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Assessment of CTAS ETA Prediction Capabilities

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1 Introduction

This report summarizes the work done to date in assessing the trajectory fidelity and Estimated Time of Arrival (ETA) prediction capability of the NASA Ames Center TRACON Automation System (CTAS) software. The CTAS software suite is a series of computer programs designed to aid air traffic controllers in their task of safely scheduling the landing sequence of approaching aircraft. In particular, this report concerns the accuracy of the available measurements (e.g., position, altitude, etc.) that are input to the software, as well as the accuracy of the final data that is made available to the air traffic controllers.

The data presented here was obtained on February 2, 1994, at Denver Stapleton Airport. For simplicity the aircraft analyzed were broken into two categories, jets and turboprops. Since each type of aircraft has its own flight characteristics, this provided for a natural breakpoint for which the aircraft could be studied. For example, jets usually fly at higher altitudes and higher airspeeds than the turboprops. It should be pointed out that the amount of time jet aircraft are typically "on screen" is not as great as for the turboprops. This results directly from the fact that jets are first picked up on radar during the cruise phase (typically Mach 0.7 and 35,000 ft) at a range of approximately 250 n.mi. (and usually less than 300 n.mi.) from the airport. Due to the relatively high cruising speeds, the data record is generally only 20-30 minutes long. On the other hand, turboprops are generally first seen climbing to their cruise altitude. Couple this with the slower speeds of the turboprops, and this type of aircraft is on screen for most of its flight. The data records for the turboprop aircraft are fairly long and show a wide variation of velocities, ETAs, etc. Another reason for including turboprop aircraft in the analysis is that they are beginning to make up a larger percentage of the air traffic since larger carriers are relying more on small, "regional" airlines.

2 Analysis Routines

Although the CTAS software has an analysis program called AN that allows one to gather various statistics on a particular data set, this program proved somewhat difficult to use to compare different types of trajectory data (i.e. heading and groundspeed as a function of position). There was also no easy way to get a least-squares fit of the estimated times of arrival (ETAs) for a particular flight and to look at the deviation of the aircraft from this fit. There was also a recognized need to determine the true airspeed of each aircraft in order to evaluate the particular profile flown by the pilot during descent. To do this easily, MATLAB was utilized. MATLAB allows user-defined, "C-like scripts" to be written that easily process data.

The first need identified was to be able to derive the least-squares fit of the ETA curve for a specific flight. MATLAB was used to calculate the least-squares fit to the data as well as its deviation the straight line fit. The time range of the least- squares fit was from the time that the aircraft first appeared on screen until the ETA was frozen. The second need identified was to study the trajectory in detail in order to see how the ETAs were influenced by changes in the trajectory. Wind data is used to get the true airspeed (TAS) of the aircraft given the position, altitude, groundspeed and heading of the aircraft. The wind data is given as an x and y (east and north) component which are functions of position and altitude. A 2-D linear interpolation was performed over the (x, y) grid to get the components of the wind velocity at the point of the aircraft. This was done at the altitudes immediately above and below the aircraft. A 1-D linear interpolation in the z (altitude) direction was then performed in order to get the wind velocity at the aircraft's altitude. The groundspeed was resolved into its (x, y) components using the available heading information. Then the wind velocity was subtracted to give the true airspeed. Altitude versus TAS plots were then produced with lines corresponding to constant calibrated airspeed (CAS) and Mach number overlaid to determine the "type" of descent profile that the aircraft flew.

The remaining data was used to reconstruct the trajectory as a function of position and time. This allowed a direct correlation of certain events in the trajectory (for example, a sudden change in groundspeed) to changes in the ETA and how its deviation from the least-squares fit was affected. This also allowed for a comparison of the accuracy of the different data. For example, one such comparison is to look at the north position versus the east position (y vs. x) and the heading vs. the east position (ψ vs. x) in order see the how the heading evolves as the position of the aircraft changes. This ultimately shows the accuracy of the heading information as compared to the positional data of the aircraft.

3 Analysis

As stated above, the analysis is broken into two subsections. The first is for a small sample of jet traffic, and the second is for a small sample of turboprops. These flights, for the most part, were straight-in flights with minimal maneuvering until the aircraft reached the feeder gate. Overall, traffic in this particular data set was "light." There was also no evidence of controller initiated delays for any of the arrivals. It is believed that an analysis of this baseline scenario when traffic is light will reveal any problems in the accurate determination of the state of an aircraft and the effect of these errors on the aircraft's ETA. An analysis of the wind data for this day is also included in this section in order to demonstrate the influence of the winds on the aircraft's groundspeed.

