Project Report

ATC-294

Comparison of Active TCAS Slant Range Measurements with Interpolated Passive Position Reports for Use in Hybrid Surveillance Applications: Measurements from the June 1999 Los Angeles Basin Flight Tests

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16. Abstract

Traffic Alert and Collision Avoidance System (TCAS) hybrid surveillance is a technique that makes use of both active surveillance data from the interrogation reply sequence and passive psoition estimates received from Mode S extended squitters. This technique allows TCAS to use passive surveillance once the data have been validated by comparison with active data. The maximum allowable range difference for validation specified by the International Civil Aviation Organization (ICAO) is 200 meters. Data from twenty encounters recorded during flight tests conducted in the Los Angeles Basin in June 1999 were analyzed. The results show that the ICAO specified limits were never exceeded and serve to validate the 200 meter limit.

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EXECUTIVE SUMMARY

The Traffic Alert and Collision Avoidance System (TCAS) is a safety system designed to display other aircraft traffic to pilots and to provide alerts and coordinated resolutions necessary to avoid conflicts. TCAS works by actively interrogating other nearby transponder-equipped aircraft, measuring the range and bearing of those aircraft, and tracking them. The FAA has required TCAS on all commercial aircraft with more than thirty passenger seats in U.S. airspace. In addition, the International Civil Aviation Organization (ICAO) has recently issued a world-wide mandate for an Airborne Collision Avoidance System (ACAS), the international version of TCAS.

As the density of TCAS-equipped aircraft increases, it is desirable to explore techniques for reducing the TCAS interrogation rate. One such technique is hybrid surveillance, which makes use of both active surveillance data (position measurements obtained from the standard TCAS interrogation/reply sequence) and passive surveillance data (position estimates from received Mode S extended squitters). The technique allows TCAS to use passive surveillance information from a target once the passive data have been "validated" by comparison with active data. The validation technique is important since it allows TCAS to retain its role as an independent safety system.

The maximum allowable range difference for validation specified by the ICAO ACAS SARPs (International Civil Aviation Organization, Airborne Collision Avoidance System, Standards and Recommended Practices) is 200 meters. However, measurements were needed to fully validate these requirements.

MIT Lincoln Laboratory participated in flight tests conducted by the Federal Aviation Administration (FAA) in June 1999 in the Los Angeles Basin to measure the interference environment and test the performance of the Mode S extended squitter. There were periods during the testing when data useful to hybrid surveillance analysis were recorded. A total of twenty encounters involving four different aircraft were analyzed.

During each encounter, TCAS active range measurements were recorded. "Own" aircraft positions were estimated through linear interpolation of GPS position reports to match the time of the active range measurement. The "target" aircraft positions as reported in the Mode S extended squitter were also interpolated. The positions were converted to 3-D Cartesian coordinates and a passive interpolated range was computed. The difference or delta range was defined as the active range minus the interpolated passive range. The delta ranges were plotted versus system time and versus range between aircraft for every encounter. Summary histograms of the delta ranges for all encounters were derived.

The validation of the SARPs limit for active/passive range comparison was the primary goal of the work described in this report. A secondary goal was the examination of the active/passive range differences for use in future activities that require the fusion of various sources of surveillance data. Results demonstrate that the range difference specified by the ICAO ACAS SARPS as the maximum allowable difference for validation of reported position was never exceeded and serves to validate the 200 meter range difference limit.

ACKNOWLEDGMENTS

Ann Drumm provided valuable expertise on the principles of operation of TCAS and hybrid surveillance and in reviewing this report.

L-3 Communications Corporation provided the TCAS-2000 units and Mode S transponders designed to transmit extended squitters. These units were formerly owned by Honeywell, Incorporated and generated all of the data analyzed in this report. Note that these were experimental units, developed before the existence of final detailed requirements for either extended squitter or hybrid surveillance. This was the only such equipment in existence at that time, and the fact that L-3 was willing to make these units available to Lincoln Laboratory made possible the analysis described in this report. In addition, L-3 Communications supplied software for data extraction from the TCAS-2000 units. L-3 Communications engineers, in particular Stacey Rowlan and Laurie Wyatt, provided valuable assistance in the interpretation of these data.

Ed Glowacki of the FAA's William J. Hughes Technical Center pre-processed the TCAS data tapes and provided them to MIT Lincoln Laboratory.

Kenneth Saunders and Barbara Chludzinski wrote the programs for reducing the recorded TCAS surveillance data. These programs extract the active surveillance data and long and short squitter data received from other aircraft.

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1. INTRODUCTION

The Traffic Alert and Collision Avoidance System (TCAS) is a safety system designed to display other aircraft traffic to pilots and to provide alerts and coordinated resolutions necessary to avoid conflicts. TCAS works by actively interrogating other nearby transponder-equipped aircraft, measuring the range and bearing of those aircraft, and tracking them. The FAA has required TCAS on all commercial aircraft with more than thirty passenger seats in U.S. airspace. In addition, the International Civil Aviation Organization (ICAO) has recently issued a worldwide mandate for an Airborne Collision Avoidance System (ACAS), the international version of TCAS.

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The maximum allowable range difference for validation specified by the ICAO ACAS SARPs [1] (International Civil Aviation Organization, Airborne Collision Avoidance System, Standards and Recommended Practices) is 200 meters. However, measurements were needed to fully validate these requirements.

MIT Lincoln Laboratory participated in flight tests conducted by the Federal Aviation Administration (FAA) in June 1999 in the Los Angeles Basin to measure the interference environment and test the performance of the Mode S extended squitter. There were periods during the testing when data useful to hybrid surveillance analysis were recorded. A total of twenty encounters involving four different aircraft were analyzed.

During each encounter, TCAS active range measurements were recorded. "Own" aircraft positions were estimated through linear interpolation of GPS position reports to match the time of the active range measurement. The "target" aircraft positions as reported in the Mode S extended squitter were also interpolated. The positions were converted to 3-D Cartesian coordinates and a passive interpolated range was computed. The difference or delta range was defined as the active range minus the interpolated passive range. The delta ranges were plotted versus system time and versus range between aircraft for every encounter. Summary histograms of the delta ranges for all encounters were derived.

Chapter 2 of this report describes the Los Angeles flight tests. Chapter 3 discusses the sources of errors in active and passive range measurements. Chapter 4 describes the method of analysis of each encounter, Chapter 5 presents a summary of the results, and Chapter 6 presents the conclusions.

The validation of the SARPs limit for active/passive range comparison was the primary goal of the work described in this report. A secondary goal was the examination of the active/passive range differences for use in future activities that require the fusion of various sources of surveillance data.

2. LOS ANGELES BASIN FLIGHT TESTS

2.1 Flight Test Overview

The Federal Aviation Administration (FAA) conducted flight tests in the Los Angeles Basin to measure the interference environment and test the performance of 1090 MHz Extended Squitter [2,3]. The flight tests were conducted on four days (June 16-19, 1999) and involved an instrumented Boeing 727 (N40) and Convair 580 (N49) supplied by the FAA's W. J. Hughes Technical Center (WJHTC). Two other aircraft, a United Parcel Service Boeing 727 (N904UP) and a Honeywell Citation (N189H), participated during portions of the four days of testing. In addition, N40 and N49 took data on June 14, 1999, during their flight to Los Angeles. There was also a ground station that recorded data, but these data were not pertinent to this analysis. A summary of the aircraft that participated in the tests and their equipment is presented in Figure 1.

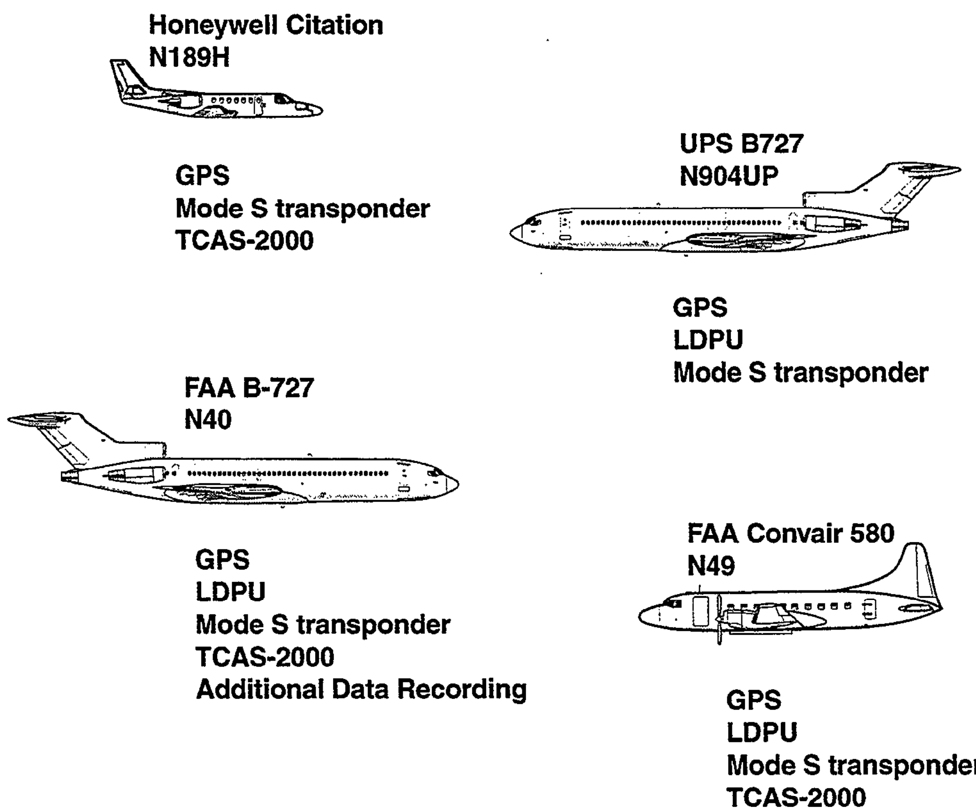


Figure 1. Aircraft and equipment participating in the Los Angeles Basin Flight Test.

The significance of the equipment is as follows. All aircraft were equipped with Global Positioning System (GPS) units that provided updated position reports once per second. All aircraft were also equipped with L-3 Communications supplied Mode S transponders capable of transmitting extended squitters on 1090 MHz. Extended squitters containing GPS position reports were transmitted approximately twice per second. Three of the aircraft were also equipped with TCAS-2000 units supplied by L-3 Communications. These units actively interrogated target aircraft and record the target measured range and bearing and reported altitude. These units also recorded own GPS position reports and GPS position reports contained in Mode S extended squitters received from other aircraft. The TCAS-2000 units were the source of the raw data for this analysis.

In addition, three of the aircraft were equipped with Link and Display Processing Units (LDPU) provided by UPS Aviation Technologies. The LDPU contains a 1090 MHz receiver and a Mode S reply processor and was used to supply processed data to several devices used in the measurement program. The LDPU was significant to this analysis in one important aspect. The LDPU receives once per second position reports from the GPS and extrapolates those reports to provide estimated position reports five times per second to the Mode S transponder. The Mode S transponder which transmits extended squitters twice per second will transmit the last updated or extrapolated position report. Because the N189H configuration did not extrapolate position, the Mode S transponder on that aircraft reported the last position supplied by the GPS. The significance of this is illustrated in Figure 2. The position report contained in the second squitter could be up to one second old. The 1090 MHz Minimum Operational Performance Standards [4] (MOPS) requires the faster update rate, so production extended squitter equipment can be expected to perform the extrapolation. For the flight testing, N189H was equipped with an experimental configuration.

The LDPU data were also used in generating the aircraft tracks plots shown in this report and used to illustrate relative aircraft positions. However, only data recorded on the TCAS-2000 units were used to compare active interrogation slant range measurements with computed ranges based on extended squitter position reports.

2.2 *Hybrid Surveillance Measurements*

The main purpose of these flight tests was to measure the interference environment and performance of the 1090 MHz extended squitter, not to provide data for hybrid surveillance analysis. However, there were periods during the testing when data useful to hybrid surveillance analysis were recorded. Periods of interest occurred whenever any of the three TCAS-equipped aircraft was within active surveillance range (approximately 20-30 nm) of another test aircraft. During this time, the TCAS 2000 unit recorded three key types of information: the TCAS active slant range measurements, its own aircraft position reports, and the Mode S extended squitter position reports received from the test aircraft. Position reports were based on GPS units on the respective aircraft. For this report, only TCAS data recorded on N40 and N49 were analyzed. From these two aircraft, there were twenty different "encounters" that were suitable for hybrid surveillance analysis. Two of these encounters are subdivided into two parts because of a TCAS data recording reset that created a gap in the recorded data. These encounters last from less than a minute to over twenty minutes. For this report, "own" aircraft are N40 or N49 and target aircraft are N40, N49, N904UP, and N189H.

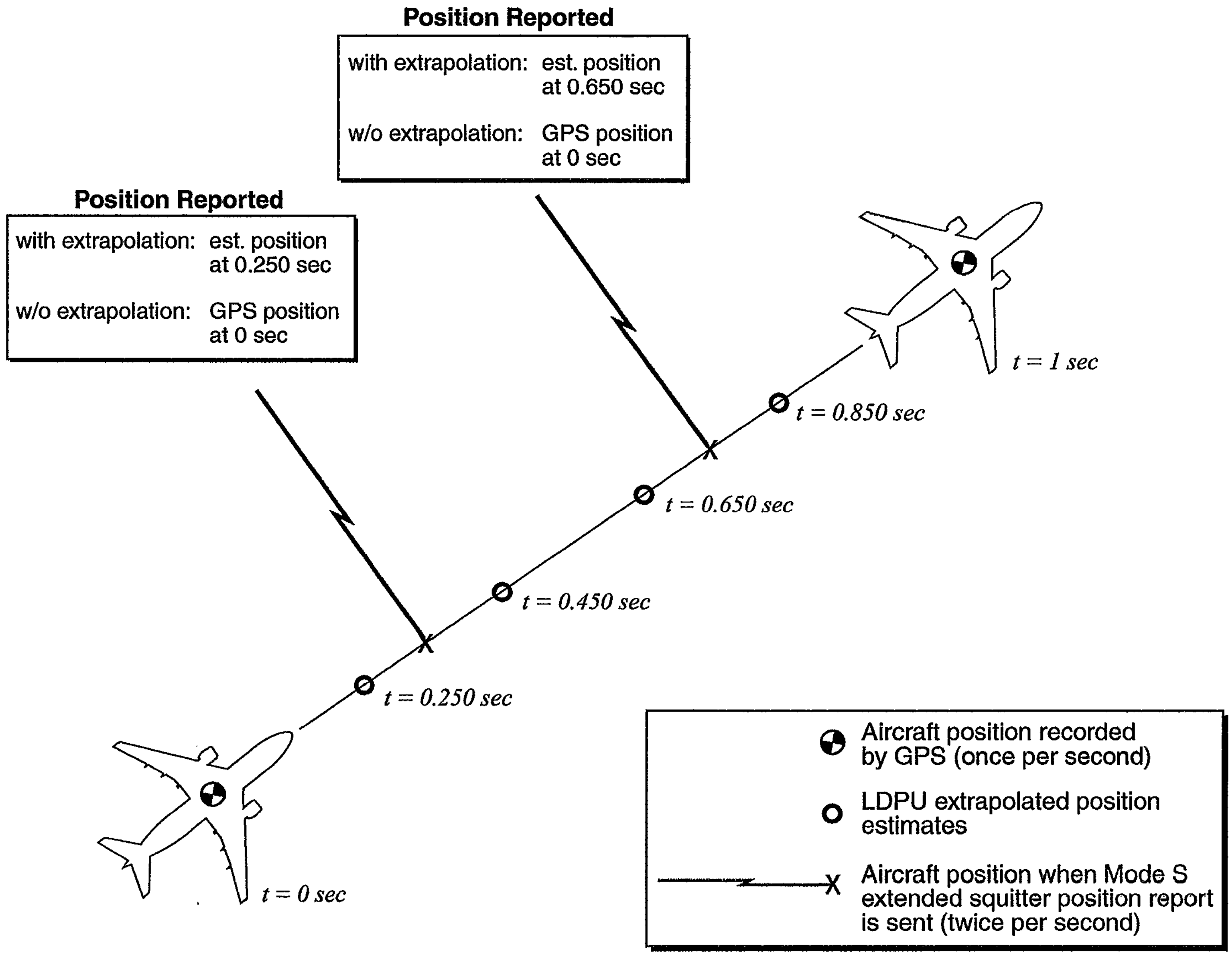


Figure 2. Effect of extrapolation on Mode S extended squitter position report.

3. SOURCES OF ERRORS IN MEASUREMENTS

3.1 Active Measurements

The active slant range is computed by measuring the elapsed time between an active TCAS interrogation from "own" ship and the receipt of a corresponding reply from the Mode S transponder on the "target" aircraft. The computation assumes a 128 μsec transponder turnaround time on the target aircraft. According to the Minimum Operational Performance Standards (MOPS) for Mode S transponders [5], this 128 μsec turnaround time has a tolerance of ±0.25 μsec with a jitter of ±0.08 μsec. This would result in a particular transponder introducing a bias error that remained essentially constant of approximately ±37.4 meters with a measurement to measurement jitter of approximately ±12.0 meters. All of the transponders used in these tests were L-3 Communications Corporation XS950 Mode S transponders. It is unknown whether or not a particular manufacturer might have a similar bias in like manufactured units. The characteristics of production ADS-B capable transponders manufactured by L-3 and other manufacturers are yet to be determined.

3.2 Passive Measurements

The passive range measurements were computed by interpolating own and target aircraft position reports (latitude, longitude, and altitude) to correspond with the TCAS system time of active range measurement. These position reports were used to compute slant range by first using algorithms to convert the positions to a 3D Cartesian coordinate system [6] and then computing the range directly. The ranges were also independently computed using algorithms developed for surveillance systems range computations [7]. Agreement was within approximately 0.5 meters.

There are at least three sources of error in the passive range computations. First are errors in the aircraft reported positions due to uncertainties in the GPS reports. The Standard Positioning Service (SPS), at the time of the flight tests, provided predictable accuracies of 100 meters 2 drms, 95% in the horizontal plane [8]. Errors in GPS position are due to intentional dither of the C/A code (which has since been discontinued), errors in estimating ionospheric delay propagation, and Geometric Dilution of Precision (GDOP) due to satellite geometry. The nature of the error sources implies that there should be some correlation in position error to aircraft in the same vicinity. That in turn should result in less error in range computation than if the errors were uncorrelated.

A second source of error results from the interpolation of position reports to correspond with the times of the active interrogation. Care was taken to verify that there were no large gaps in own or target position reports. TCAS interrogations are transmitted once every five seconds until the target aircraft is perceived to be a potential threat. Then, the interrogation rate is increased to once per second. Own and target aircraft GPS positions recorded on the TCAS-2000 were interpolated to match these times. Based on the GPS position update rates and very low accelerations observed during these encounters, errors due to interpolation are considered negligible.

Third, there will be an error in range calculations due to the time required for the target aircraft to read its GPS position, store that in the transponder, send the position report via Mode S extended squitter, and have the receiver aircraft decode and time-stamp the target aircraft position. This results in an error that is dependent on the time delay and the velocity vector of the target aircraft relative to own ship. The effect is that the target aircraft seems to be reporting the position it was at some Δ time past. Figure 3 illustrates this effect for a crossing target aircraft. Initially, the computed range is larger than the actual range, but after the target aircraft passes, the computed range is shorter than the actual range. Similarly, in a head-on crossing, the target aircraft computed range is longer than the actual range before the crossing and shorter after the crossing.

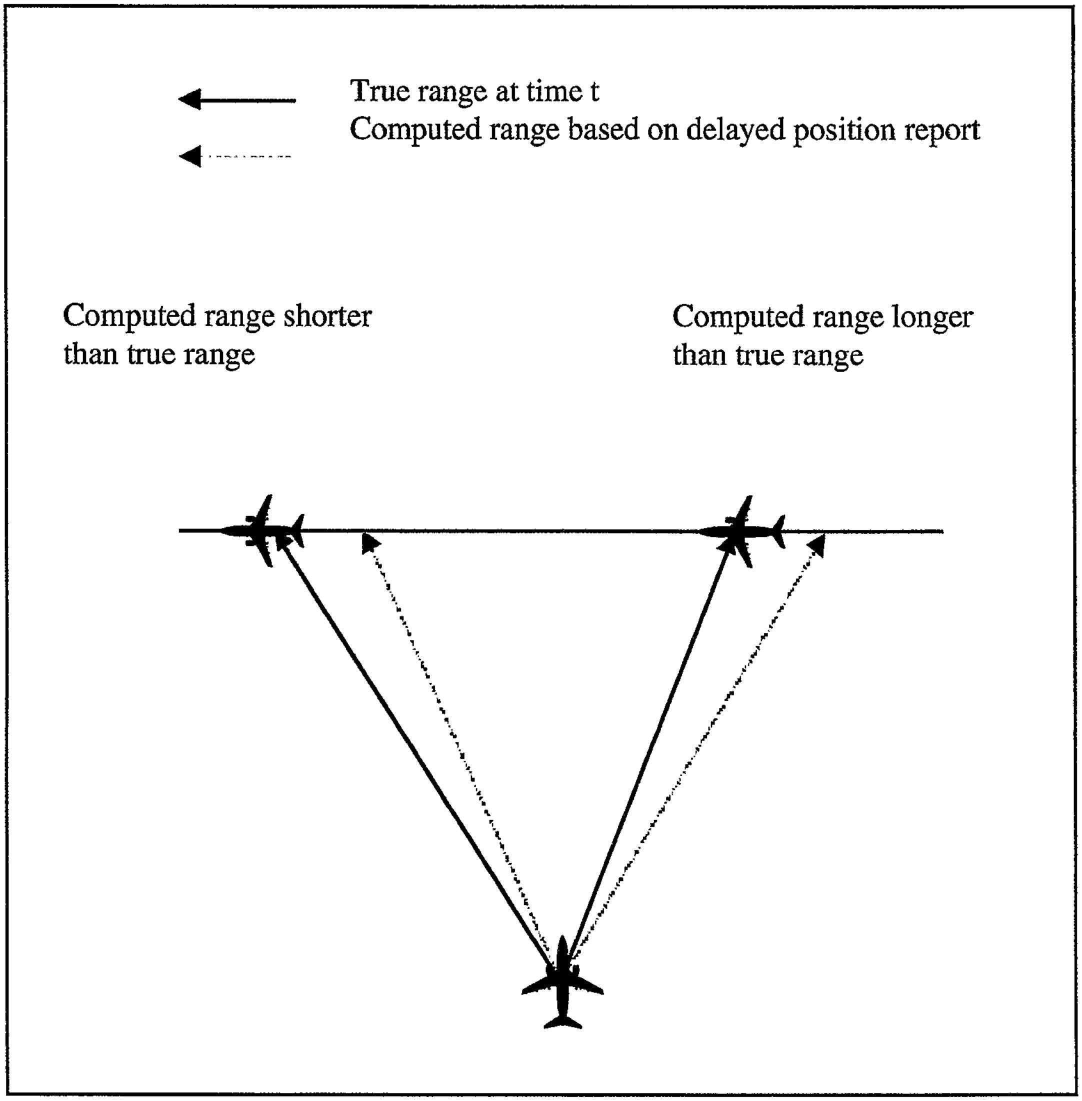


Figure 3. Illustration of Range Bias Introduced by the Delay in Recording of Target Aircraft Position.

Note that the magnitude of the difference is a function of the *ground speed of the target aircraft* and *relative angles of the velocity vectors* of the two aircraft. Thus, the errors will be larger for a head on crossing than for a right angle crossing illustrated above. The effect is to cause a bimodal distribution in the measurements of the range differences with the two peaks corresponding to measurements before and after the crossings.

The GPS navigation avionics updates the position report once per second. Aircraft equipped with LDPUs transmit GPS position reports that are extrapolated ahead of the last GPS report to estimate the position at 250, 450, 650, and 850 millisecond intervals. The extrapolation will significantly reduce the bimodal characteristic of the measurements as compared with other experimental equipment not yet providing extrapolated data. In the Los Angeles tests, all aircraft except N189H were equipped with LDPUs.

4. METHOD OF ANALYSIS OF ENCOUNTERS

4.1 Encounter Analysis

A total of twenty encounters were analyzed. Each encounter was analyzed using the same procedure that will be described here for one encounter. The results of each analysis are given in the Appendix and summarized in Table 1 in Section 5. The encounter used here as an example is encounter 1. Own aircraft was N40 and the target aircraft was N49. The encounter involved N40 overtaking N49 on June 14, 1999 after both aircraft departed Fort Smith, Arkansas. The tracks of the aircraft are shown in Figure 4.

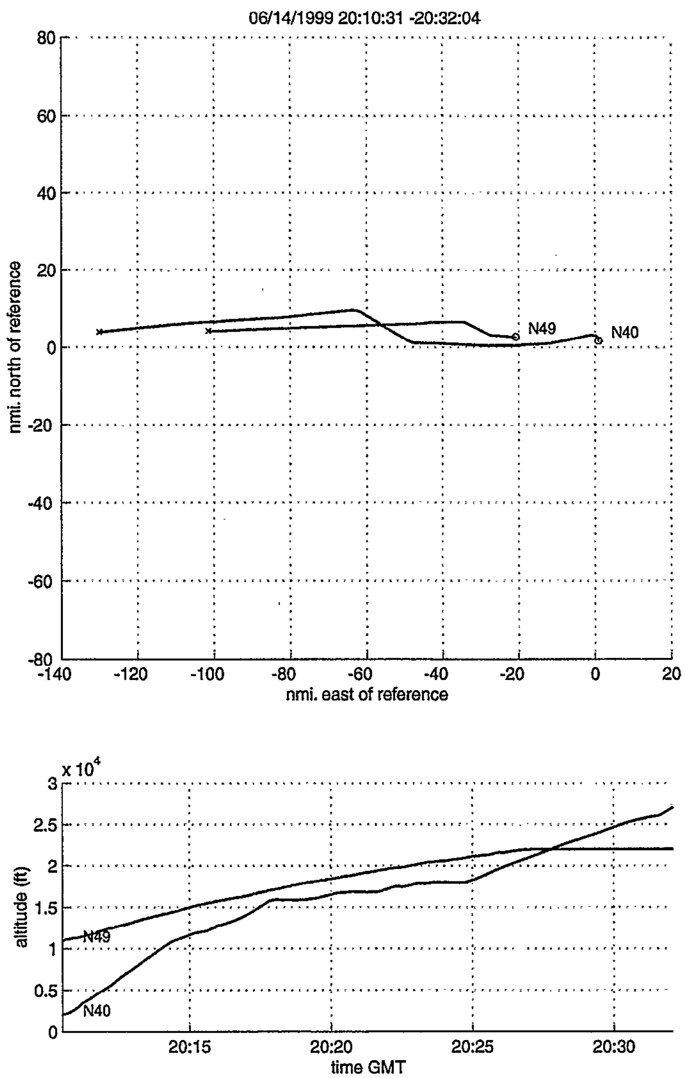


Figure 4. Position of N40 and N49 During Overtake June 14, 1999, Western Arkansas.

The position data are the GPS reported own position data available from each aircraft's LDPU. An "o" marks the position at the start of the data recording time period and an "x" denotes the position at the end of the time period. Data recording interrupts will be noted on some encounters. For all encounters except 1 & 2, which took place in western Arkansas, the positions are referenced to the ground station just west of the Los Angeles International Airport. In Figure 4, the positions are referenced to the departure point. The times referenced in the title of Figure 4 and all other plots are automatically generated from the data to ensure accuracy. On June 18, all times recorded aboard N40 were exactly two hours different from the actual time. This is because, on this day only, the TCAS recorded personal computer (PC) time was inadvertently miss-set by two hours. This is reflected in the plots in the Appendix for encounters 11 through 15 where the position times differ from the data analysis times by two hours. The PC times are included in the data as an aid in comparing the data with other data sources and are approximate although believed to be within ±1 second. These times are not used in comparing active slant range with passive interpolated range; for that comparison only TCAS system time is used. TCAS system time is the time, in seconds, since system power-up.

4.2 Recorded Data

Data of interest are recorded during periods when both active and passive range measurements are available. The data file analyzed in this case contains active range measurements made by N40 on N49 during the overtake and extended squitters received from N49. Figure 5 is a plot of the Δ time gaps between active interrogations

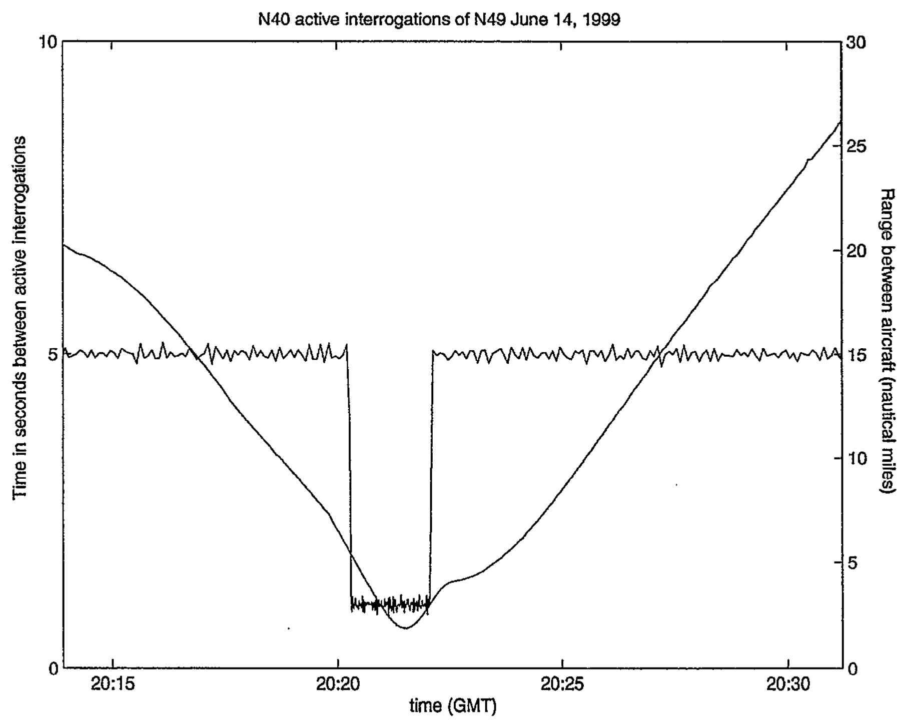


Figure 5. Active Interrogations of N49 by N40 on June 14, 1999.

and range between aircraft, both as a function of time. We see active interrogation every five seconds until the target aircraft (N49) is considered a possible threat. At that point, average active interrogation rate increases to once a second.

The next step is to check for time gaps in the received squitter position reports. The concern is that the interpolation of target aircraft position will be compromised during coasting periods.

4.3 Data Reduction

Each TCAS active range measurement is recorded along with the TCAS system time at which the range measurement was made. A linear interpolation is then performed on the GPS reported "own" position reports to estimate the position (latitude, longitude, and altitude) of own aircraft at the time of the active range measurement. Another interpolation is performed on the "target" aircraft positions as reported in the Mode S extended squitter. The positions are converted to 3-D Cartesian coordinates and a passive interpolated range is computed. The difference or delta range is defined as the active range minus the interpolated passive range. Because of the time delay in reporting target aircraft position, there is an expected bias based on the geometry of the relative velocity vectors as described above. The delta range is plotted versus system time and versus range between aircraft. This is illustrated in the first two sub-plots in Figure 6. The third subplot is a histogram of delta range measurements over the time period of the event. The mean and standard deviation are computed and printed on the plot. Because the distributions are not Gaussian, care should be taken not to attribute Gaussian confidence intervals to the standard deviations.

4.4 Interpretation of Results

The delta range histogram exhibits a bimodal characteristic due to the time delay bias of the target aircraft as described in Section 2.2 and illustrated in Figure 3. This is most easily seen in the plot of delta range versus system time during the overtake. The active minus the passive range is approximately 111 meters before the overtake and 57 meters after the overtake. This effect was consistent in all of the observed events. Note that there are more measurements before the crossing than after the aircraft pass. This can be seen by the distribution of the density of data points in the first two subplots. It is due to the increase in active interrogations before the crossing. The mean of the delta range measurements for this encounter was slightly positive (87 meters).

Notice that there is no apparent change in delta range as a function of range or time before or after the overtake, only as the overtake occurs and there is a change in the geometry of the relative velocity vectors of the aircraft. This is consistent with observations in the other encounters.

This procedure was carried out for every encounter. In cases where the data recording was interrupted during an encounter, the analysis was broken into two parts.

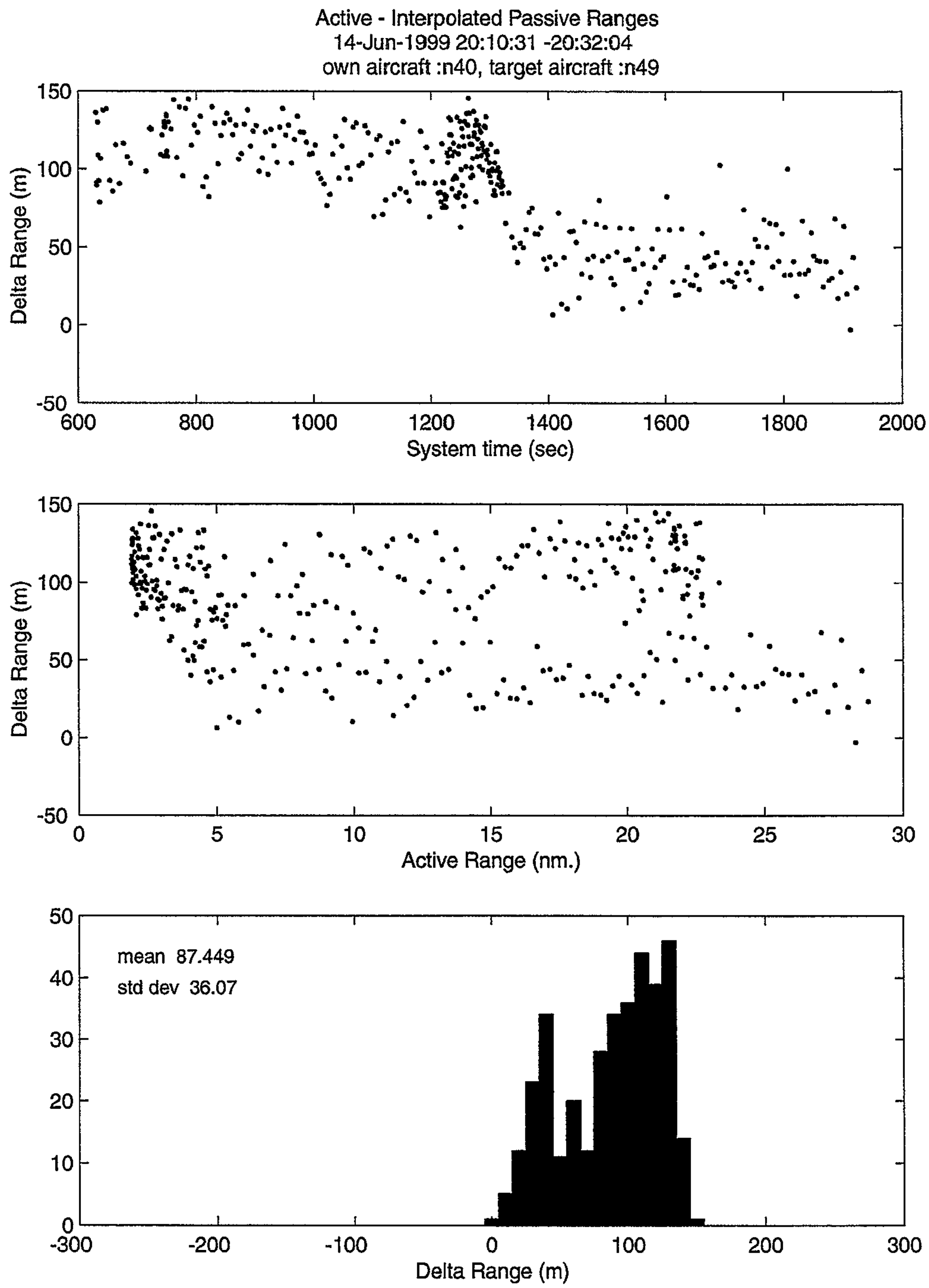


Figure 6. Active - Interpolated Passive Ranges for the N40 overtake of N49 June 14, 1999.

5. SUMMARY OF RESULTS

5.1 Goals and Methodology

The primary goal of this effort was validation of the SARPs limits for active/passive range comparison. The SARPs recommendation is that passive and active range data agree within 200 meters in order for the passive data to be considered valid. For purposes of this report, the 200 meter limit was considered to be valid if the delta range measurements corresponding to production equipment were within 200 meters. A summary of the delta range measurements is given in Section 5.2 and Table 1. As shown in Figure 7, for encounters with extrapolated updates, i.e., equivalent to production equipment, all delta range measurements were within 200 meters.

The secondary goal was examination of active/passive range differences for use in future activities that require the fusion of various sources of surveillance data. Additional discussions of the data related to this goal are contained in Section 5.3

There were twenty encounters analyzed using the methods described in Section 4. The data were recorded on N40 or N49 and the target aircraft were N40, N49, N904UP, and N189H. Table 1 summarizes the encounters analyzed. μ refers to the mean of all measured values of active range minus the interpolated passive range during the encounter. σ refers to the standard deviation. Encounters with N189H as the target aircraft are shaded to indicate there were no extrapolated updates of GPS position data. Plots of the positions of the aircraft and the delta range measurements for each individual encounter are listed in the Appendix.

5.2 Validation of SARPs Requirements

One approach at summarizing the data is to simply combine all delta range measurements (active minus interpolated passive range) made for all twenty encounters. However, one aircraft, N189H, did not provide extrapolated updates (five times per second) of the GPS position reports to the transponder. Therefore, data from this aircraft are fundamentally different than data from the other three aircraft. For that reason, the data on encounters from this aircraft are separated from the data of the other aircraft. Figures 7 and 8 are histograms showing all delta ranges measurements for all encounters listed in Table 1. Figure 7 is for aircraft with extrapolated updates and represents thirteen encounters. Figure 8 is a compilation of all encounters with data received from N189H and represents seven encounters. For the encounters represented in Figure 7, all delta range measurements are within 200 meters.

The first observation from the data shown in Figure 7 is that the agreement between the TCAS slant range measurements and the computed passive range measurements is quite good and that the data have very small tails with no spurious outliers. The reason for the overall bias is not known. Since the bias is small, it may simply be due to the small sample of four transponders that were observed, all from the same manufacturer. Regardless, the agreement is remarkably good. Examination of the individual encounters in the Appendix shows no indication that the range differences are a function of range.

Table 1. Summary of Encounters with Mean and Standard Deviations of Delta Range Measurements
(Shading indicates aircraft with no position extrapolation)

	own aircraft	target aircraft	description	date	duration mm:ss	µ (m)	σ (m)
1	N40	N49	N40 overtakes N49 during climbout	6/14	10:55 prior 10:38 after	111 57	19 30
2	N49	N40	"	"	11:45 prior 15:25 after	11 85	27 35
3	N40	N904UP	N40 reverses course to fly 45 degrees to UPS904	6/16	0:30 prior 3:26 after turn	32 93	23 14
4	N49	N40	N49 following N40, 20 miles in trail	6/16	1:52	74	21
5	N49	N40	N49 flies inbound to coast while N40 orbits LAX	6/16	1:32 1:53	56 33	32 13
6	N49	N904UP	N49 flies inbound to coast, UPS flies north up coast	6/16	3:09	68	18
7	N40	N49	maneuvering to landings	6/17	5:47	79	21
8	N49	N189H	head-on crossing	6/17	0:15 prior 3:44 after	-88 178	44 43
9	N49	N189H	N189H overtakes N49 from behind then N49 reverses course	6/17	8:14 overtake 4:00 turn 4:29 opposite	-66 80 207	42 105 54
10	N49	N40	maneuvering to landings	6/17	8:28	43	22
11	N40	N189H	far apart crossing	6/18	3:09	84	43
12	N40	N189H	head on, data stopped before crossing	6/18	3:15	-50	33
13	N40	N189H	head on after crossing	6/18	2:07	218	49
14	N40	N189H	head on crossing slight turn by both aircraft (same track)	6/18	1:39 prior 1:27 after	-66 209	46 39
15	N40	N189H	diverging at right angles, far apart	6/18	2:28	114	43
16	N49	N40	N40 overtakes N49 during departure	6/18	7:04	10	32
17	N40	N49	N49 departing, N40 departing behind at right angles	6/19	3:00	120	17
18	N40	N49	N49 crosses at right angles in front of N40	6/19	3:15	106	20
19	N49	N40	N49 departing, N40 departing behind at right angles. Same as 17	6/19	3:35	35	27
20	N49	N40	right angles departing continuation of right angles departing ending with "U" turn by N49	6/19	0:16 4:50	21 57	15 17

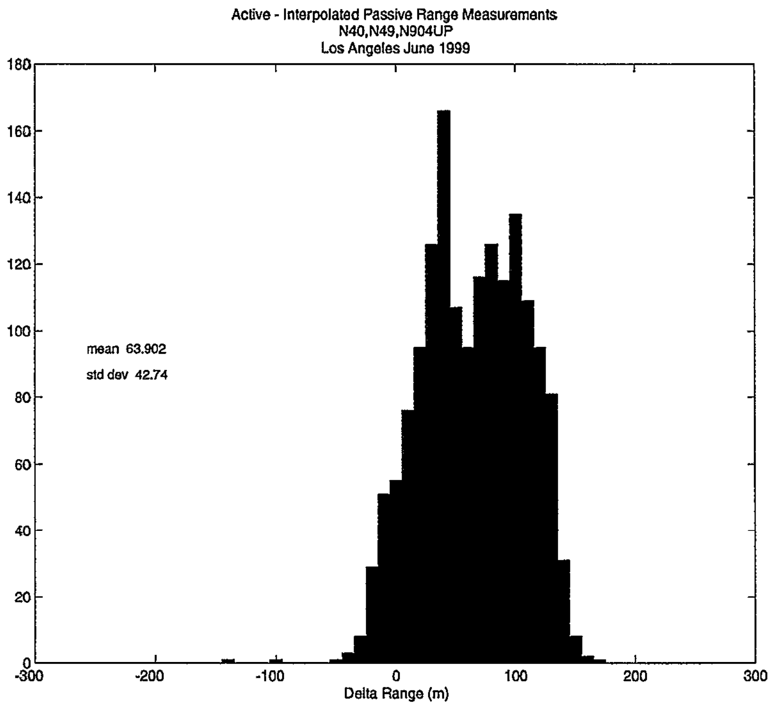


Figure 7. Summary of Active - Passive Range Measurements for all Encounters with Extrapolated Updates.

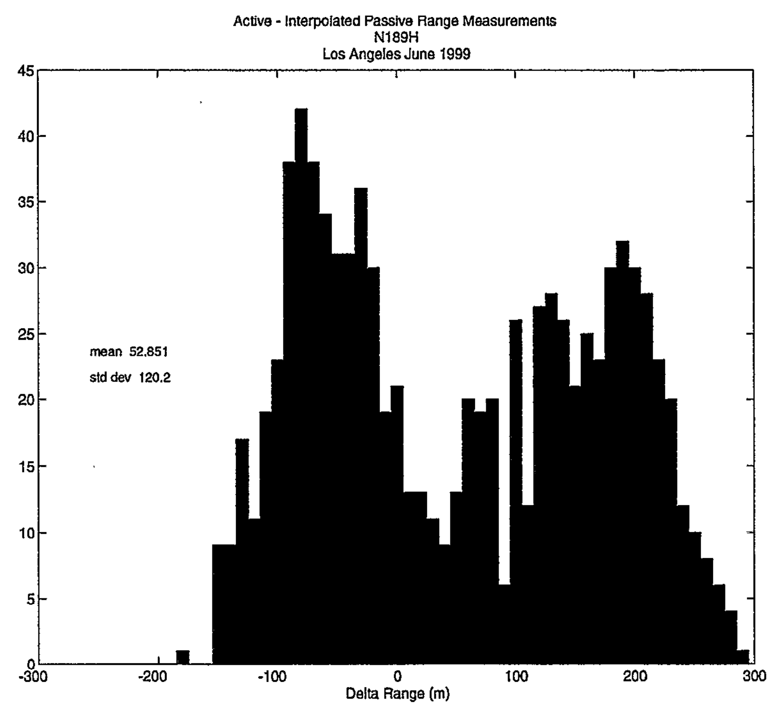


Figure 8. Summary of Active - Passive Range Measurements for all Encounters without Extrapolated Updates.

