDOP for Stouffers, Region, and Terminal C.

APPENDIX C - ACCURACY INVESTIGATION

This Appendix describes algorithm enhancements investigated by Lincoln Laboratory on the test vehicle data collected on 18 May 1995. These investigations were performed independently of the Cardion MWS because the MWS did not have a reliable means to reprocess raw R/T reply TOAs and because the Cardion software was not available to modify and experiment with. The results of these investigations highlighted various problems with the R/T and MWS processing and R/T site surveys.

Lincoln applied a smoothing filter that provided an estimate of the time of arrival offsets between the R/Ts, and the rate of change of the offsets. A closed form solution that took into account the heights of the R/Ts was used to compute the position of the test vehicle. For each squitter emitted by the SSV test vehicle, all possible positions were computed using the 3, 4, or 5 R/T receptions, as the case might have been. This would correspond to either 1 solution, 4 solutions, or 10 solutions. A plot of the positions was made for each of the possible 10 R/T triads, and an eleventh plot was made superimposing all triad solutions. The plots are shown in Figures C-1 to C-11 and are discussed below. The dots in the figures are about 30 feet in height (five dots across the 150-foot runway width). There is an obvious rotation of the tracks with respect to the map, which stimulated the joint effort of Lincoln and Cardion to ascertain the source of survey errors. It was found to be due to the Cardion translation of R/T site latitudes and longitudes using the U.S. Army conversion for eastern, instead of western, Georgia.

Figure C-1 (Delta, Ford, Stouffers). Within the triangle, the x and y spreads are 20 feet or less, corresponding to a standard deviation of less than 10 feet. At the far left, the x spread is 350 feet, as would be predicted by the GDOPs, which are 16.5. No attempt was made to develop algorithms to edit out the spurious positions in this or subsequent plots.

Figure C-2 (Delta, Ford, Region). Performance is good everywhere. This is encouraging, because this triangle is never the preferred on GDOP basis except in a small region by the Delta hangar.

Figure C-3 (Delta, Ford, Terminal C). Performance is good except at the left where the GDOP is about 15. There are several spurious traces, which are due to hardware errors in the R/T that report the TOA of the wrong preamble pulse in the squitter.

Figure C-4 (Delta, Stouffers, Region). Performance is good except in the upper right area were GDOP is from 10 to 25.

Figure C-5 (Delta, Stouffers, Terminal C). The performance is good except in the upper right where the GDOP is about 10. The performance is surprisingly good in the lower right, in front of the Delta hangars on runway 26L where the GDOP is 17. No explanation is available.

Figure C-6 (Delta, Region, Terminal C). The performance is good except at the far right, where GDOP plays a role, and in the region x = -.04, y = 0.4. The cause is not known.

Figure C-7 (Ford, Stouffers, Region). The performance is good considering the extreme obtuseness of the triangle. Despite the triangle shape, the GDOP is under 10 everywhere. What is not explained is the poorer than expected performance on the eastern side. This might be due to multipath corruption. This triad is never the first choice based on GDOP.

Figure C-8 (Ford, Stouffers, Terminal C). The performance is good everywhere.

Figure C-9 (Ford, Region, Terminal C). The performance is good everywhere, except at the eastern extremes.

Figure C-10 (Stouffers, Region, Terminal C). The performance is good except at the east, and north east areas, where GDOPs reach over 30.

Figure C-11 Superposition (all 10 Triads). The superposition plot indicates that the triads do not register. The most likely cause of these intertriad biases is survey errors. At this point, a recalculation of the x,y's corresponding to the surveyed latitudes and longitudes was performed. Time and resources did permit applying the new values to the May 18 data, but when they were entered into the MWS, the rotation was essentially eliminated. Operational multilateration systems must have accurate surveys and/or incorporate algorithms to observe the intertriad biases on each reply for which more than 3 TOAs are available. These observations should then be smoothed and stored in a dynamic table that is used to correct for the biases before outputting the positions to the user.

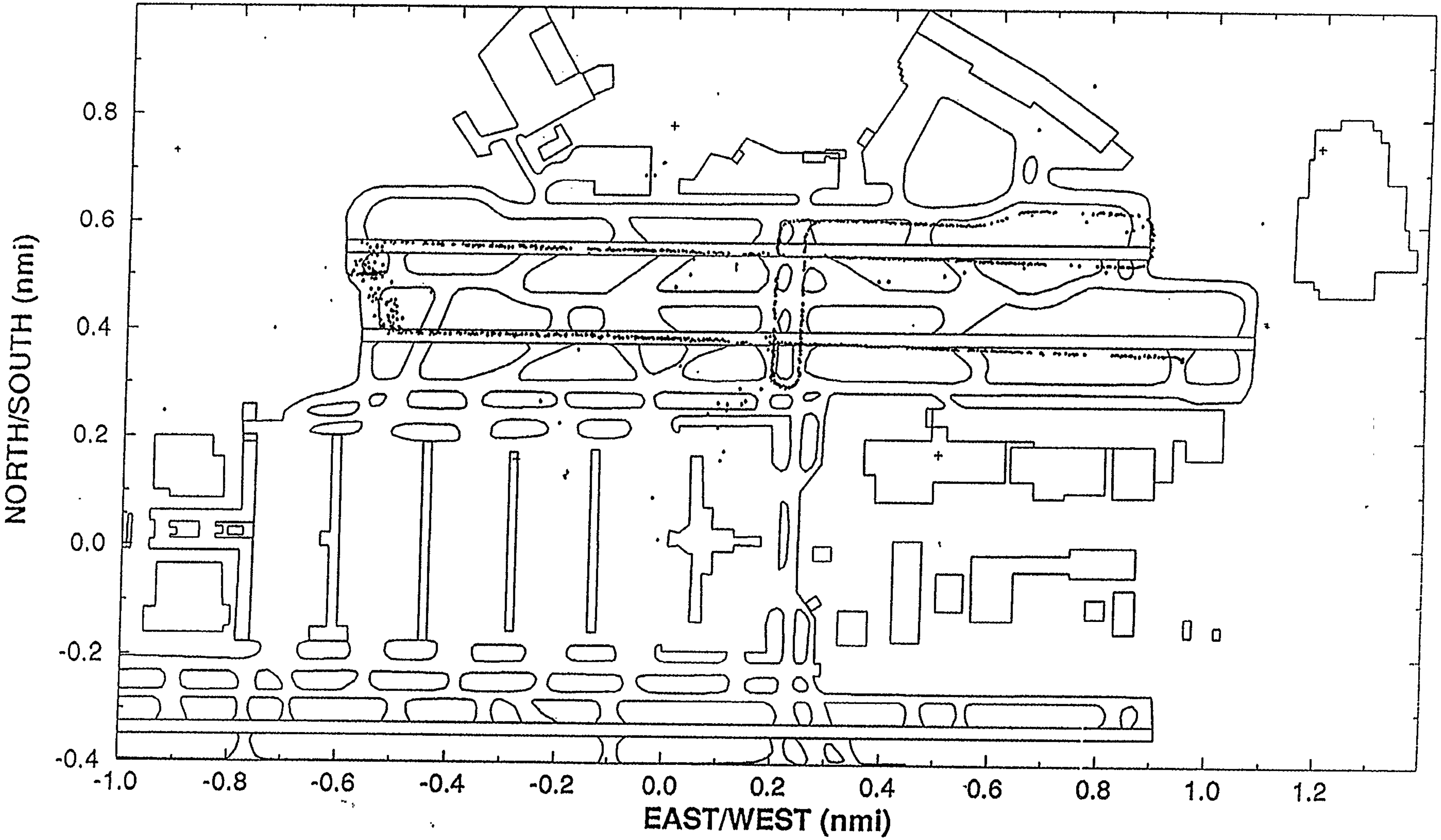


Figure C-1. Short squitter multilateration on SSV test target, by MIT Lincoln Laboratory playback (using unrefined survey). RT's are Delta, Ford, and Stouffers.

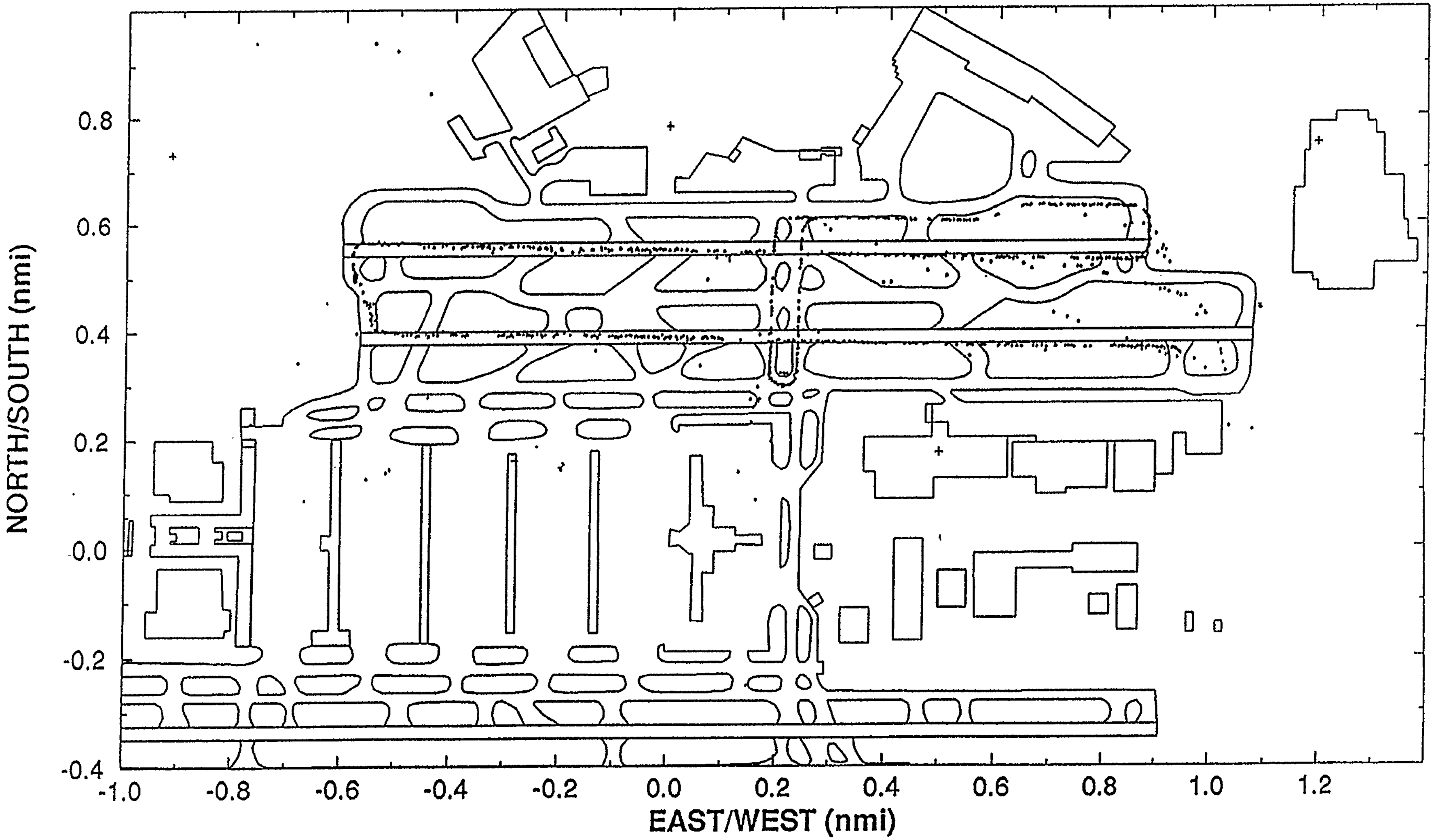


Figure C-2. Short squitter multilateration on SSV test target, by MIT Lincoln Laboratory playback (using unrefined survey). RT's are Delta, Ford, and Region.