3.1 Wind Analysis

The static wind data used for this analysis was measured over a range of 250 miles west to 325 miles east of Denver Stapleton, and 260 miles north to 225 miles south of the airport. The altitude range ran from 5,000 feet to 40,000 feet above mean sea level. The wind velocities as a function of position are shown in Figures 1 to 5 for the altitudes of 5,000, 10,000, 20,000, 30,000, and 40,000 feet. It is evident that the winds are primarily east, with southeast and northeast components at different locations. This is more easily seen at the higher altitudes where winds north of the airport are east-southeast, while south of the airport winds are east-north east. The wind speed varies from 20 knots at 5000 feet to 100 knots at 40000 feet. There is no indication of a circulation pattern that would be associated with a front or a pressure cell. However, it appears that the jet stream is carrying the winds primarily eastward at altitude.

3.2 Jets

The purpose of this section is to investigate the causes of ETA variations over time for a number of selected flights. Specifically, long-term trends in ETA were analyzed as well as the short random deviations of the ETA from its least-squares fit. The aircraft selected were chosen due to the fact that the flights occurred during a light traffic period and appear to be unobstructed by other aircraft in the area. There appears to be minimal controller intervention. Eleven different jet flights were chosen to be analyzed. All flights occur between 00:45:00 and 04:15:00 UTC Time (18:45:00 and 10:15:00 Mountain Standard Time) on Wednesday Feb. 2, 1994. This corresponds to the evening traffic period, when incoming air traffic is typically not as heavy as the morning and late afternoon "rushes". All the aircraft are also landing on Runway 26L or 26R, which is into the prevailing wind for this day. A matrix showing the particular flights considered and the type of aircraft are given below as well as the gate crossed, the slope of each least-squares fit and the deviation of the ETA data from the least-squares fit.

Flight	A/C Type	Feeder Gate	Slope of ETA (min/hr)	Deviation (sec)
AAL1873	MD80	Kiowa	-4.307	81.59
COA182	MD80	Byson	-1.049	16.19
COA407	737	Kiowa	-1.47	87.69
COA715	MD80	Kiowa	-0.2418	40.71
COA791	MD80	Keann	2.013	119.8
COA1105	727	Kiowa	-4.838	130.2
COA1765	727	Kiowa	-1.062	33.5
DAL1933	727	Drako	1.408	28.97
UAL1431	737	Byson	-0.8912	17.71
UAL1619	737	Drako	2.606	61.42
UPS481	757	Drako	-1.283	29.05

The significance of the slope of the least-squares fit to the ETA curve is that it shows the long-term trend of the ETA as it evolves over time. The average slope of the ETAs for the flights above was -0.83 min/hr (-50 sec/hr) and the average deviation from the least-squares fit was 58.8 seconds. This reflects that the ETA estimates were good for this sample space of aircraft. Typical ETA versus time plots are given in Appendix A. The ETAs include the initial transients from when the aircraft are first picked up on radar. It is during this period when the largest deviations generally occur. The TMA does not have an adequate sample of data in order to accurately determine the state of the aircraft and there is also a problem with the procedure that is used to get the initial state estimates. As a result, there is a lack of precision in the first few ETA calculations. Typically, the groundspeed and heading errors are the largest. In fact, heading is always undefined for the first few samples. For the analysis here, all undefined headings were assumed to be the same as the first defined heading. The groundspeed typically takes several samples before it may be accurately determined. A typical variation in groundspeed at the earliest times that the aircraft is in the Center is 50 knots.

After the initial transients associated with the aircraft appearing on screen have subsided, the short term variation of the ETA curve about the least-squares fit is typically "small". Variations are likely correlated to changes in groundspeed and ultimately heading as the aircraft's heading determines the course of a particular aircraft. For example, there is a 15 knot groundspeed variation that occurs on UPS841 at approximately 03:45:00 UTC

Time (Figure 6). It was graphically determined that the nominal heading for the flight at this time should have been 97 degrees (Figure 7). At this time the heading jumps to approximately 109 degrees, an error of 12 degrees. The ETA variation that occurs is less than 10 seconds from the least-squares fit. This heading error is "small" when compared to some that have occurred in other aircraft during the cruise portion of their flight, as it is not uncommon to see the heading during cruise change by a much as 25 degrees. In fact, there is a 25 degree heading change on UPS841 at approximately 03:43:00 UTC Time. Unfortunately, there is no easy way to filter the heading estimate of the aircraft. A reason that filtering is difficult is that when an aircraft is initiating a turn, the filter does not know whether or not the heading change is a turn or whether it is an error and should be filtered. The heading variations are believed to be caused by two sources. The first is that it is difficult for an aircraft to be flown at an exact heading due to the presence of winds and turbulence. These errors will tend to be rather small (less than 10 degrees). The second is due to the positional errors that arise from the radar data. The latter is known to exist since the positional (x, y) data was used to calculate a "raw" heading. This raw heading was found by taking the first backward difference of the y data and dividing by a corresponding backward difference of the x data. This ratio was then converted to a heading using the following relationship: $\psi_{raw} = 90 - \frac{180}{\pi} \arctan \frac{\Delta y}{\Delta x}$. This raw heading was then overlaid with the heading as calculated by the radar to show the effects of position errors in determining an accurate heading of the aircraft. The raw heading and the radar filtered heading for UPS841 are overlaid as shown in Figure 8. Here, it can be seen that there is a period during the cruise where the raw heading has a fairly large amplitude. At this instant, the 25 degree heading change occurs. Hence, this is a result of an inaccuracy in the position of the aircraft at this time. This can be seen in the xy plot where a small segment of the groundtrack begins to fluctuate.