The effect of updating the GPS position five times per second is evident in comparing Figures 7 and 8. The bimodal characteristic of the data due to the time lag effect is much more pronounced in the data without the higher update rate. It is important to note that the 1090 MHz MOPS[3] require the higher update rate. The LDPU acted as an emulation of the expected performance of all production equipment. A slight bimodal characteristic can be noted in Figure 7 and is easier to detect in certain individual encounters listed in the Appendix. Discussion with UPS Aviation Technologies revealed that subsequent to the Los Angeles tests, the LDPU software was updated to change the extrapolated position times from 250, 450, 650, and 850 milliseconds to 300, 500, 700, and 900 milliseconds to better estimate the time bias. The effect of this should be to tighten the distribution illustrated in Figure 7 even more.

The data collection rate depended on the relative geometry of the aircraft. In some cases, active interrogations increased and thus so did the delta range measurements. However, the geometry also determined the time bias of the passive range measurements as described in Section 3.2. The encounters were chosen based on the availability of active range measurements and may not reflect the delta range measurements that might be encountered in normal flight. It is important to note that the data were limited to two recording aircraft and four target aircraft, and that all target aircraft were equipped with an L-3 Communications Mode S transponder.

5.3 Additional Results and Observations

5.3.1 Additional Data Summaries

Another way to summarize the data is to take the mean of the means listed in Table 1. This process weights each encounter (or part of an encounter) equally regardless of the number of data points. The mean of the eighteen individual means listed in Table 1 for target aircraft performing position extrapolation is 60.6 meters, not significantly different than the mean of all of the individual measurements shown in Figure 7, 63.9 meters.

Since there were only two recording aircraft, N40 and N49, we can separate the eighteen individual means for target aircraft performing position extrapolation into two components representing the two recording aircraft. There are seven individual means listed in Table 1 in which N40 was the recording aircraft and the target aircraft was performing position extrapolation. The mean of means for N40 is 85.4 meters. There are eleven individual means in Table 1 in which N49 was the recording aircraft and the target aircraft was performing position extrapolation. The mean of means for N49 is 44.8 meters. Because of the limited number of cases, it is not clear whether or not this difference is statistically significant.

Similarly, the individual means listed in Table 1 can be broken up by target aircraft. There are 10 means in which N40 was the target with a mean of means of 42.5 meters. There are 5 means in which N49 was the target with a mean of means of 95 meters. There are 11 means in which N189H was the target with a mean of means of 74.5 meters and there are 3 means in which N904UP was the target with a mean of means of 64 meters.

5.3.2 Overtake Encounter

There are several individual encounters that offer additional insights into the results. Encounters 1 and 2 are the same encounter recorded by two different aircraft. The encounter is a slow over-take of N49 by N40 during climb-out. In one case, N40 is the own aircraft and N49 is the target aircraft and in the other case N49 is the own aircraft and N40 the target aircraft. The data are unique in this analysis in that it offers over twenty minutes of uninterrupted data recording of the same event as recorded by two aircraft. Table 1 shows that the mean of the delta ranges changes from 111 meters before the over-take to 57 meters after the over-take as recorded on N40. The mean of the delta ranges recorded aboard N49 changes from 11 meters to 85 meters. These changes are consistent with the bias introduced by the time delay of the target ship reporting its position as described earlier except that there exists an overall bias consistent with that observed in the summary data presented in Figure 7. That is, if there were no overall bias one would expect that N40 would measure positive delta ranges before the over-take and negative delta ranges after the over-take. The delta ranges measurements do make a shift down in magnitude with the over-take but remain positive. The data as averaged in Table 1 include the actual over-take event itself. If we examine the data in the Appendix for these encounters and take out the moments of over-take, it is estimated that the mean shifts from 110 meters to 40 meters for N40 own ship and N49 target ship measurements. For N49 own ship and N40 target ship measurements the means change from approximately 0 meters to 110 meters. This is a 70 meter change for N40 measuring N49 and a 110 meter change for N49 measuring N40. These results are consistent with the fact that N40 had a higher ground speed than N49. If we look at encounter 16, another overtake of N40 by N49 we see that N49 recorded a mean of 10 meters with N40 as the target in trail. This is consistent with the 11 meters listed in Table 1 for encounter 2 prior to the over-take. The increase by 50 milliseconds in the extrapolation times mentioned above should reduce this time bias.

5.3.3 Effect of One Second Update

It is interesting and instructive to examine individual encounters involving N189H, which did not have the extrapolated GPS position updates, as the target aircraft. As explained above and illustrated in Figure 2, the GPS position in this case is updated only once per second. Encounters 8, 12, 13, and 14 are all head on crossings with N189H as the target aircraft. Encounter 8 is recorded aboard N49. The mean of delta ranges before the crossing is -88 meters and the mean after the crossing is 178 meters. The shift is consistent with a delay in the target aircraft reported position. Again, we see an overall positive bias. The change in delta range measurements from before the crossing until after the crossing is 266 meters. Note that this is significantly larger than the changes observed in encounters 1 and 2. Encounters 12 and 13 are a similar head on crossing with N189H but are measured aboard N40. We see a change from -50 meters delta range before the crossing to 218 meters after the crossing, a total change of 268 meters, almost identical to that observed aboard N49 in encounter 8. Encounter 14 is another head on encounter with N189H recorded aboard N40 with consistent repeatable results; -66 meters before the crossing and 209 meters after the crossing, a change of 275 meters.

Finally, encounter 9 records an overtake of N49 by N189H as recorded aboard N49. The data averaged in Table 1 are somewhat misleading in that it averages the mean after the takeover with a turn by N49. If we examine the data during the overtake as illustrated in Figure 9, we see that the change is from approximately -65 meters in delta range to 175 meters in delta range, a total change of 240 meters which is consistent with the results for the head-on crossings. Also, after N49 turns around, the delta range measurement mean is 207 meters which is consistent with the head-on crossing encounters after the crossing. This is encouraging because we would expect

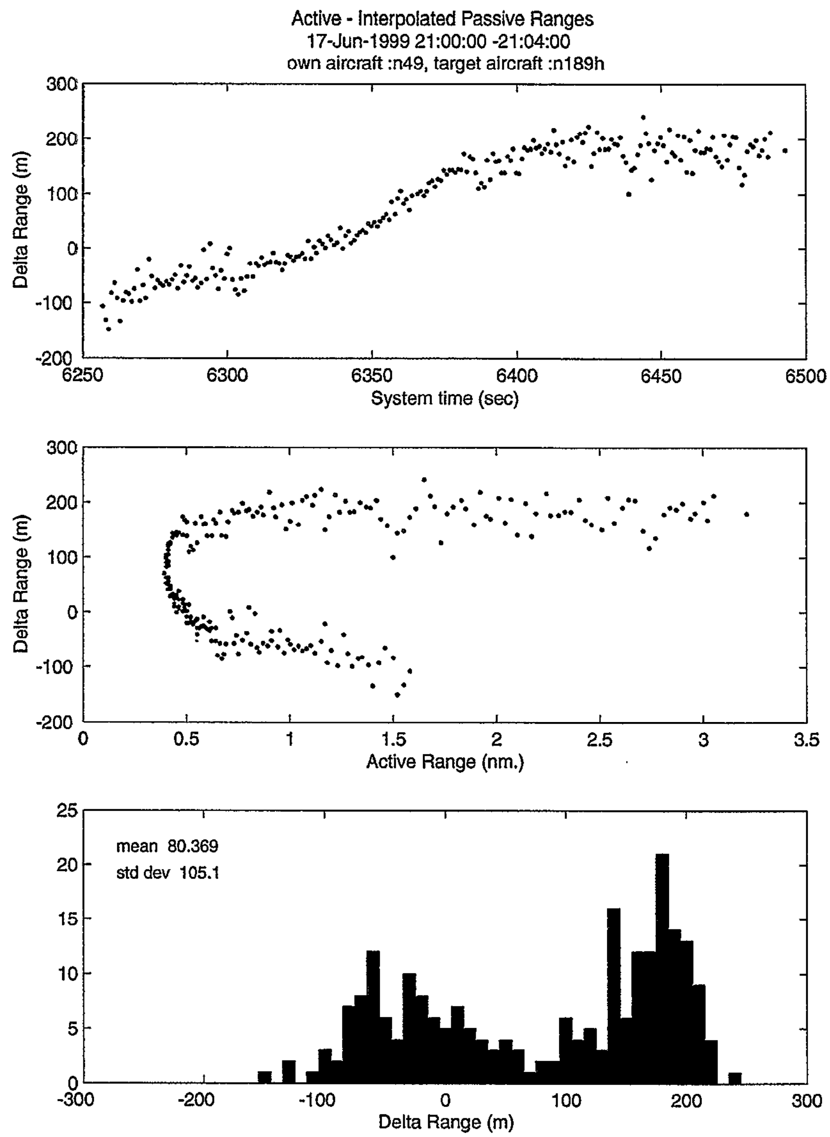


Figure 9. N189H target aircraft overtake of N49 on June 17,1999.

that a change in delta range measurements created by a time delay in recording the target aircraft position would be the same regardless of whether the event were an overtake or a head-on crossing. This seems to be the case.

An estimate can be made of the actual time delay in the reporting of the position of the target aircraft by examining the change in delta range and estimating the ground speed of the target aircraft, in this case N189H. We assume an average change in delta range of approximately 270 meters during the three head-on crossings. Examining the position plots of N189H in the Appendix for these events, we estimate ground speeds of between approximately 269 kts. and 330 kts. with an average of 294 kts. If we take half of the 270 meter delta range change, or 135 meters, it will take an aircraft traveling 294 kts approximately 0.9 seconds to cover that distance.

6. CONCLUSIONS

Data indicate that for aircraft meeting the 1090 MHz MOPS requirement of five per second GPS position update rate, passive computed range measurements consistently agree with TCAS active range measurements within 200 meters.

There is a bias in the mean of the grouped data of approximately + 64 meters; that is, on average the measured active range is 64 meters greater than the interpolated passive range. This bias is greater than can be explained by the transponder turnaround time tolerance specifications of $\pm$ 0.25 μsec ($\pm$ 37.4 meters). It is important to note that the magnitude of the bias observed in this data set would be irrelevant for TCAS operational effectiveness. Factors that can contribute to this bias include transponder and TCAS antenna cable lengths, transponder turnaround time, and TCAS range calibration. These are factors that may be calibrated out in certified standard installations.

The units aboard N40 and N49 were bench checked to verify that their turnaround times were within tolerance, however the transponder aboard N49 was at the upper limit of the tolerance and the transponder aboard N40 was in the middle of the specifications. This is consistent with the observation that the bias for N49 as a target was greater than for N40 as a target.

The standard deviation of the delta ranges is approximately 43 meters. The time tag bias described in section 3.2 and illustrated in Figure 1 will account for an unknown portion of this deviation. The data exhibit a sharp cutoff in the tails of the distribution; that is, there are no outliers.

There was no indication that the differences in range measurements were a function of range.

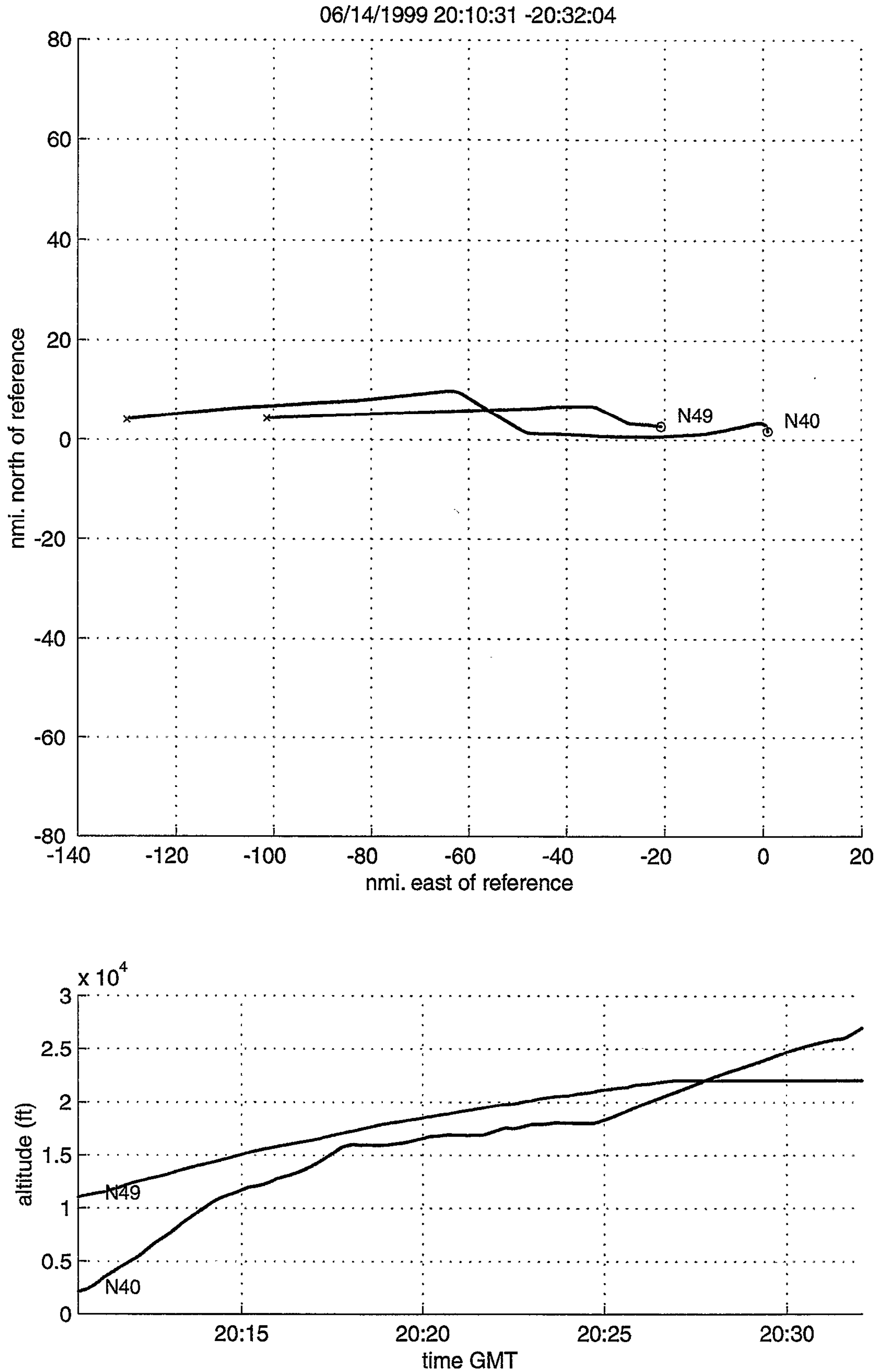
There were no indications of erratic passive range measurements.

The validation of the SARPs limit for active/passive range comparison was the primary goal of the work described in this report. A secondary goal was the examination of the active/passive range differences for use in future activities that require the fusion of various sources of surveillance data. Results demonstrate that the range difference specified by the ICAO ACAS SARPs as the maximum allowable difference for validation of reported position was never exceeded and serves to validate the 200 meter range difference limit. The SARPs represent the first attempt at specifying range limit differences for airborne surveillance data fusion. This report is the first look at any data to validate the 200 meter limit. No active and passive data have been available until the Los Angeles tests. From this data, we conclude that the 200 meter limit can be supported with production equipment and that we can commit to proceed with hybrid surveillance development based on the current SARPs requirements.

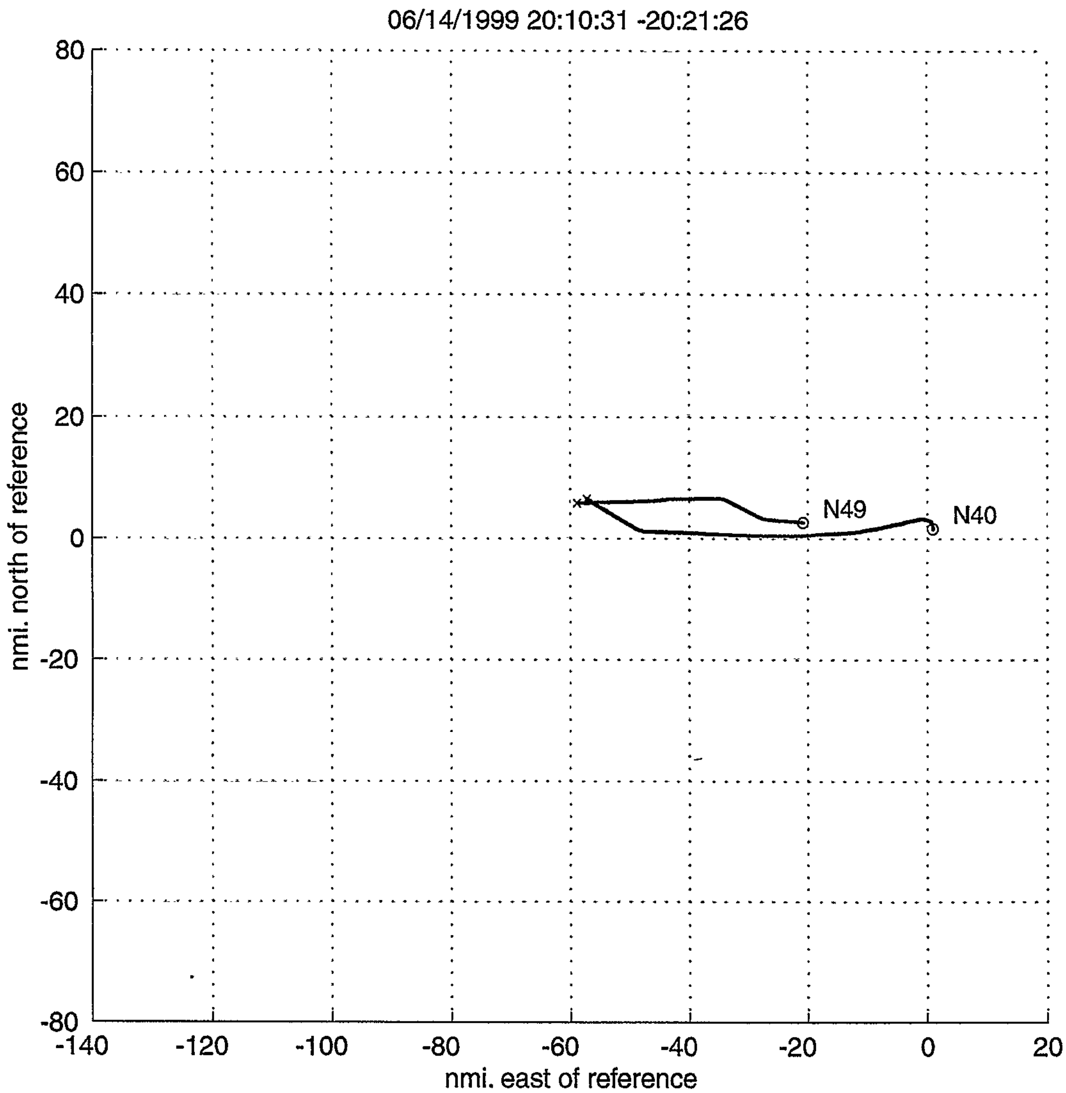
APPENDIX – DATA ON INDIVIDUAL ENCOUNTERS

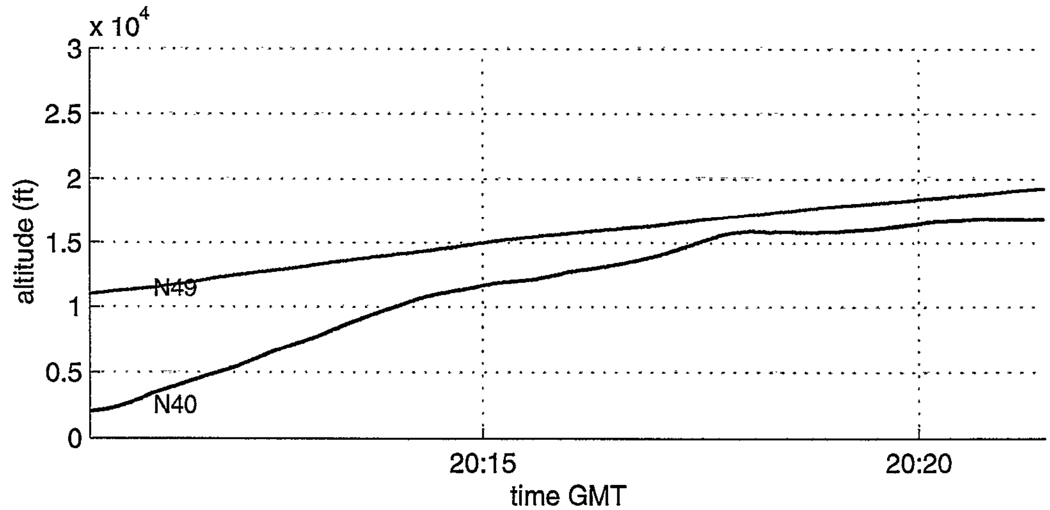
Encounters 1 and 2

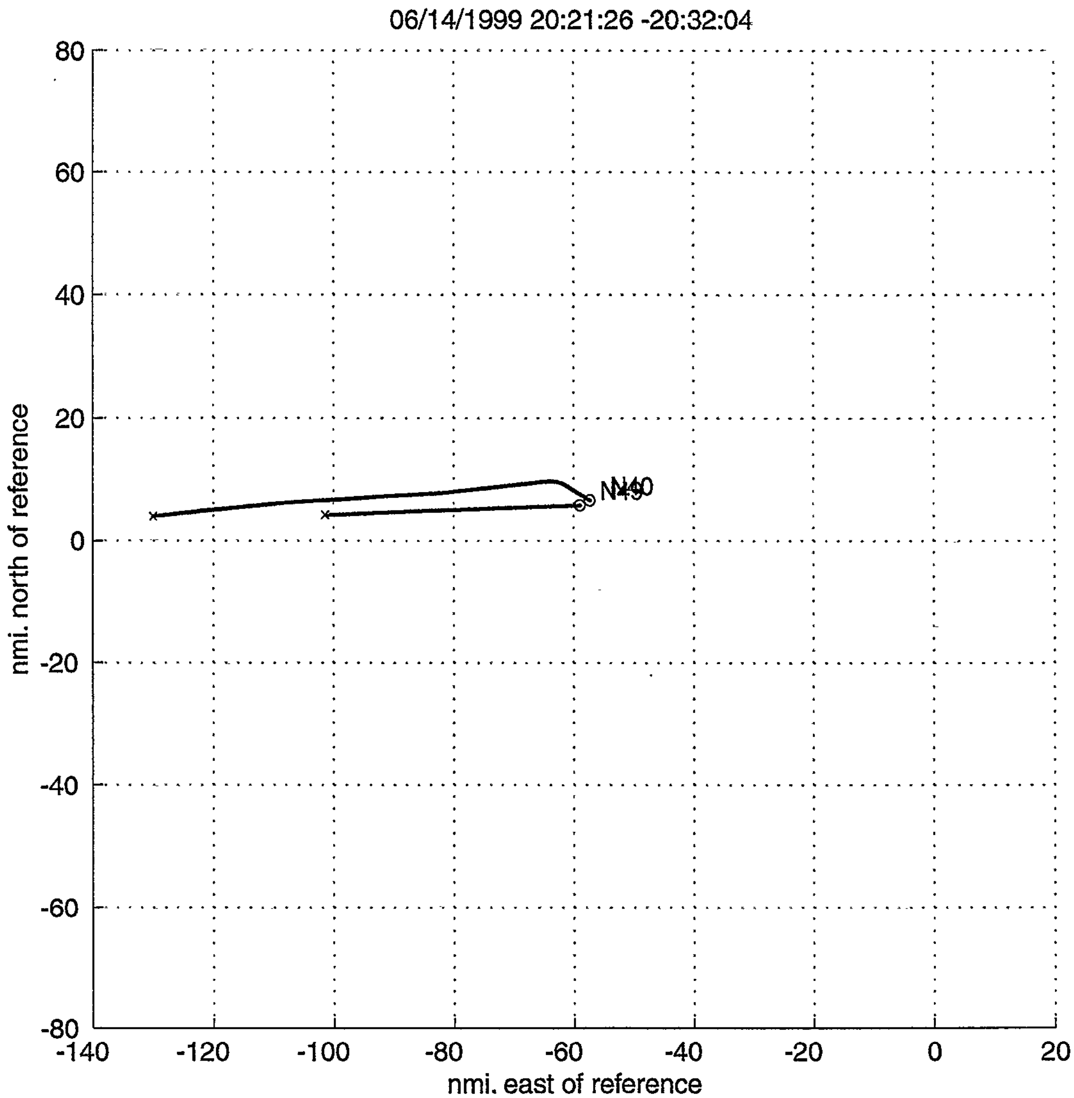
N40 overtakes N49 during climbout



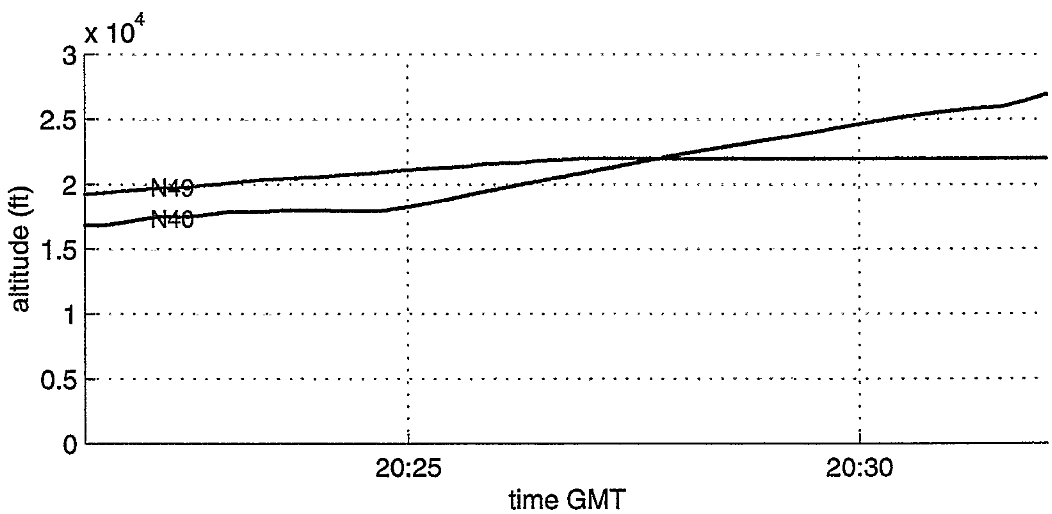
06/14/1999 20:10:31 -20:32:04
nmi. north of reference
nmi. east of reference
N49
N40
80
60
40
20
0
-20
-40
-60
-80
-140
-120
-100
-80
-60
-40
-20
0
20
x 10^4
altitude (ft)
time GMT
3
2.5
2
1.5
1
0.5
0
20:15
20:20
20:25
20:30
N49
N40


06/14/1999 20:10:31 -20:21:26
nmi. north of reference
nmi. east of reference
N49
N40
80
60
40
20
0
-20
-40
-60
-80
-140
-120
-100
-80
-60
-40
-20
0
20

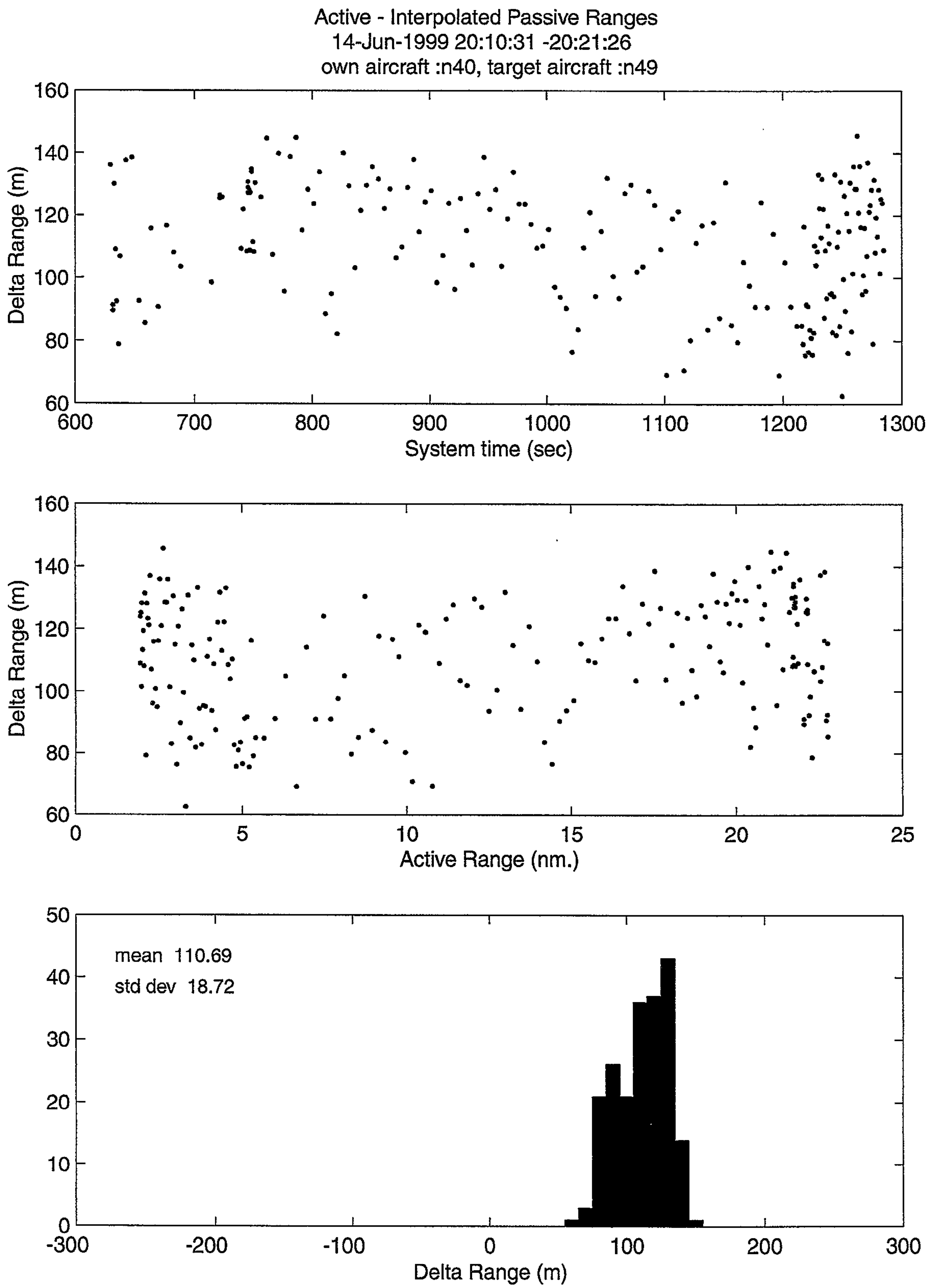

x 10^4
altitude (ft)
time GMT
N49
N40
3
2.5
2
1.5
1
0.5
0
20:15
20:20



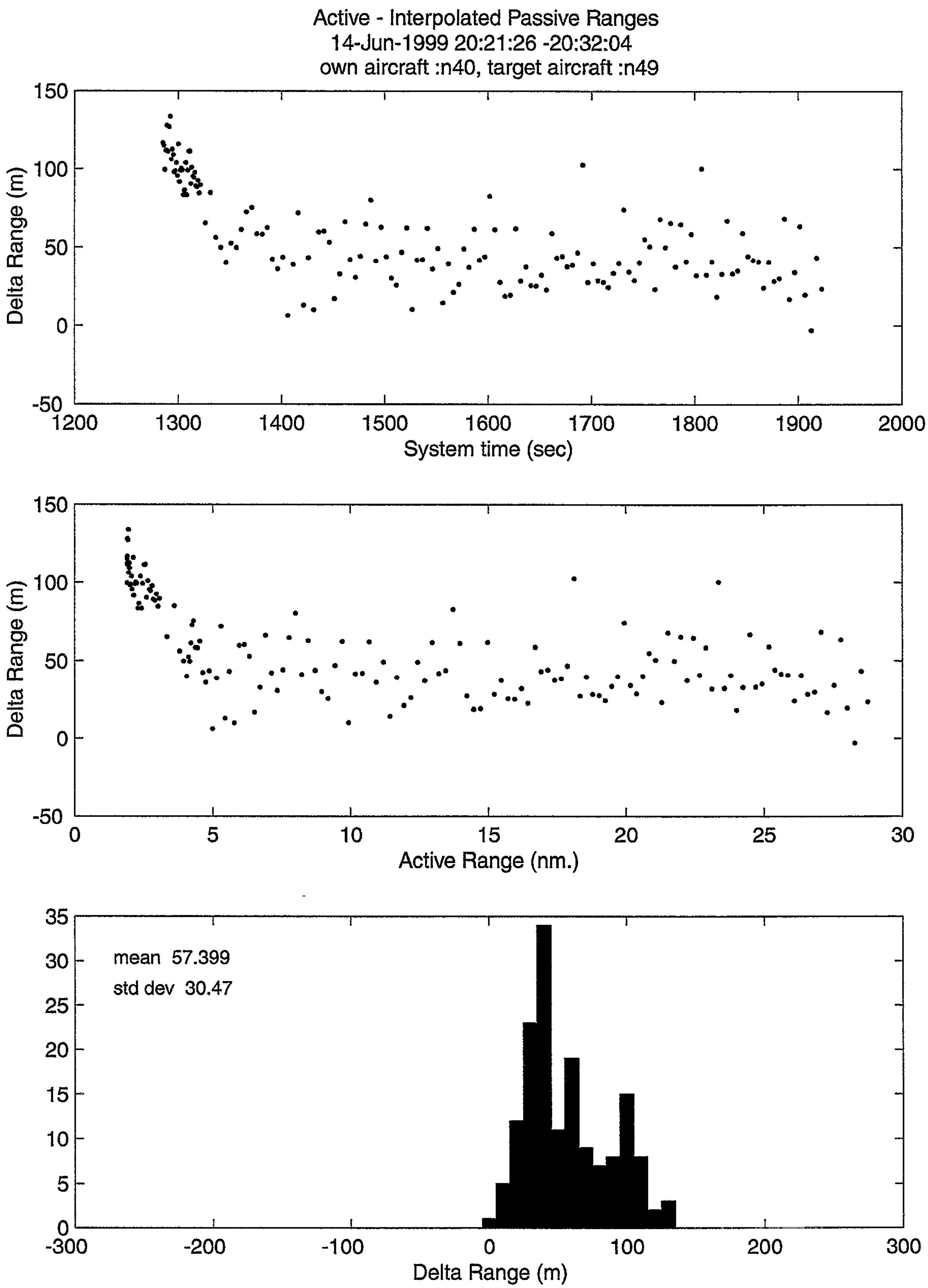
06/14/1999 20:21:26 -20:32:04
80
60
40
20
0
-20
-40
-60
-80
nmi. north of reference
-140
-120
-100
-80
-60
-40
-20
0
20
nmi. east of reference
N40
N49

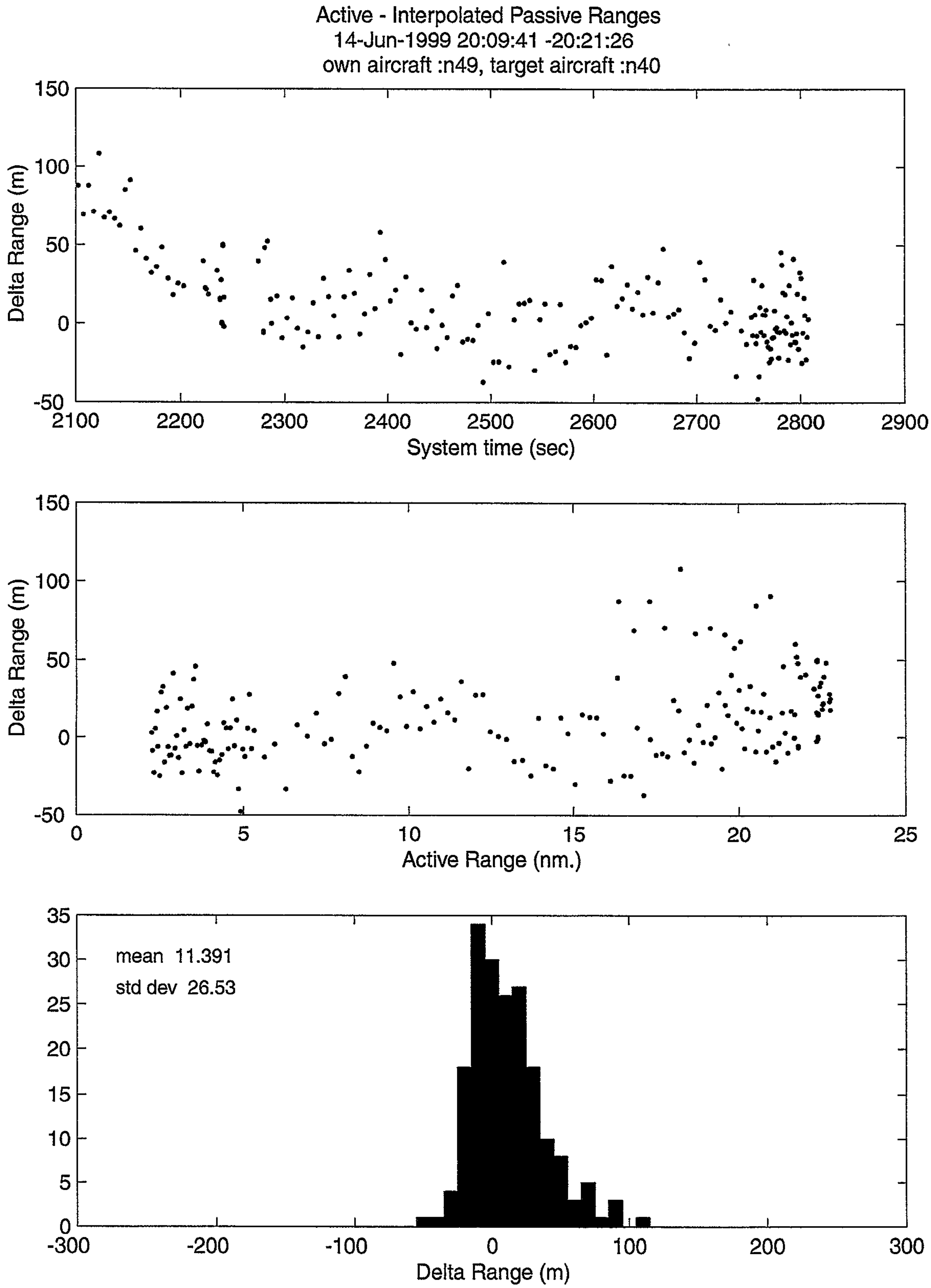


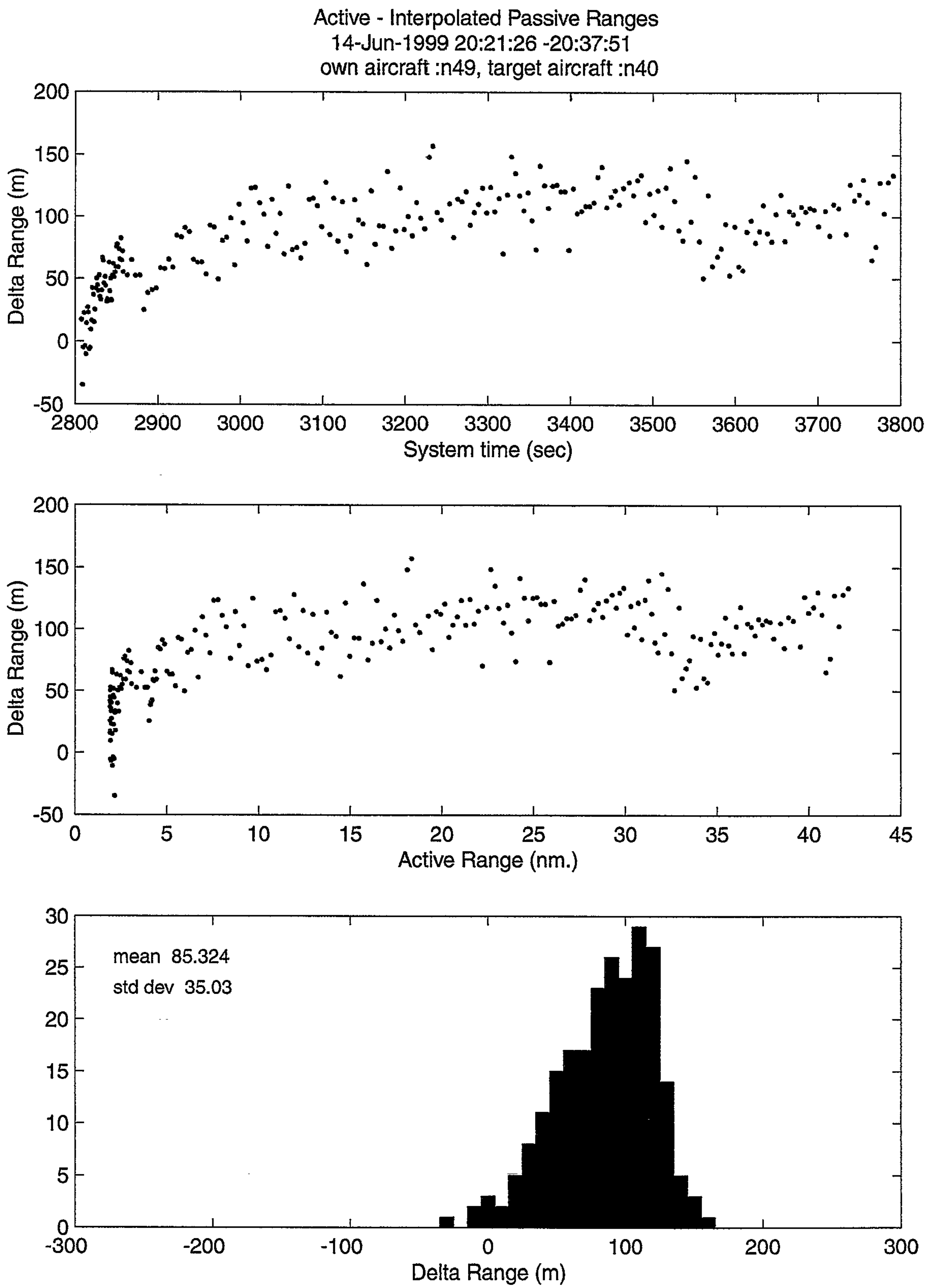
x 10^4
3
2.5
2
1.5
1
0.5
0
altitude (ft)
N49
N40
20:25
20:30
time GMT



Active - Interpolated Passive Ranges
14-Jun-1999 20:10:31 -20:21:26
own aircraft :n40, target aircraft :n49
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 110.69
std dev 18.72
Delta Range (m)


Active - Interpolated Passive Ranges
14-Jun-1999 20:21:26 -20:32:04
own aircraft :n40, target aircraft :n49
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 57.399
std dev 30.47
Delta Range (m)