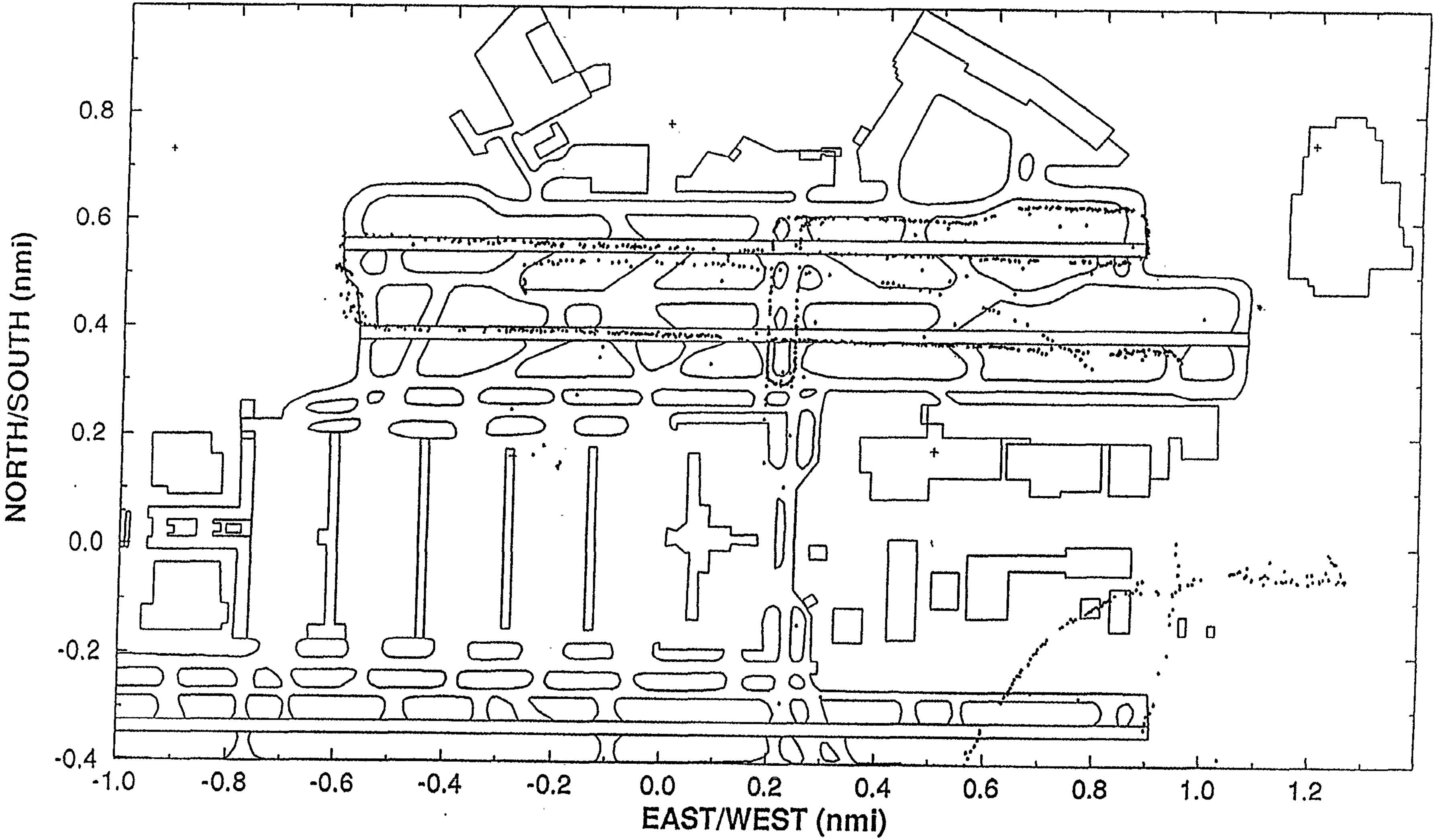


Figure C-3. Short squitter multilateration on SSV test target, by MIT Lincoln Laboratory playback (using unrefined survey). RT's are Delta, Ford, and Terminal C.

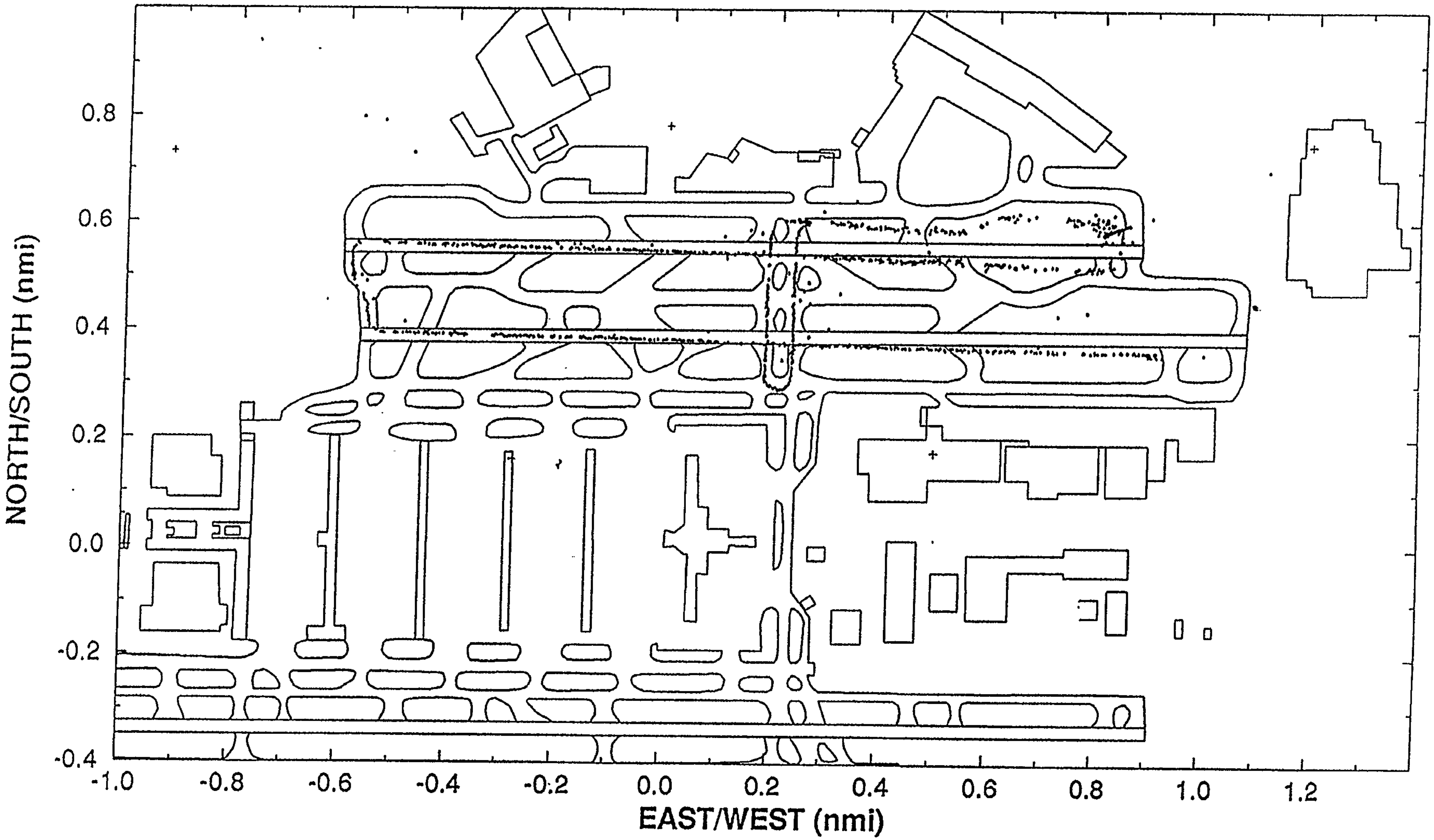


Figure C-4. Short squitter multilateration on SSV test target, by MIT Lincoln Laboratory playback (using unrefined survey). RT's are Delta, Stouffers, and Region.

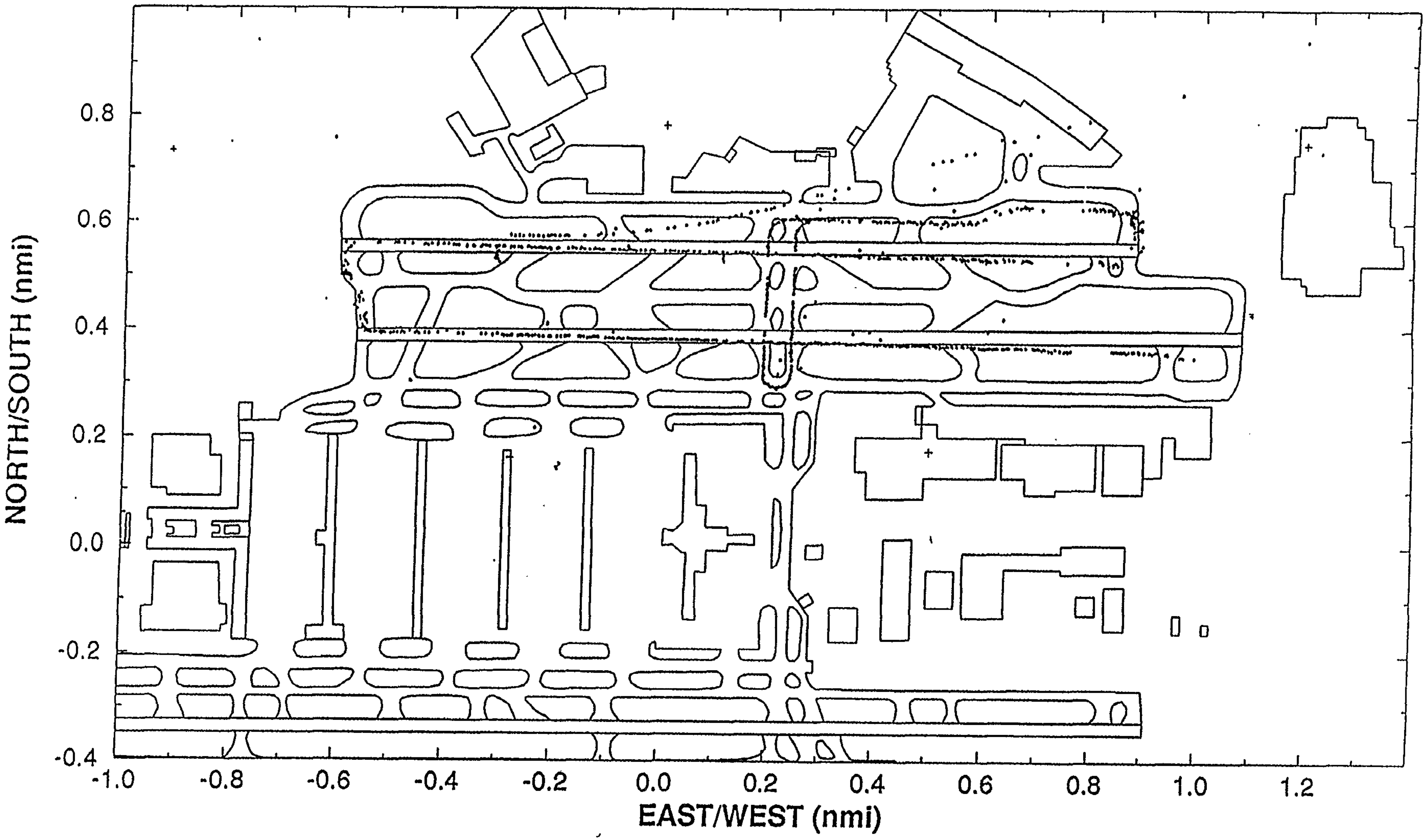


Figure C-5. Short squitter multilateration on SSV test target, by MIT Lincoln Laboratory playback (using unrefined survey). RT's are Delta, Stouffers, and Terminal C.

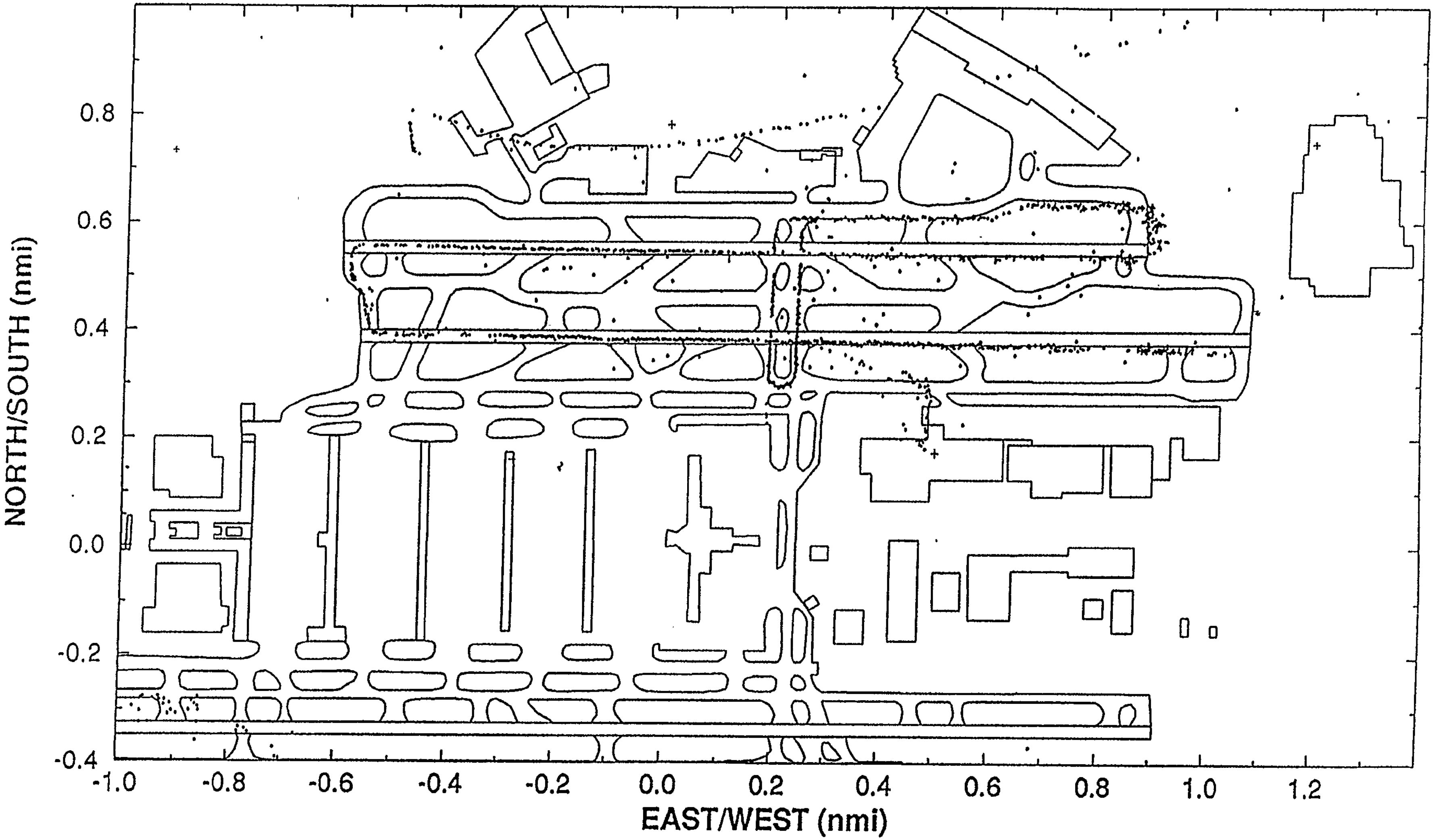


Figure C-6. Short squitter multilateration on SSV test target, by MIT Lincoln Laboratory playback (using unrefined survey). RT's are Delta, Region, and Terminal C.

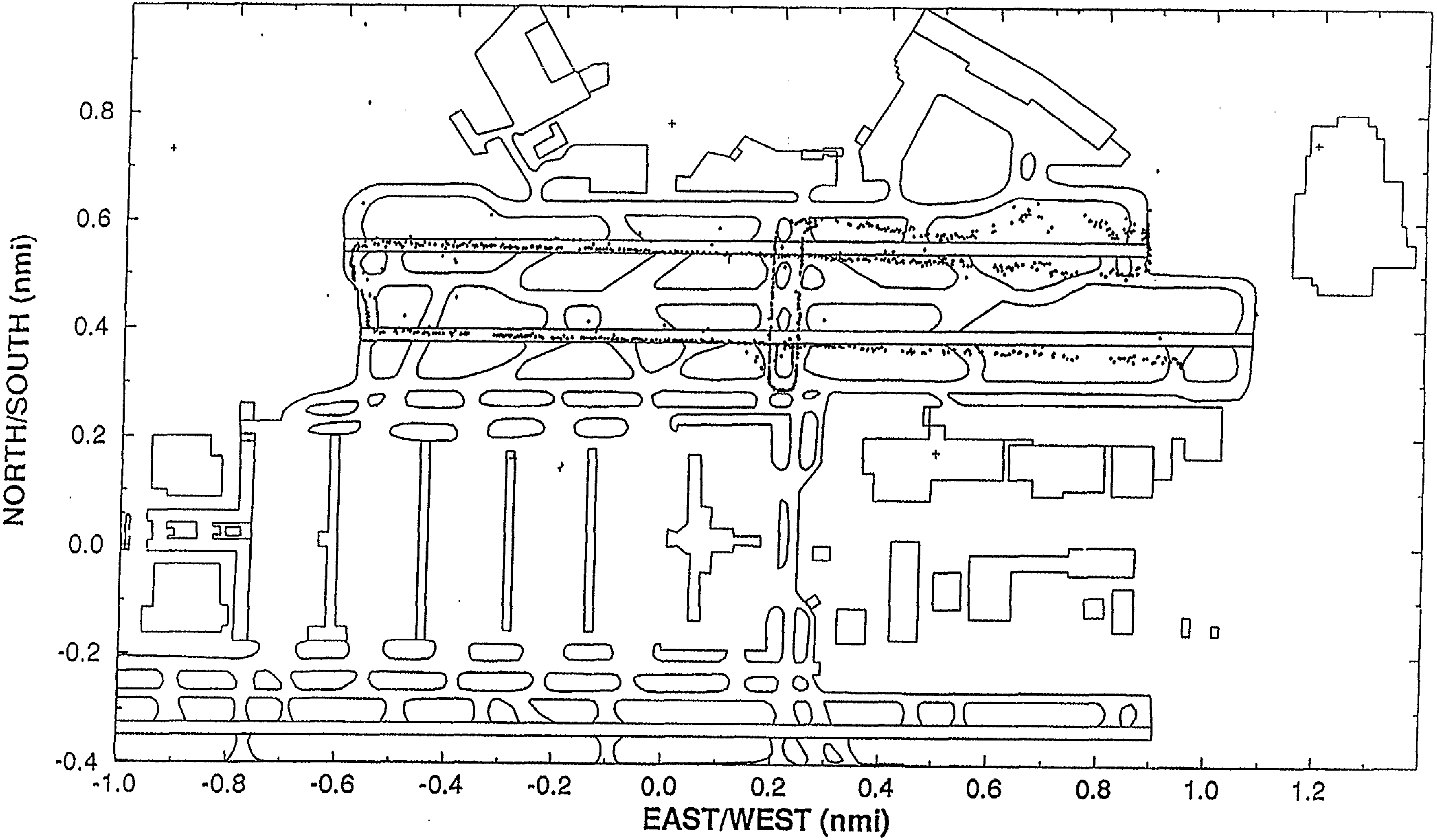


Figure C-7. Short squitter multilateration on SSV test target, by MIT Lincoln Laboratory playback (using unrefined survey). RT's are Ford, Stouffers, and Region.

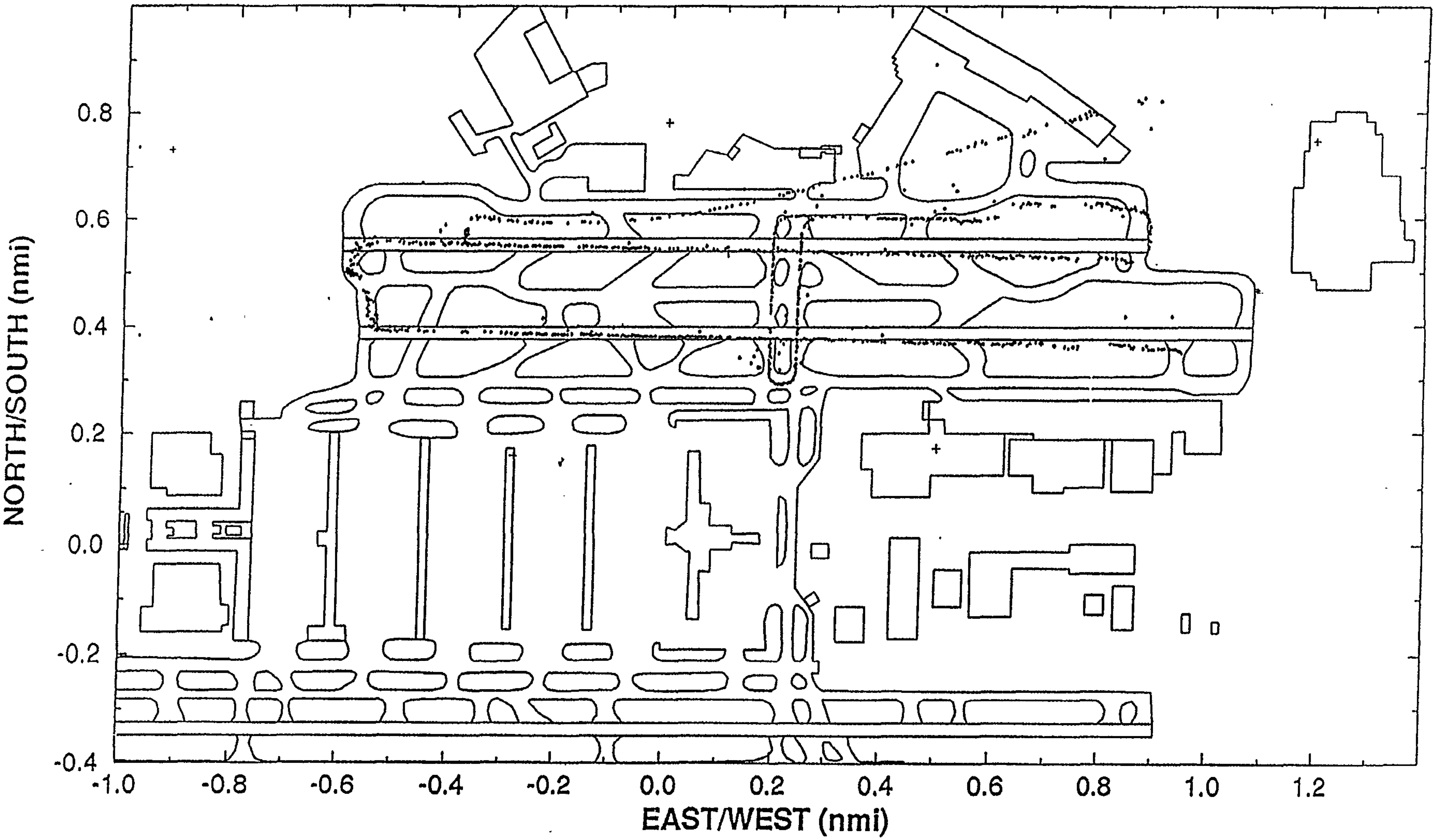


Figure C-8. Short squitter multilateration on SSV test target, by MIT Lincoln Laboratory playback (using unrefined survey). RT's are Ford, Stouffers, and Terminal C.

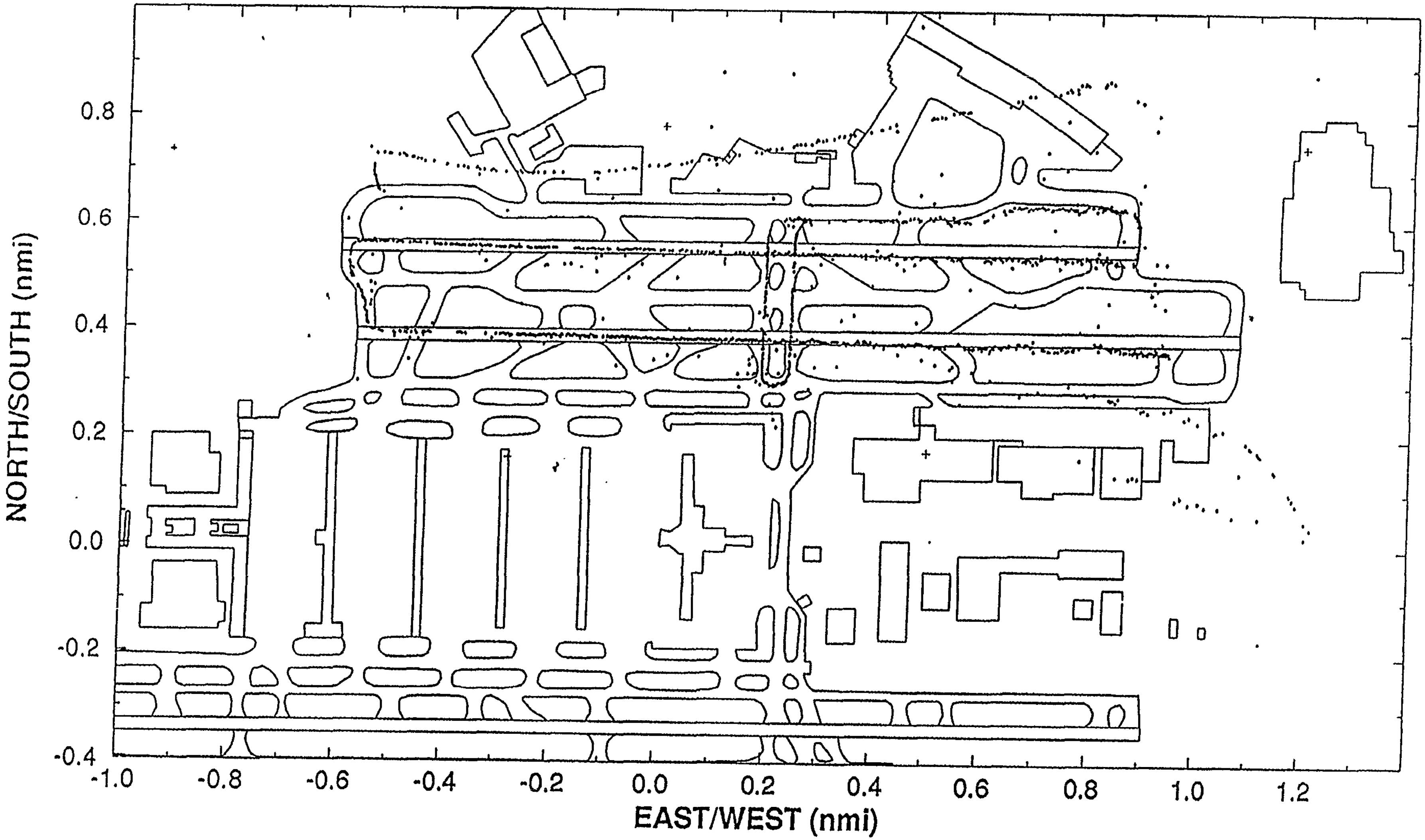


Figure C-9. Short squitter multilateration on SSV test target, by MIT Lincoln Laboratory playback (using unrefined survey). RT's are Ford, Region, and Terminal C.