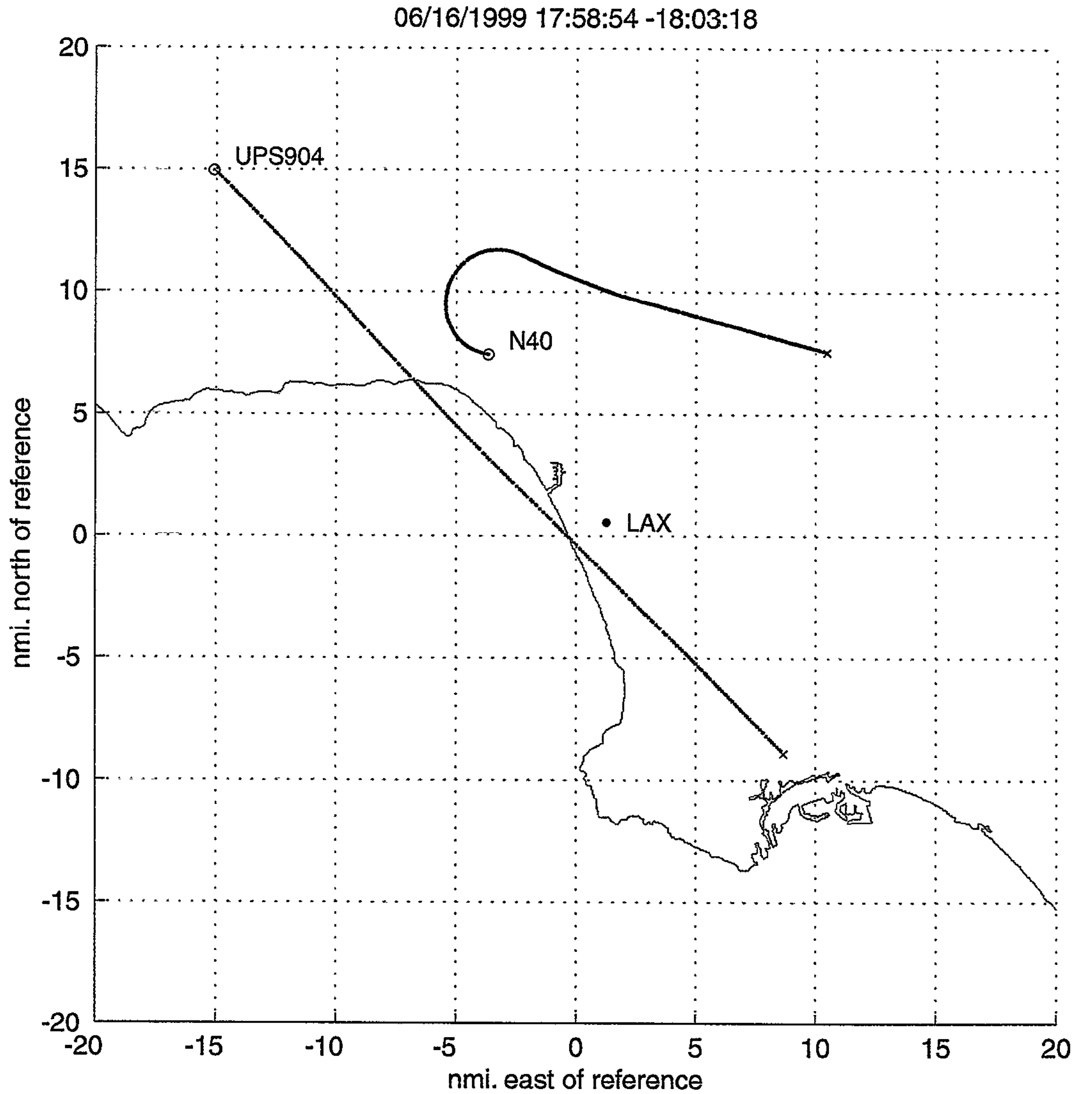

Active - Interpolated Passive Ranges
14-Jun-1999 20:09:41 -20:21:26
own aircraft :n49, target aircraft :n40
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 11.391
std dev 26.53
Delta Range (m)

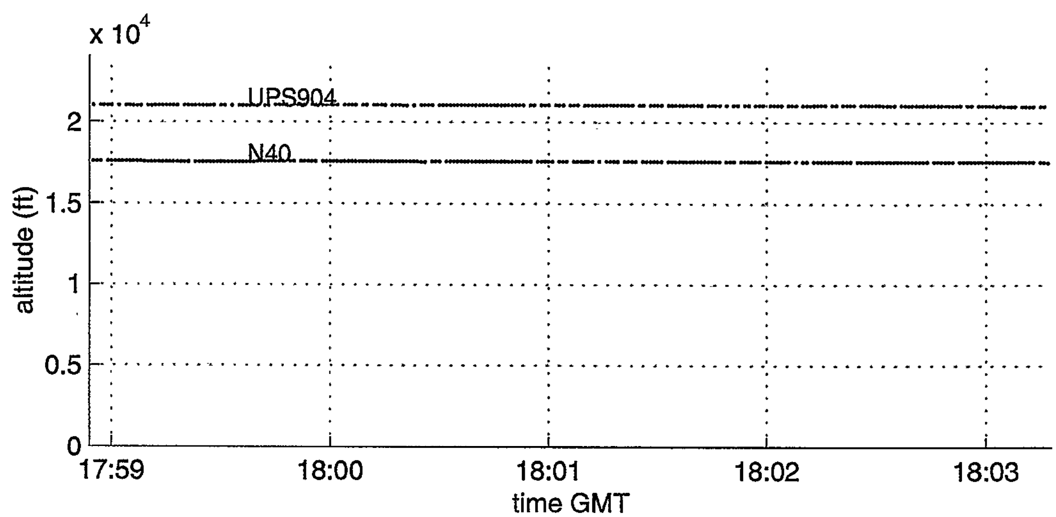


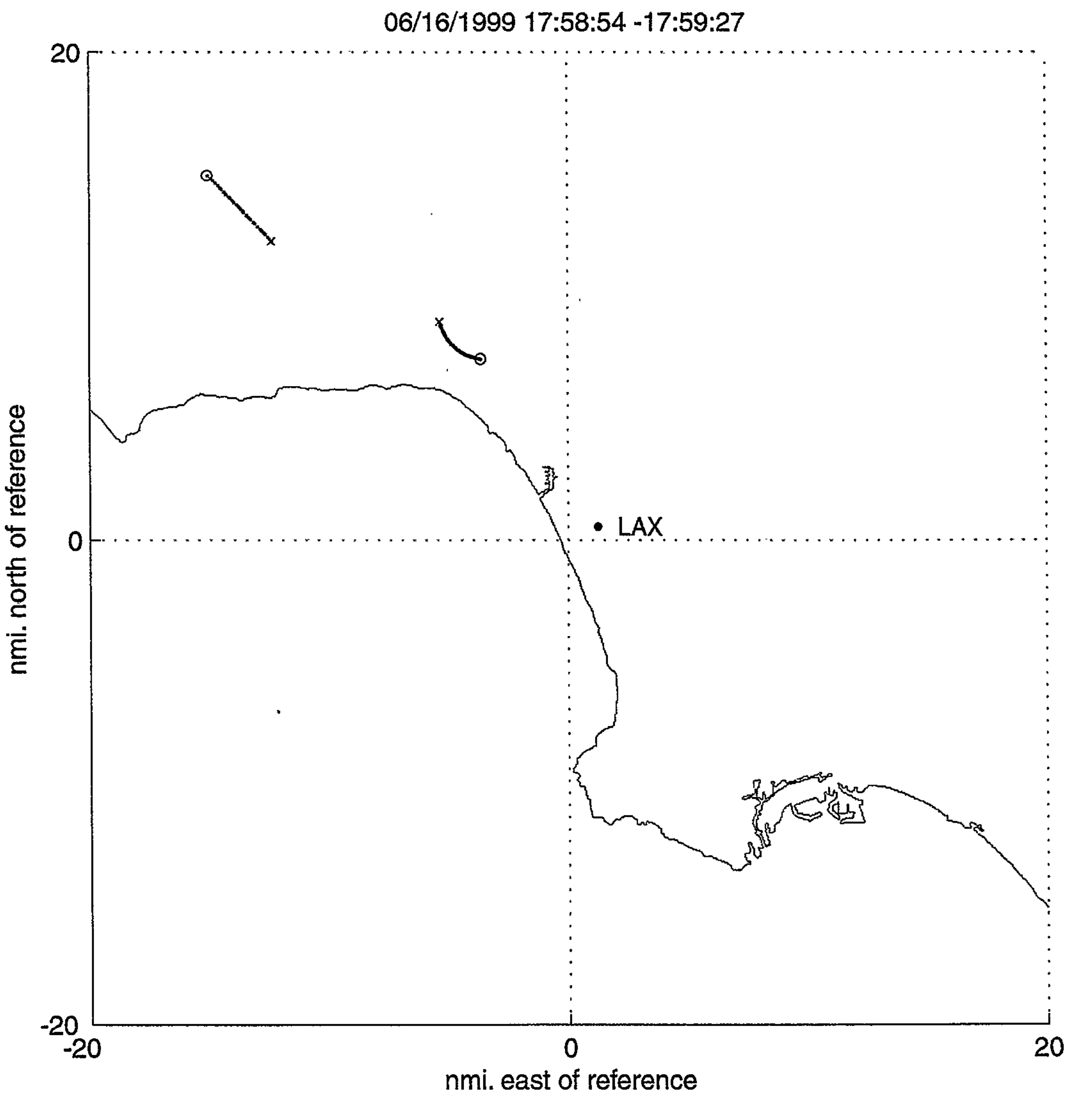
Active - Interpolated Passive Ranges
14-Jun-1999 20:21:26 -20:37:51
own aircraft :n49, target aircraft :n40
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 85.324
std dev 35.03
Delta Range (m)

Encounter 3

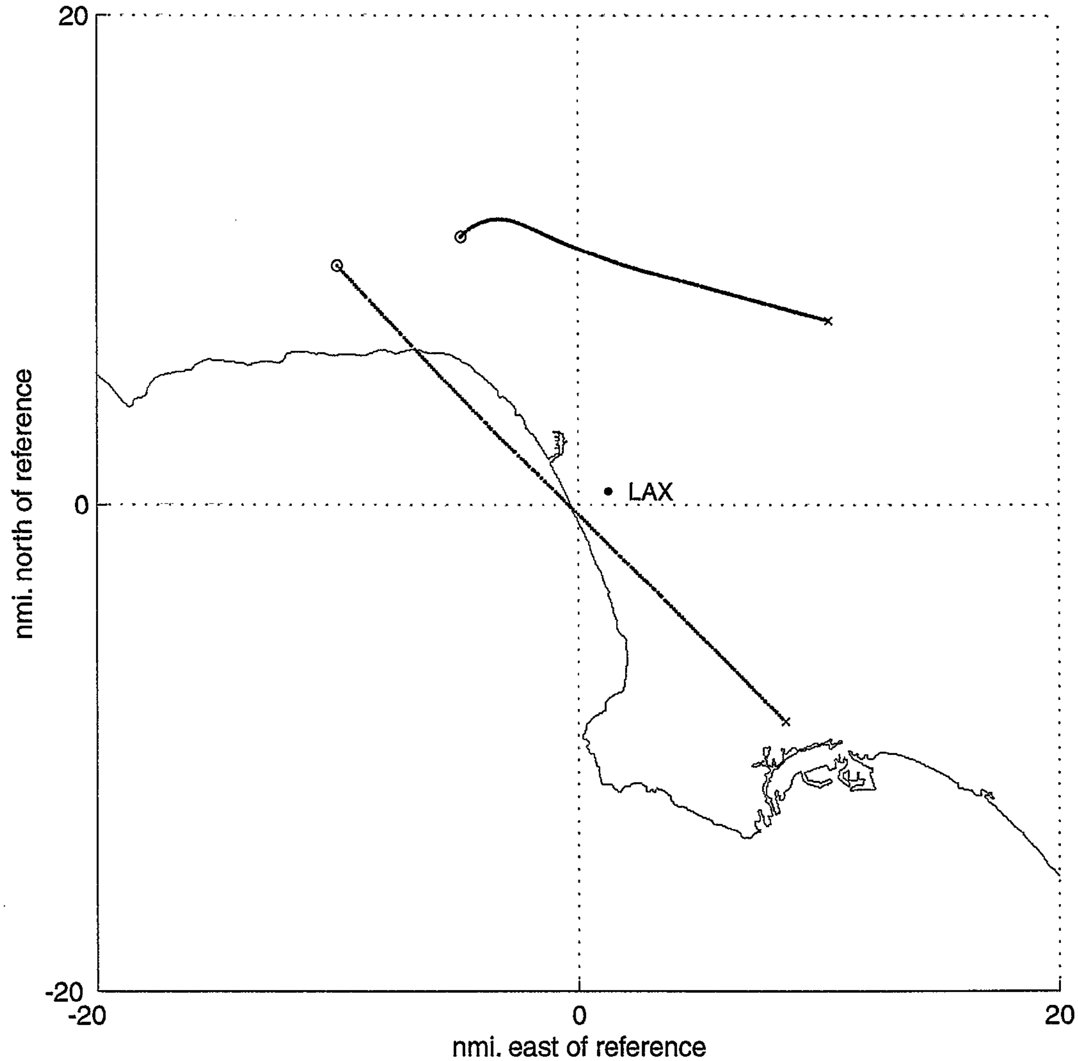
N40 reverses course to fly 45 degrees to UPS 904

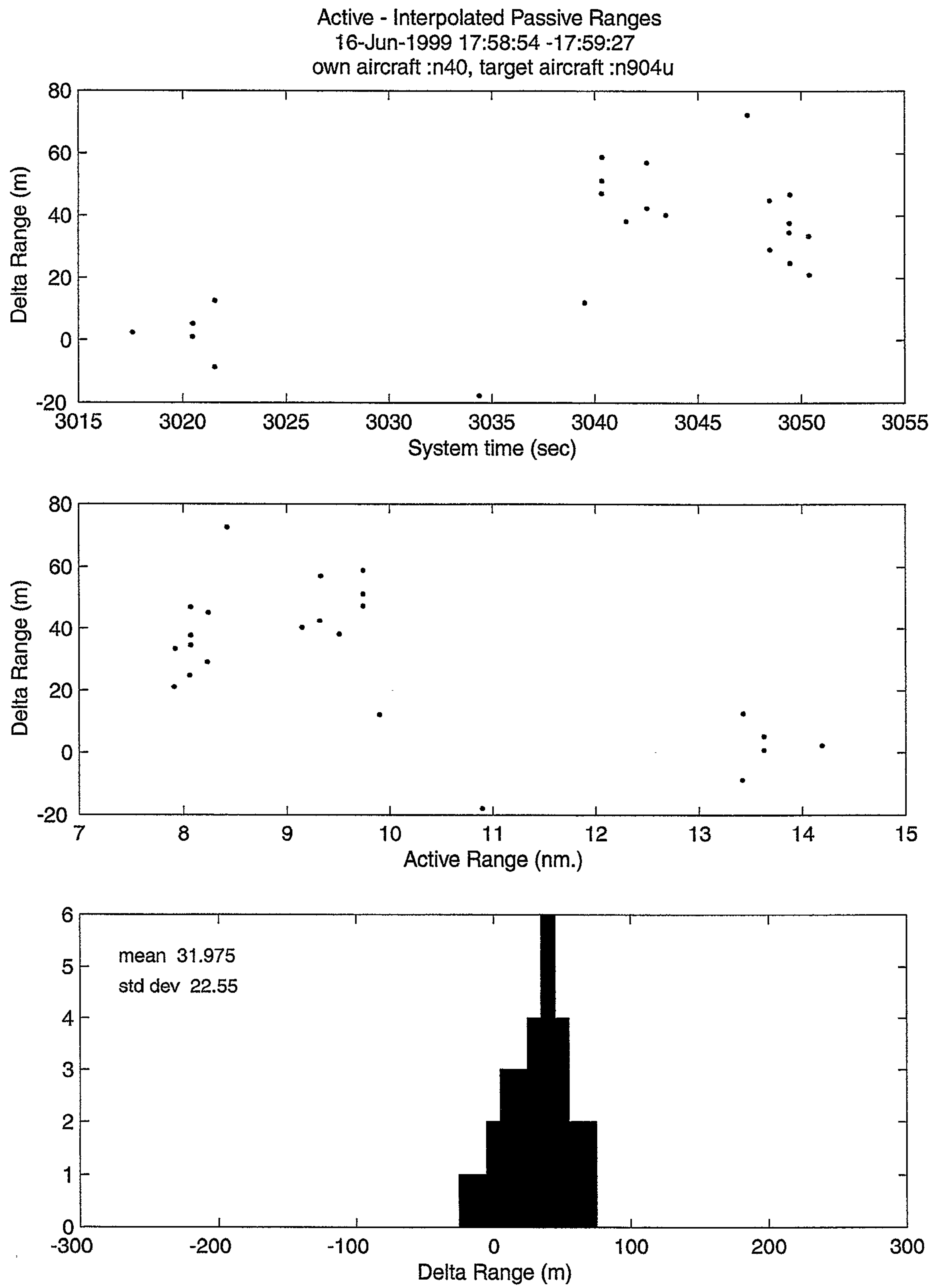

06/16/1999 17:58:54 -18:03:18
UPS904
N40
LAX
nmi. north of reference
nmi. east of reference
20
15
10
5
0
-5
-10
-15
-20
-20
-15
-10
-5
0
5
10
15
20


x 10^4
UPS904
N40
altitude (ft)
2
1.5
1
0.5
0
17:59
18:00
18:01
18:02
18:03
time GMT

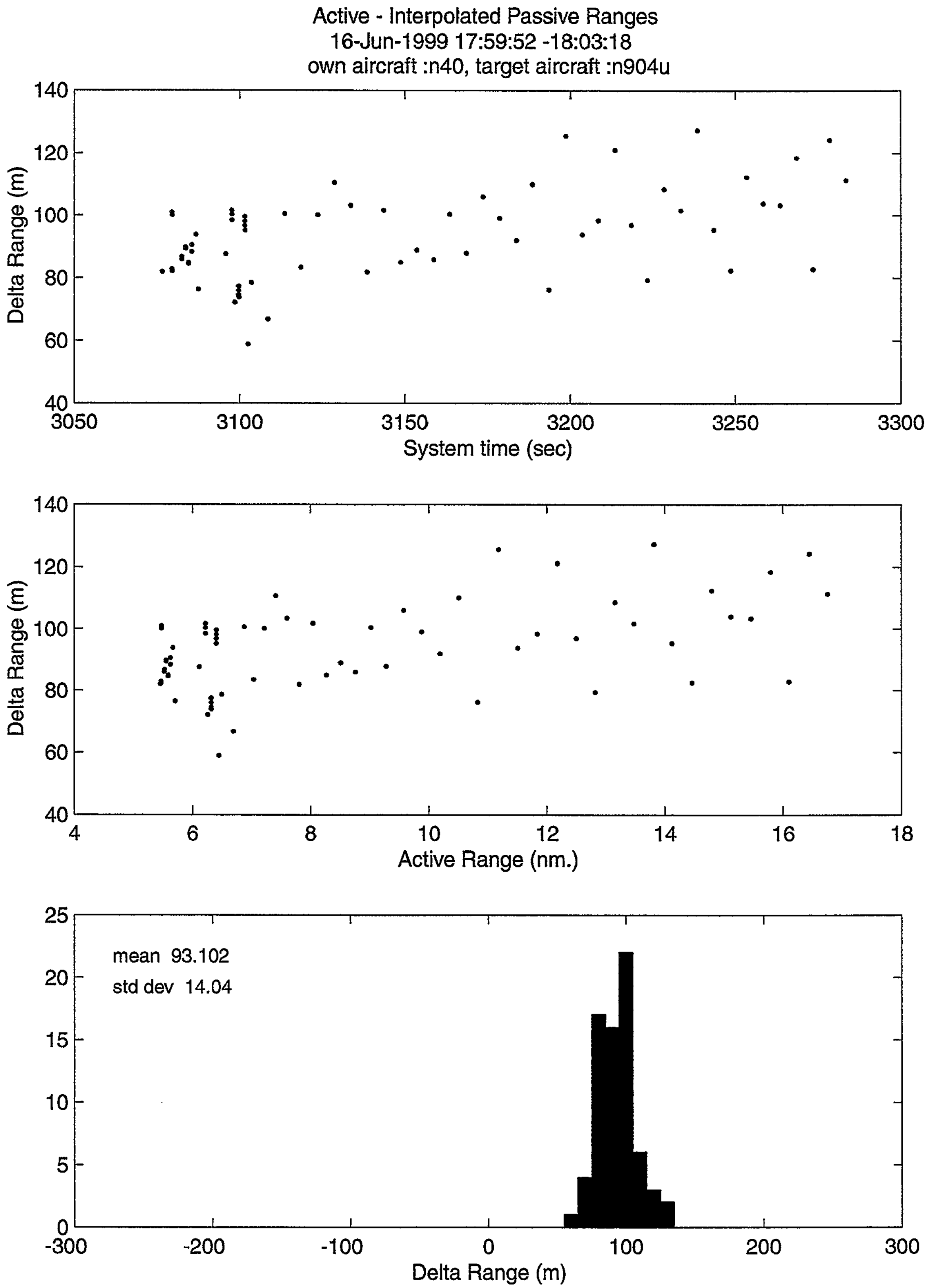

06/16/1999 17:58:54 -17:59:27
20
0
-20
-20
0
20
nmi. north of reference
nmi. east of reference
LAX

06/16/1999 17:59:52 -18:03:18





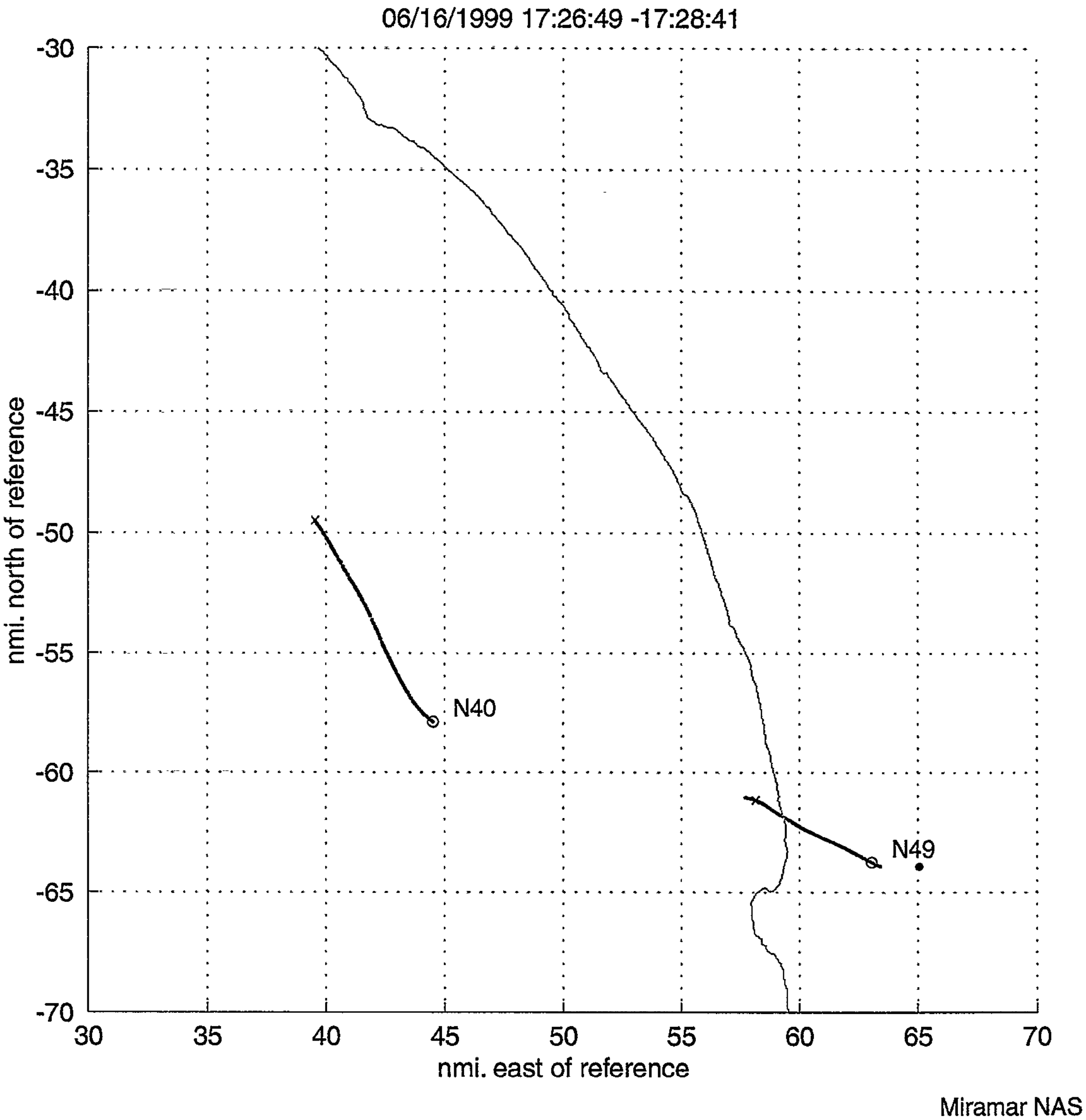
Active - Interpolated Passive Ranges
16-Jun-1999 17:58:54 -17:59:27
own aircraft :n40, target aircraft :n904u
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 31.975
std dev 22.55
Delta Range (m)

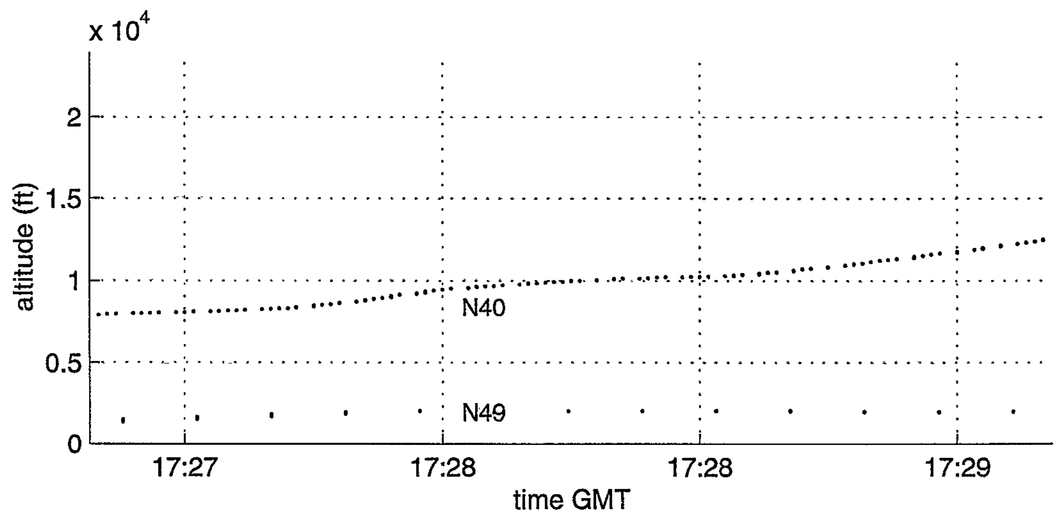


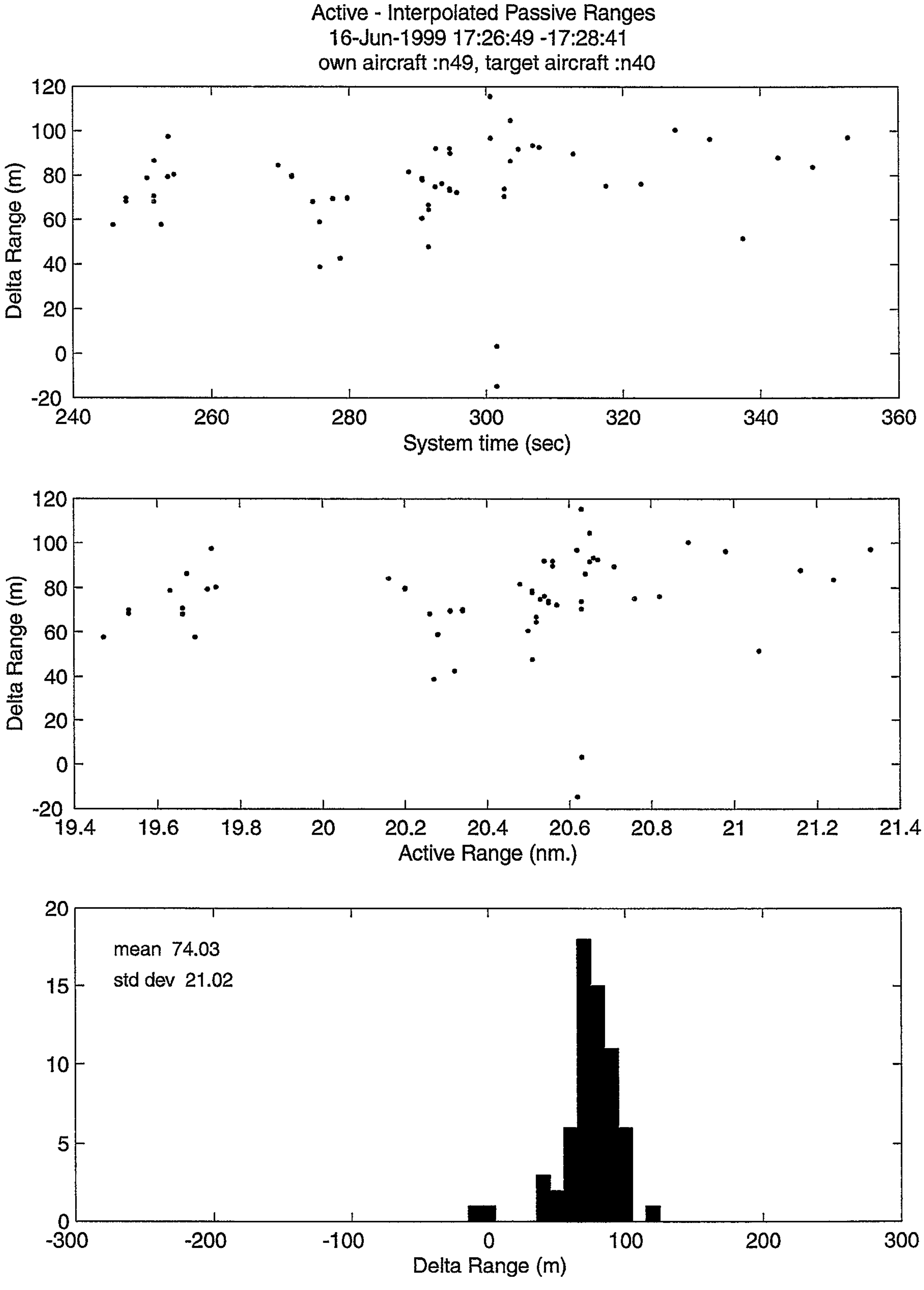
Active - Interpolated Passive Ranges
16-Jun-1999 17:59:52 -18:03:18
own aircraft :n40, target aircraft :n904u
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 93.102
std dev 14.04
Delta Range (m)

Encounter 4

N49 following N40, 20 miles in trail

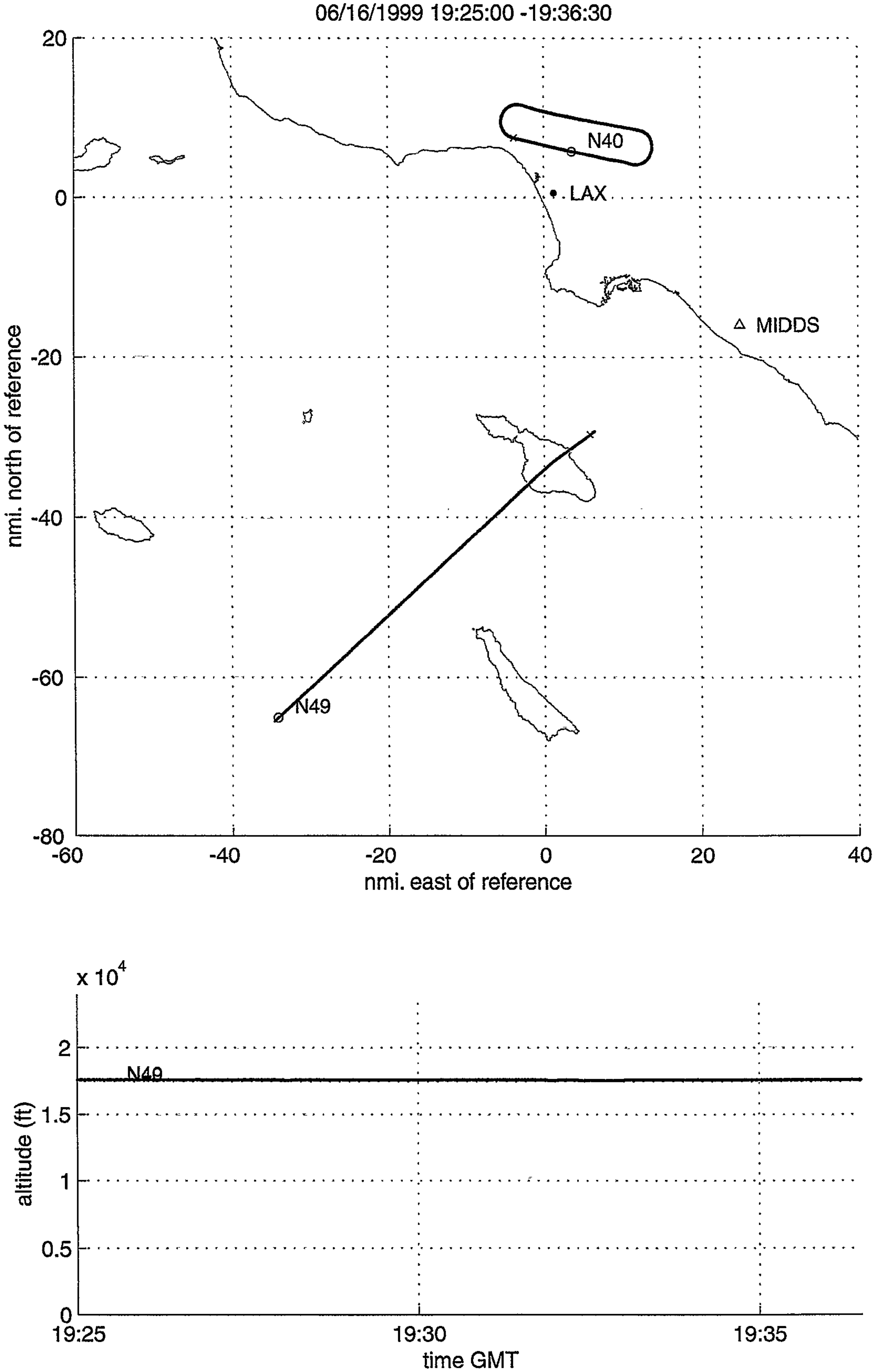

06/16/1999 17:26:49 -17:28:41
-30
-35
-40
-45
-50
-55
-60
-65
-70
nmi. north of reference
30
35
40
45
50
55
60
65
70
nmi. east of reference
N40
N49
Miramar NAS

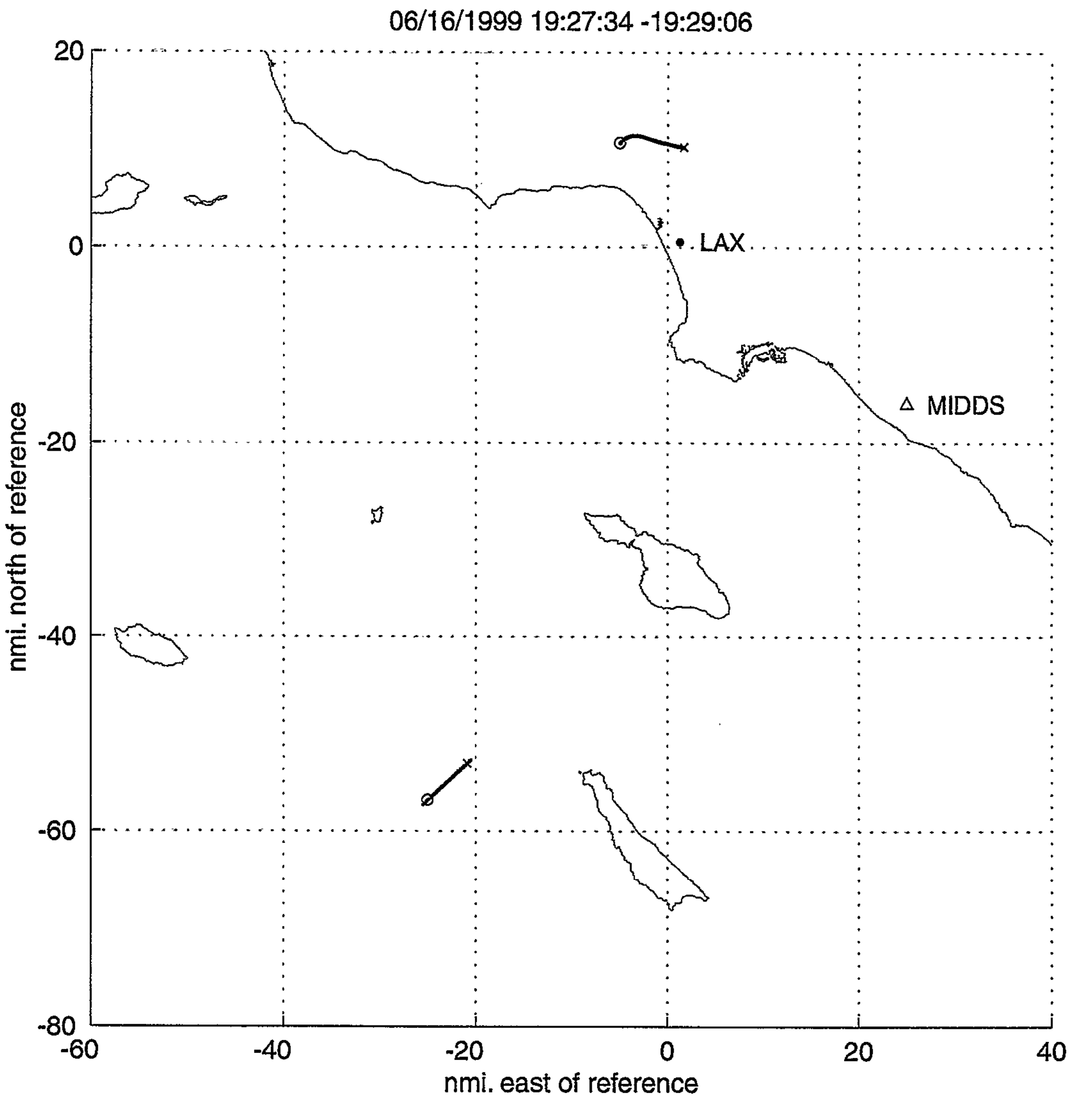

x 10^4
2
1.5
1
0.5
0
altitude (ft)
N40
N49
17:27
17:28
17:28
17:29
time GMT


Active - Interpolated Passive Ranges
16-Jun-1999 17:26:49 -17:28:41
own aircraft :n49, target aircraft :n40
Delta Range (m)
System time (sec)
Active Range (nm.)
mean 74.03
std dev 21.02
Delta Range (m)

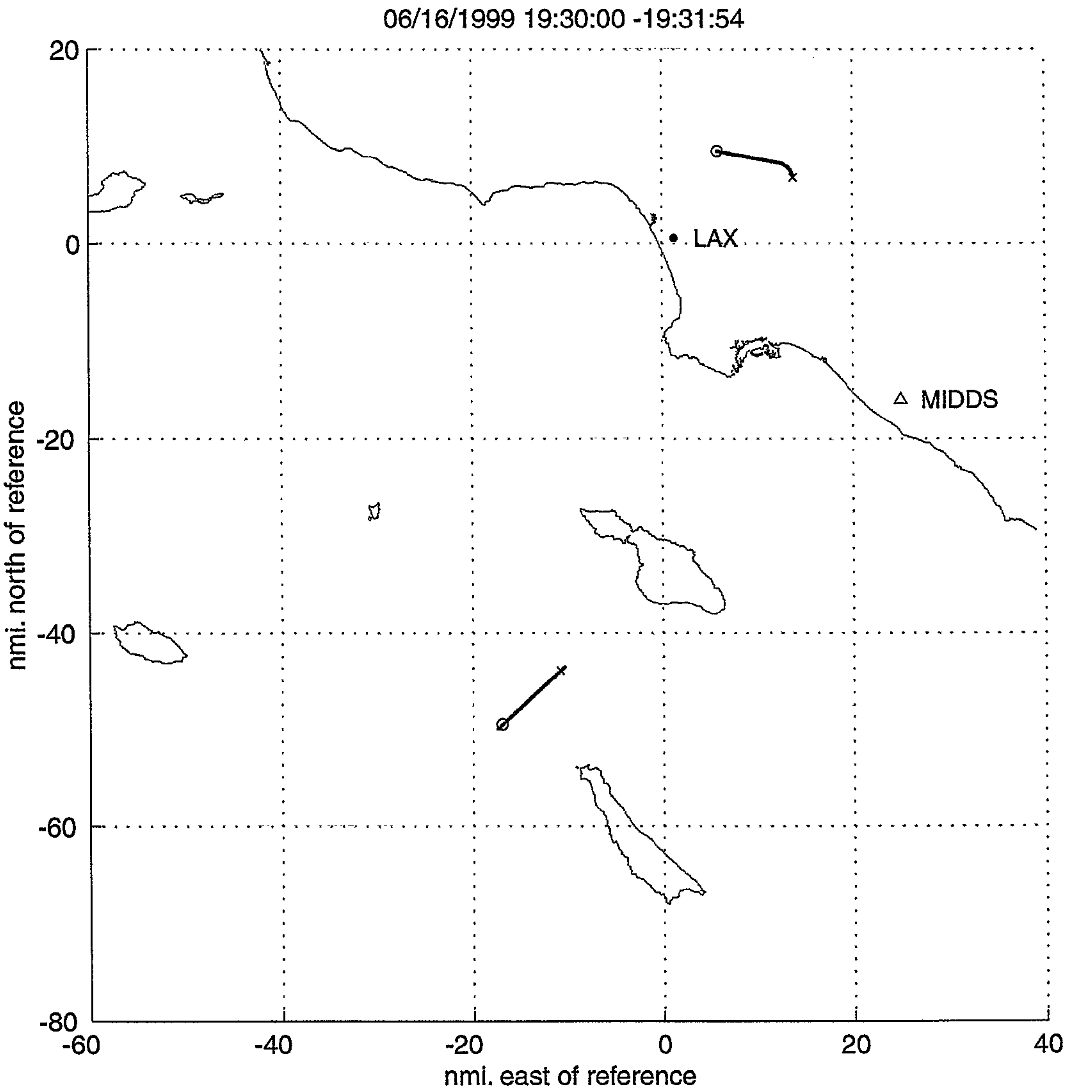
Encounter 5

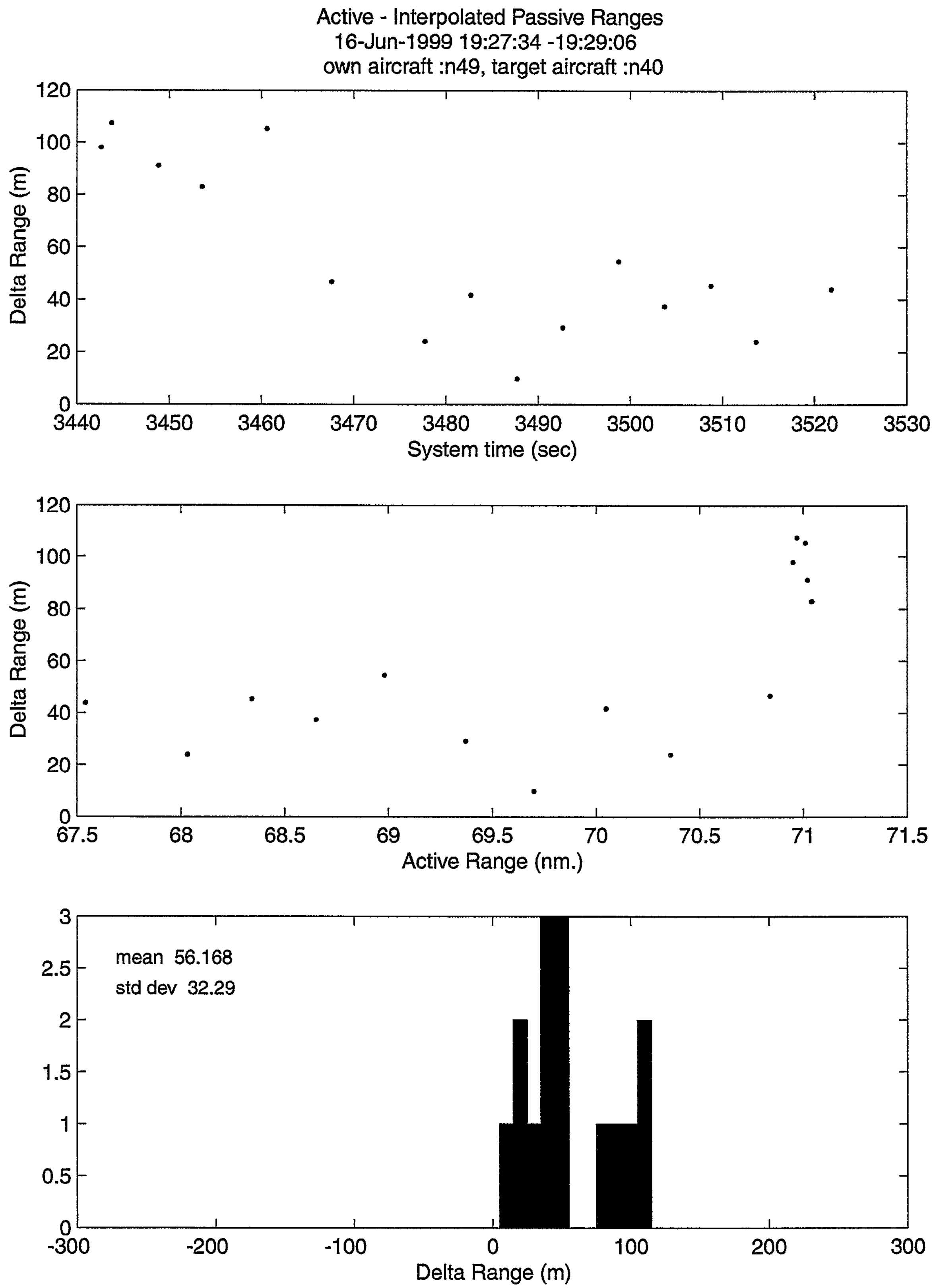
N49 flies inbound to coast while N40 orbits LAX