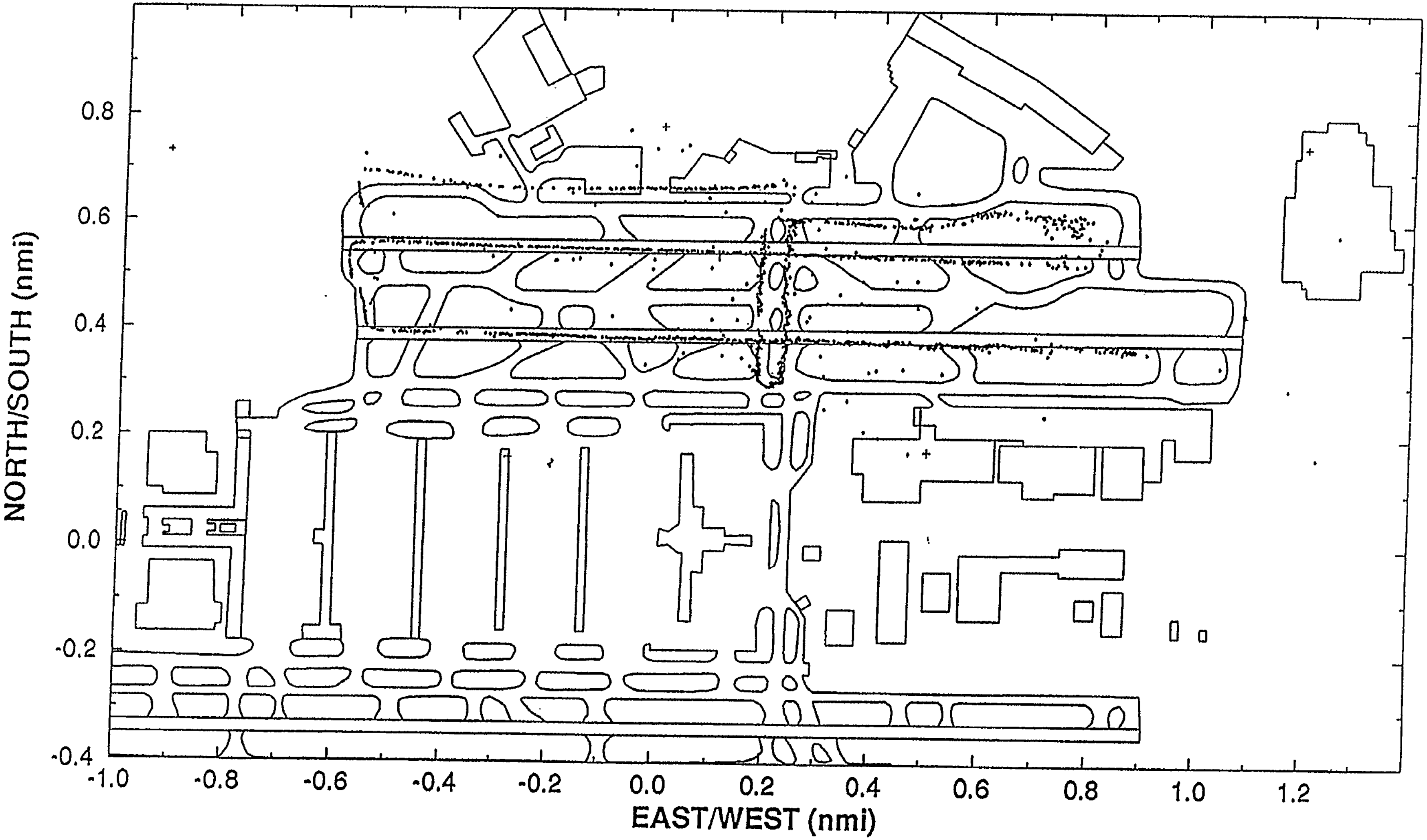


Figure C-10. Short squitter multilateration on SSV test target, by MIT Lincoln Laboratory playback (using unrefined survey). RT's are Stouffers, Region, and Terminal C.

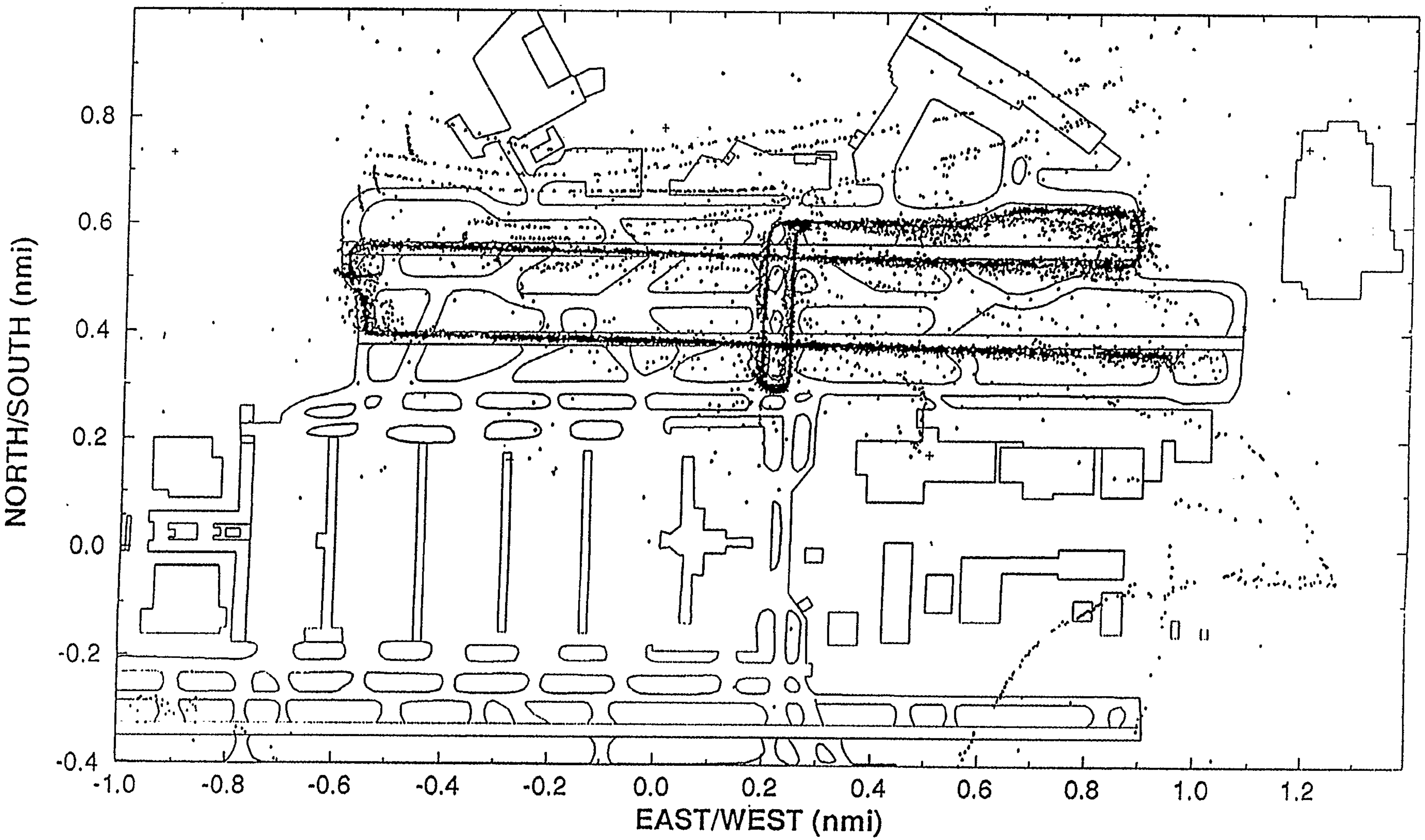


Figure C-11. Short squitter multilateration on SSV test target, by MIT Lincoln Laboratory playback (using unrefined survey). Overlay of ten solution sets, one for each set of 3 RT's selected from 5 (Delta, Ford, Stouffers, Region, and Terminal C.)

APPENDIX D – INTERROGATING R/T'S

This Appendix contains partitions of Figure 5-6. Each Figure D-1 through D-5 shows the Figure 5-6 data according to the interrogating R/Ts, Delta, Ford, Stouffers, Region, and Terminal C, respectively.

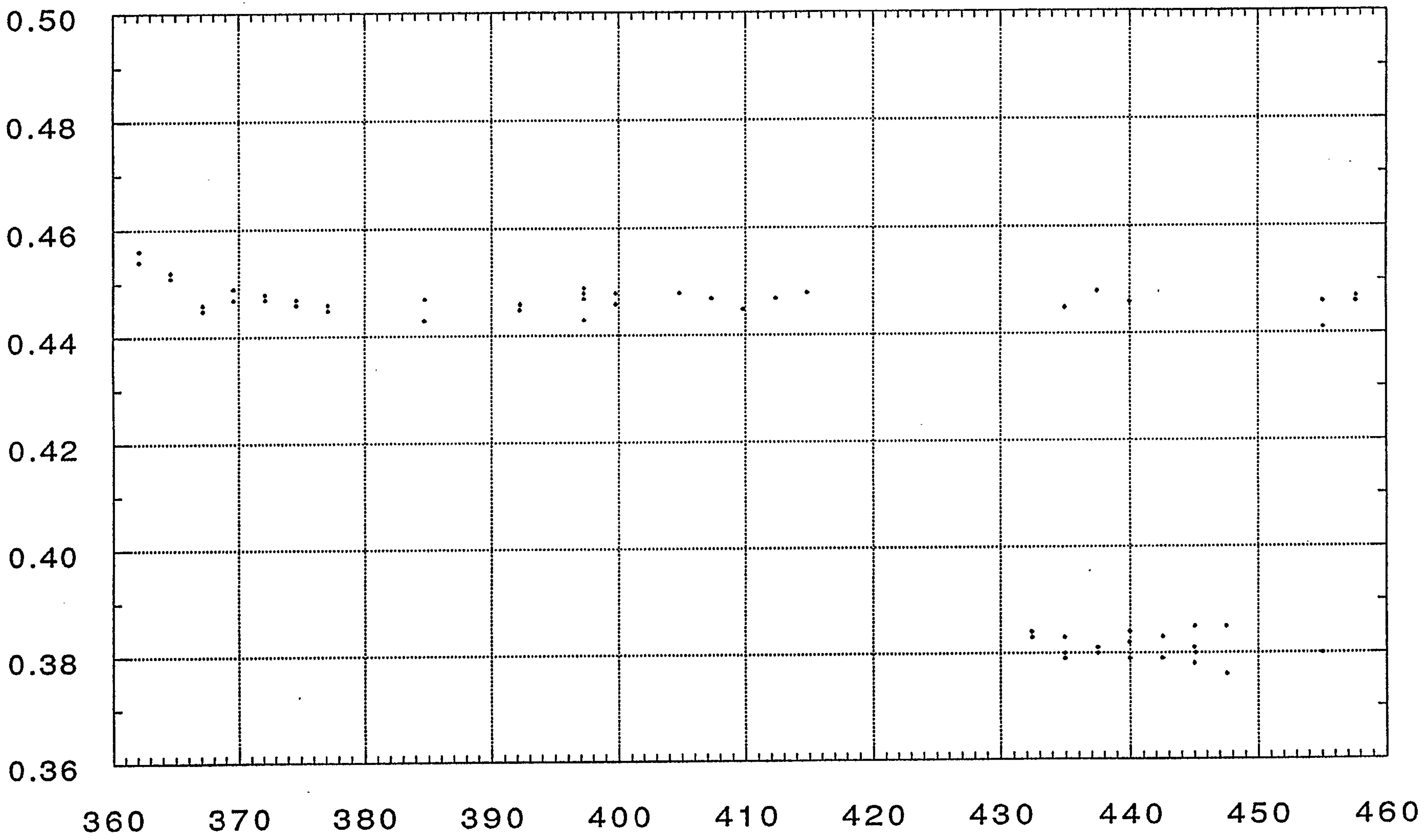


Figure D-1. One hundred seconds of y Positions vs Time for Targets 5250 and 7145, Interrogations by Delta.

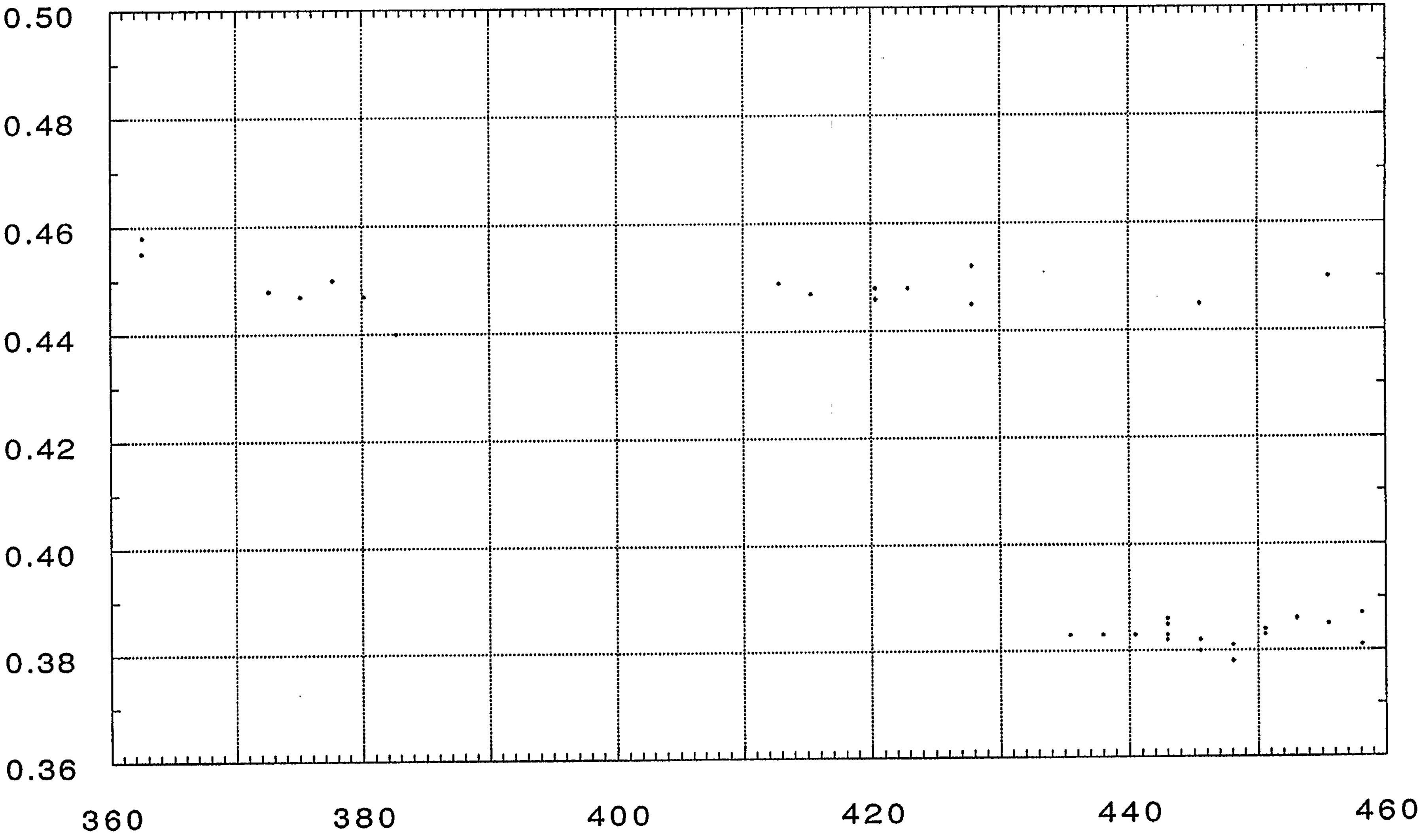


Figure D-2. One hundred seconds of y Positions vs Time for Targets 5250 and 7145, Interrogations by Ford.

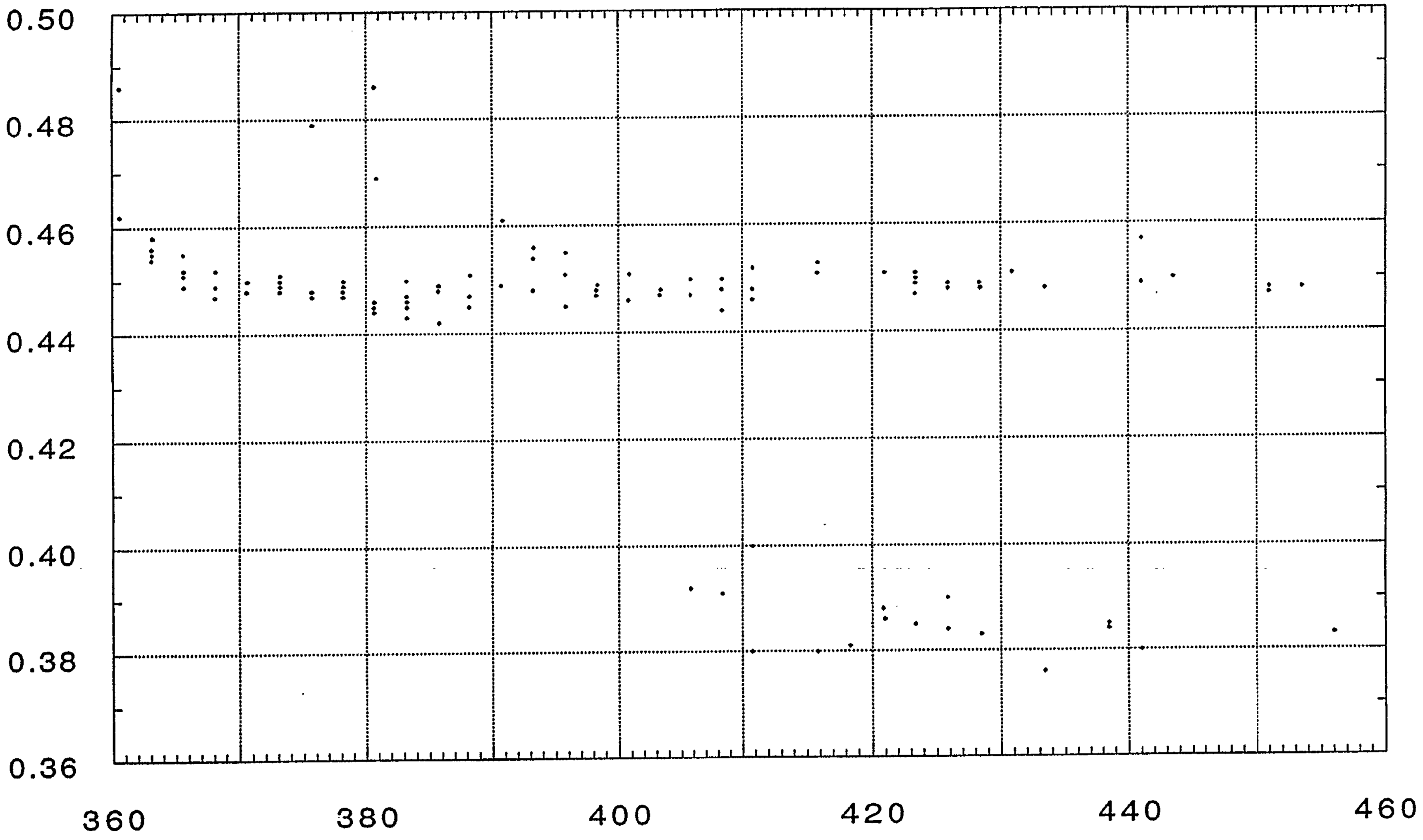


Figure D-3. One hundred seconds of y Positions vs Time for Targets 5250 and 7145, Interrogations by Stouffers.

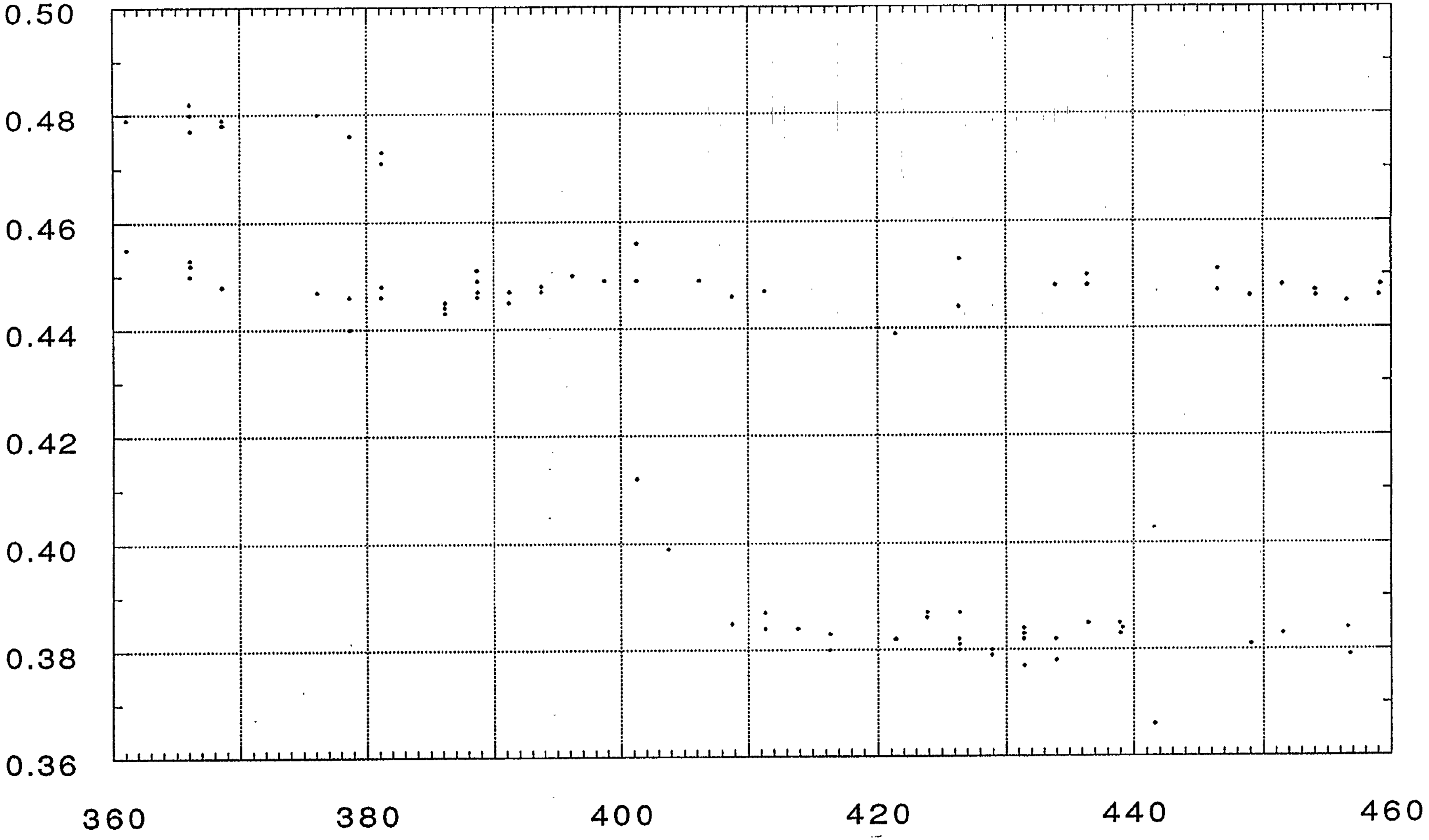


Figure D-4. One hundred seconds of y Positions vs Time for Targets 5250 and 7145, Interrogations by Region.

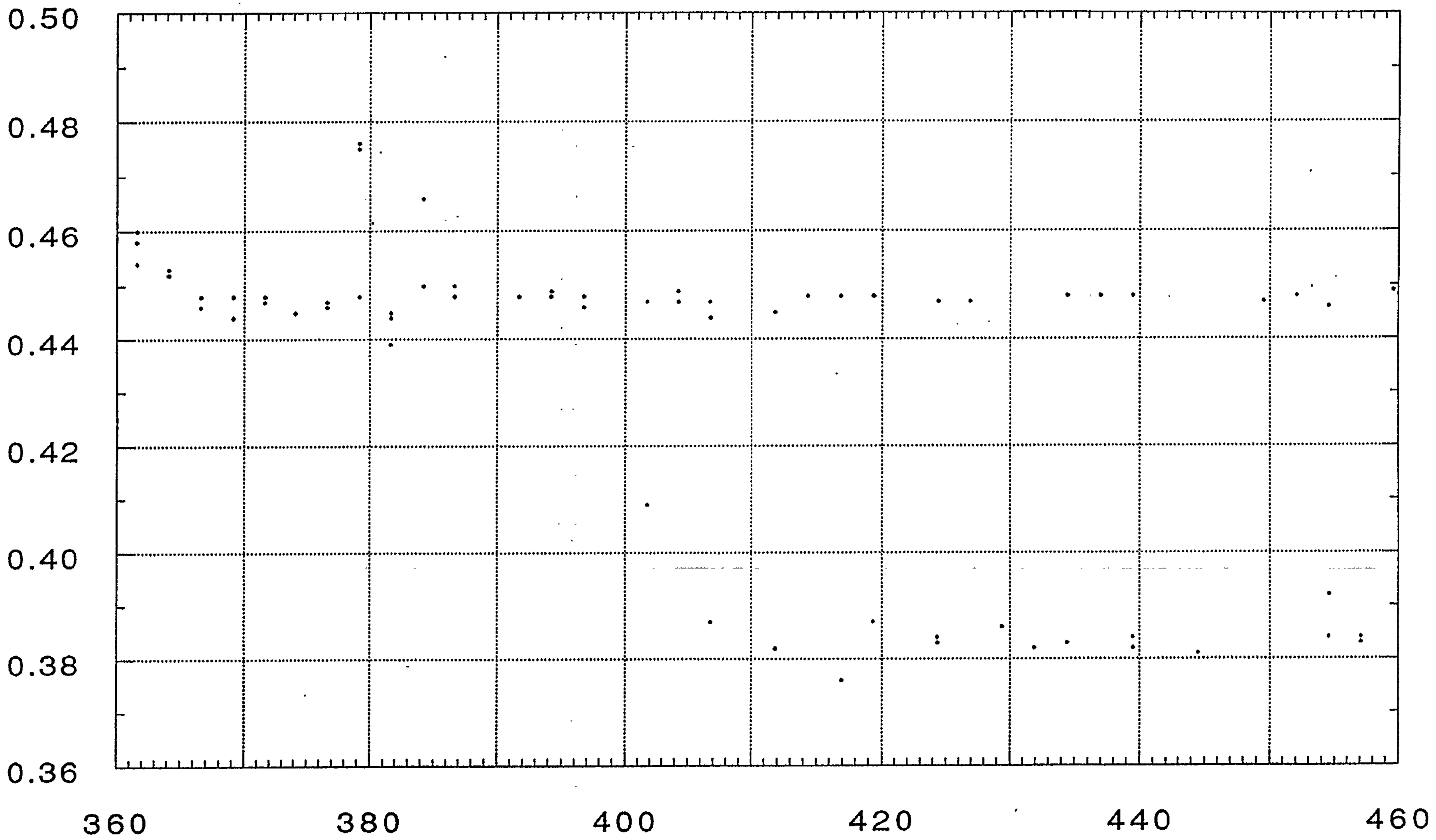


Figure D-5. One hundred seconds of y Positions vs Time for Targets 5250 and 7145, Interrogations by Terminal C.

APPENDIX E – TIME DIFFERENCES OF ARRIVAL

Figures E-1 through E-10 in this Appendix show time differences of arrival for the 10 pairs of R/Ts and for each case. Case a, at the bottom of each figure, shows the DTOA's when both receptions have either code 2761 or 6310, and for the 4 dB bin width whisper shout sequence. The middle figure is the same except it is for the 8 dB wide sequence. The top figure shows all DTOA's, that is for all the interrogations, and without regard to the code of either of the receptions. In each figure, the solid lines represent the approximate predicted DTOAs for the two targets, based on a polynomial curve fit over all time of the positions that were reported in the recorded files.