06/16/1999 19:25:00 -19:36:30
20
0
-20
-40
-60
-80
nmi. north of reference
-60
-40
-20
0
20
40
nmi. east of reference
N40
LAX
MIDDS
N49
x 10^4
2
1.5
1
0.5
0
altitude (ft)
N49
19:25
19:30
19:35
time GMT

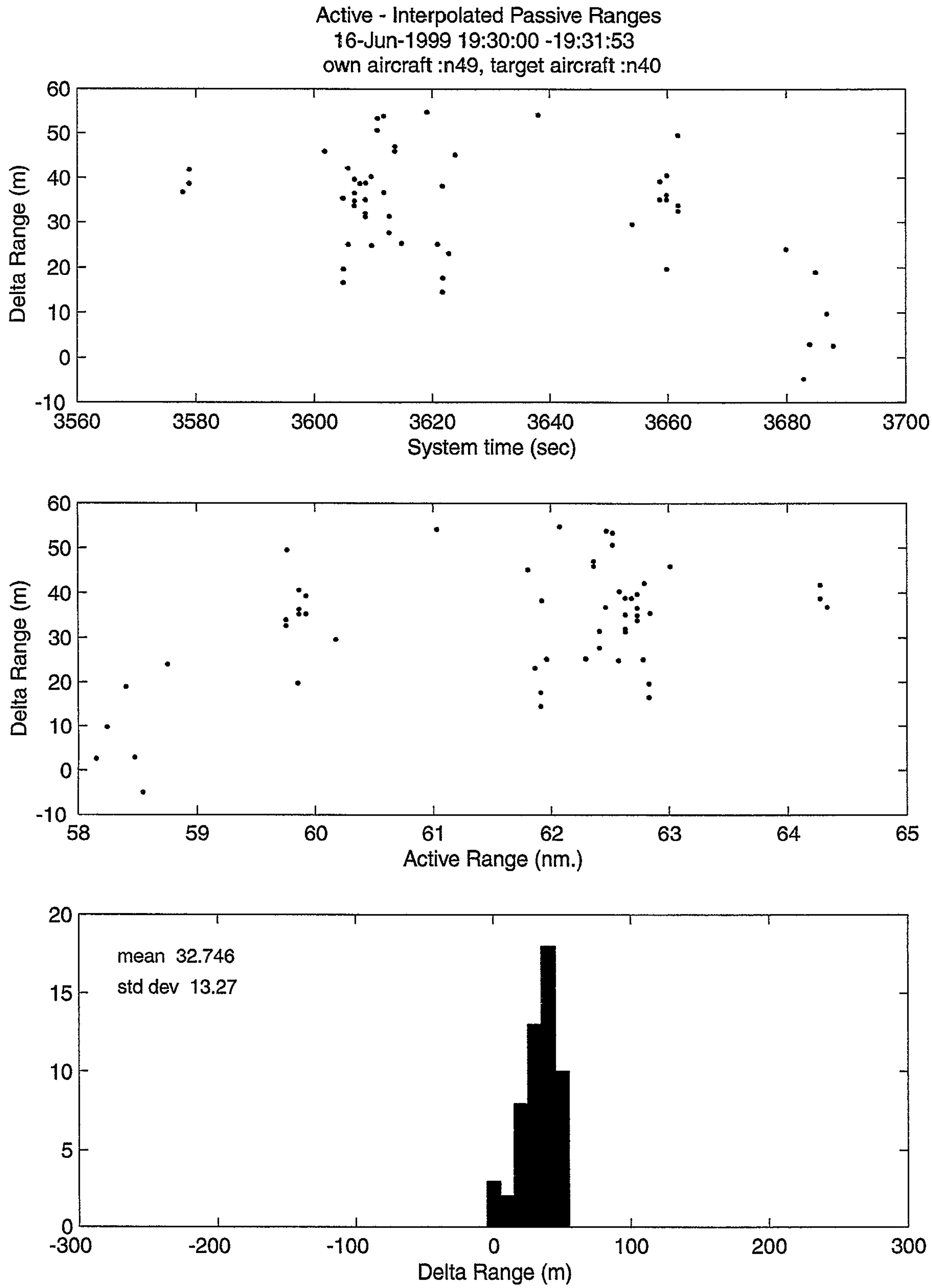


06/16/1999 19:27:34 -19:29:06
LAX
MIDDS
nmi. north of reference
nmi. east of reference
20
0
-20
-40
-60
-80
-60
-40
-20
0
20
40


06/16/1999 19:30:00 -19:31:54
LAX
MIDDS
nmi. north of reference
nmi. east of reference
20
0
-20
-40
-60
-80
-60
-40
-20
0
20
40

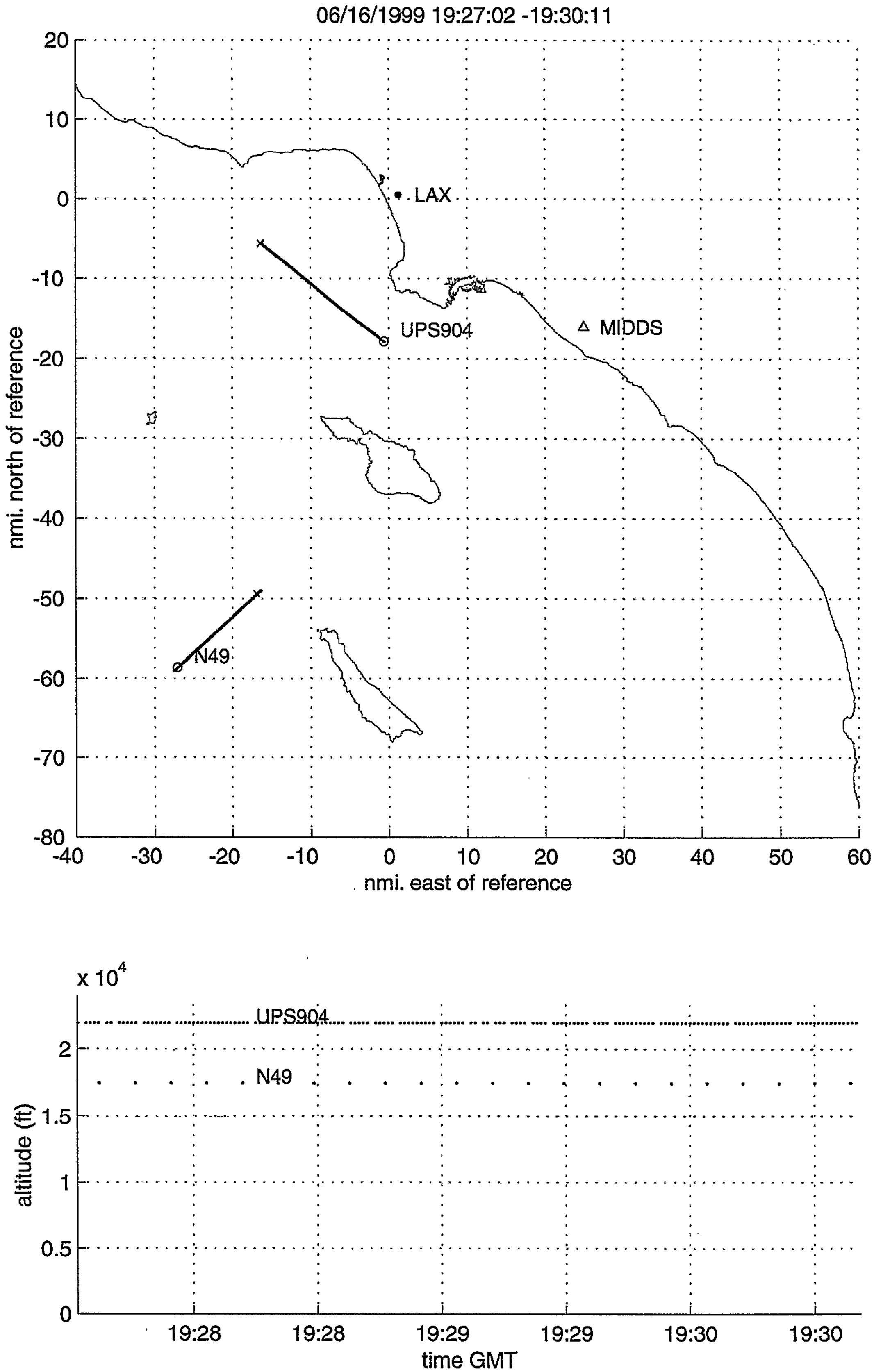


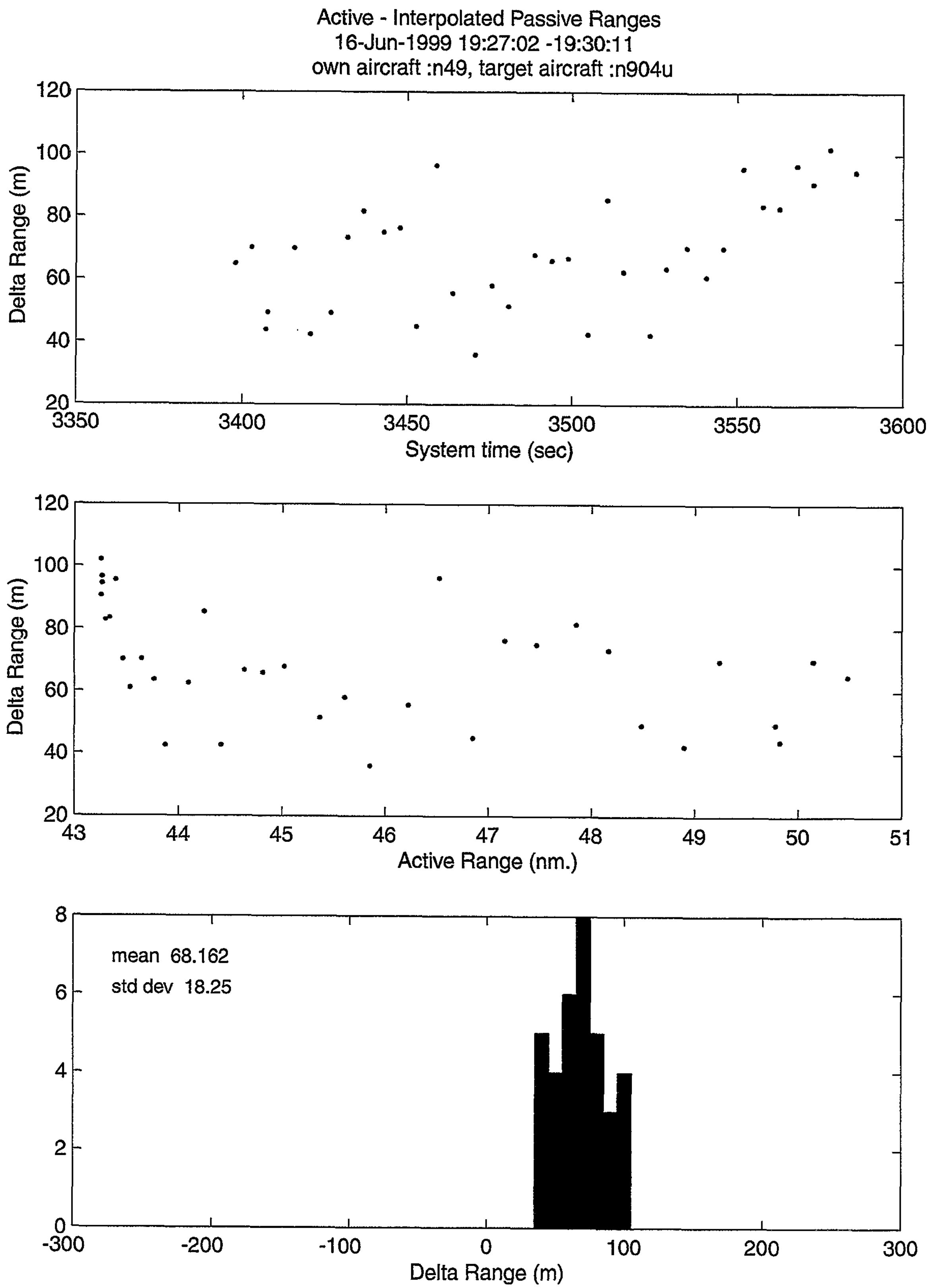
Active - Interpolated Passive Ranges
16-Jun-1999 19:27:34 -19:29:06
own aircraft :n49, target aircraft :n40
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 56.168
std dev 32.29
Delta Range (m)


Active - Interpolated Passive Ranges
16-Jun-1999 19:30:00 -19:31:53
own aircraft :n49, target aircraft :n40
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 32.746
std dev 13.27
Delta Range (m)

Encounter 6

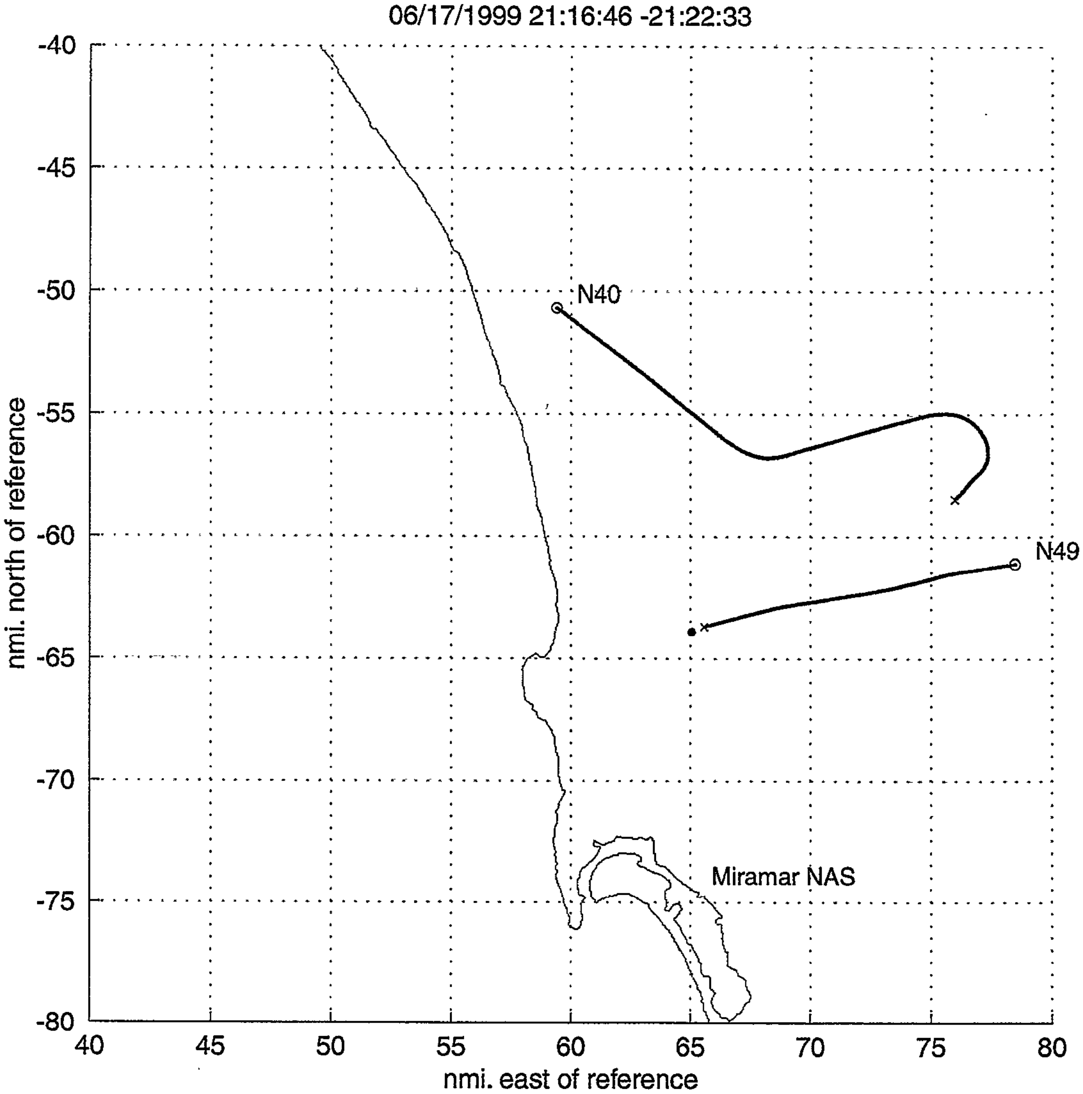
N40 flies inbound to coast
UPS flies north up coast


06/16/1999 19:27:02 -19:30:11
LAX
UPS904
MIDDS
N49
nmi. north of reference
nmi. east of reference
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-40
-30
-20
-10
0
10
20
30
40
50
60
x 10^4
UPS904
N49
altitude (ft)
2
1.5
1
0.5
0
19:28
19:28
19:29
19:29
19:30
19:30
time GMT

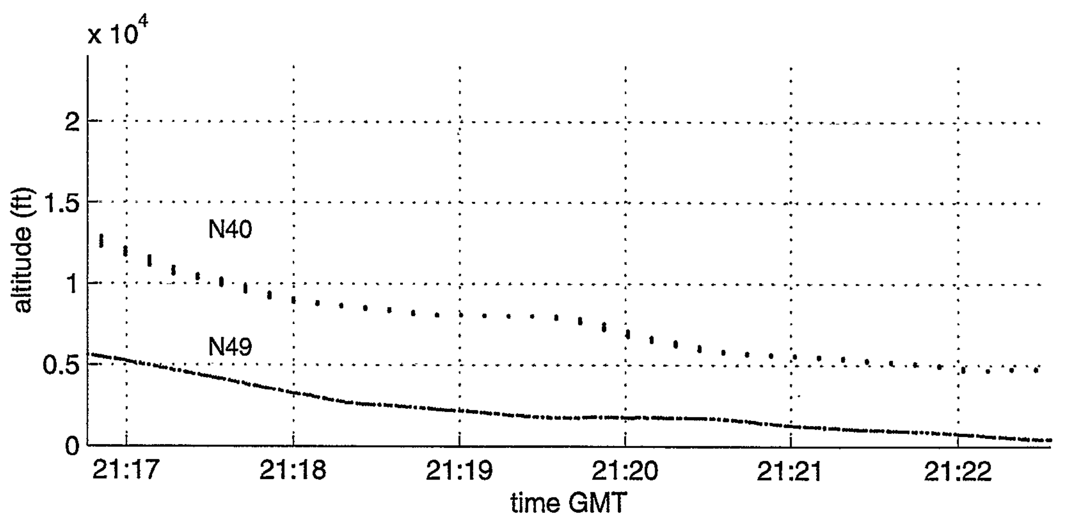

Active - Interpolated Passive Ranges
16-Jun-1999 19:27:02 -19:30:11
own aircraft :n49, target aircraft :n904u
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 68.162
std dev 18.25
Delta Range (m)

Encounter 7

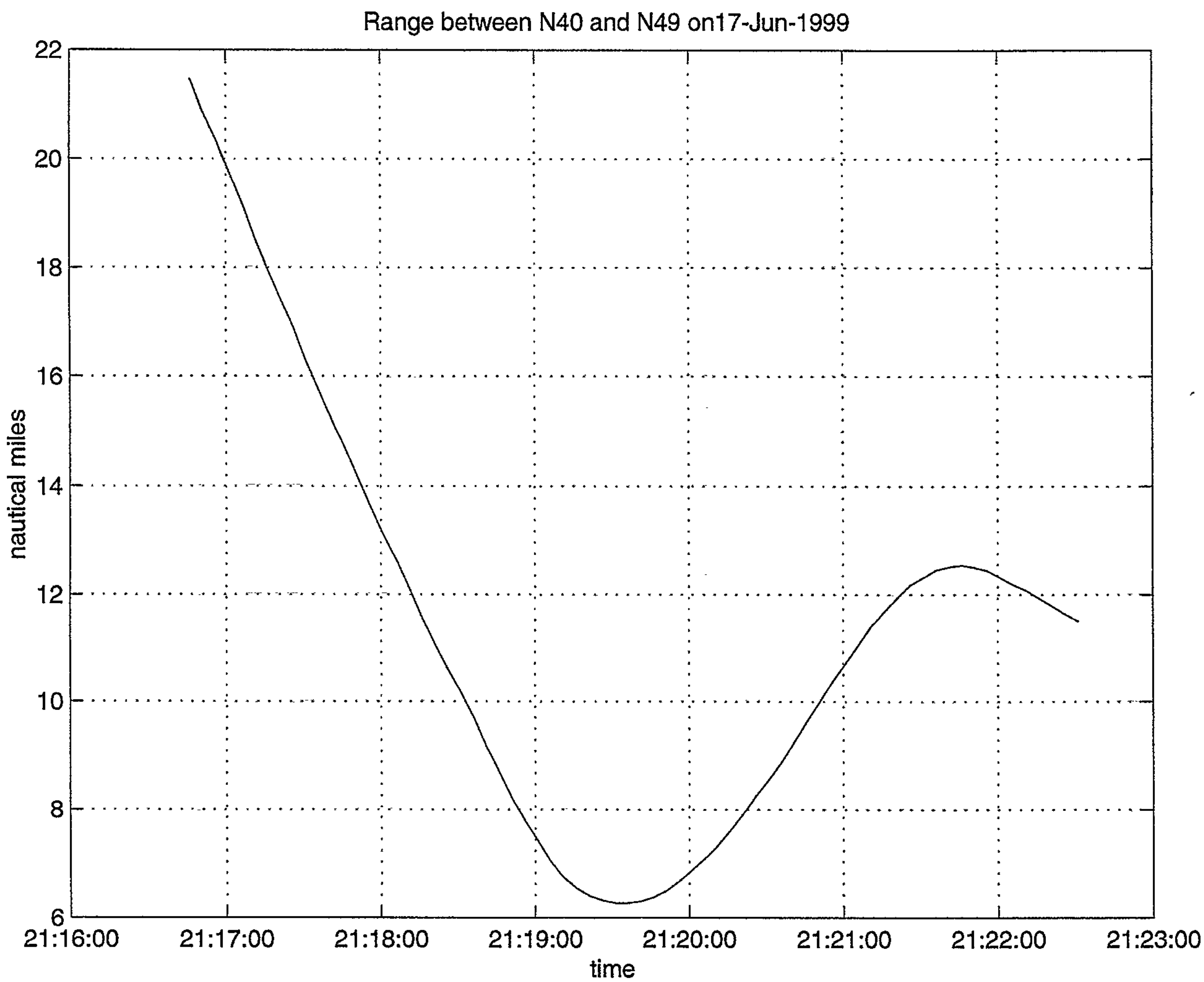
N40 and N49 maneuvering to landings

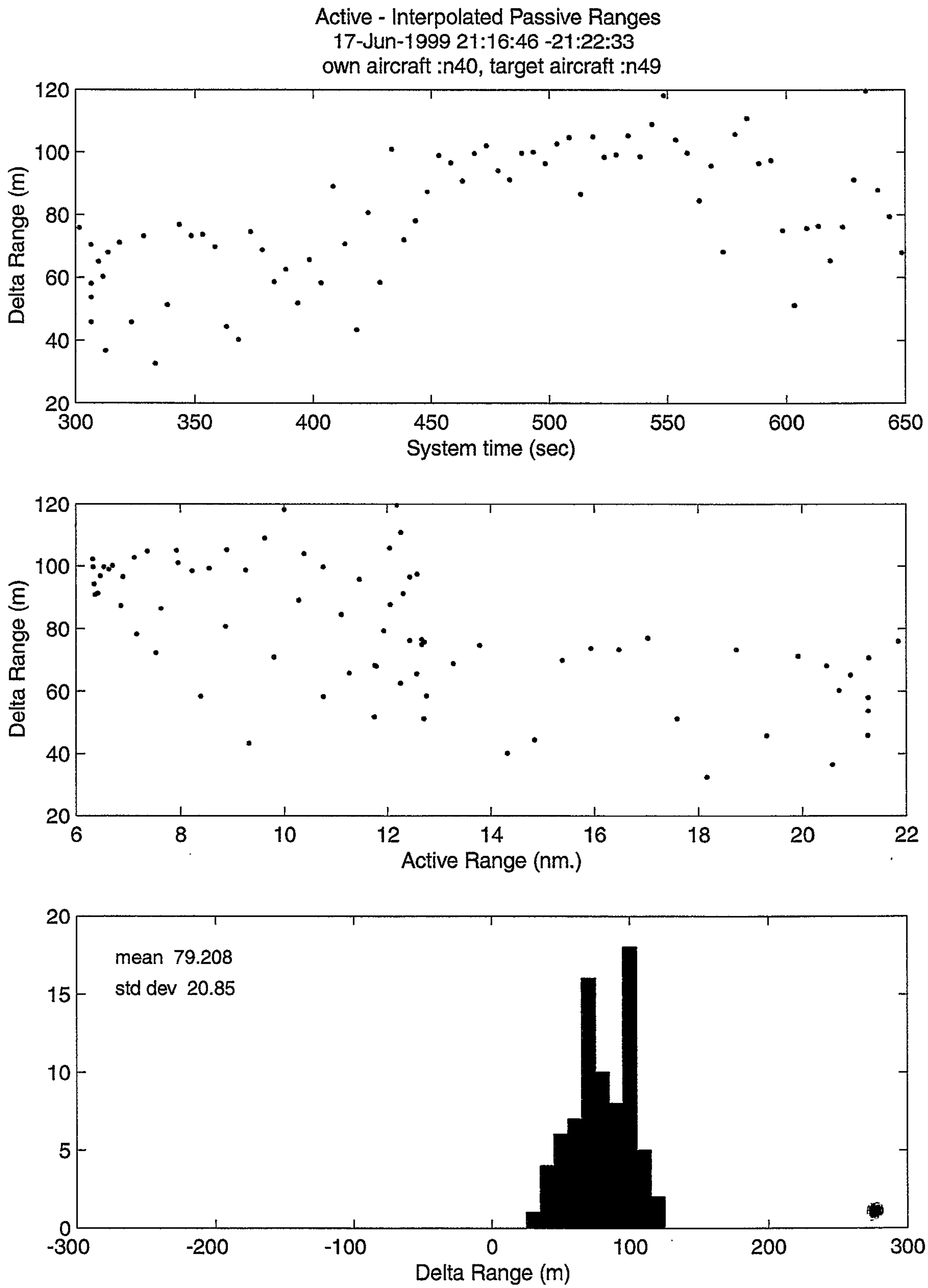


06/17/1999 21:16:46 -21:22:33
N40
N49
Miramar NAS
nmi. north of reference
nmi. east of reference
-40
-45
-50
-55
-60
-65
-70
-75
-80
40
45
50
55
60
65
70
75
80



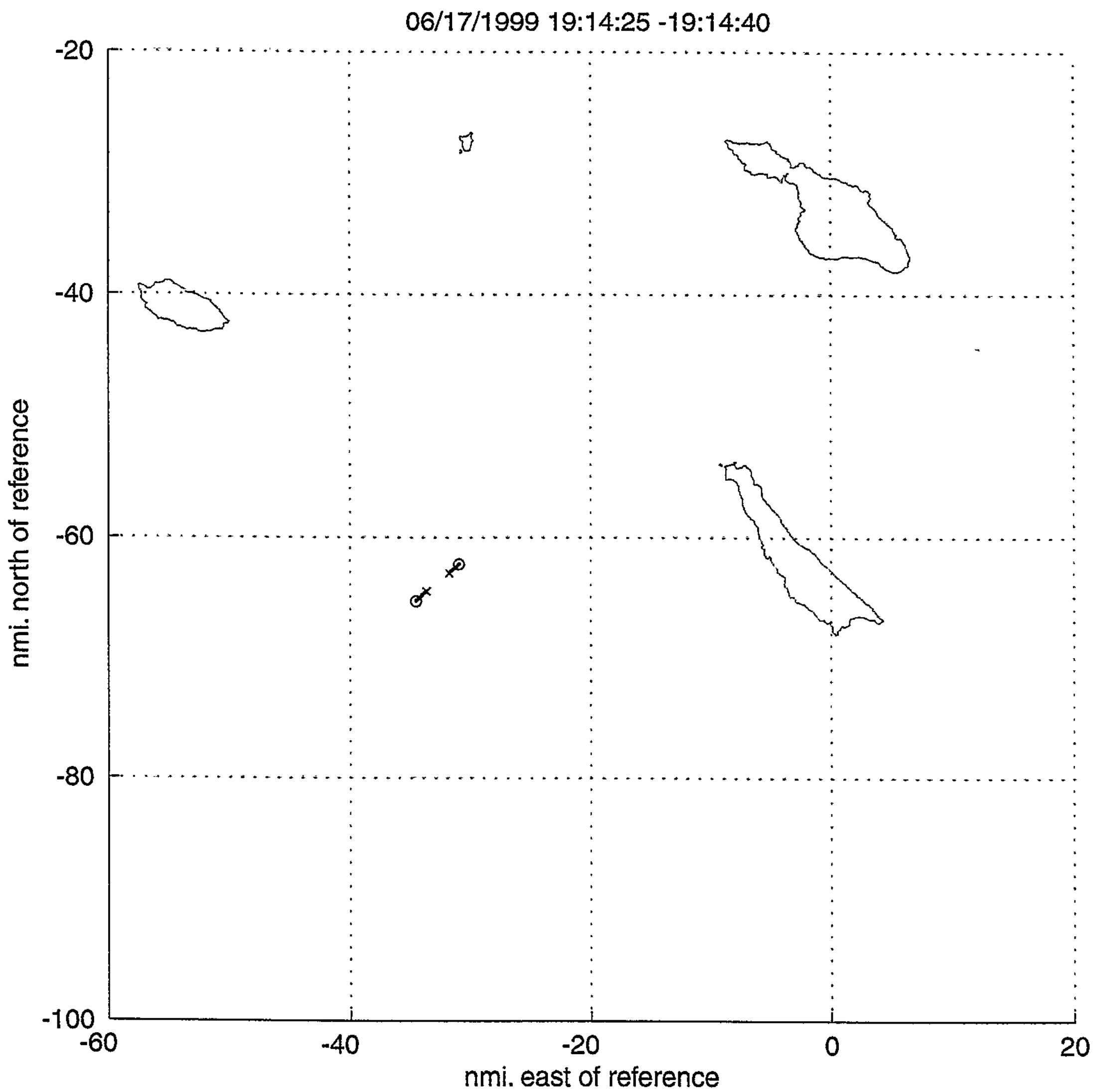
x 10^4
N40
N49
altitude (ft)
time GMT
2
1.5
1
0.5
0
21:17
21:18
21:19
21:20
21:21
21:22


Range between N40 and N49 on17-Jun-1999
nautical miles
22
20
18
16
14
12
10
8
6
21:16:00
21:17:00
21:18:00
21:19:00
21:20:00
21:21:00
21:22:00
21:23:00
time

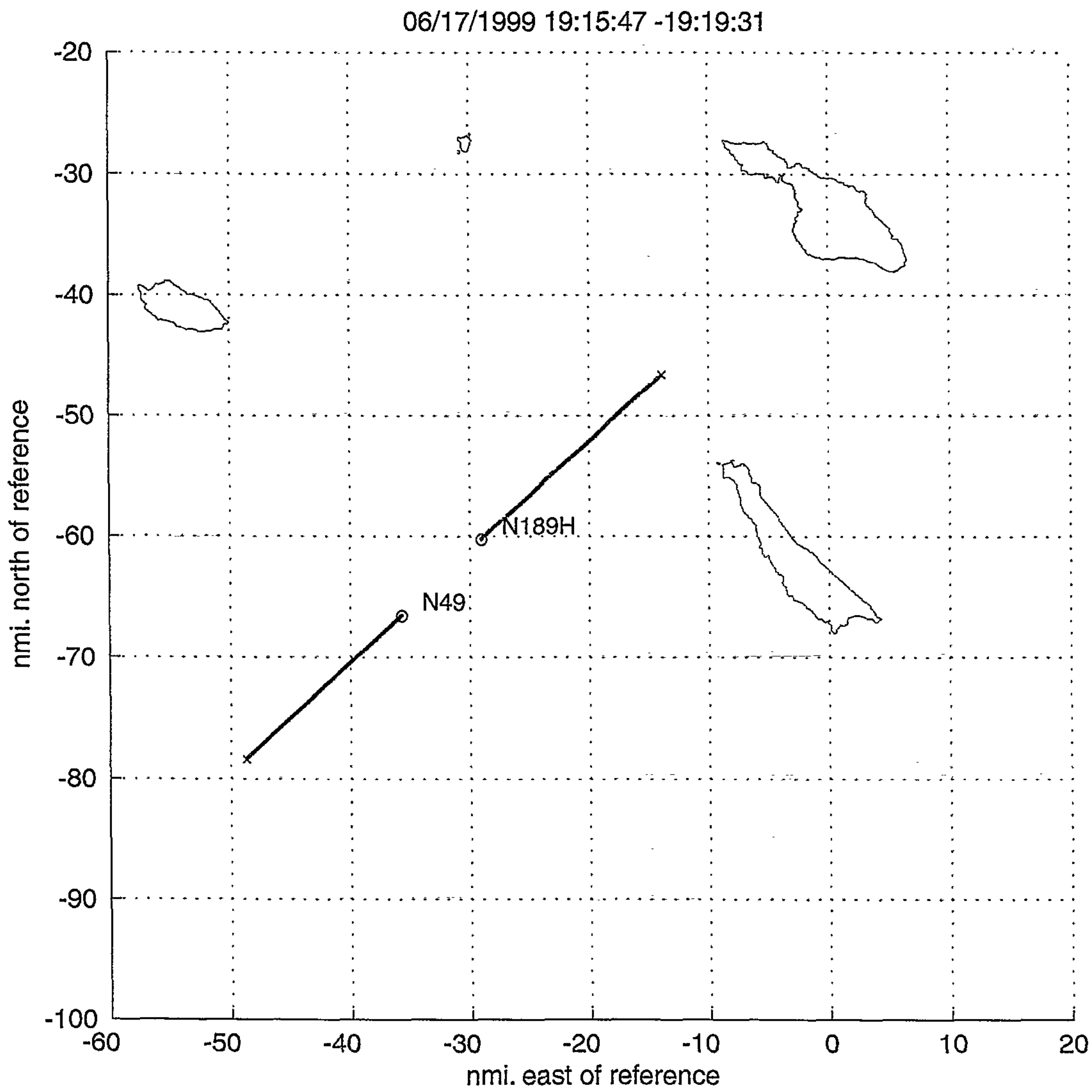

Active - Interpolated Passive Ranges
17-Jun-1999 21:16:46 -21:22:33
own aircraft :n40, target aircraft :n49
Delta Range (m)
System time (sec)
Active Range (nm.)
mean 79.208
std dev 20.85
Delta Range (m)

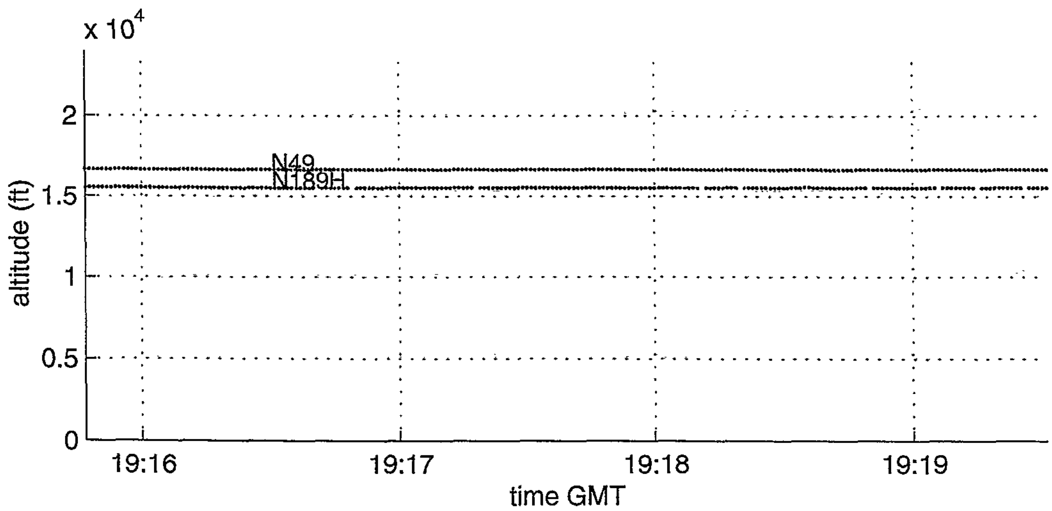
Encounter 8

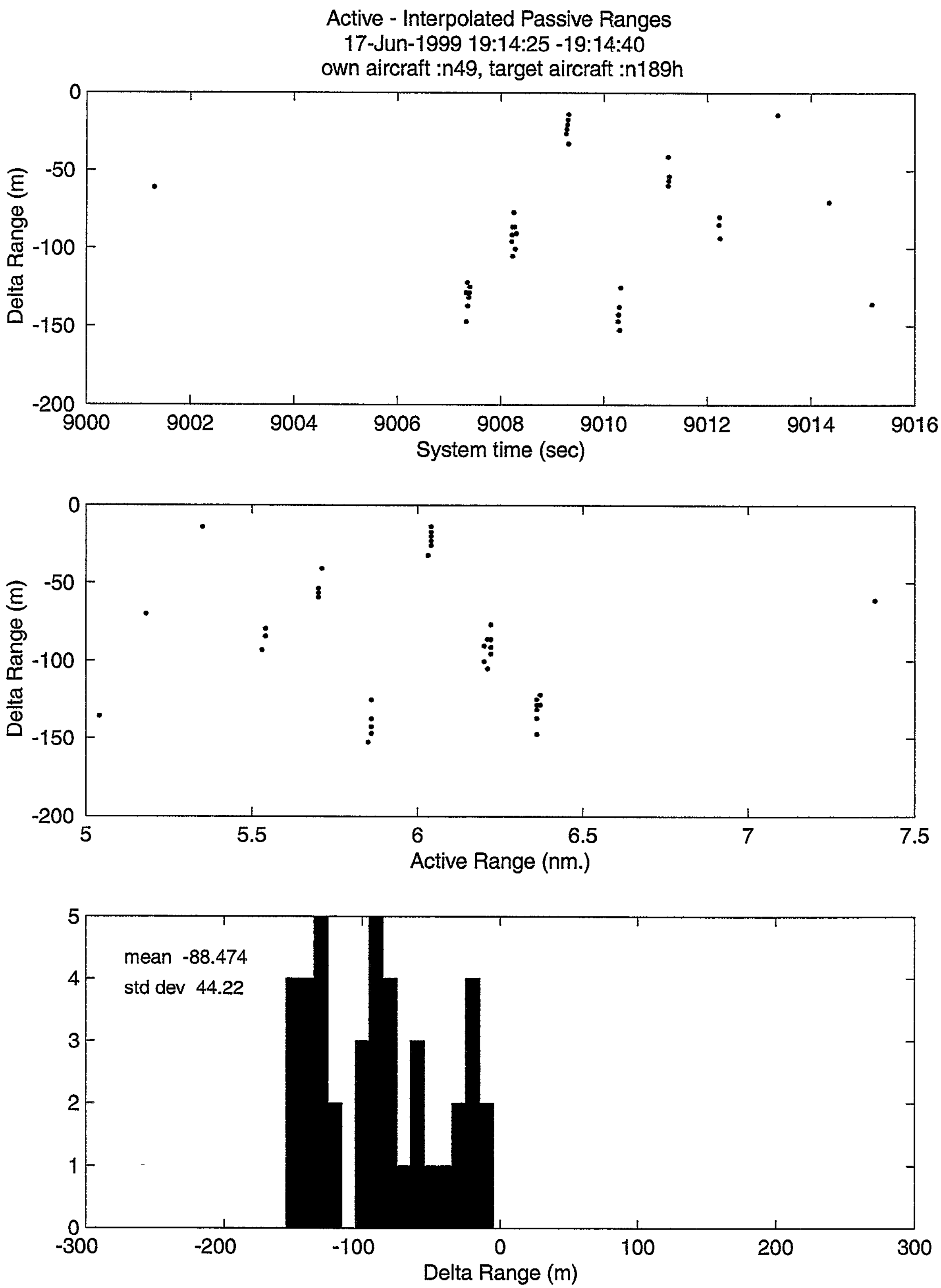
N49 and N189H head-on crossing

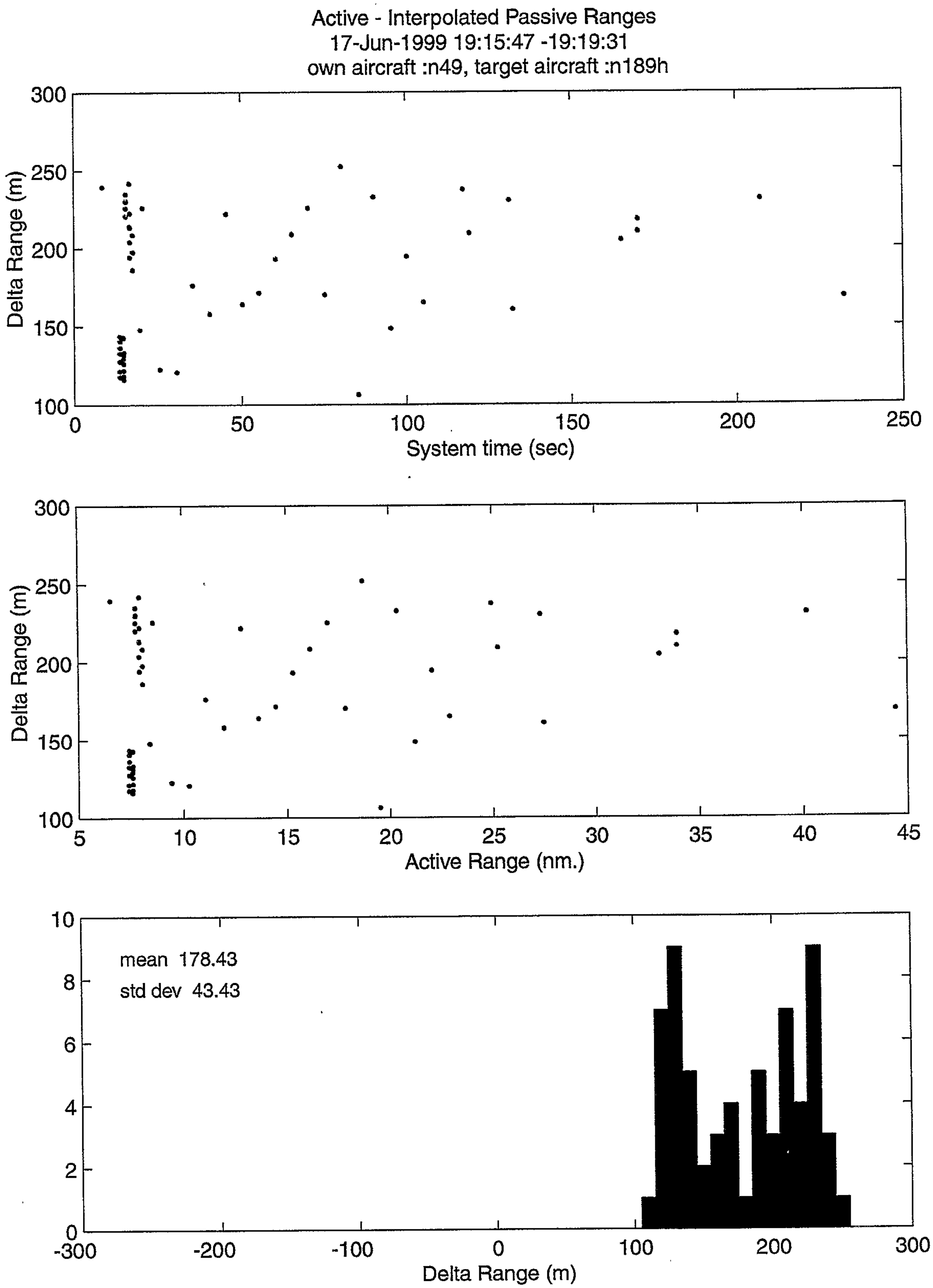


06/17/1999 19:14:25 -19:14:40
-20
-40
-60
-80
-100
nmi. north of reference
-60
-40
-20
0
20
nmi. east of reference


06/17/1999 19:15:47 -19:19:31
N189H
N49
nmi. north of reference
nmi. east of reference
-20
-30
-40
-50
-60
-70
-80
-90
-100
-60
-50
-40
-30
-20
-10
0
10
20


x 10^4
N49
N189H
altitude (ft)
time GMT
2
1.5
1
0.5
0
19:16
19:17
19:18
19:19

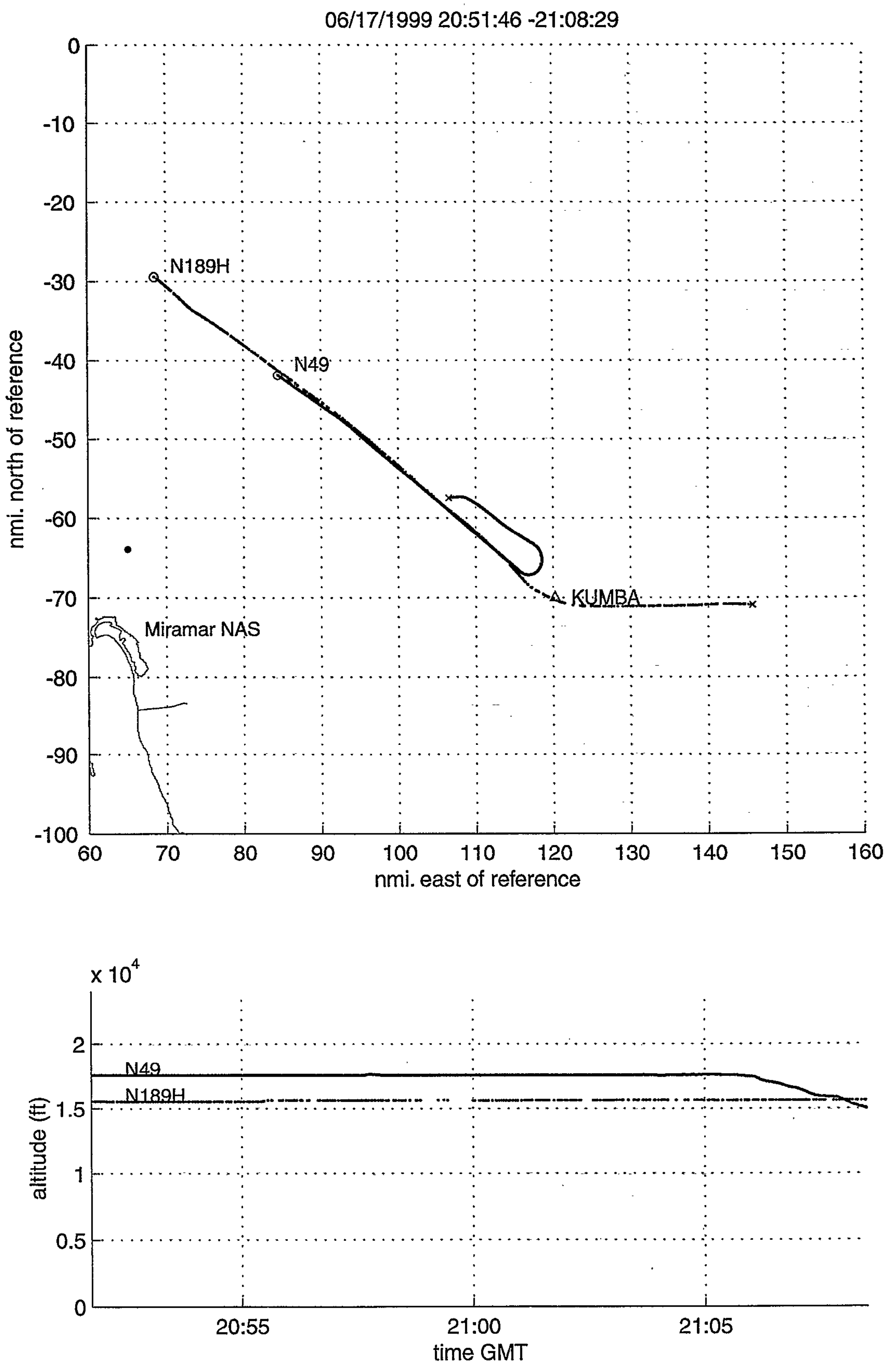

Active - Interpolated Passive Ranges
17-Jun-1999 19:14:25 -19:14:40
own aircraft :n49, target aircraft :n189h
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean -88.474
std dev 44.22
Delta Range (m)

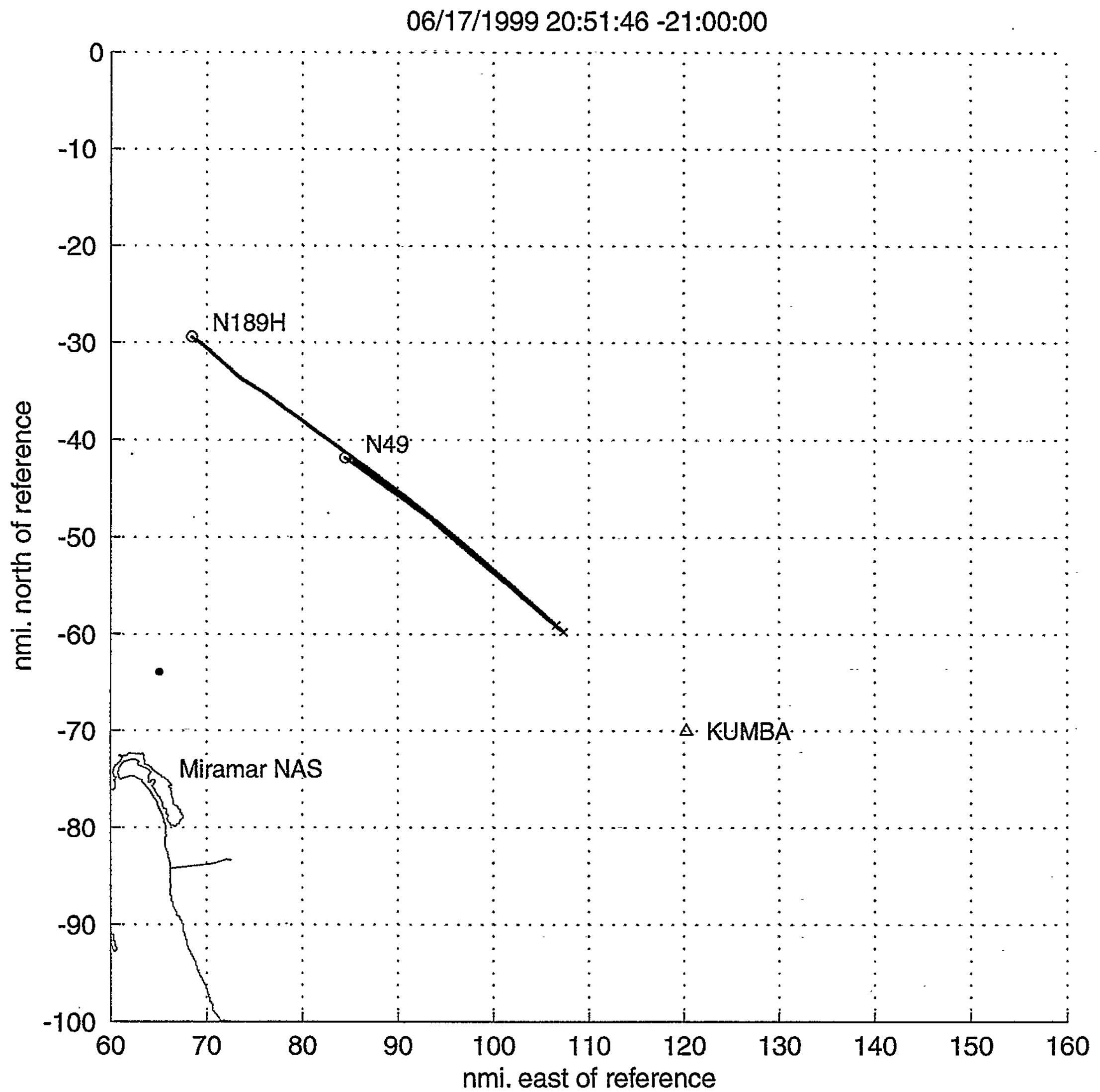


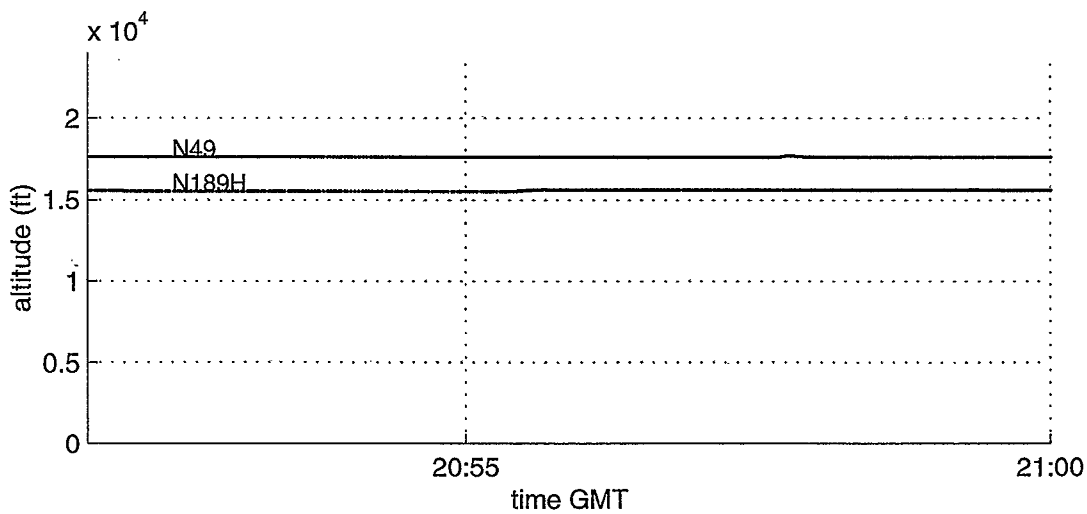
Active - Interpolated Passive Ranges
17-Jun-1999 19:15:47 -19:19:31
own aircraft :n49, target aircraft :n189h
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 178.43
std dev 43.43
Delta Range (m)

Encounter 9

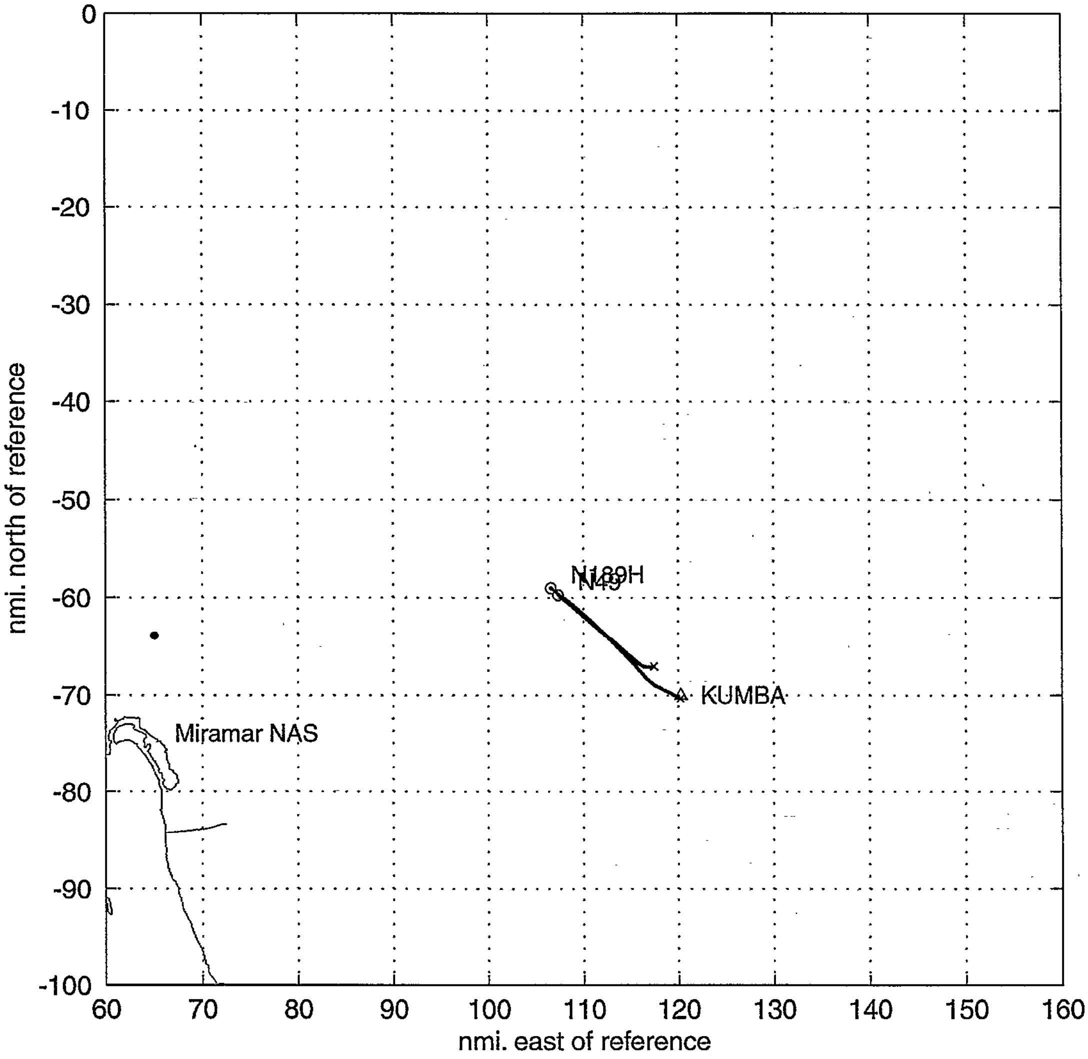
N189H overtakes N49 from behind, then N49 reverses course

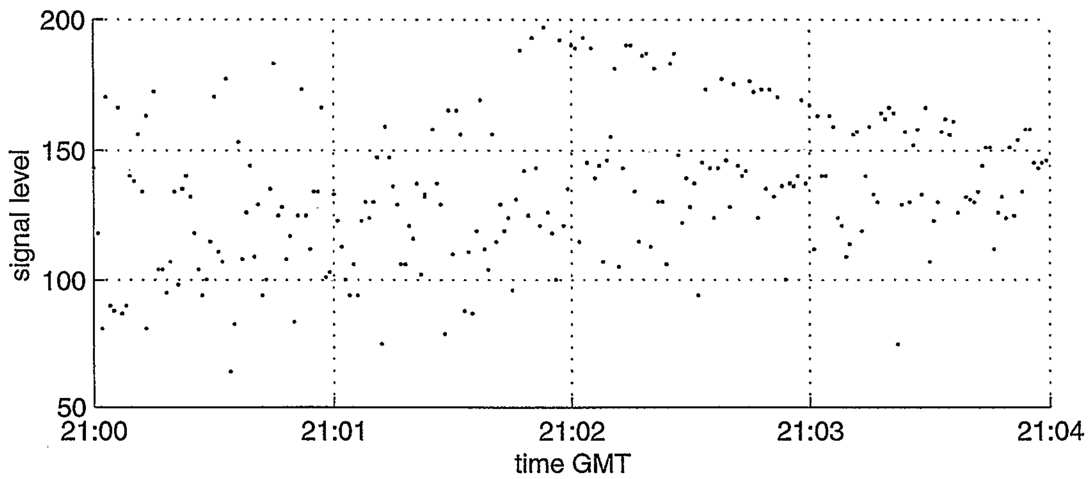

06/17/1999 20:51:46 -21:08:29
nmi. north of reference
nmi. east of reference
N189H
N49
KUMBA
Miramar NAS
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
60
70
80
90
100
110
120
130
140
150
160
x 10^4
altitude (ft)
time GMT
N49
N189H
2
1.5
1
0.5
0
20:55
21:00
21:05

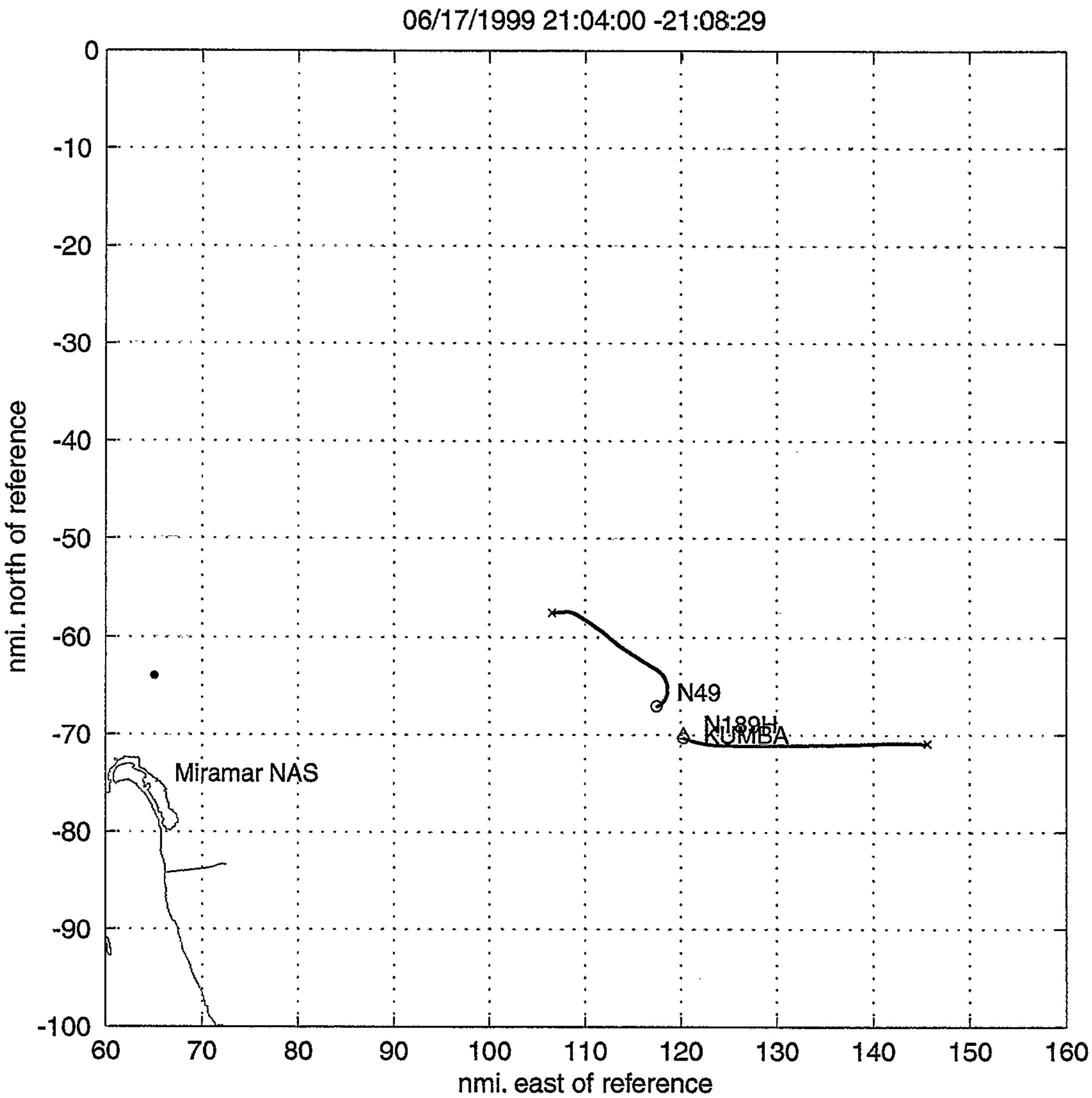

06/17/1999 20:51:46 -21:00:00
nmi. north of reference
nmi. east of reference
N189H
N49
KUMBA
Miramar NAS
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
60
70
80
90
100
110
120
130
140
150
160

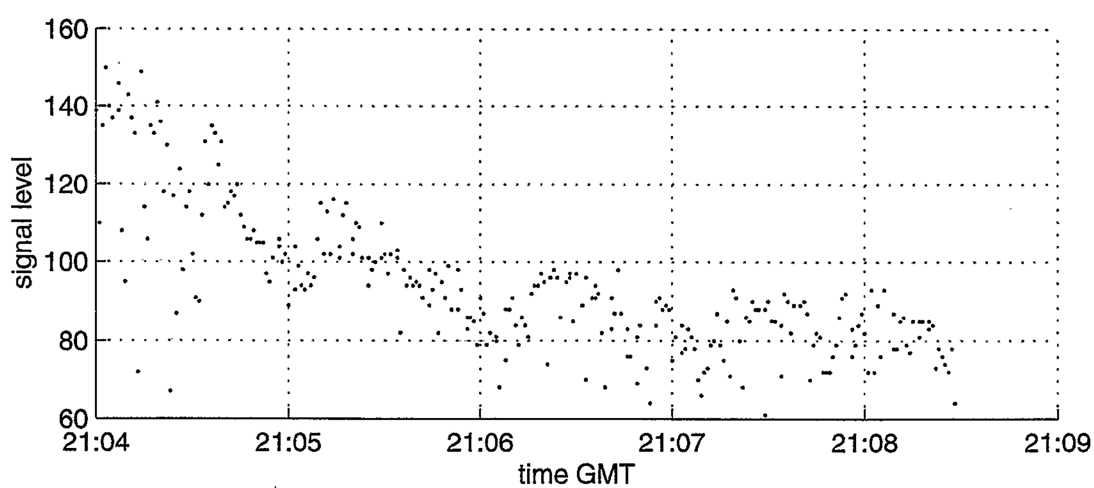

x 10^4
altitude (ft)
time GMT
N49
N189H
2
1.5
1
0.5
0
20:55
21:00

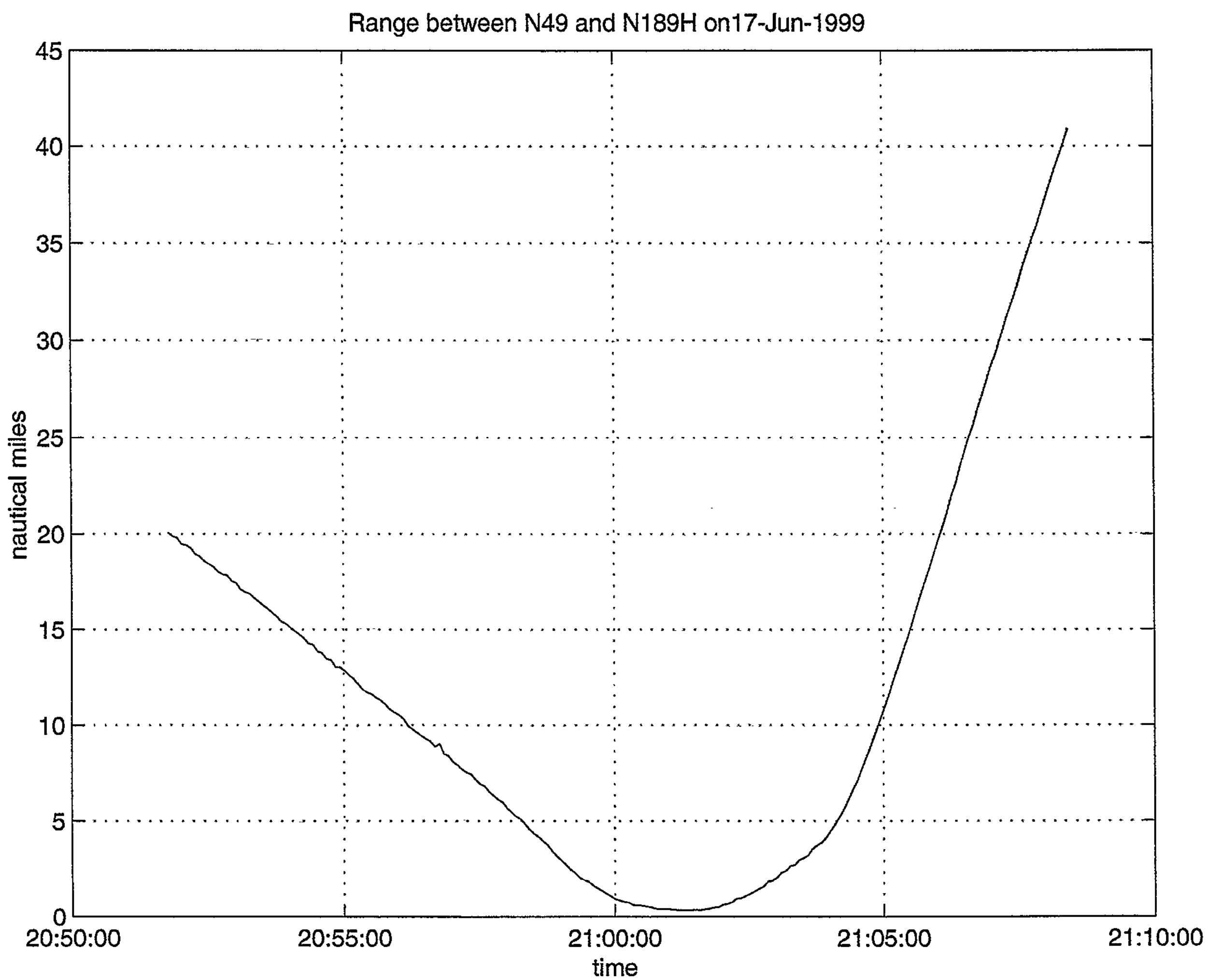
06/17/1999 21:00:00 -21:04:00



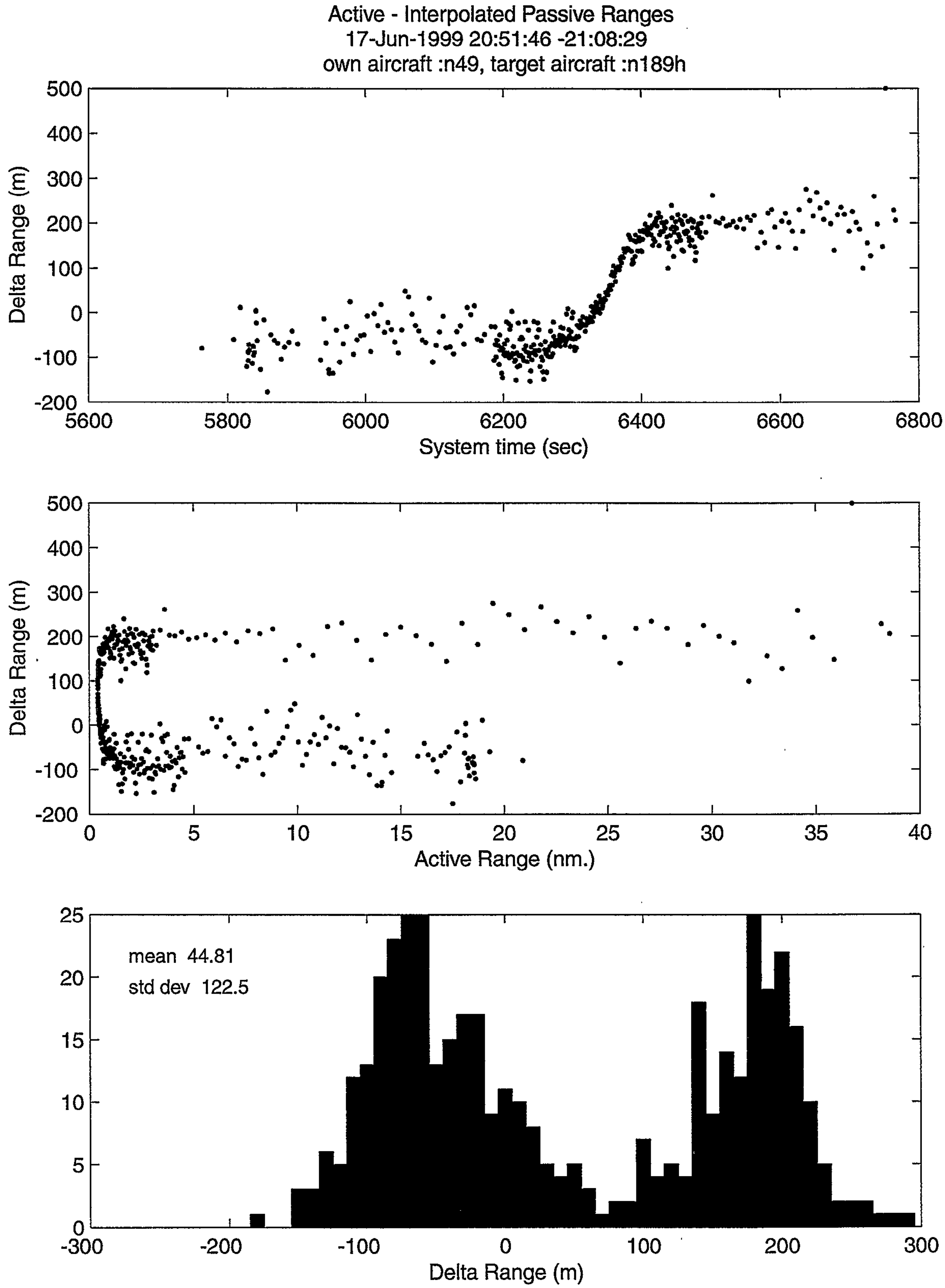


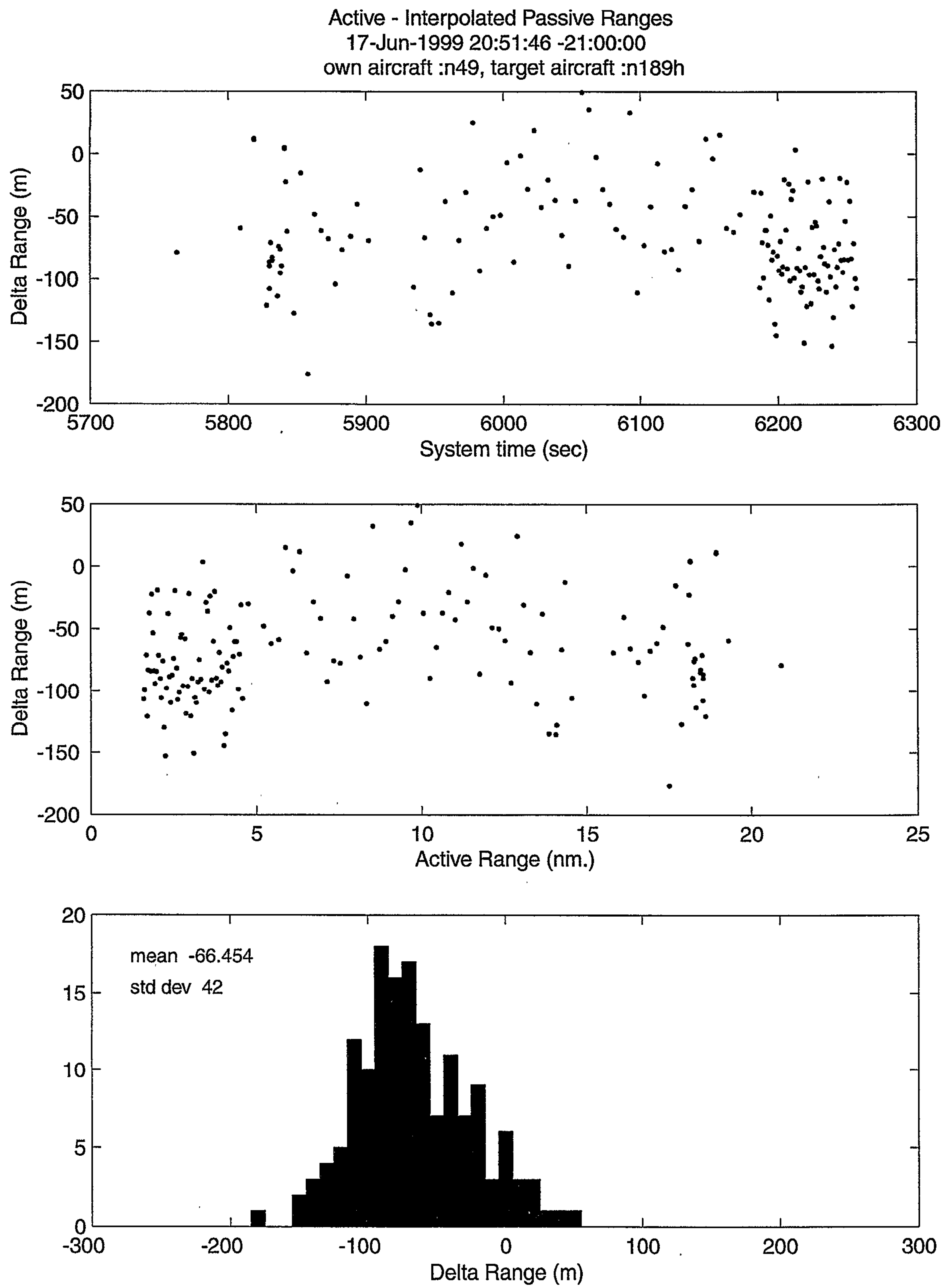

06/17/1999 21:04:00 -21:08:29
nmi. north of reference
nmi. east of reference
N49
N189H
KUMBA
Miramar NAS


signal level
time GMT

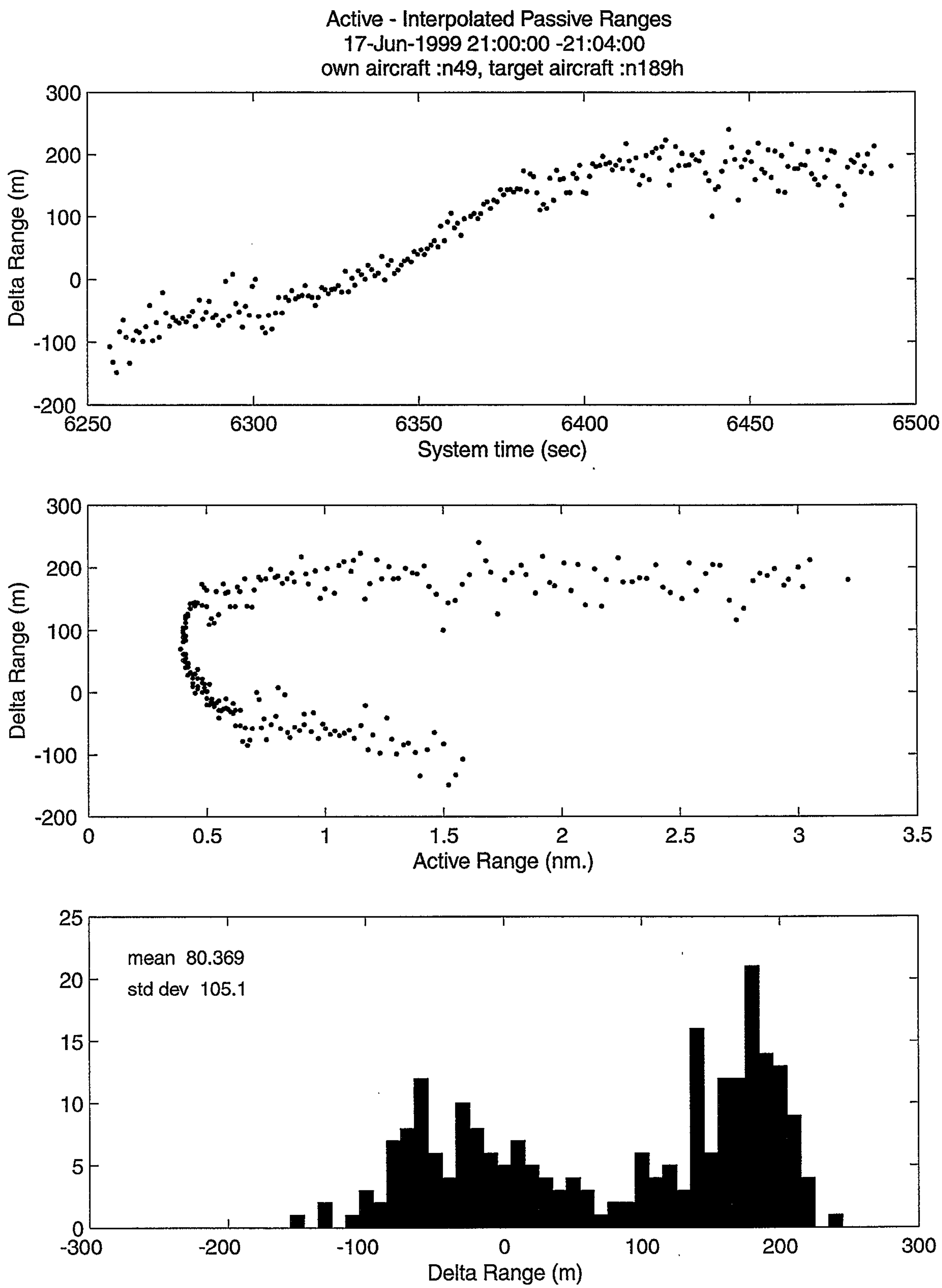


Range between N49 and N189H on17-Jun-1999
nautical miles
0
5
10
15
20
25
30
35
40
45
20:50:00
20:55:00
21:00:00
21:05:00
21:10:00
time

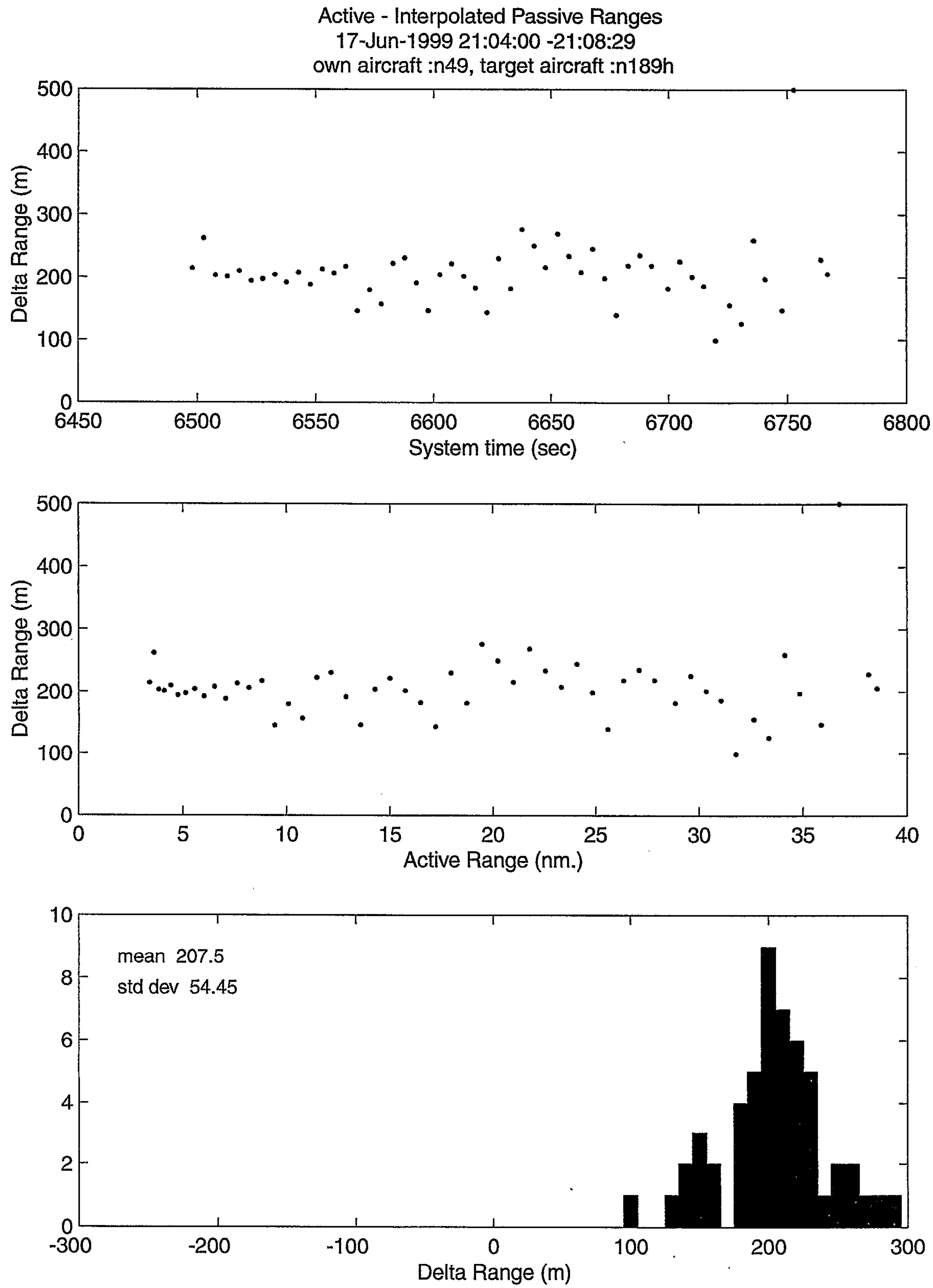

Active - Interpolated Passive Ranges
17-Jun-1999 20:51:46 -21:08:29
own aircraft :n49, target aircraft :n189h
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 44.81
std dev 122.5
Delta Range (m)



Active - Interpolated Passive Ranges
17-Jun-1999 20:51:46 -21:00:00
own aircraft :n49, target aircraft :n189h
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean -66.454
std dev 42
Delta Range (m)



Active - Interpolated Passive Ranges
17-Jun-1999 21:00:00 -21:04:00
own aircraft :n49, target aircraft :n189h
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 80.369
std dev 105.1
Delta Range (m)

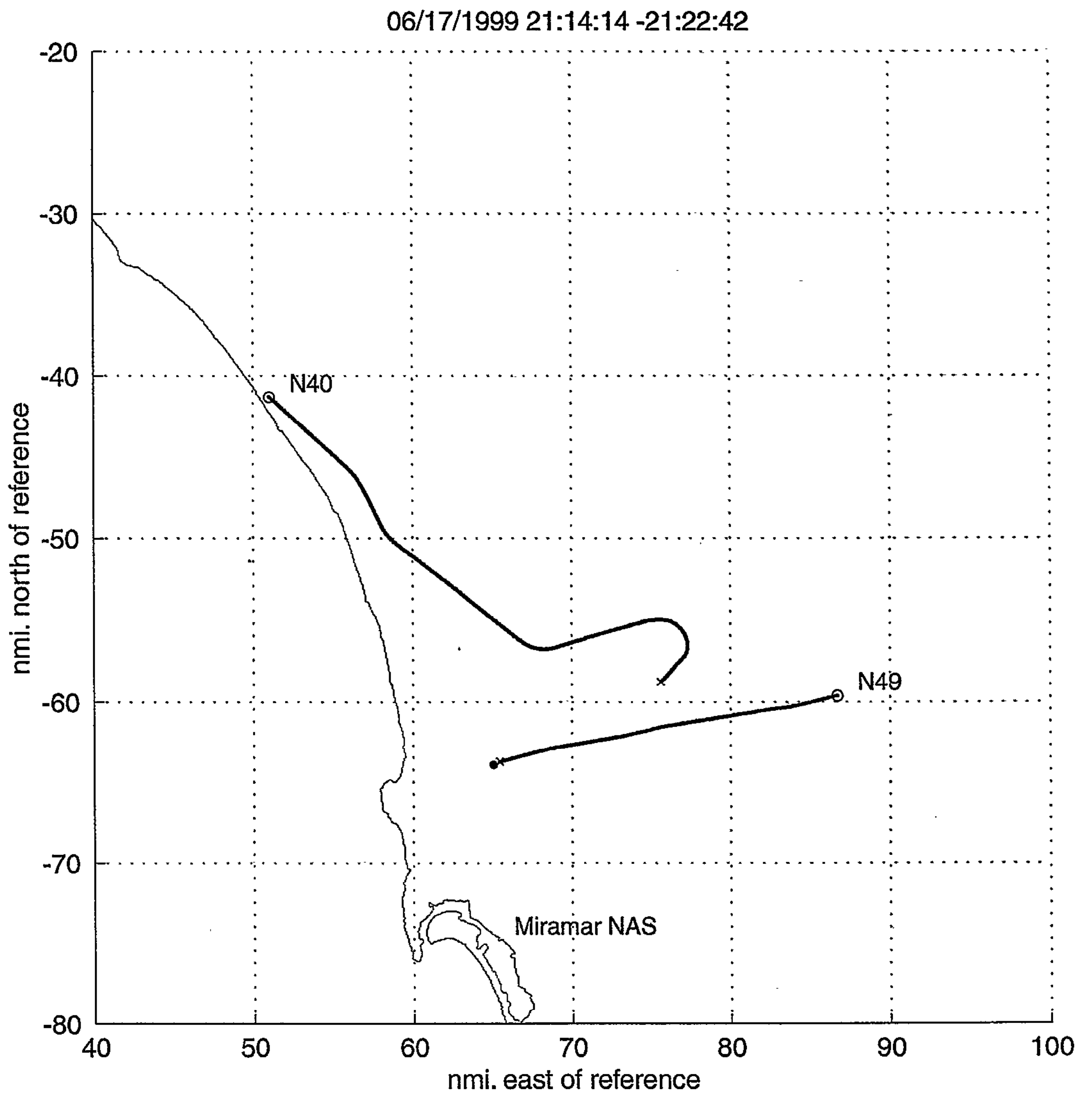


Active - Interpolated Passive Ranges
17-Jun-1999 21:04:00 -21:08:29
own aircraft :n49, target aircraft :n189h
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 207.5
std dev 54.45
Delta Range (m)