The figures show that many more DTOA's lie near the predictions if code agreement is not required. They also show many examples of consistent "streaks" that are associated with one or the other of the targets, but are displaced by hundreds of counts, corresponding to several microseconds. These streaks are due to multipath. When the streak is above the prediction, then the multipath must have arisen from the first R/T in the figures title, and when below, from the second R/T. (The DTOA's are computed as the time of arrival at the first R/T minus the second.)

The fact that the DTOA's do not lie exactly in the predictions is of no consequence, because the polynomial predictions were only made coarsely. Kalman type predictions would be made for correlation purposes in an operational algorithm.

The fact that the DTOA's are not smooth, and sometimes exhibit short term trends that do not parallel the prediction is probably due to the fact that the R/T clock calibrations had to be computed without benefit of the high order 16 bits of the times of arrival of the reference transponder, since MWS failed to record them. Also, the calibrations used to make these plots were not smoothed over time.

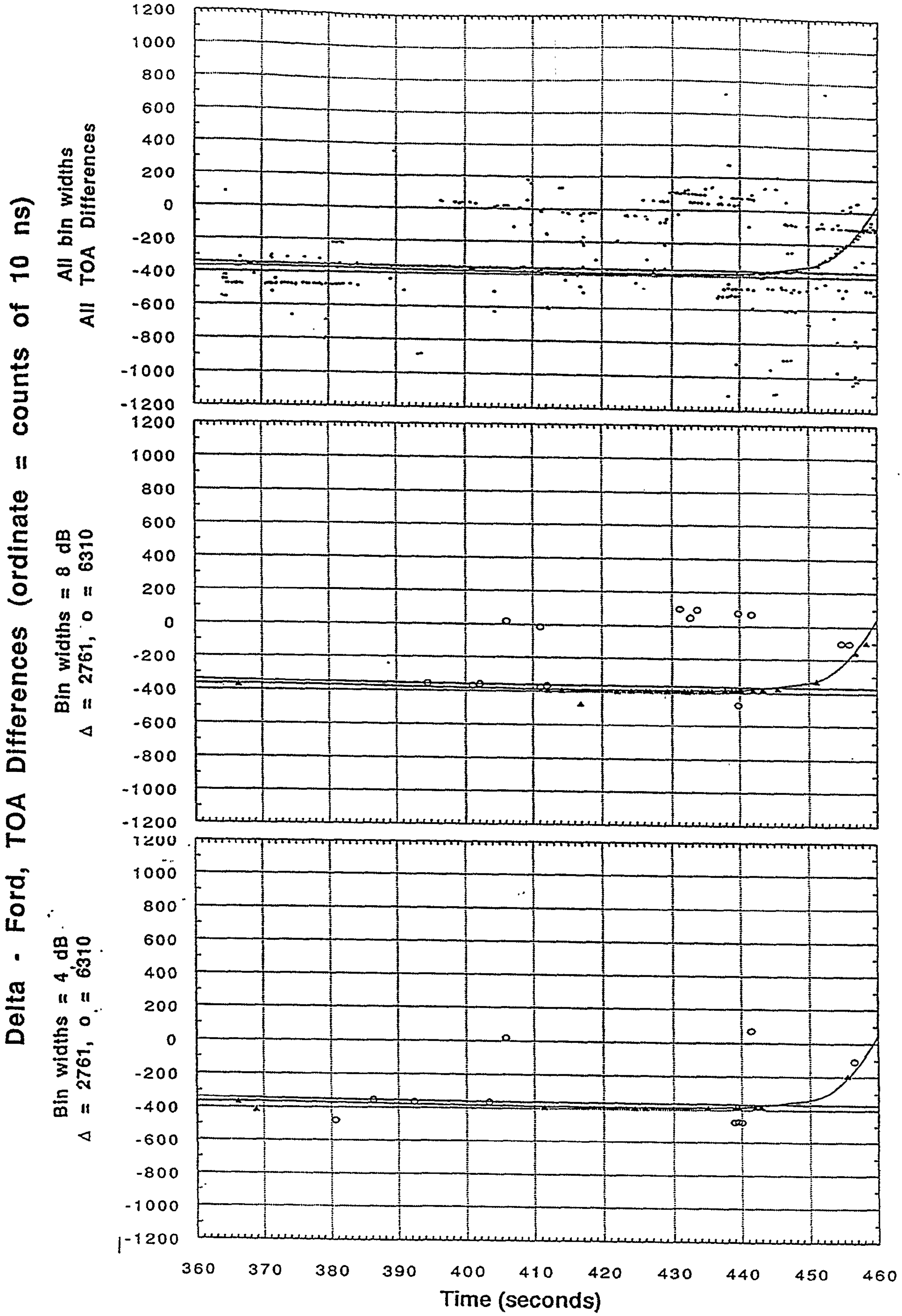
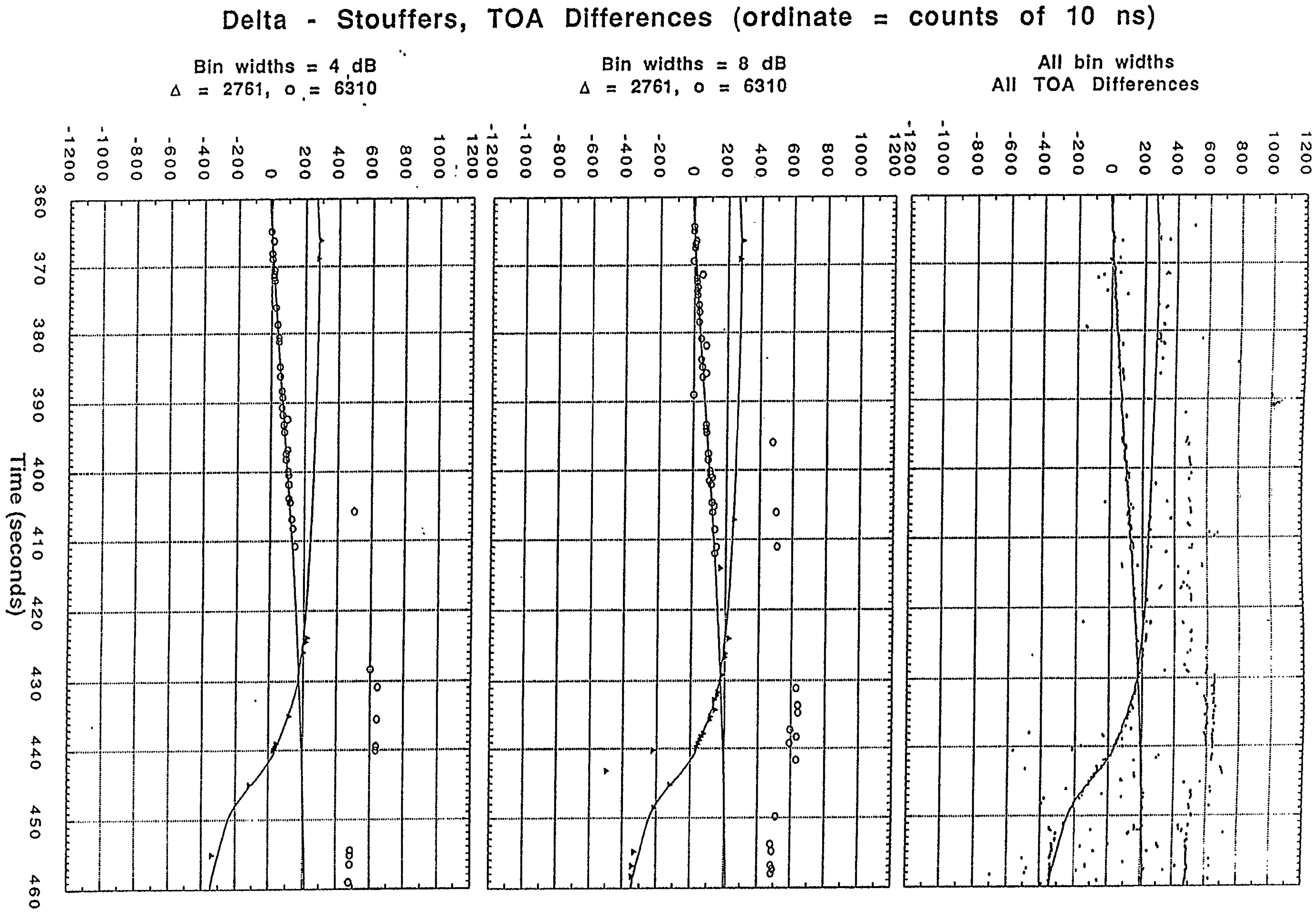


Figure E-1. Correlation of DTOAs (Delta – Ford) to predictions.



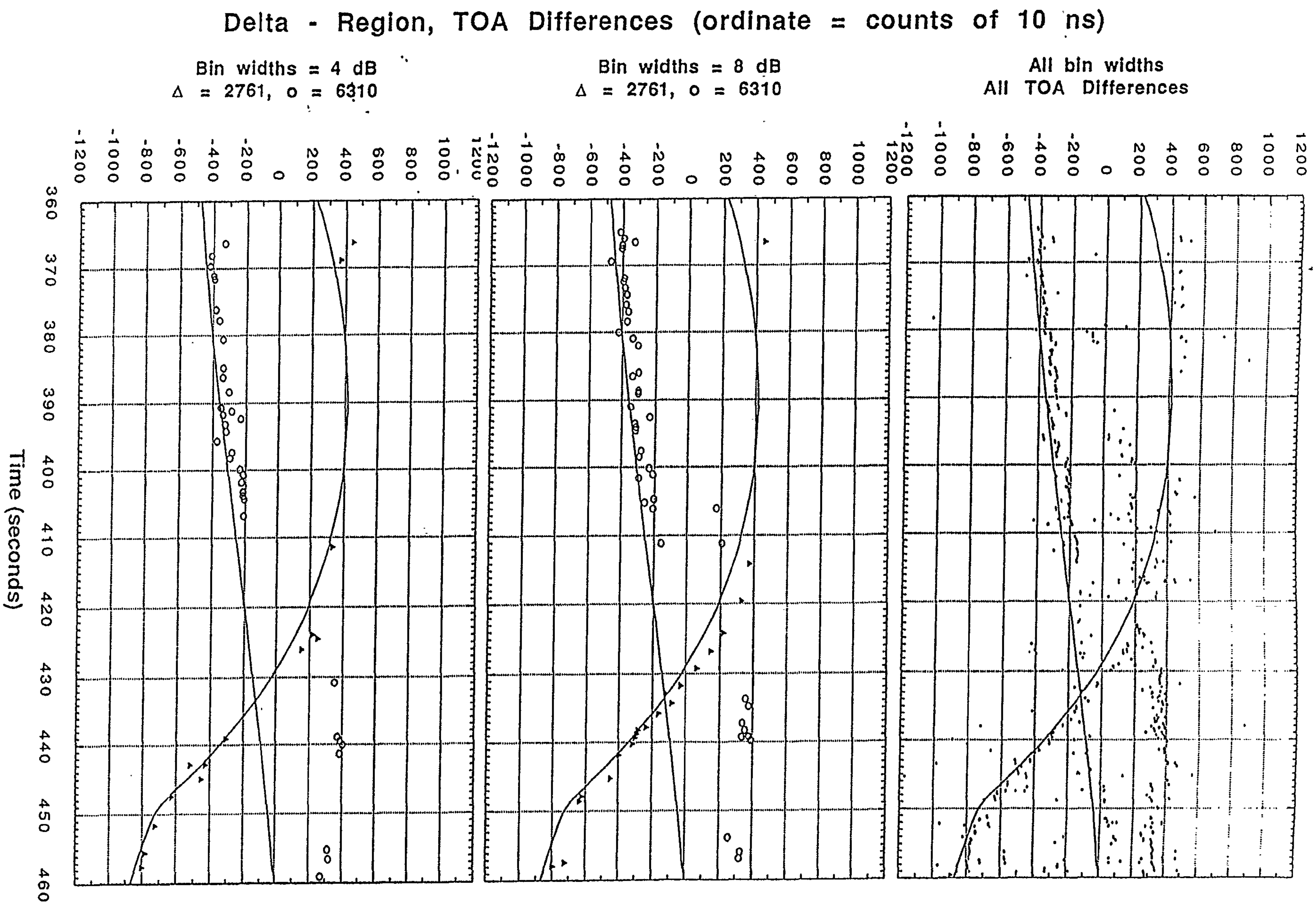
Delta - Stouffers, TOA Differences (ordinate = counts of 10 ns)

Bin widths = 4 dB
Δ = 2761, o = 6310

Bin widths = 8 dB
Δ = 2761, o = 6310

All bin widths
All TOA Differences

Figure E-2. Correlation of DTOAs (Delta – Stouffers) to predictions.



Delta - Region, TOA Differences (ordinate = counts of 10 ns)

Bin widths = 4 dB
Δ = 2761, o = 6310

Bin widths = 8 dB
Δ = 2761, o = 6310

All bin widths
All TOA Differences

Figure E-3. Correlation of DTOAs (Delta –Region) to predictions.