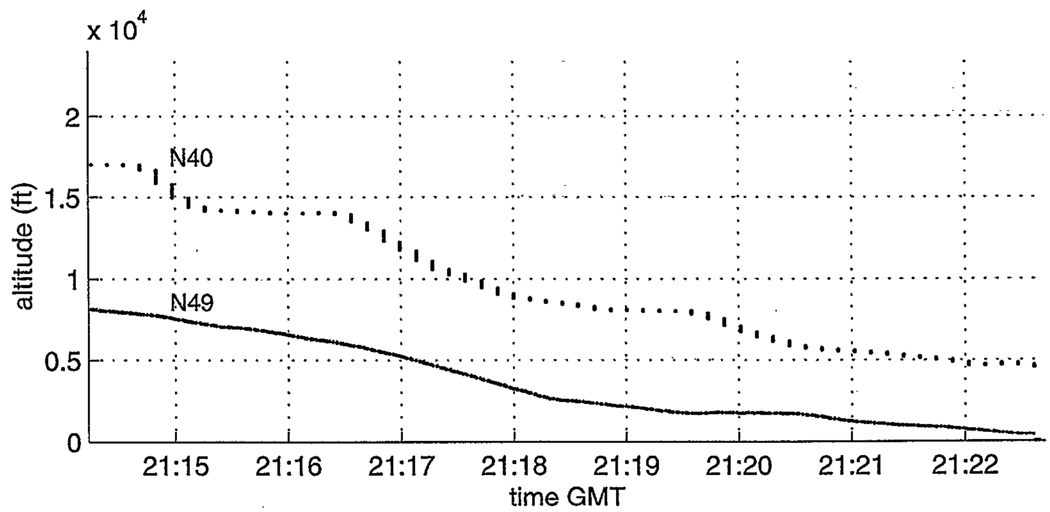
Encounter 10

N49 and N40 maneuvering to landings

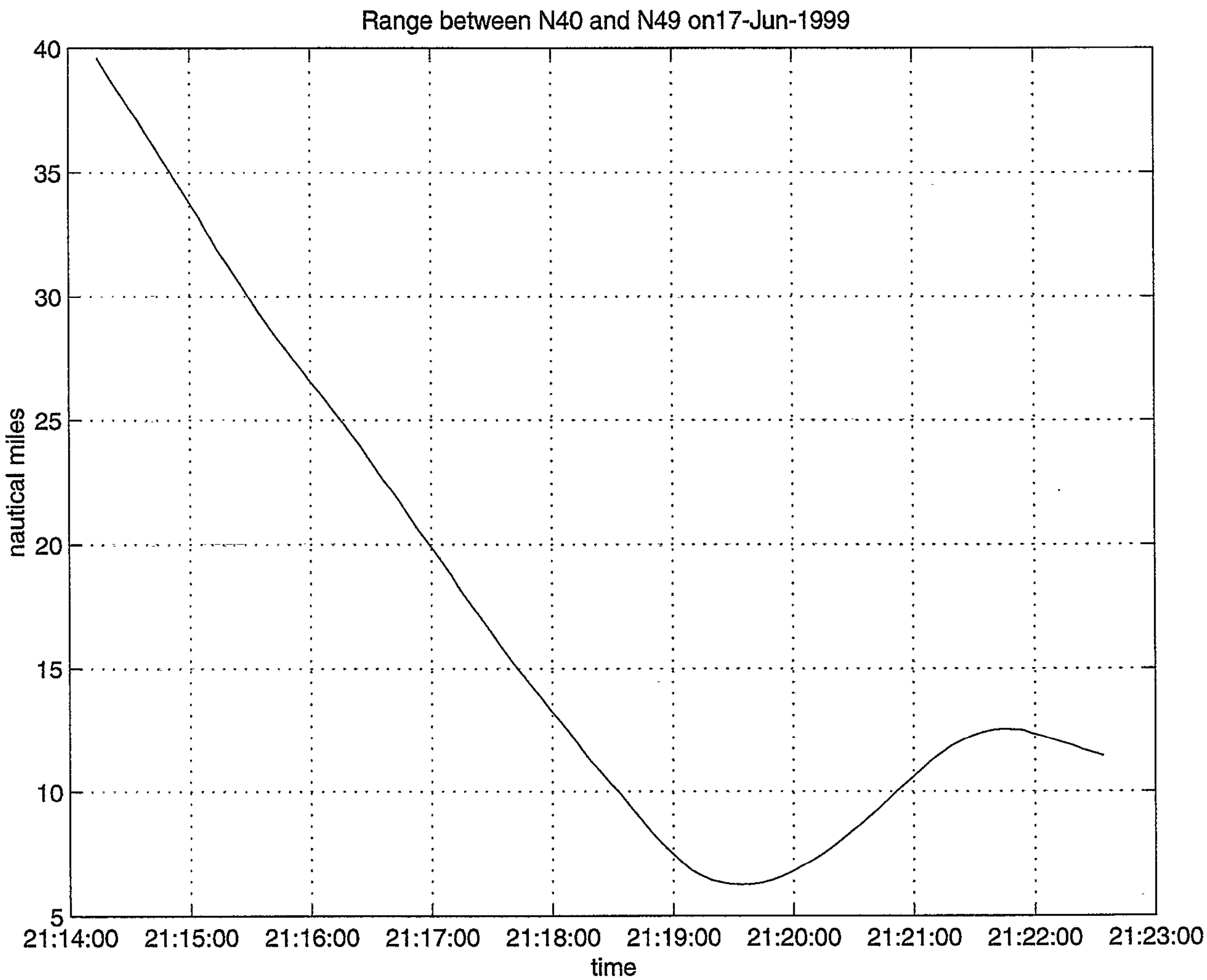
MIDDS

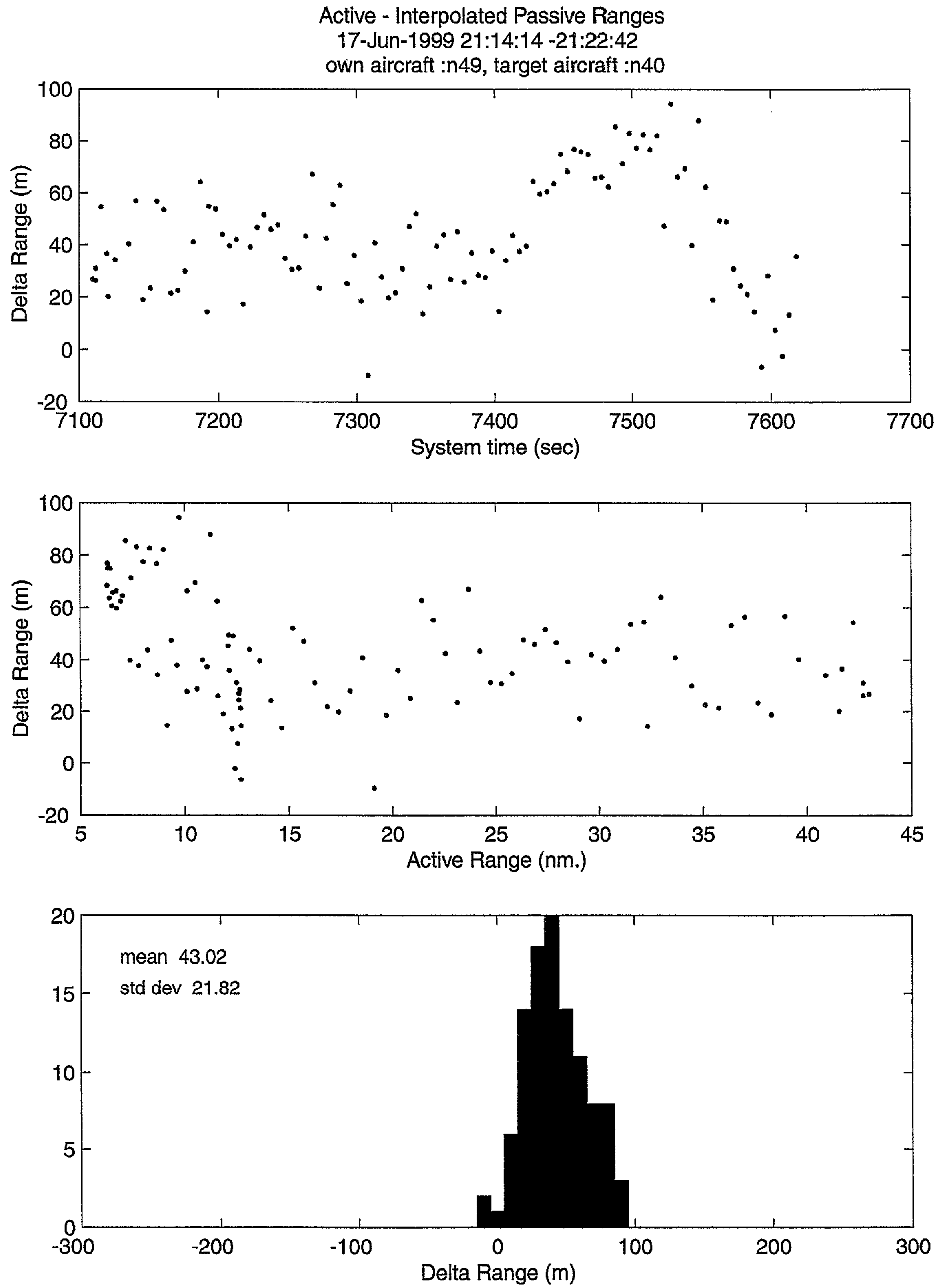


06/17/1999 21:14:14 -21:22:42
-20
-30
-40
-50
-60
-70
-80
nmi. north of reference
N40
N49
Miramar NAS
40
50
60
70
80
90
100
nmi. east of reference



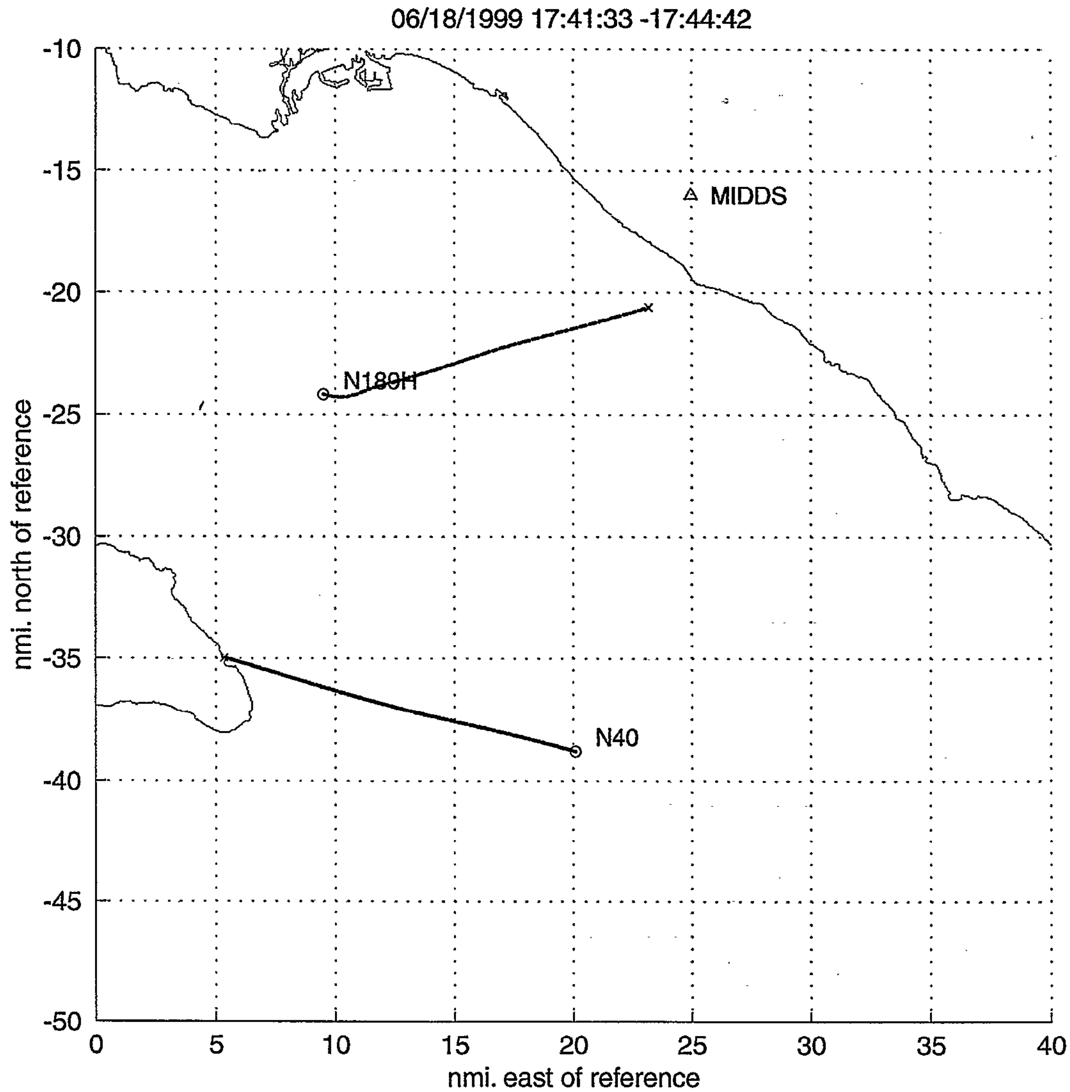
x 10^4
2
1.5
1
0.5
0
altitude (ft)
N40
N49
21:15
21:16
21:17
21:18
21:19
21:20
21:21
21:22
time GMT

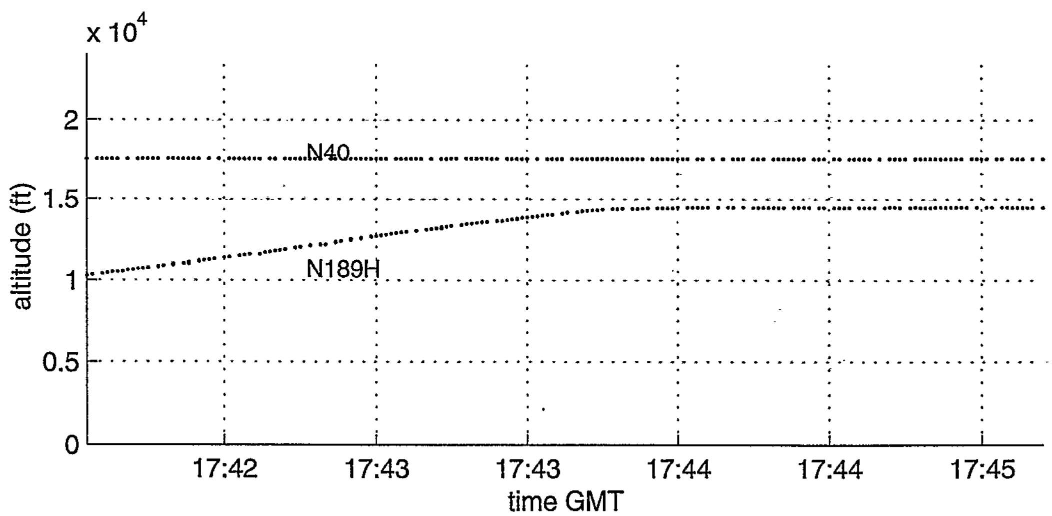

Range between N40 and N49 on17-Jun-1999
nautical miles
40
35
30
25
20
15
10
5
21:14:00
21:15:00
21:16:00
21:17:00
21:18:00
21:19:00
21:20:00
21:21:00
21:22:00
21:23:00
time


Active - Interpolated Passive Ranges
17-Jun-1999 21:14:14 -21:22:42
own aircraft :n49, target aircraft :n40
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 43.02
std dev 21.82
Delta Range (m)

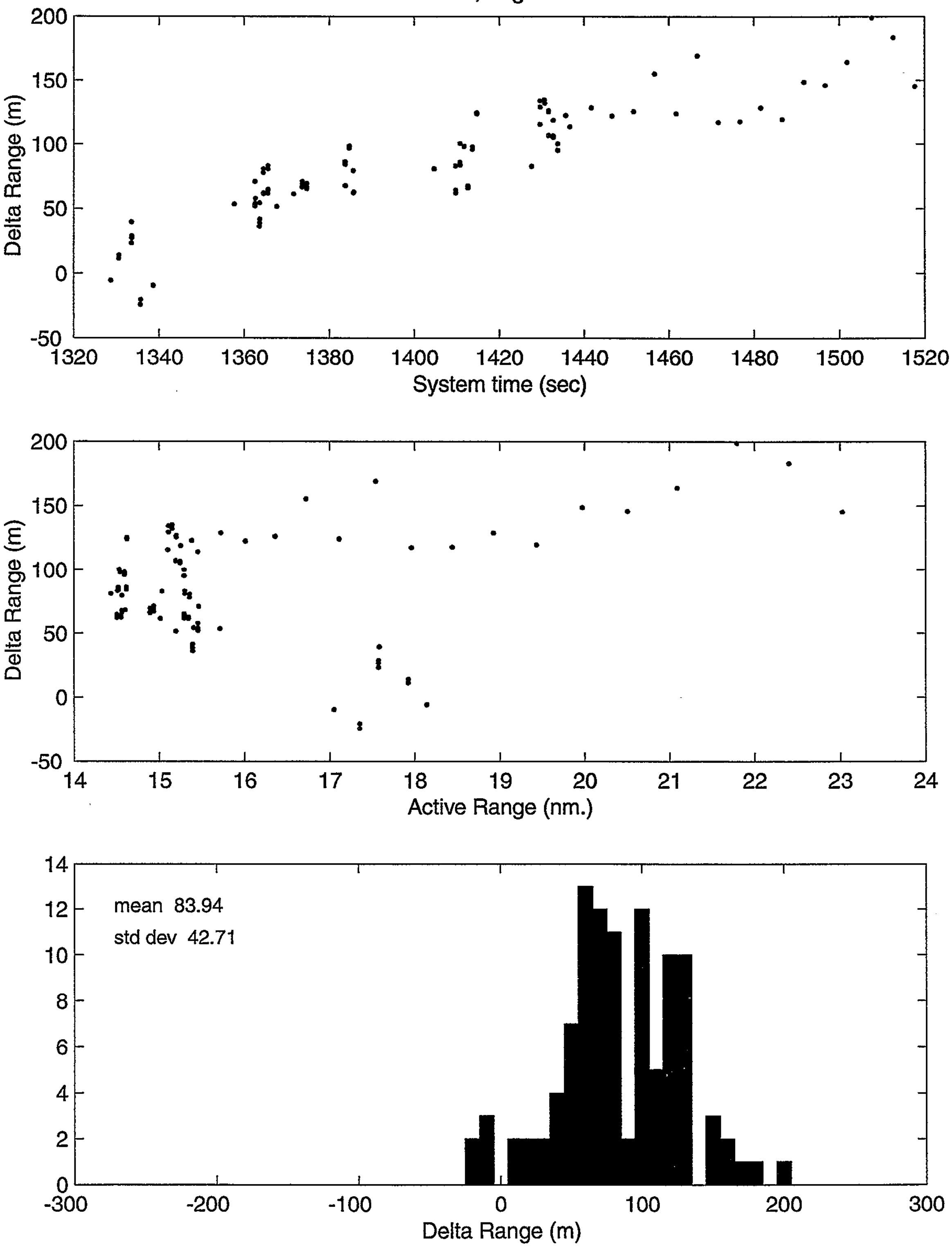
Encounter 11

N40 and N189H far apart crossing


06/18/1999 17:41:33 -17:44:42
MIDDS
N189H
N40
nmi. north of reference
nmi. east of reference
-10
-15
-20
-25
-30
-35
-40
-45
-50
0
5
10
15
20
25
30
35
40

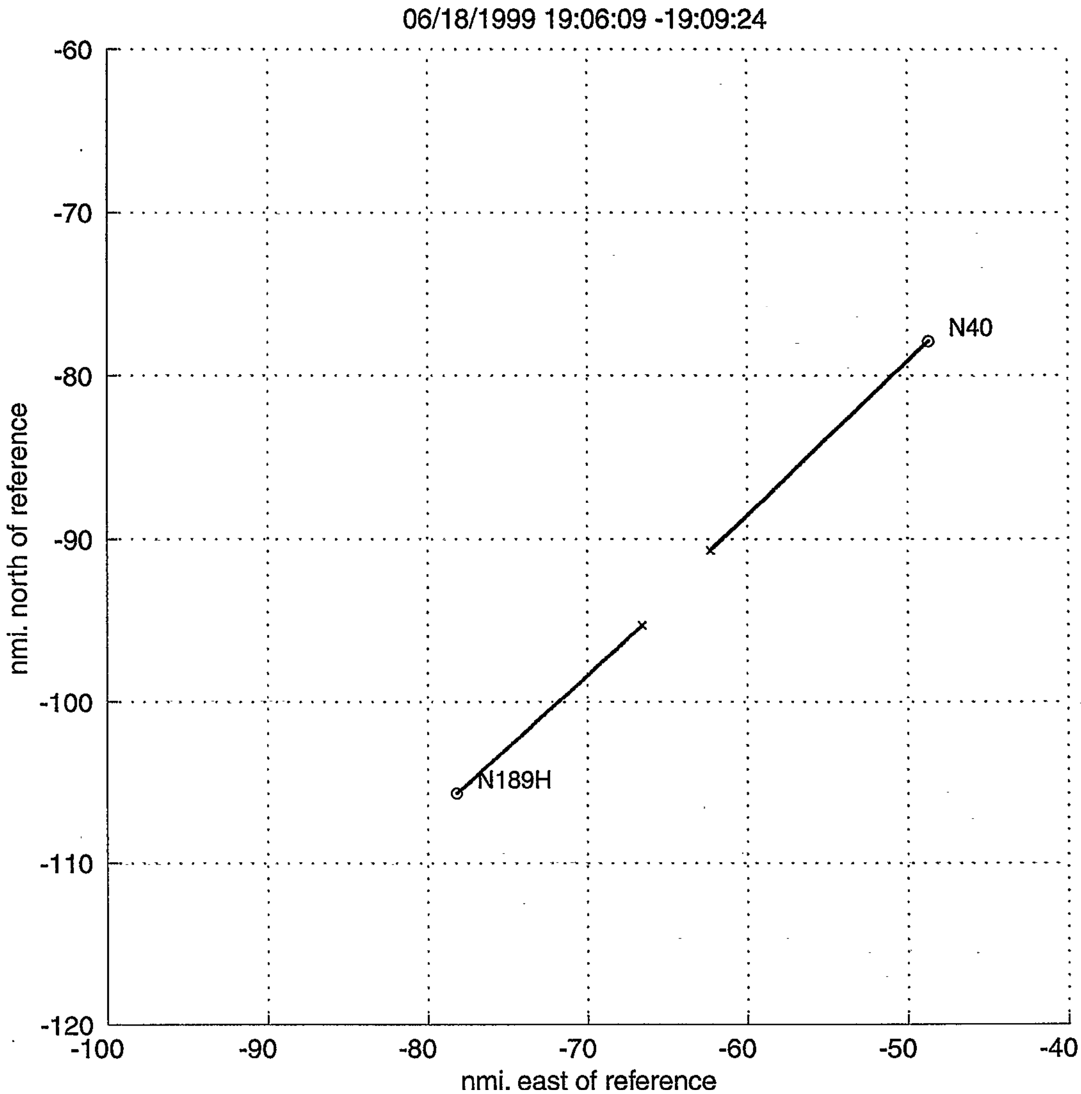

x 10^4
N40
N189H
altitude (ft)
2
1.5
1
0.5
0
17:42
17:43
17:43
17:44
17:44
17:45
time GMT

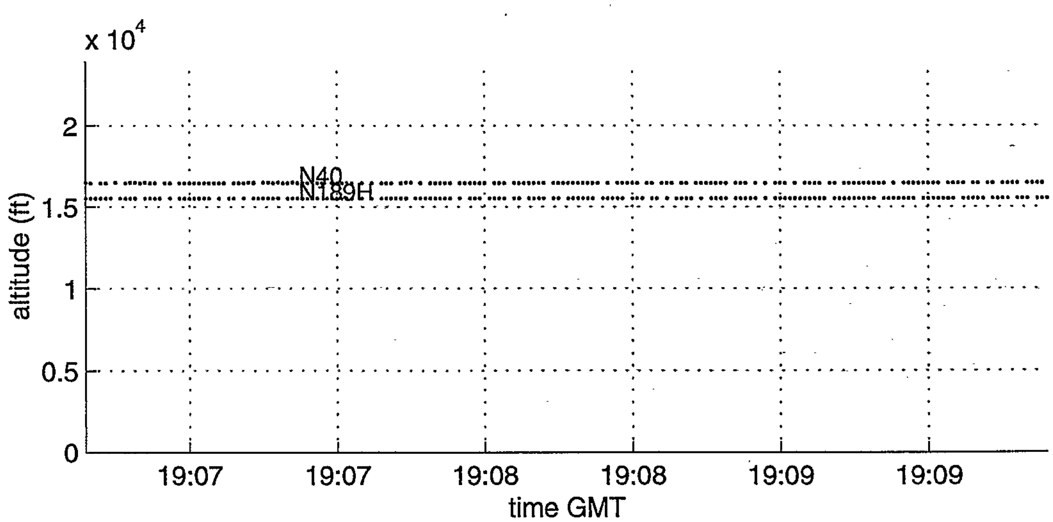
Active - Interpolated Passive Ranges
18-Jun-1999 15:41:33 -15:44:42
own aircraft :n40, target aircraft :n189h

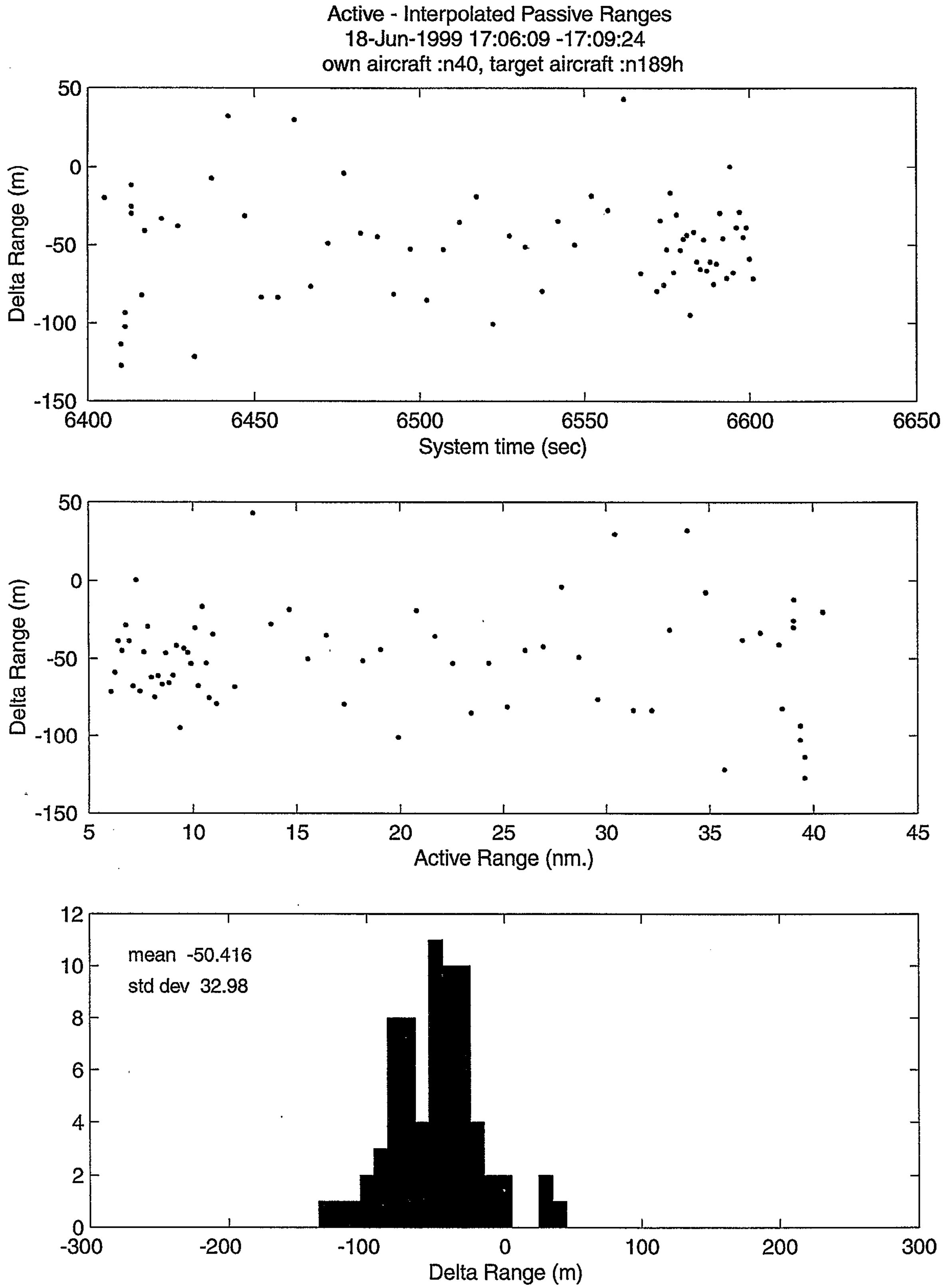


Encounter 12 and 13

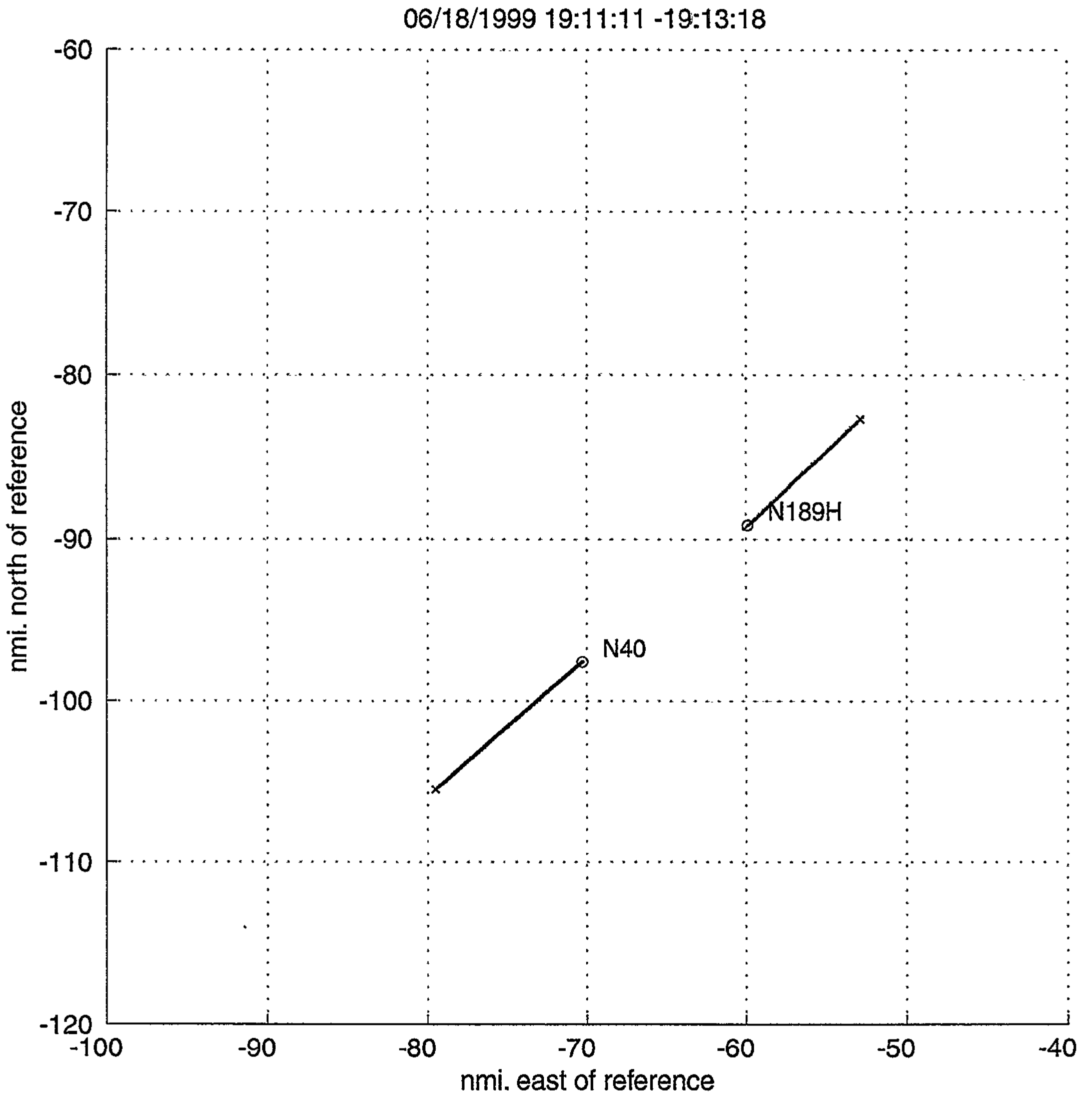
N40 and N189H head-on crossing before and after

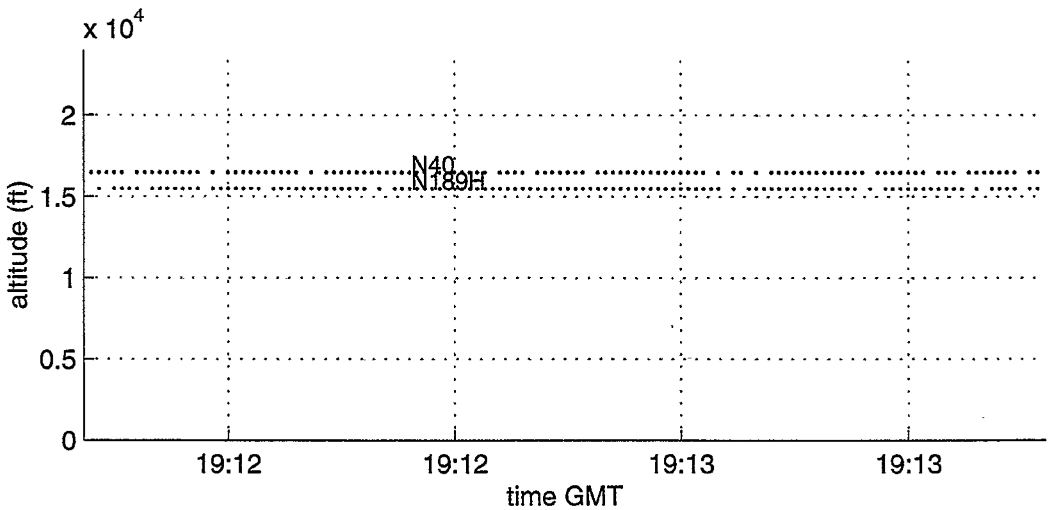

06/18/1999 19:06:09 -19:09:24
N40
N189H
nmi. north of reference
nmi. east of reference
-60
-70
-80
-90
-100
-110
-120
-100
-90
-80
-70
-60
-50
-40

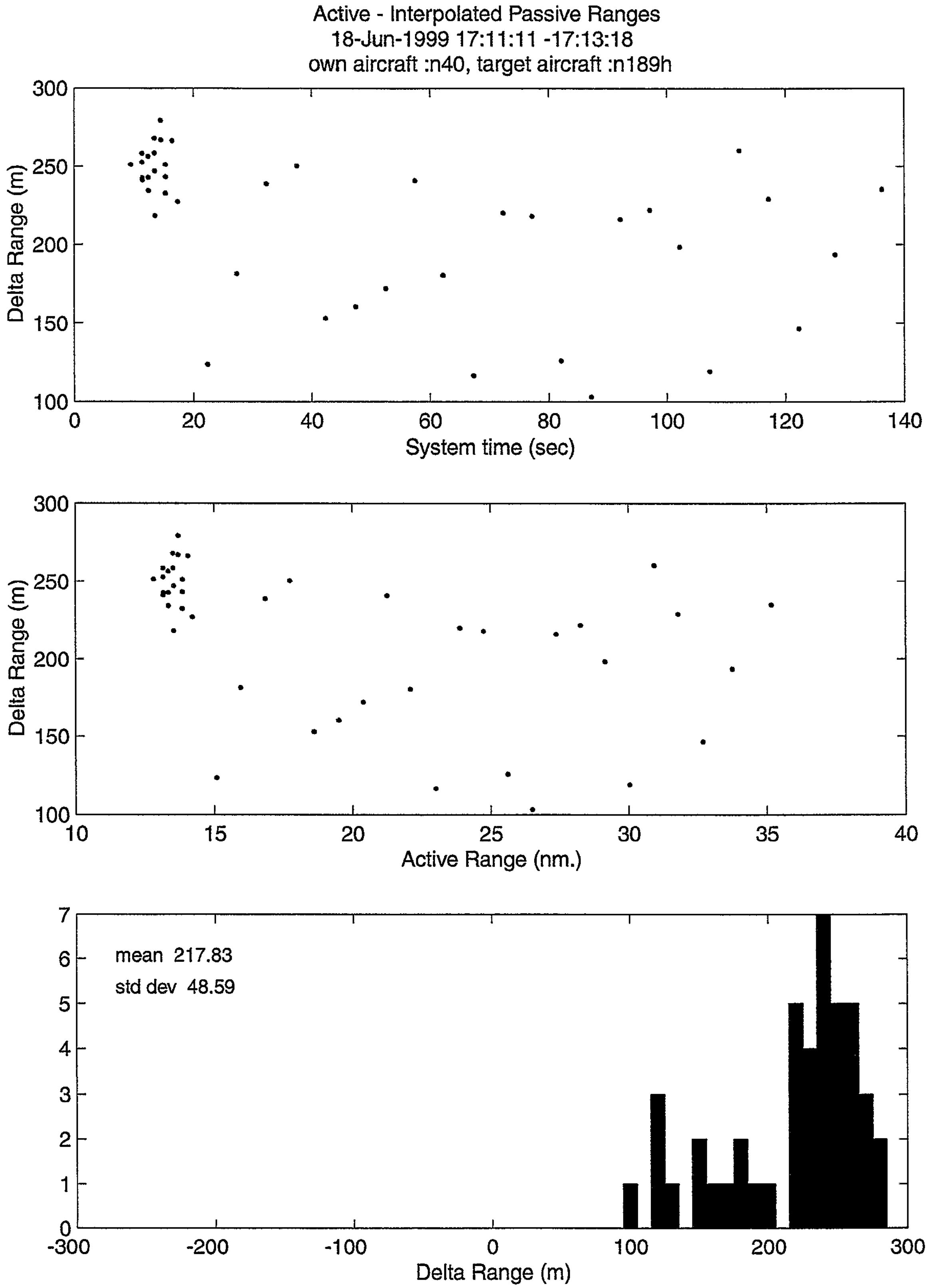

x 10^4
N40
N189H
altitude (ft)
2
1.5
1
0.5
0
19:07
19:07
19:08
19:08
19:09
19:09
time GMT



Active - Interpolated Passive Ranges
18-Jun-1999 17:06:09 -17:09:24
own aircraft :n40, target aircraft :n189h
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean -50.416
std dev 32.98
Delta Range (m)

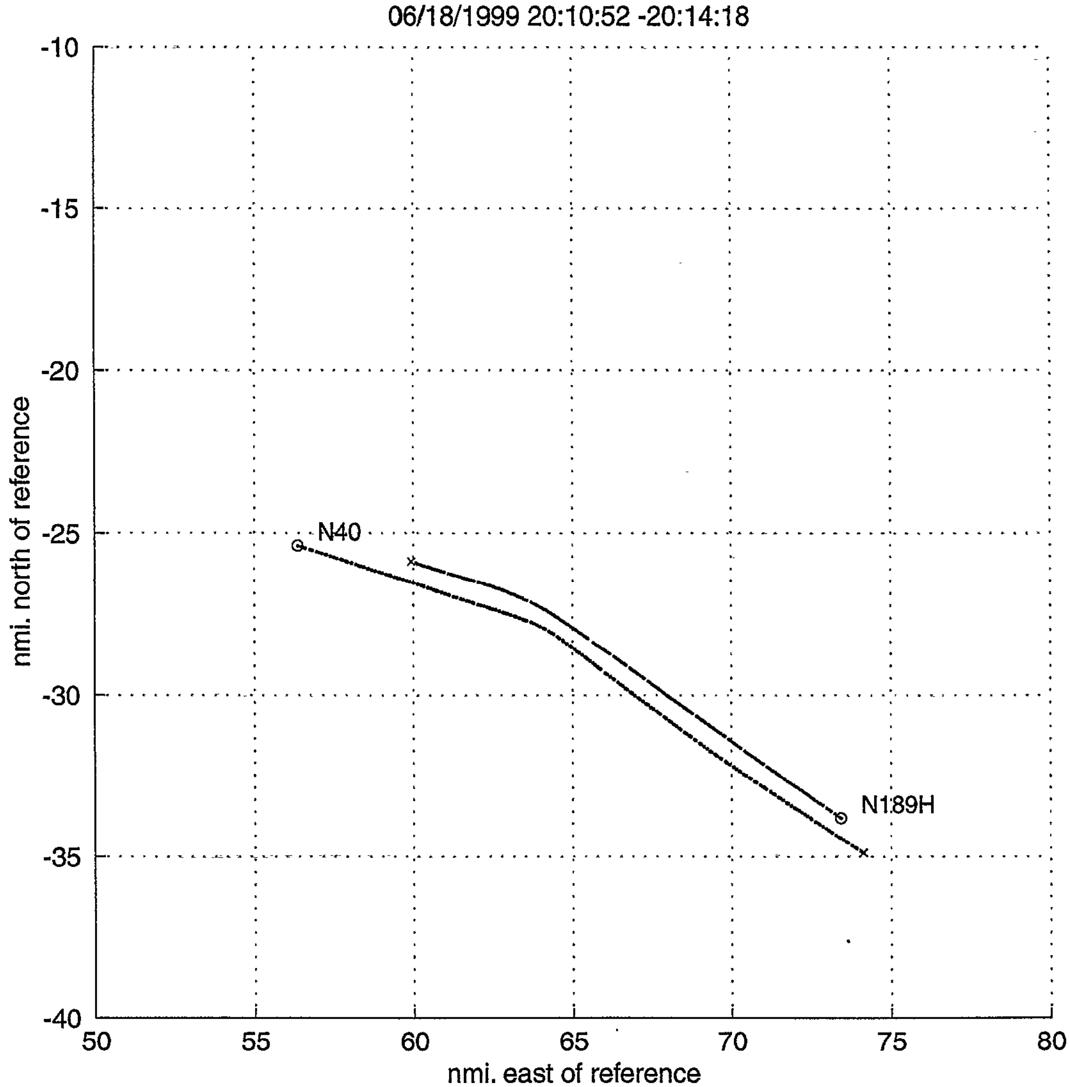

06/18/1999 19:11:11 -19:13:18
-60
-70
-80
-90
-100
-110
-120
nmi. north of reference
N189H
N40
-100
-90
-80
-70
-60
-50
-40
nmi. east of reference

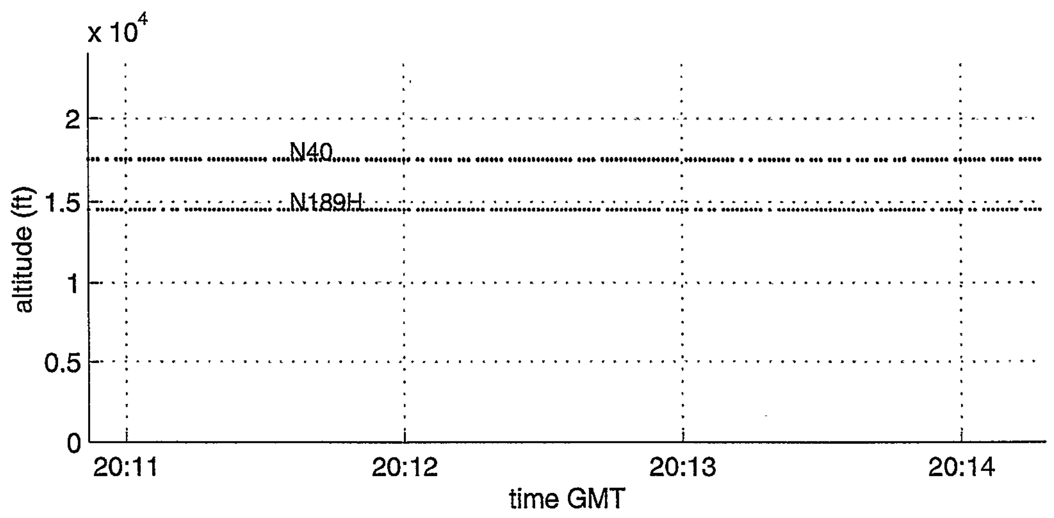

x 10^4
2
1.5
1
0.5
0
altitude (ft)
N40
N189H
19:12
19:12
19:13
19:13
time GMT

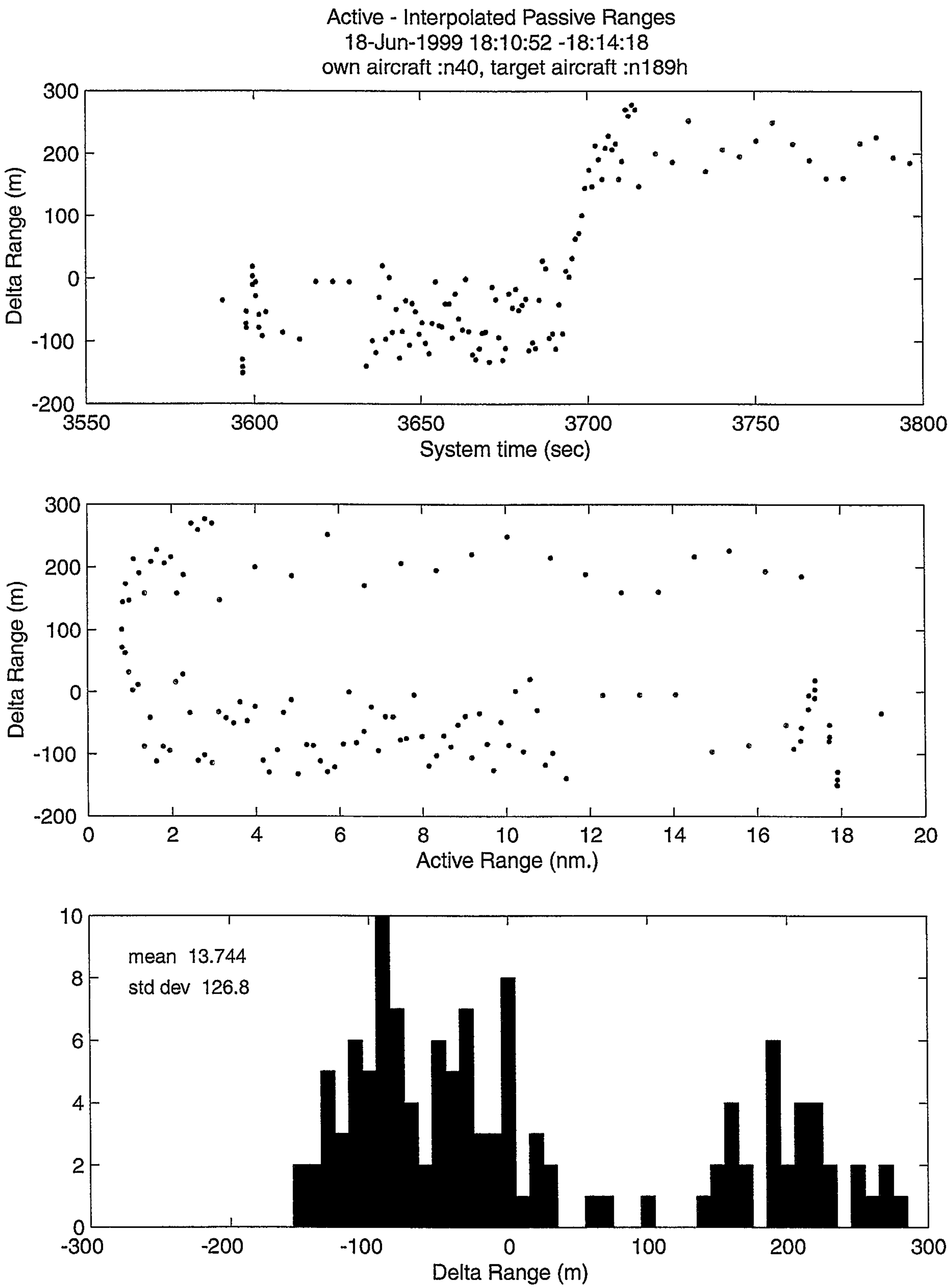

Active - Interpolated Passive Ranges
18-Jun-1999 17:11:11 -17:13:18
own aircraft :n40, target aircraft :n189h
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 217.83
std dev 48.59
Delta Range (m)

Encounter 14

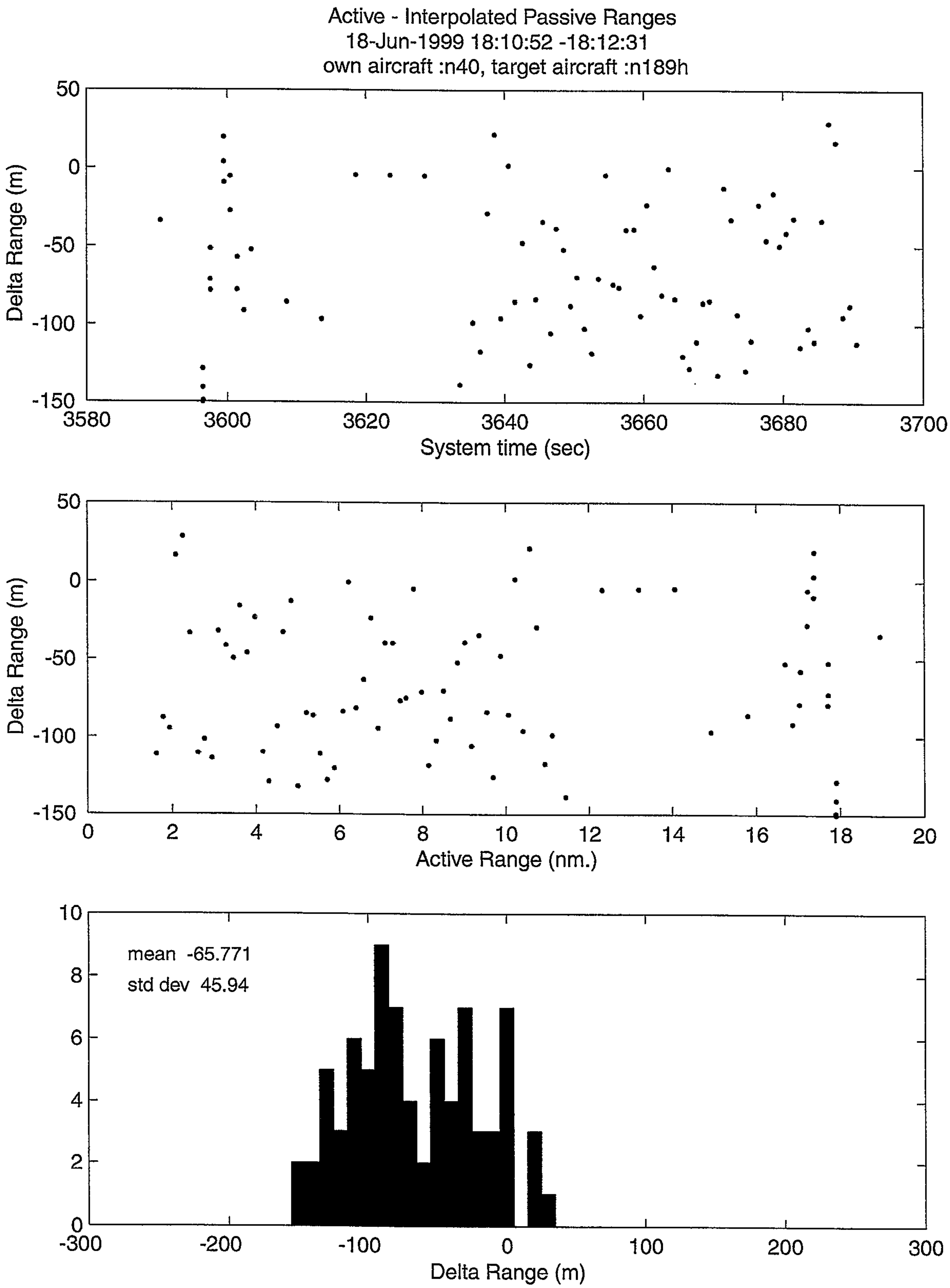
N40 and N189H head-on crossing with slight turn by both aircraft (same track)

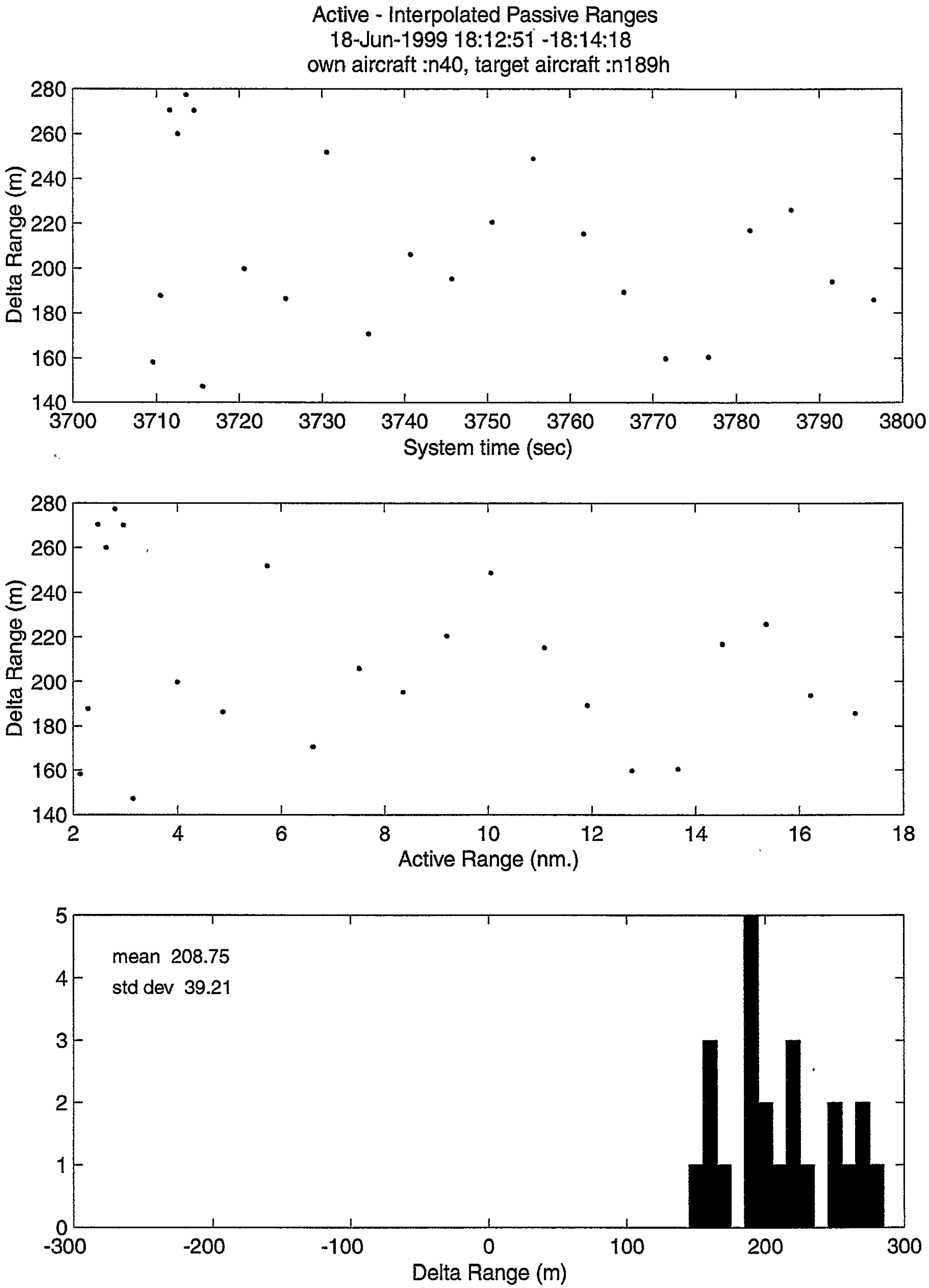

06/18/1999 20:10:52 -20:14:18
-10
-15
-20
-25
-30
-35
-40
50
55
60
65
70
75
80
nmi. north of reference
nmi. east of reference
N40
N189H


x 10^4
2
1.5
1
0.5
0
altitude (ft)
N40
N189H
20:11
20:12
20:13
20:14
time GMT



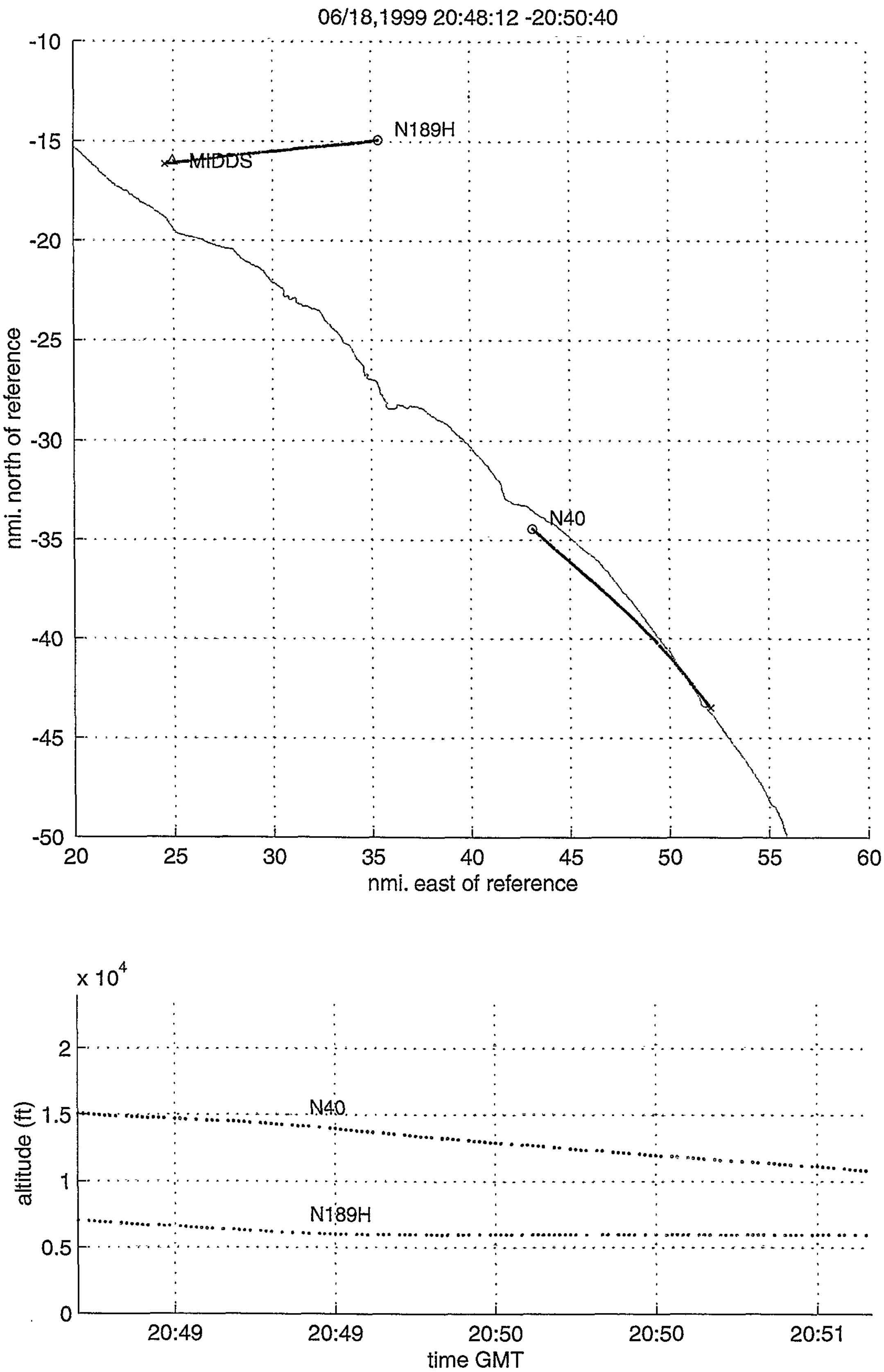
Active - Interpolated Passive Ranges
18-Jun-1999 18:10:52 -18:14:18
own aircraft :n40, target aircraft :n189h
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 13.744
std dev 126.8
Delta Range (m)


Active - Interpolated Passive Ranges
18-Jun-1999 18:10:52 -18:12:31
own aircraft :n40, target aircraft :n189h
Delta Range (m)
System time (sec)
Active Range (nm.)
mean -65.771
std dev 45.94
Delta Range (m)

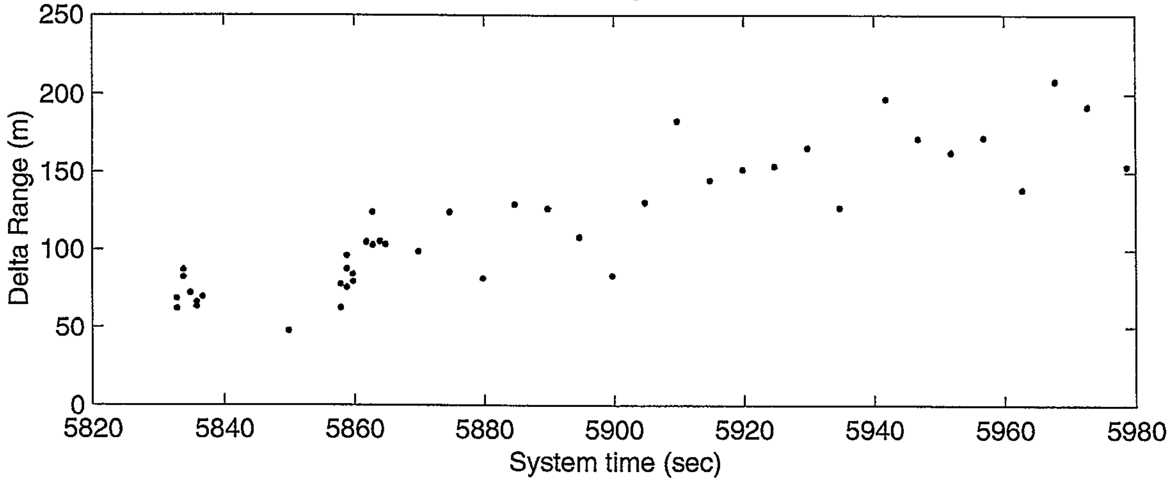

Active - Interpolated Passive Ranges
18-Jun-1999 18:12:51 -18:14:18
own aircraft :n40, target aircraft :n189h
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 208.75
std dev 39.21
Delta Range (m)

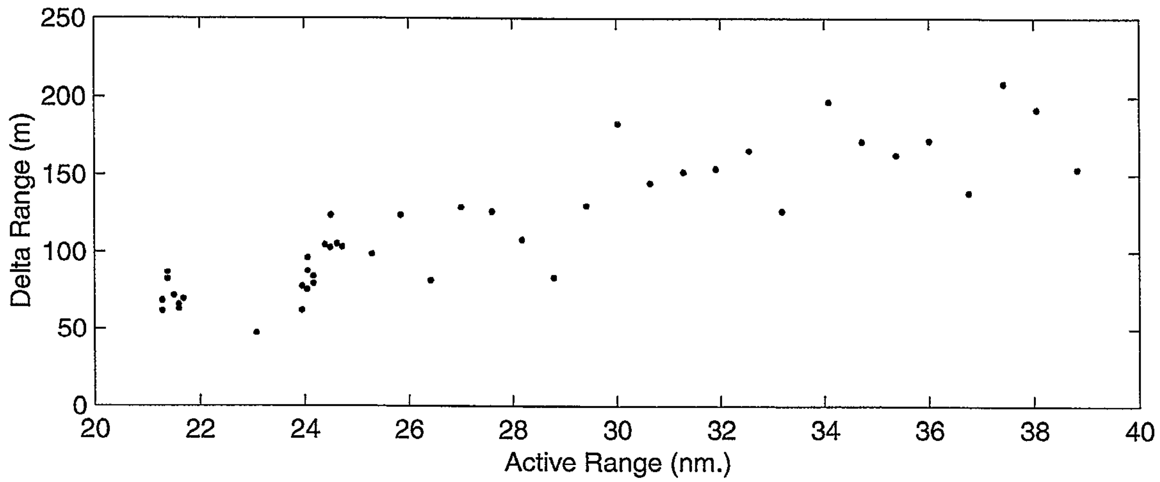
Encounter 15

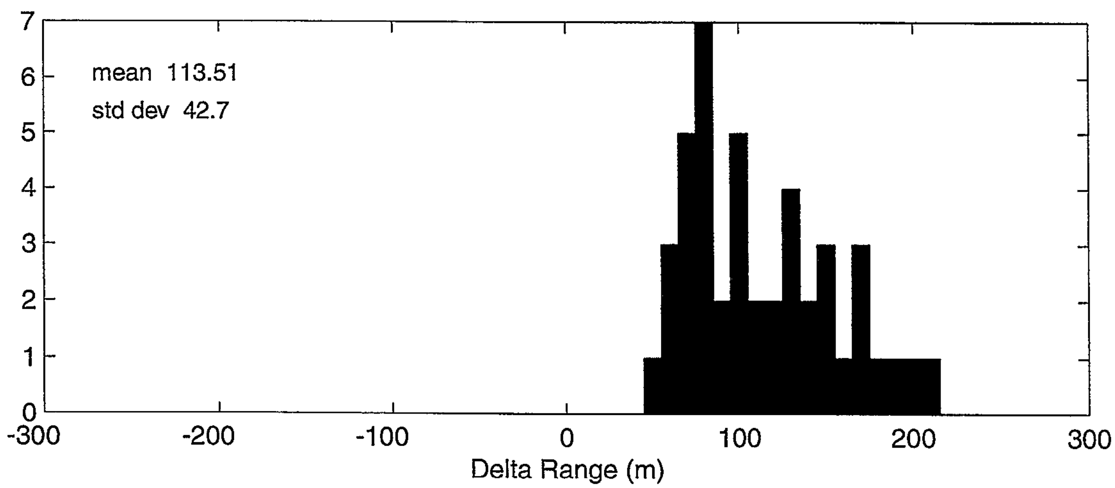
N40 and N189H diverging at right angles far apart


06/18,1999 20:48:12 -20:50:40
N189H
MIDDS
N40
nmi. north of reference
nmi. east of reference
-10
-15
-20
-25
-30
-35
-40
-45
-50
20
25
30
35
40
45
50
55
60
x 10^4
altitude (ft)
2
1.5
1
0.5
0
N40
N189H
20:49
20:49
20:50
20:50
20:51
time GMT

Active - Interpolated Passive Ranges
18-Jun-1999 18:48:12 -18:50:40
own aircraft :n40, target aircraft :n189h

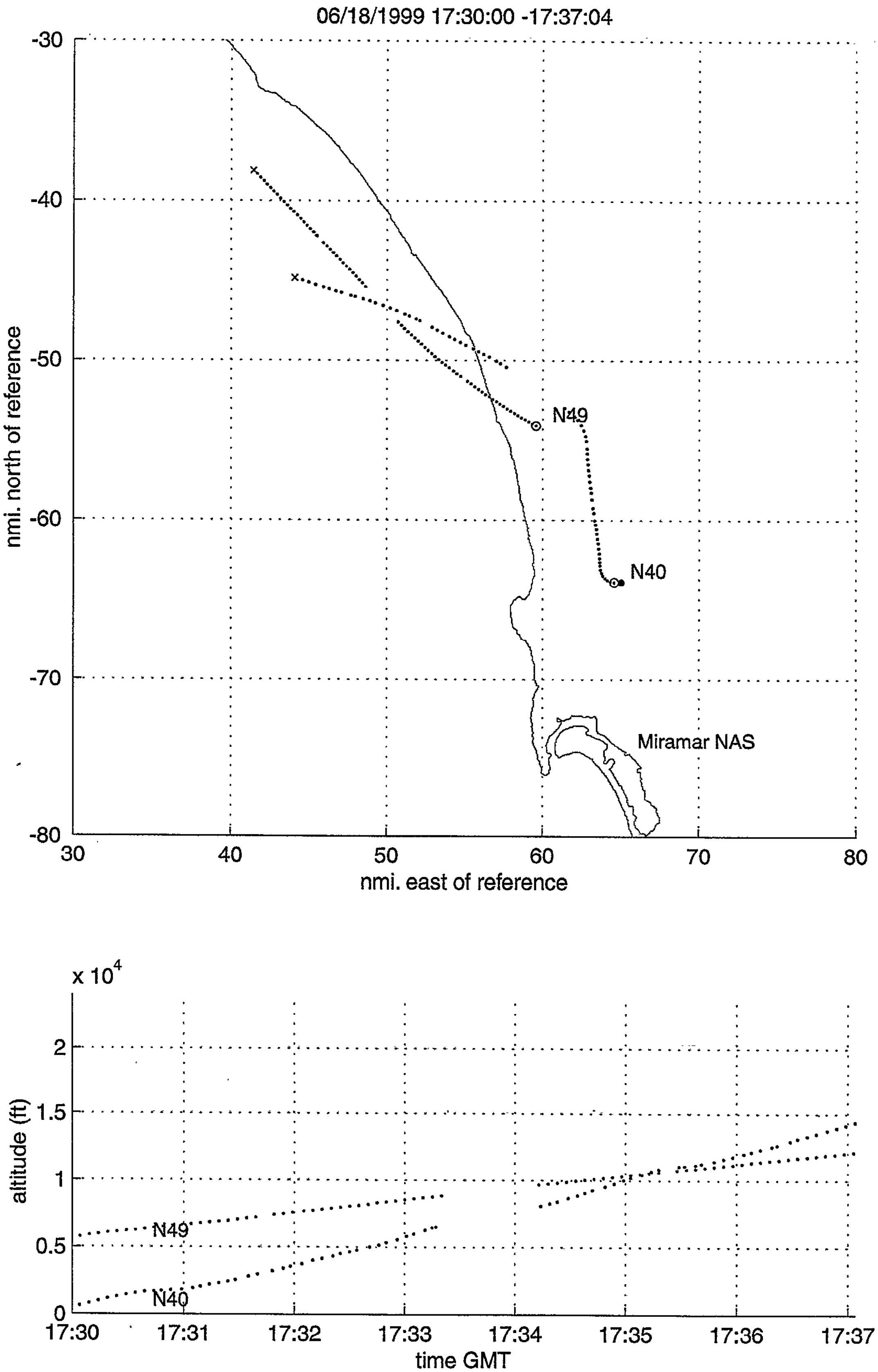




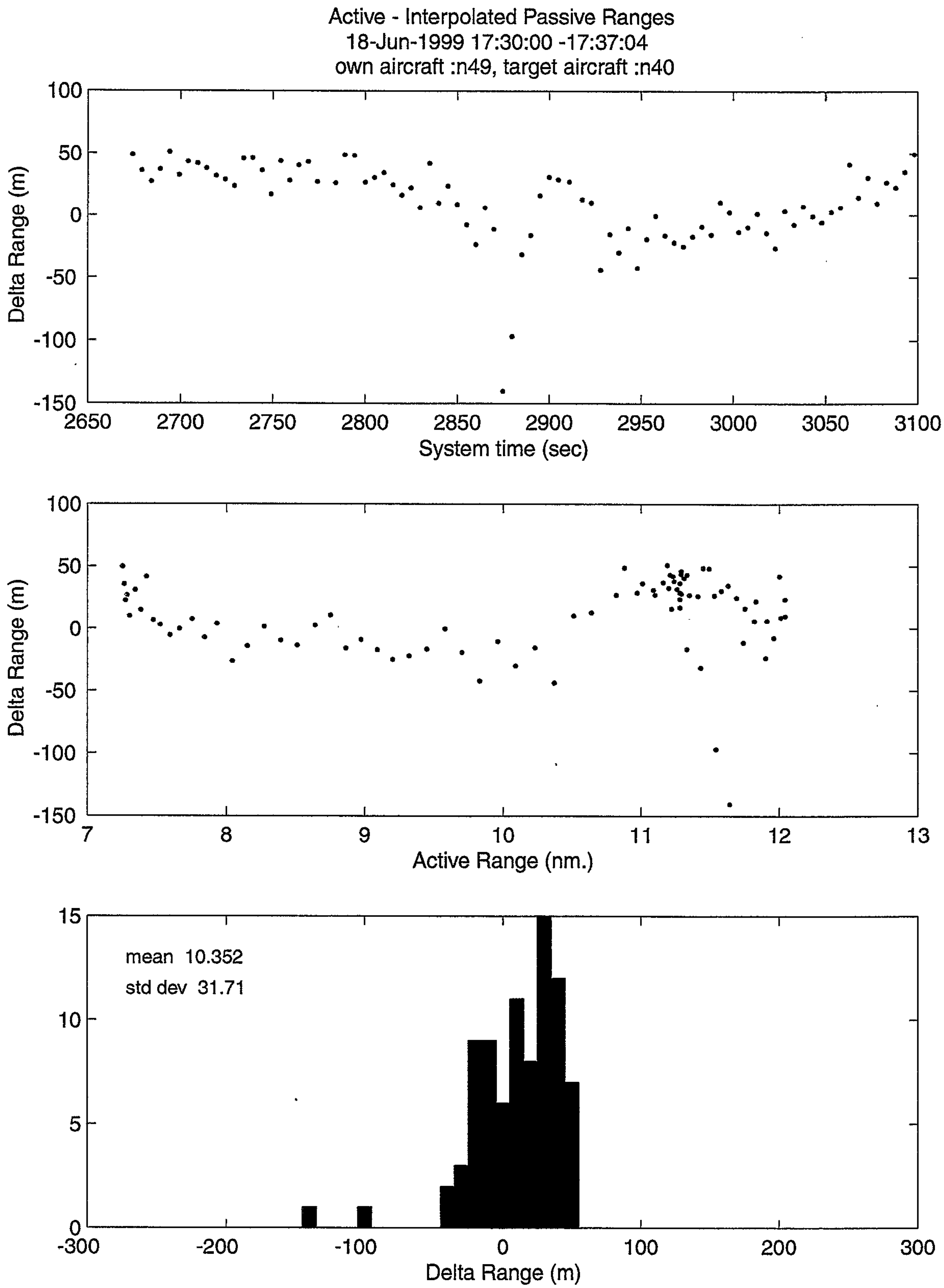


Encounter 16

N40 overtakes N49 during departure

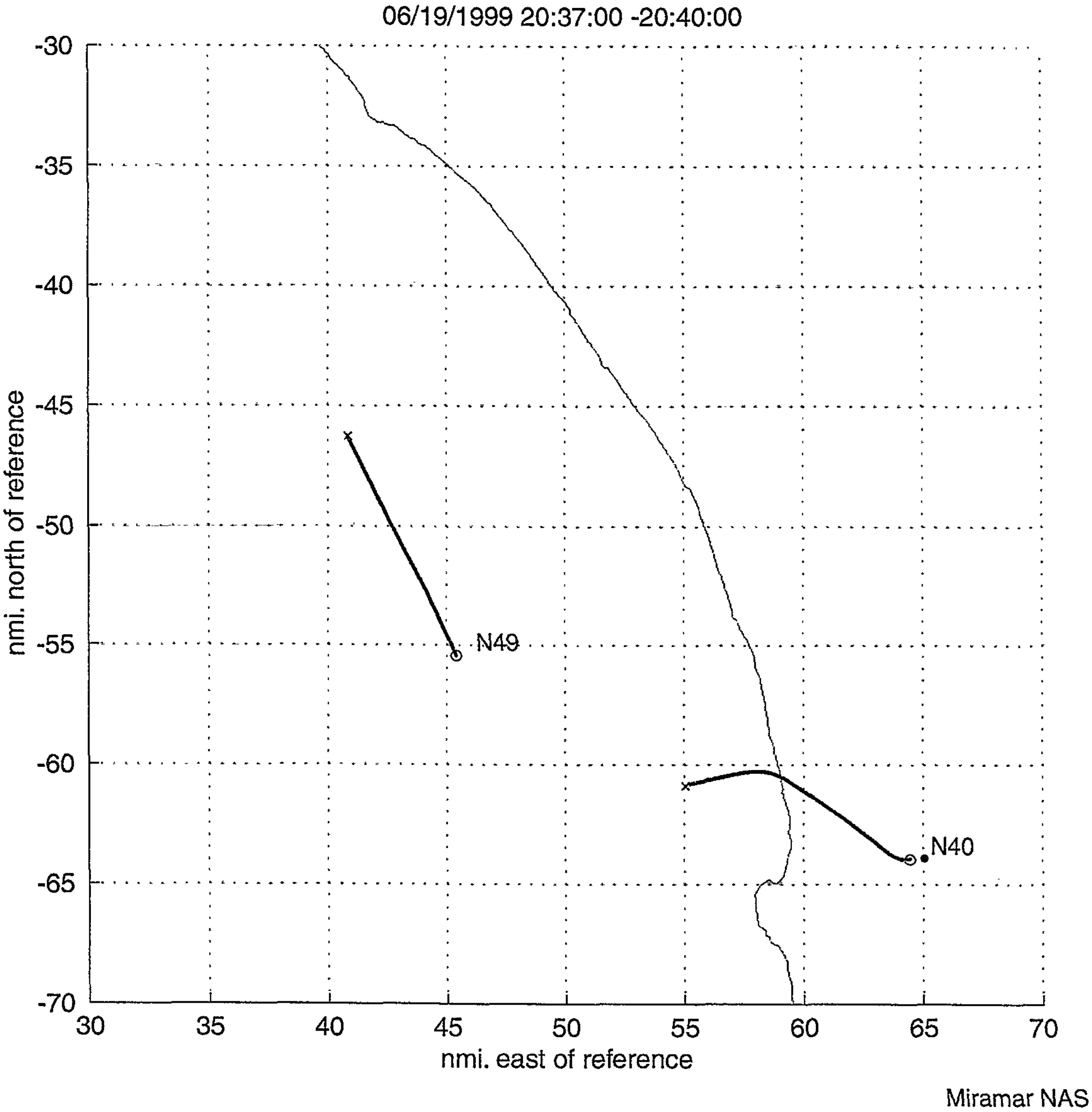


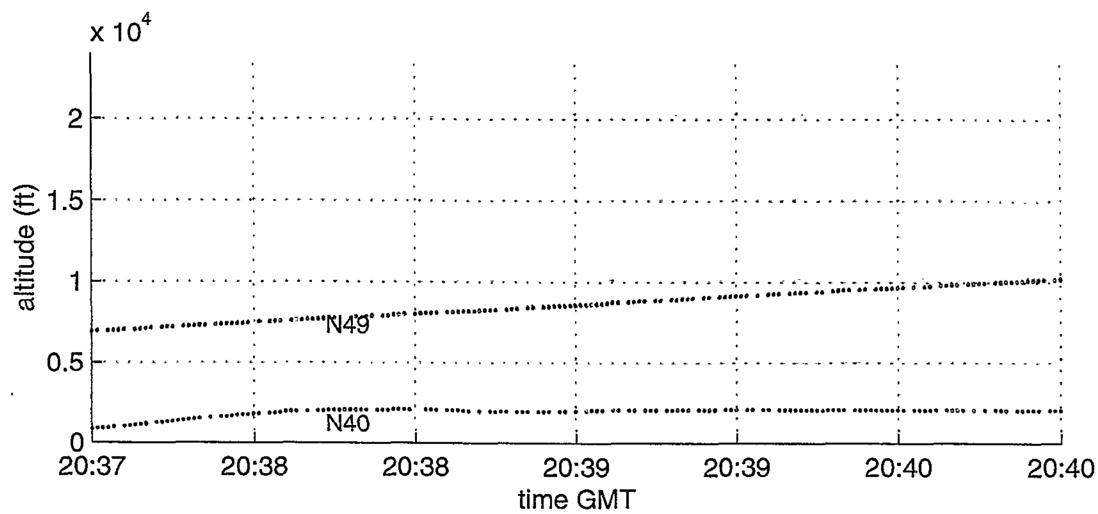
06/18/1999 17:30:00 -17:37:04
-30
-40
-50
-60
-70
-80
nmi. north of reference
30
40
50
60
70
80
nmi. east of reference
N49
N40
Miramar NAS
x 10^4
2
1.5
1
0.5
0
altitude (ft)
17:30
17:31
17:32
17:33
17:34
17:35
17:36
17:37
time GMT

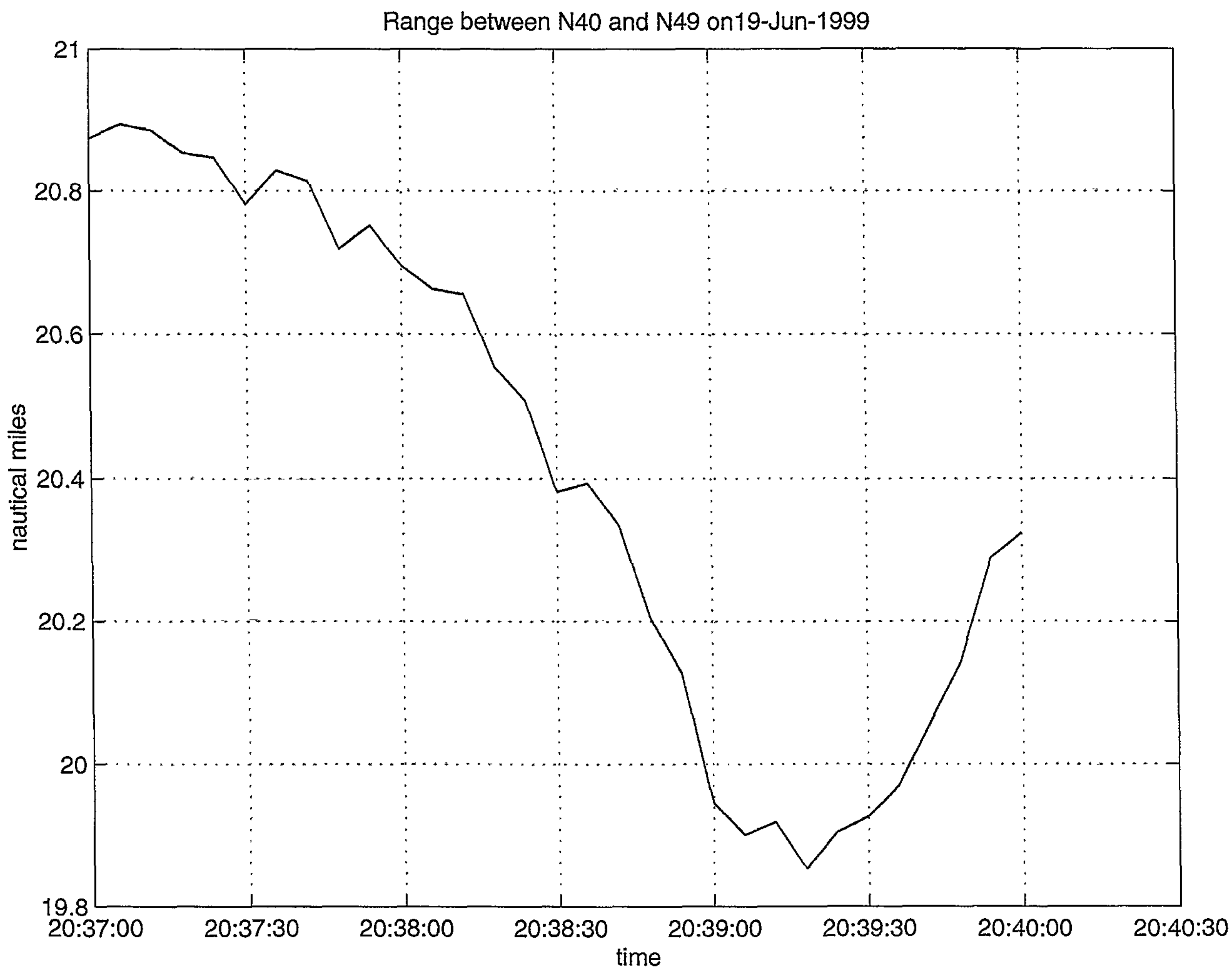

Active - Interpolated Passive Ranges
18-Jun-1999 17:30:00 -17:37:04
own aircraft :n49, target aircraft :n40
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 10.352
std dev 31.71
Delta Range (m)

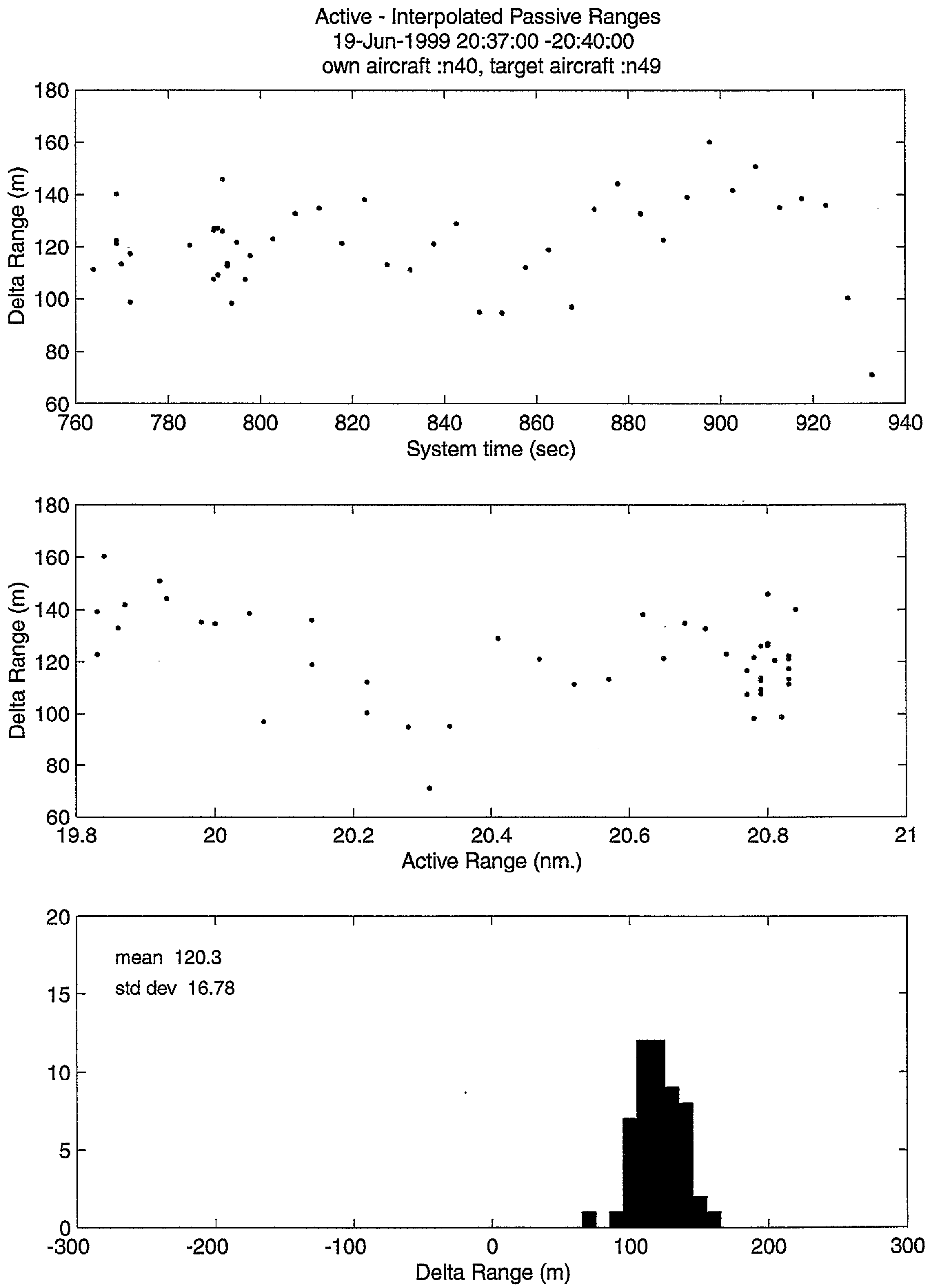
Encounter 17

N49 departing, N40 departing behind at right angles


06/19/1999 20:37:00 -20:40:00
-30
-35
-40
-45
-50
-55
-60
-65
-70
nmi. north of reference
N49
N40
30
35
40
45
50
55
60
65
70
nmi. east of reference
Miramar NAS