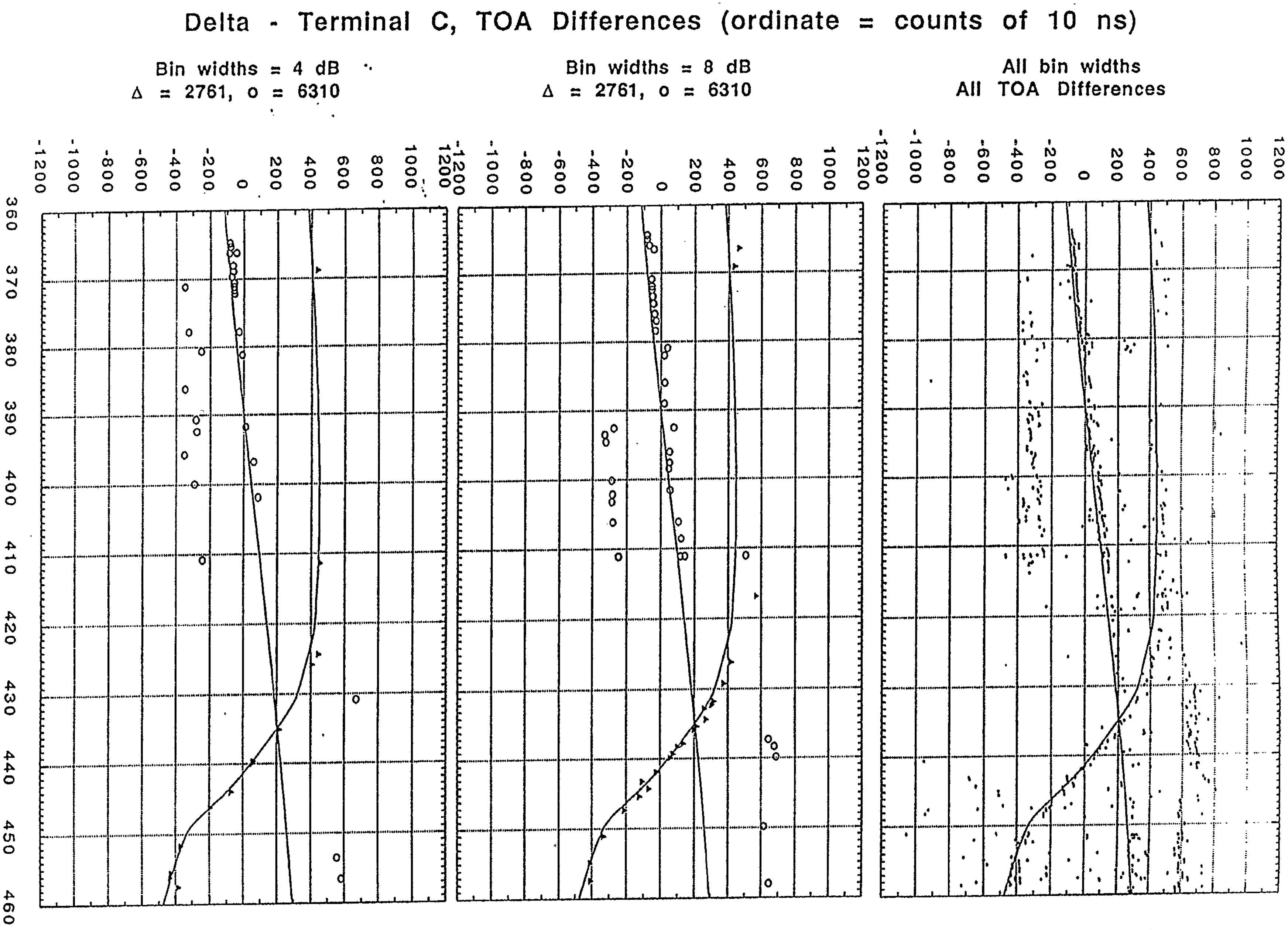


Figure E-4. Correlation of DTOAs (Delta – Terminal C) to predictions.

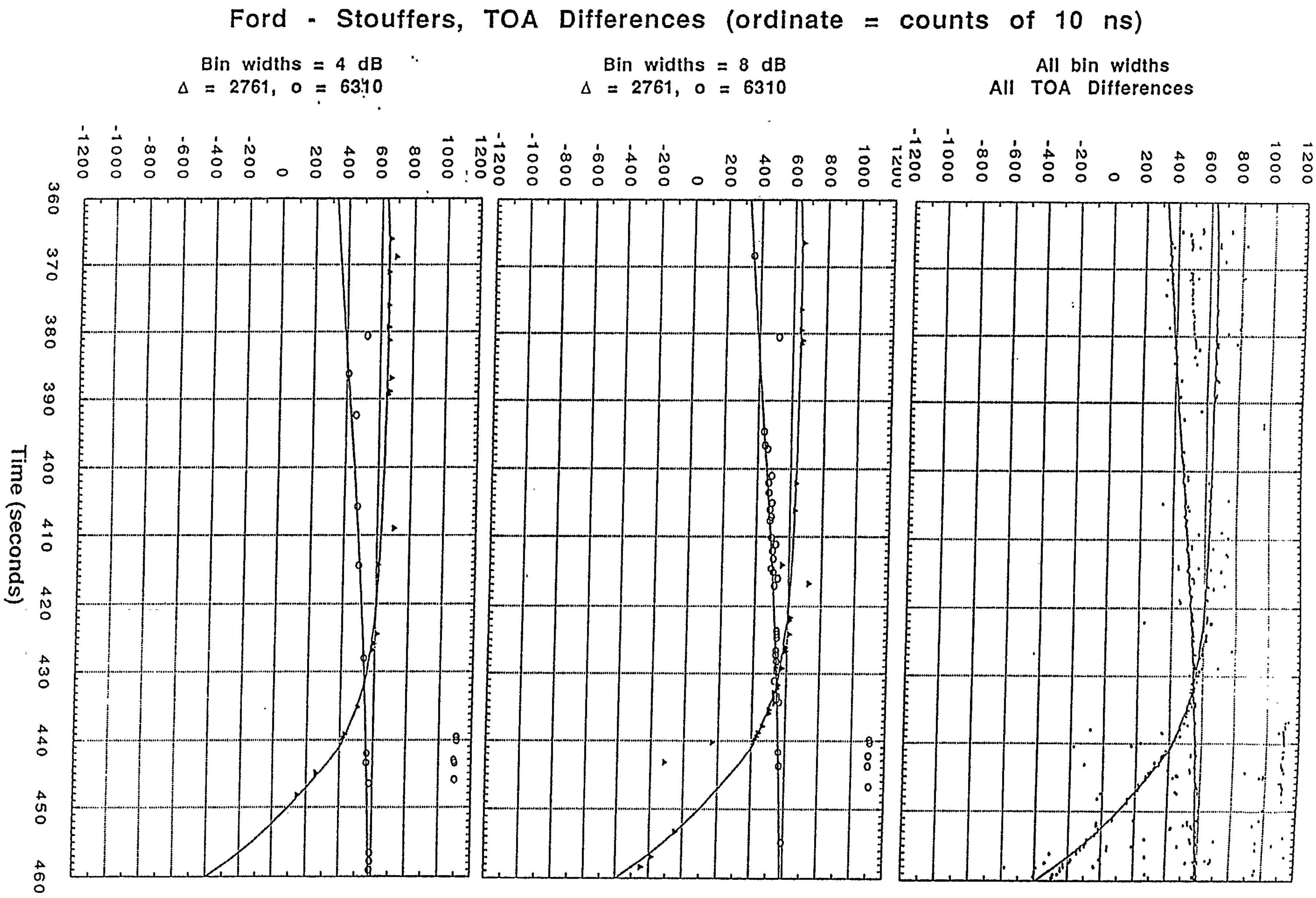


Figure E-5. Correlation of DTOAs (Ford – Stouffers) to predictions.

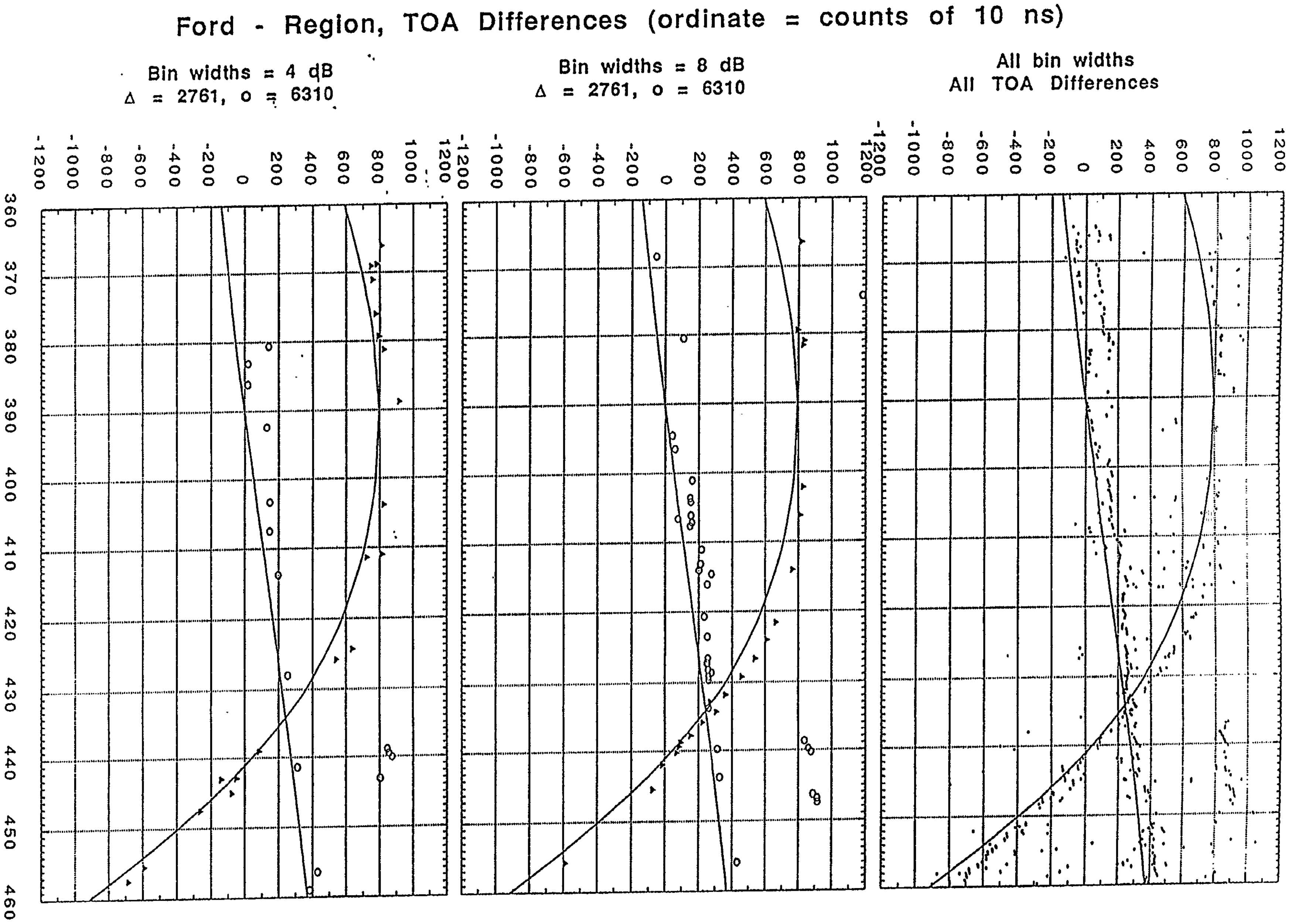
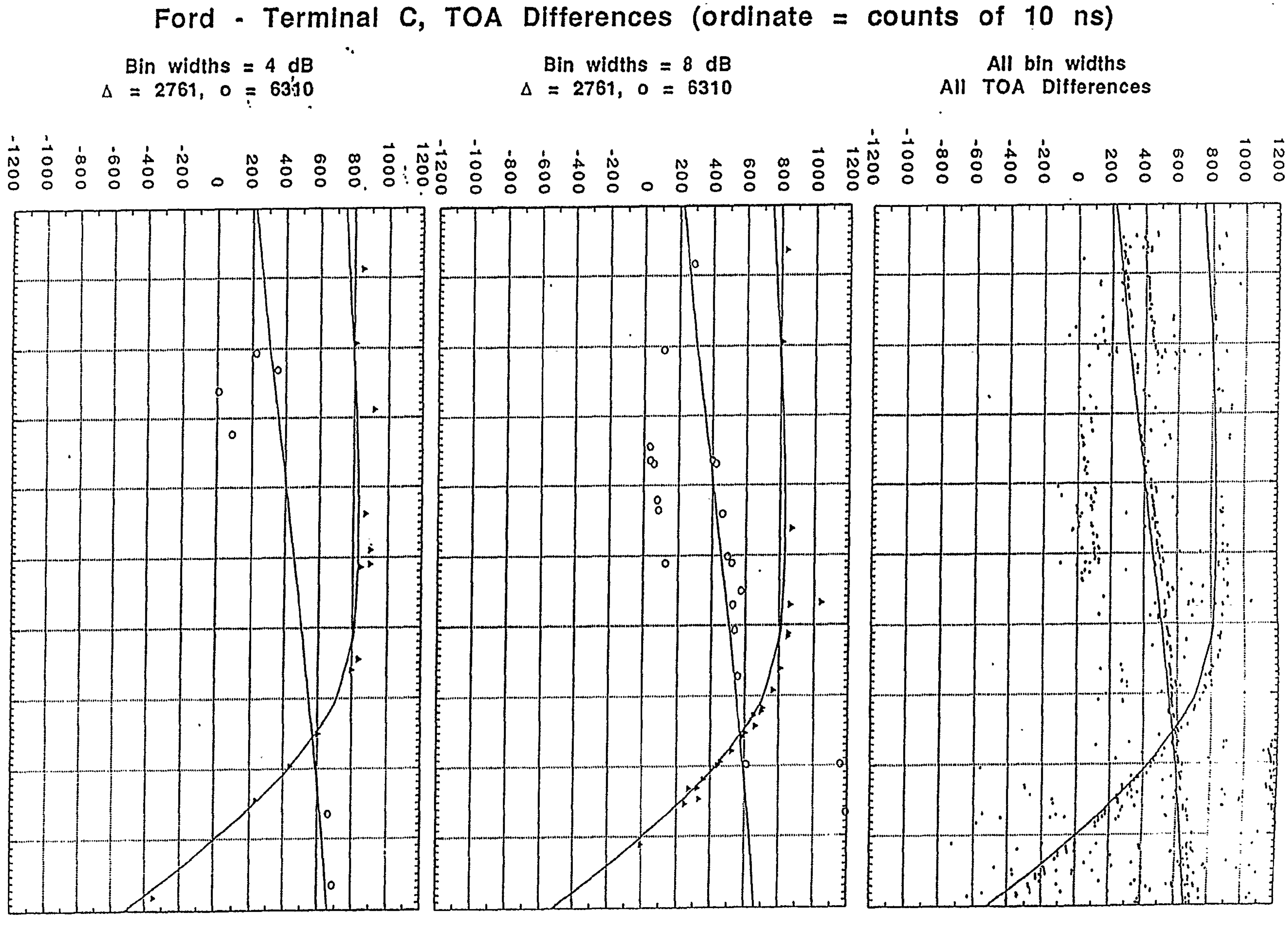


Figure E-6. Correlation of DTOAs (Ford – Stouffers) to predictions.