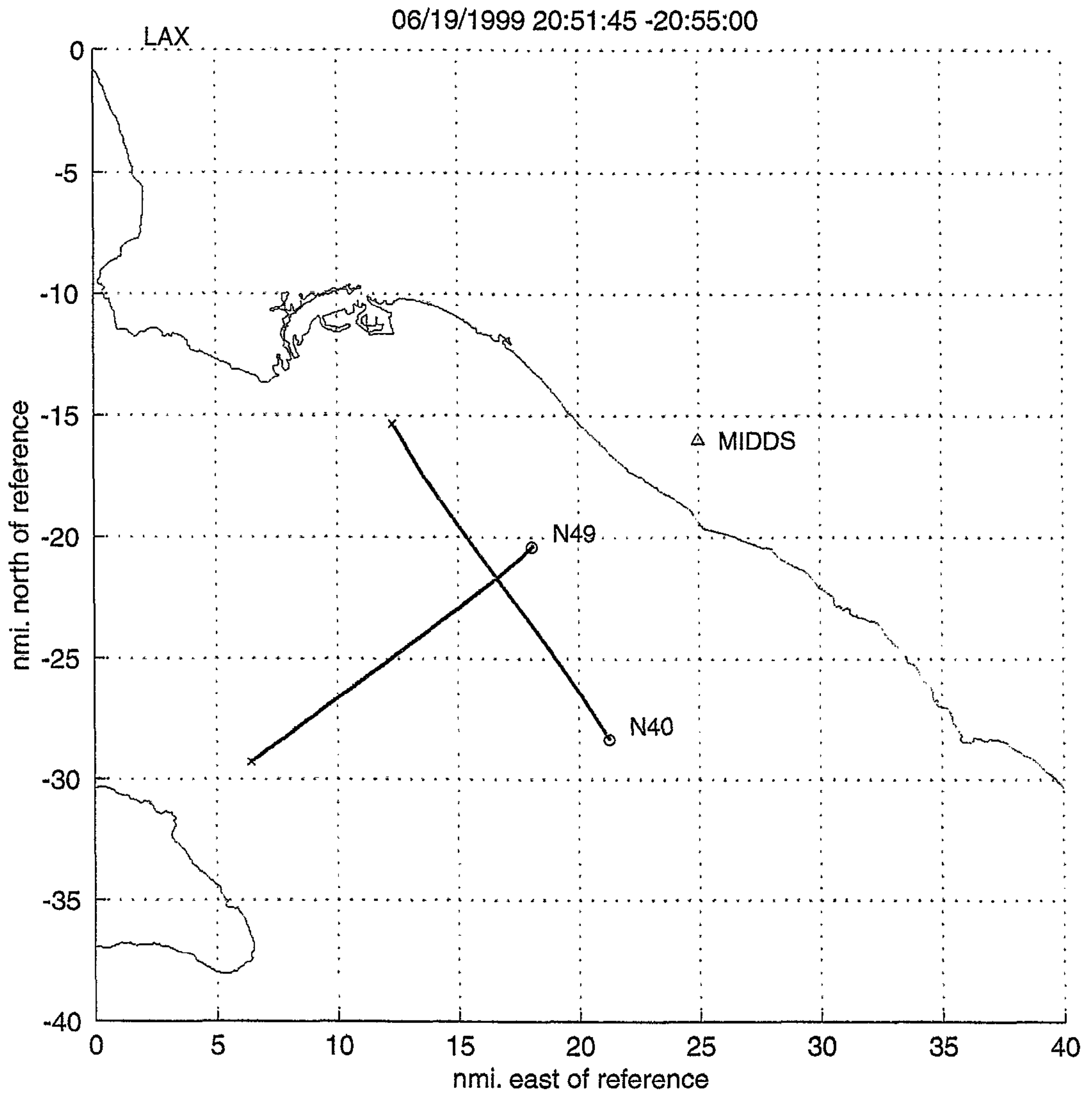

x 10^4
2
1.5
1
0.5
0
altitude (ft)
N49
N40
20:37
20:38
20:38
20:39
20:39
20:40
20:40
time GMT


Range between N40 and N49 on19-Jun-1999
21
20.8
20.6
20.4
20.2
20
19.8
nautical miles
20:37:00
20:37:30
20:38:00
20:38:30
20:39:00
20:39:30
20:40:00
20:40:30
time

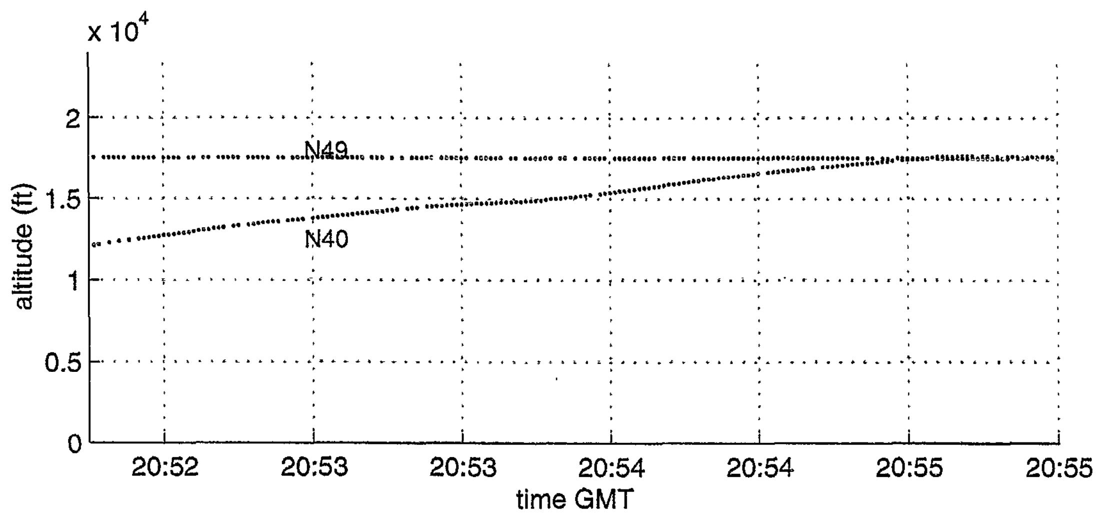

Active - Interpolated Passive Ranges
19-Jun-1999 20:37:00 -20:40:00
own aircraft :n40, target aircraft :n49
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 120.3
std dev 16.78
Delta Range (m)

Encounter 18

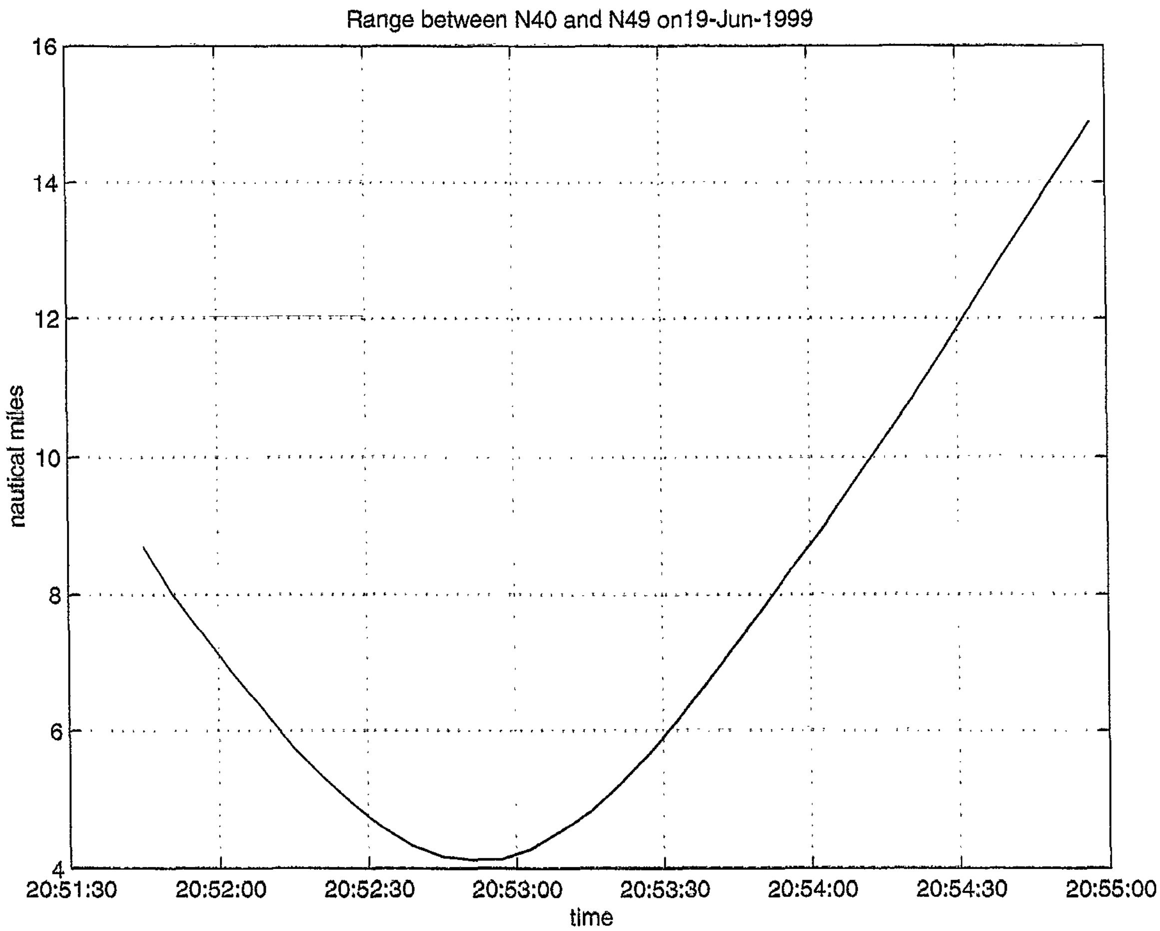
N49 crosses at right angles in front of N40



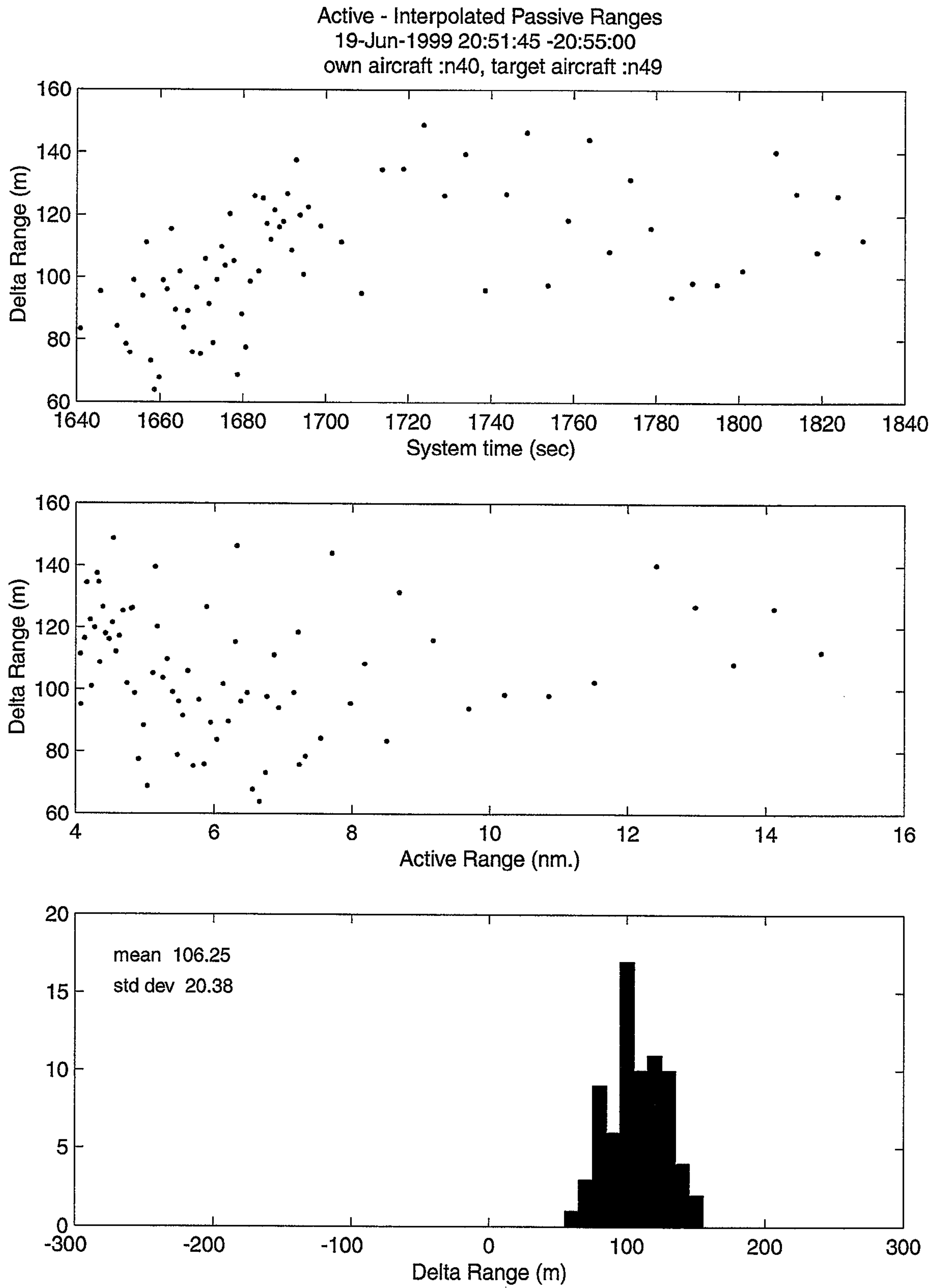
06/19/1999 20:51:45 -20:55:00
LAX
MIDDS
N49
N40
nmi. north of reference
nmi. east of reference
0
-5
-10
-15
-20
-25
-30
-35
-40
0
5
10
15
20
25
30
35
40



x 10^4
altitude (ft)
N49
N40
2
1.5
1
0.5
0
20:52
20:53
20:53
20:54
20:54
20:55
20:55
time GMT

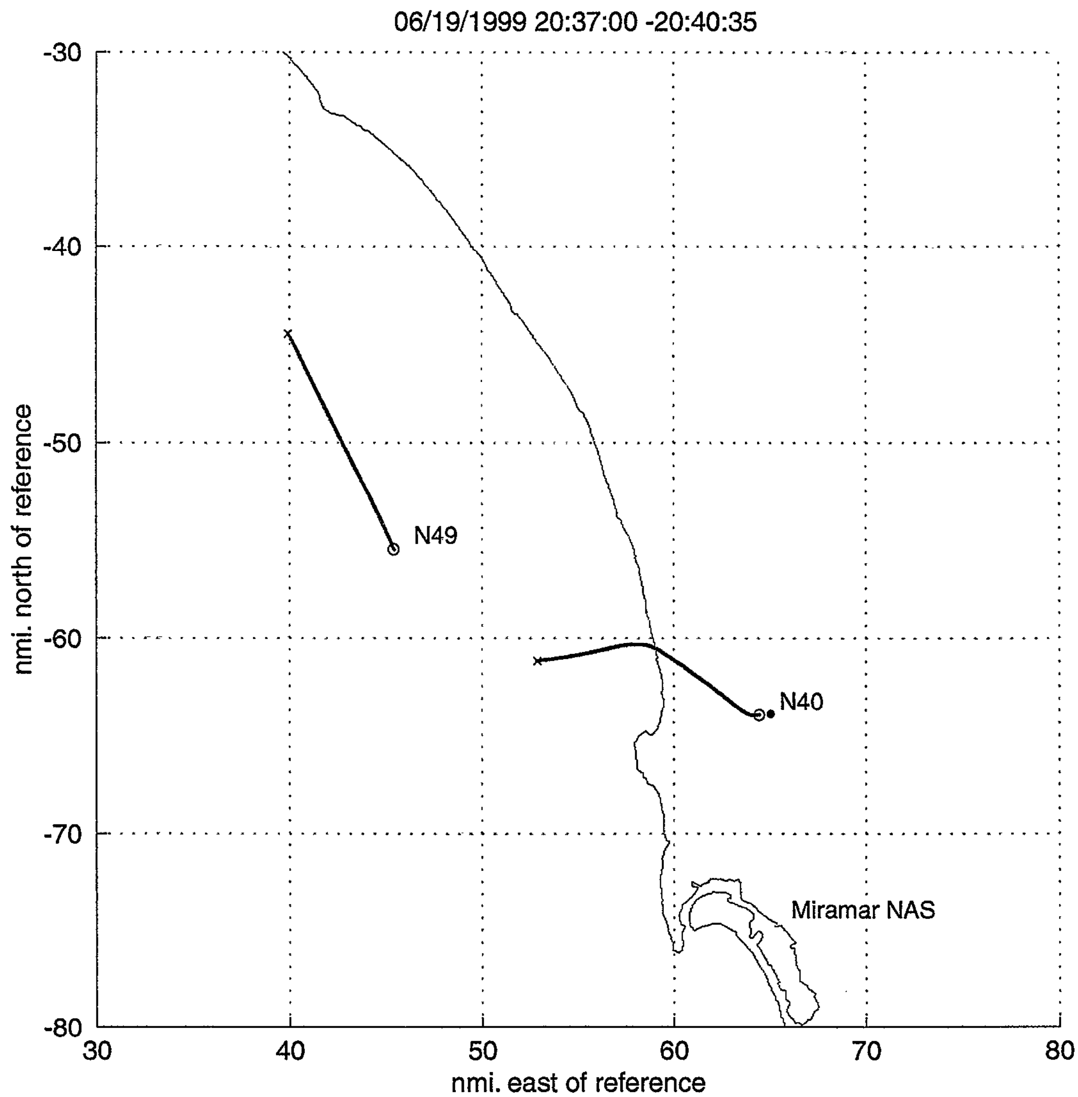


Range between N40 and N49 on19-Jun-1999
16
14
12
10
8
6
4
nautical miles
20:51:30
20:52:00
20:52:30
20:53:00
20:53:30
20:54:00
20:54:30
20:55:00
time

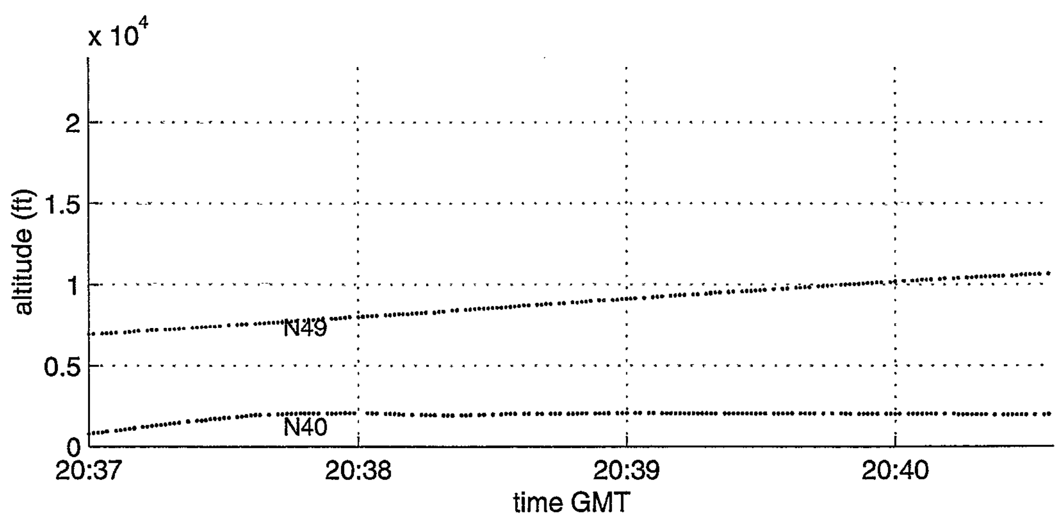

Active - Interpolated Passive Ranges
19-Jun-1999 20:51:45 -20:55:00
own aircraft :n40, target aircraft :n49
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 106.25
std dev 20.38
Delta Range (m)

Encounter 19

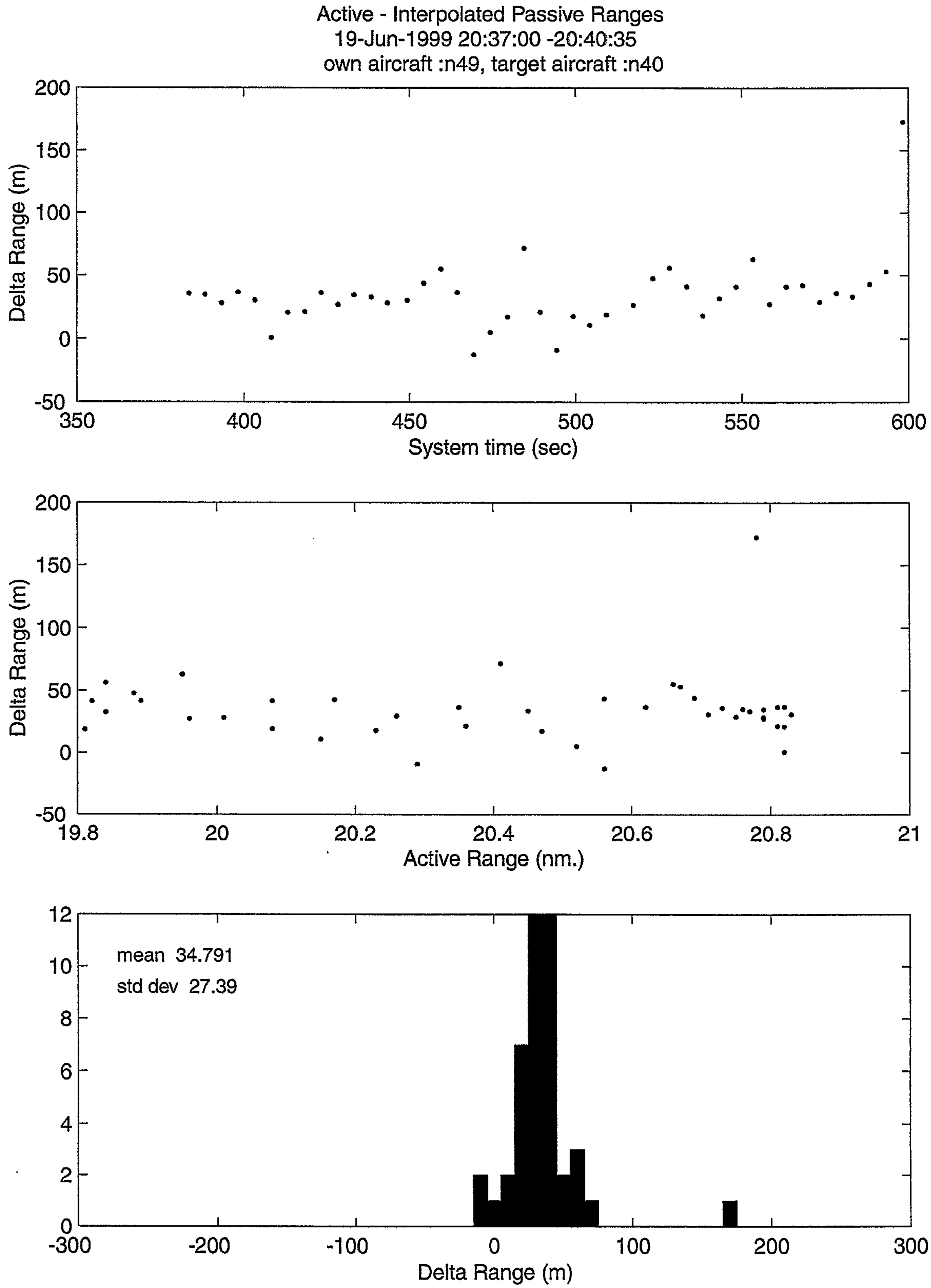
N49 departing, N40 departing behind at right angles (same as Encounter 17)



06/19/1999 20:37:00 -20:40:35
-30
-40
-50
-60
-70
-80
30
40
50
60
70
80
nmi. north of reference
nmi. east of reference
N49
N40
Miramar NAS



x 10^4
2
1.5
1
0.5
0
altitude (ft)
N49
N40
20:37
20:38
20:39
20:40
time GMT

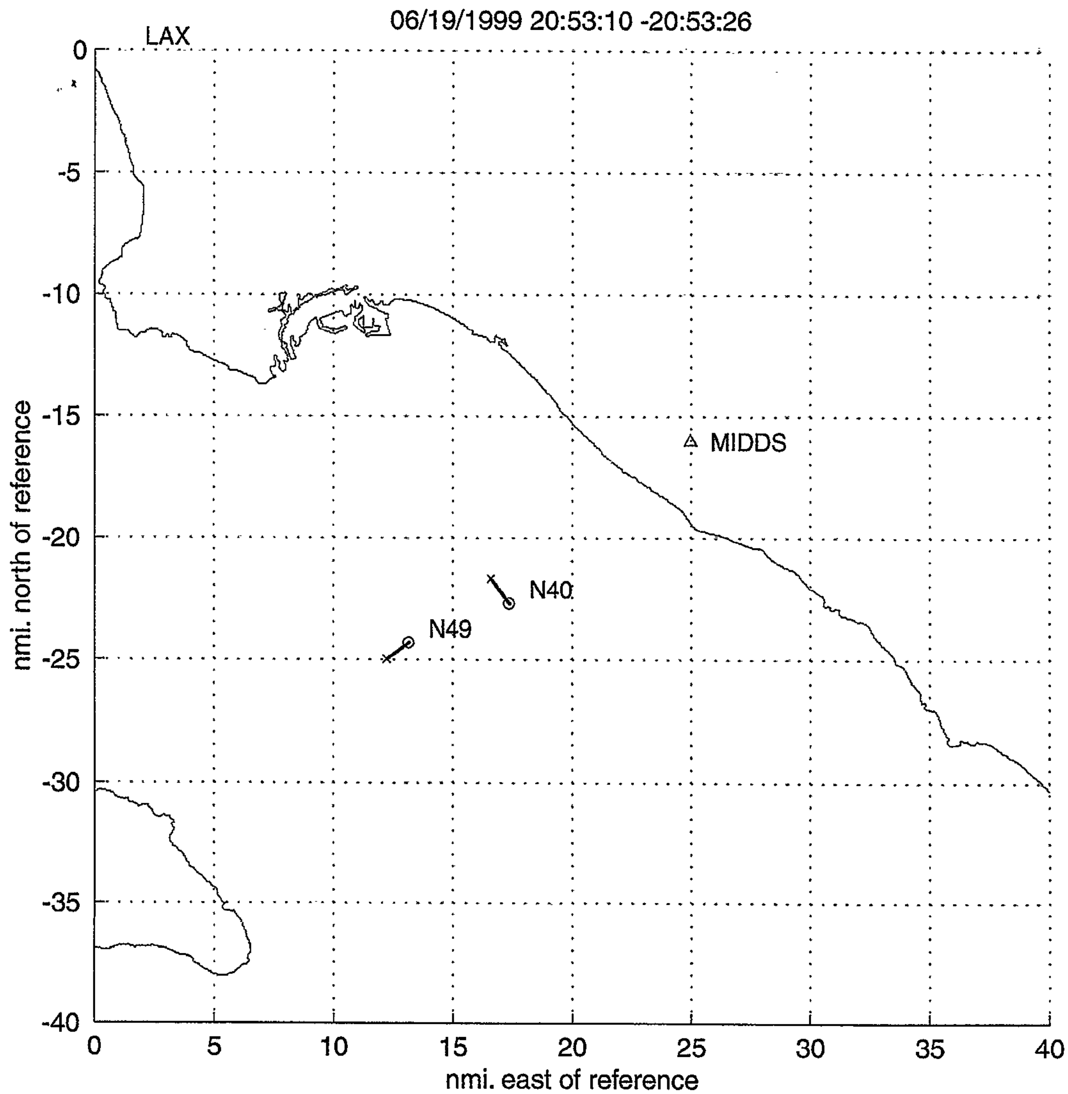


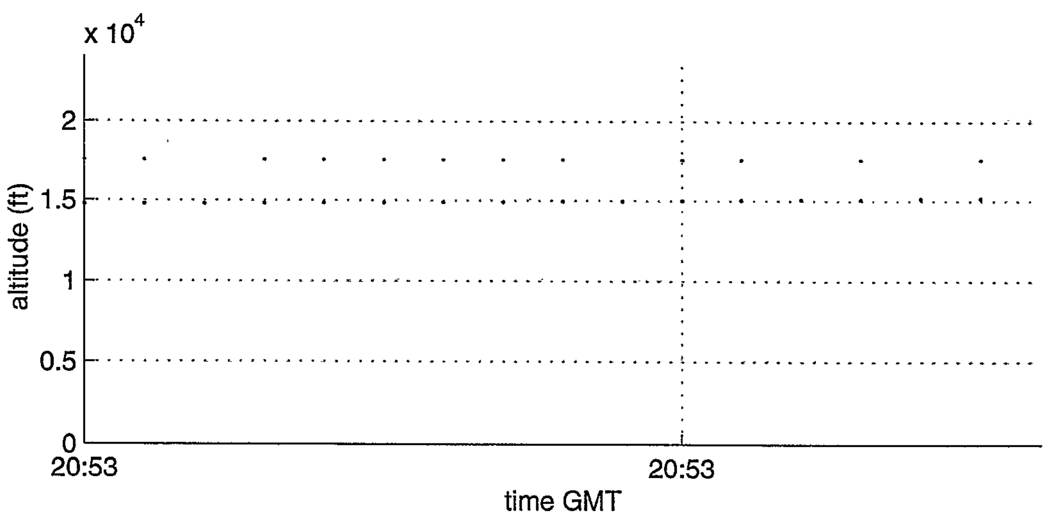
Active - Interpolated Passive Ranges
19-Jun-1999 20:37:00 -20:40:35
own aircraft :n49, target aircraft :n40
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 34.791
std dev 27.39
Delta Range (m)

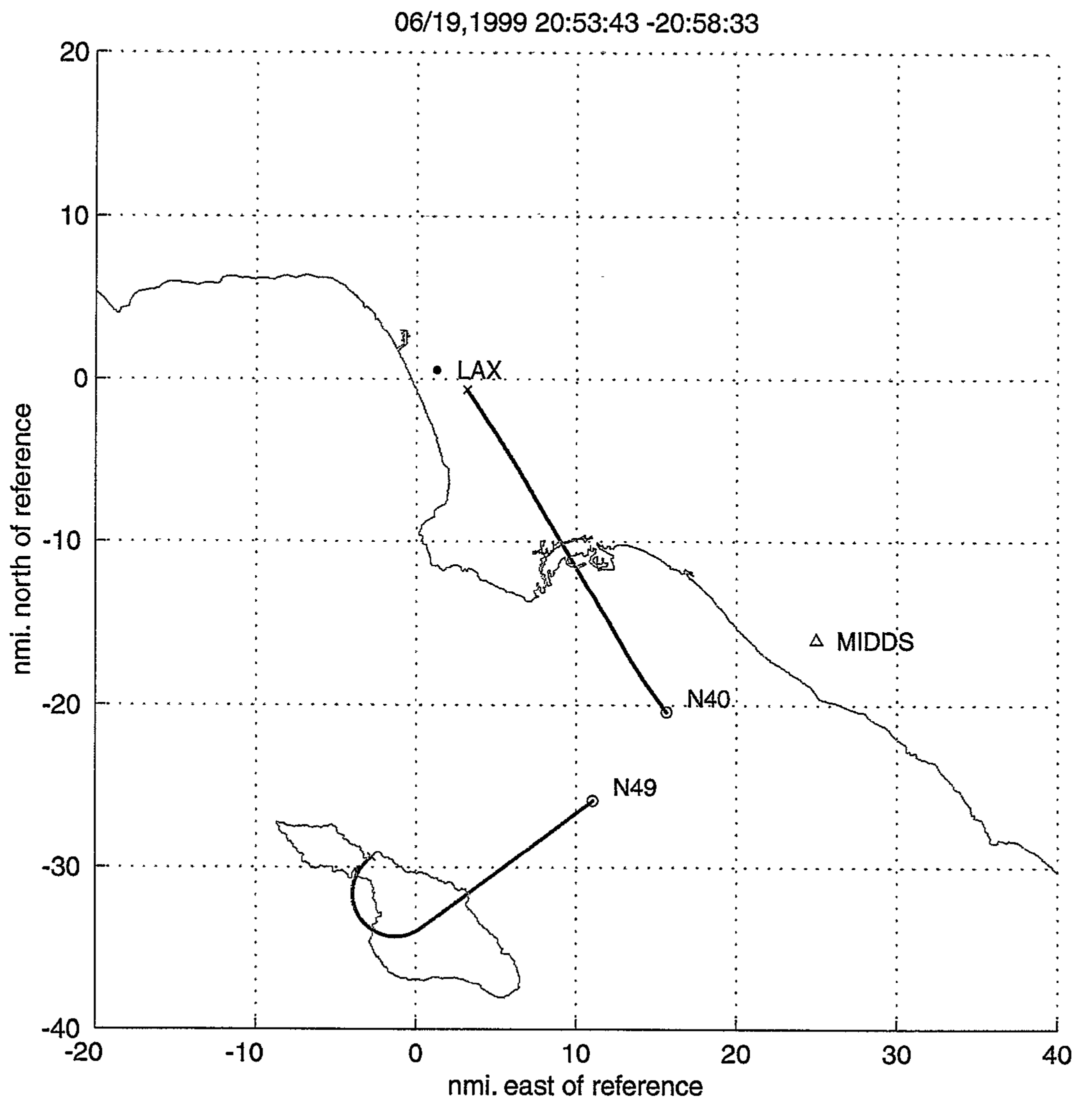
Encounter 20

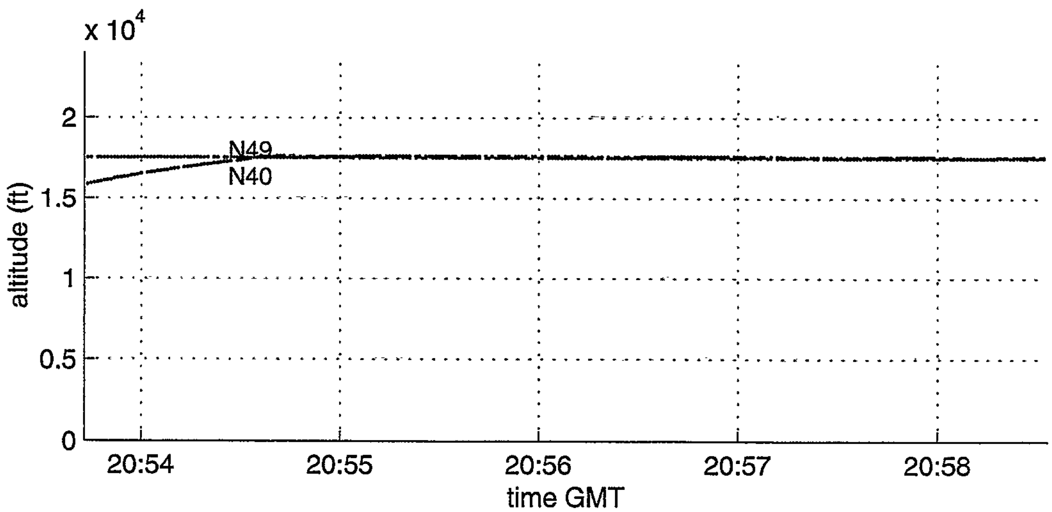
Right angle departing

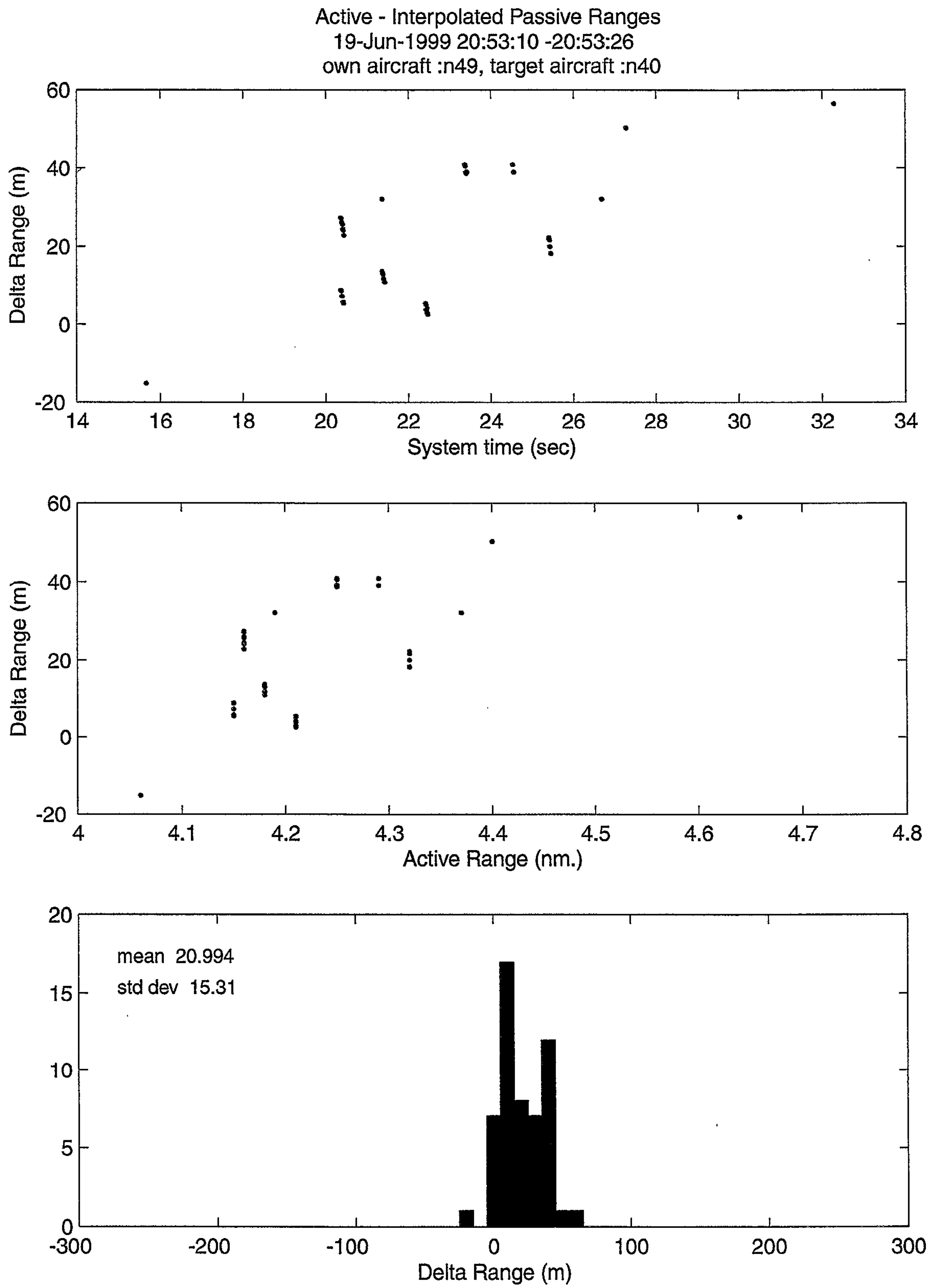
Continuation of right angles departing ending with "U" turn by N49

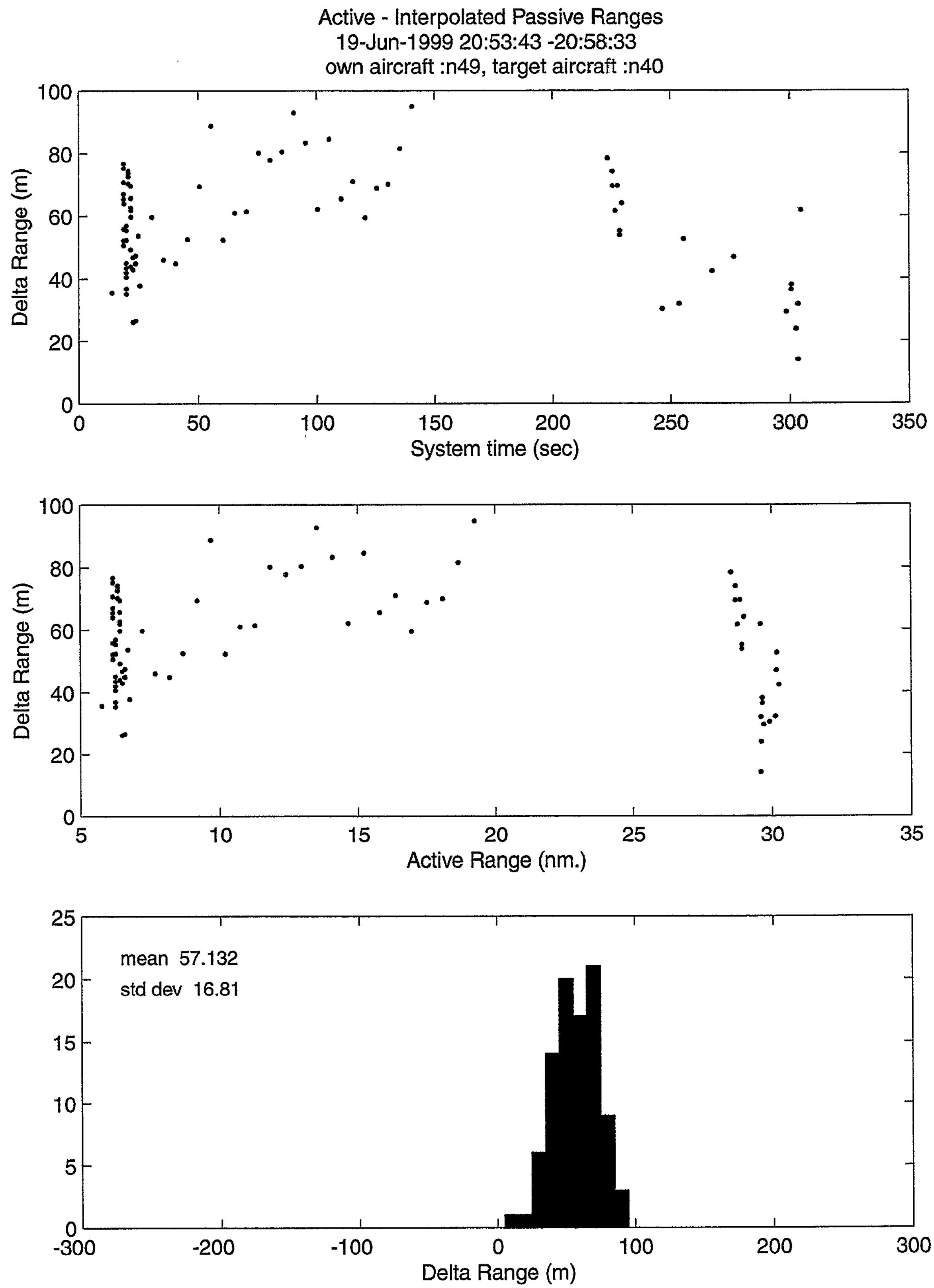

06/19/1999 20:53:10 -20:53:26
LAX
MIDDS
N40
N49
nmi. north of reference
nmi. east of reference
0
-5
-10
-15
-20
-25
-30
-35
-40
0
5
10
15
20
25
30
35
40


x 10^4
altitude (ft)
2
1.5
1
0.5
0
20:53
20:53
time GMT


06/19,1999 20:53:43 -20:58:33
nmi. north of reference
nmi. east of reference
LAX
MIDDS
N40
N49
20
10
0
-10
-20
-30
-40
-20
-10
0
10
20
30
40


x 10^4
altitude (ft)
time GMT
N49
N40
2
1.5
1
0.5
0
20:54
20:55
20:56
20:57
20:58


Active - Interpolated Passive Ranges
19-Jun-1999 20:53:10 -20:53:26
own aircraft :n49, target aircraft :n40
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 20.994
std dev 15.31
Delta Range (m)


Active - Interpolated Passive Ranges
19-Jun-1999 20:53:43 -20:58:33
own aircraft :n49, target aircraft :n40
Delta Range (m)
System time (sec)
Delta Range (m)
Active Range (nm.)
mean 57.132
std dev 16.81
Delta Range (m)

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