Ford - Terminal C, TOA Differences (ordinate = counts of 10 ns)

Bin widths = 4 dB
Δ = 2761, o = 6310

Bin widths = 8 dB
Δ = 2761, o = 6310

All bin widths
All TOA Differences

Figure E-7. Correlation of DTOAs (Ford – Terminal C) to predictions.

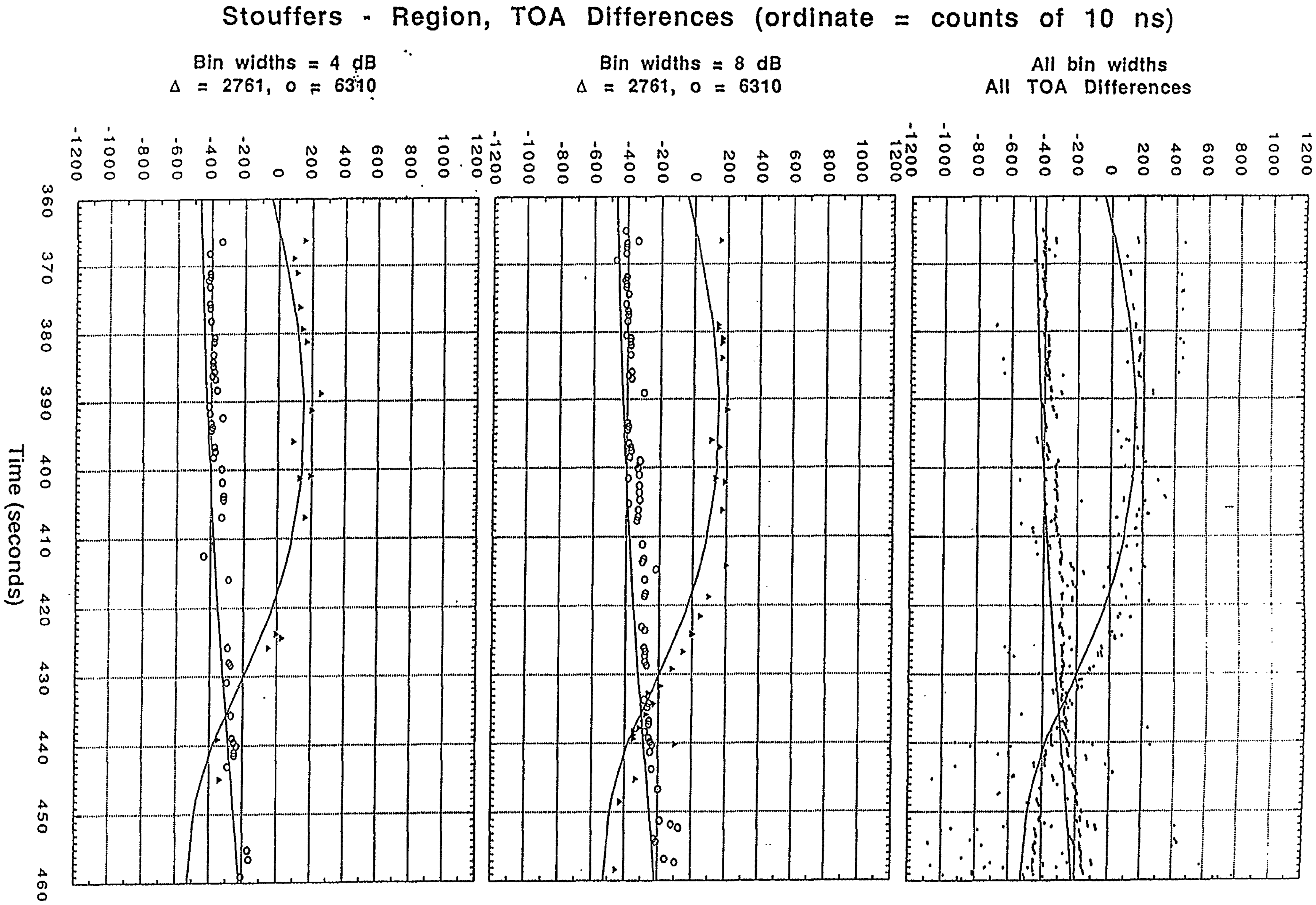


Figure E-8. Correlation of DTOAs (Stouffers – Region) to predictions.

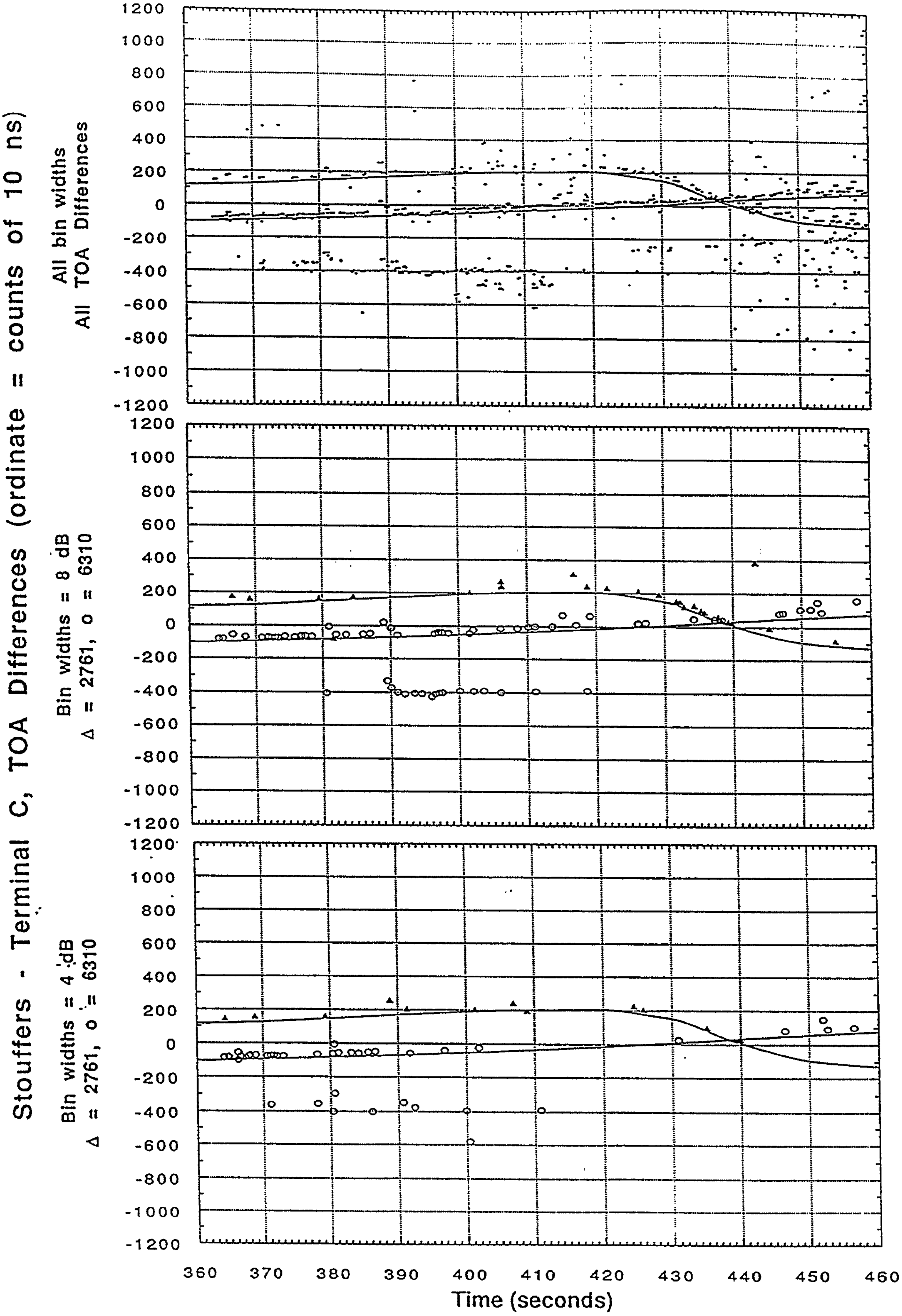


Figure E-9. Correlation of DTOAs (Stouffers – Terminal C) to predictions.

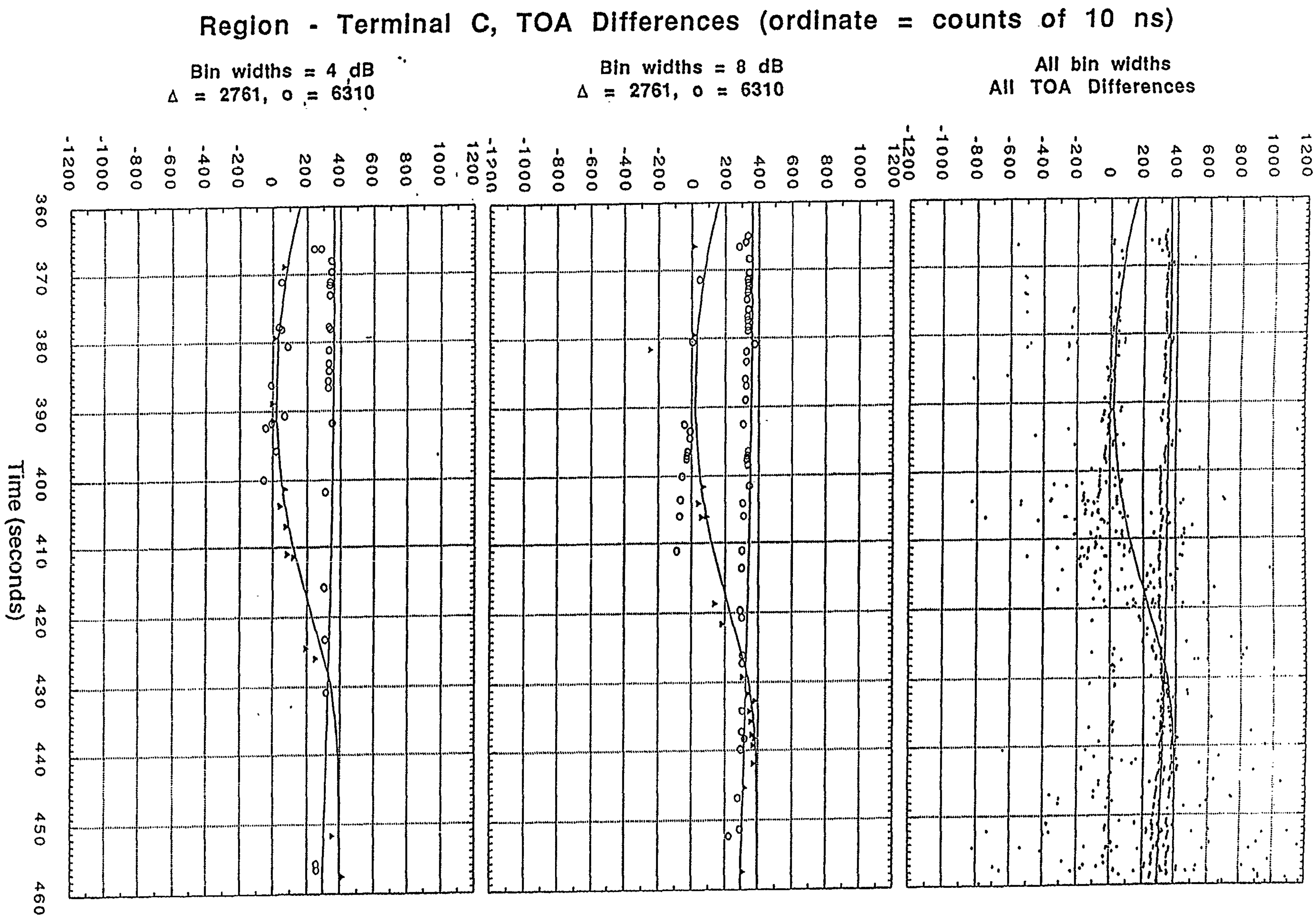


Figure E-10. Correlation of DTOAs (Region – Terminal C) to predictions.

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[2] Wood, M. L., "Propagation of Mode S Beacon Signals on the Airport Surface," MIT Lincoln Laboratory Journal, Volume 2, Number 3, 1989.

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[4] (FAA Hughes Technical Center Report)

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