The type of descent flown by the pilot is important to the accurate determination of the ETA. The type of descent, whether it is a standard profile (SP) descent, a "fast" descent, or a "slow" descent has an appreciable impact on the ETA. The ETA, which determines the scheduled time of arrival (STA), will affect the amount of delay for a specific aircraft. The difference between STA and ETA for a particular aircraft is the amount of delay for that aircraft. Hence if one aircraft in a particular landing sequence has a delay, a small group of aircraft, or possibly the entire sequence, after the delayed aircraft may possibly be have to be delayed since spacing constraints between aircraft cannot be violated. A typical profile flown by the aircraft listed above is to descend at a constant Mach number to a predetermined altitude. At the predetermined altitude, the aircraft then flies at a constant CAS until a new altitude is achieved. The aircraft decelerates until it reaches the proper landing speed. Typical landing speeds are supposed to be around 175 KCAS. However, an aircraft landing at this speed rarely occurs with the aircraft in this sample space. The altitude versus TAS plot shown in Figure 9 shows this particular type of profile as flown by UPS841 (note that this is for the filtered groundspeed). The aircraft starts at Mach 0.8 and 33000 feet. The aircraft descends at Mach 0.8 to 24000 feet. At this instant, the aircraft is also at a CAS of approximately 350 KCAS. The aircraft maintains this speed until it reaches an altitude of 13000 feet. Then UPS841 slows to 300 KCAS while maintaining this altitude. Finally, the aircraft descends to the runway threshold and decelerates to 250 KCAS (Figure 9). This particular aircraft, a Boeing 757, has a landing speed of 132 KCAS at maximum landing weight (approximately 198000 lbs). This error is rather significant and can be attributed to the filtering algorithm used by the radar to determine groundspeed. In fact, when compared with the raw groundspeed as provided in the AN program analysis file, the filtered groundspeed tends to be significantly different from the raw groundspeed during the final stages of descent (Figure 10).

The second descent profile predominantly seen is a descent at a constant CAS (typically 250-300 KCAS) until the aircraft reaches a specified altitude. After reaching this altitude, the aircraft then slows to landing speed at the runway threshold. This is the type of descent flown by COA1765 (Figure 11). The aircraft begins its descent from 31000 feet at 280 KCAS. The aircraft descends at 300 KCAS until it reaches the feeder fix (17500 feet). The aircraft then begins to decelerate to 200 KCAS at the runway threshold. Again, there is a significant error in the landing speed. This error is again attributed to the groundspeed filtering algorithm as was discussed above.

3.3 Turboprops

The objective of this section is to investigate the causes of ETA variations over time for a number of selected turboprop flights. The aircraft selected were chosen due to the fact that the flights were during a light traffic interval and appear to be unobstructed by other aircraft in the area. There also appears to be minimal controller intervention. There were eight turboprop flights selected for analysis. Again, these eight particular flights appear to be undelayed and straight-in. These flights are given in the table below with the corresponding feeder gate, the slope of the least-squares fit of the ETA curve, and the deviation of the ETA data from the least-squares fit. All aircraft are landing on either 26L or 26R. The turboprop flights occur between 00:54:00 and 03:24:00 UTC Time on February 2, 1994.

Flight	Feeder Gate	Slope of ETA (min/hr)	Deviation (sec)
ASH7561	Byson	-8.462	133.6
ASH7636	Kiowa	-4.371	173.8
ASH7654*	Kiowa	-3.598	44.45
BTA2209*	Kiowa	-2.257	141.2
BTA2296*	Drako	4.489	97.48
BTA2398	Drako	6.469	263.2
GLA5846	Keann	-8.364	305.1

*Denotes aircraft picked up in cruise

Inspection of the slopes of the least-squares fit and the deviation of the ETAs from this line shows that the ETAs for the turboprops are more widely varying than for the jet aircraft. In fact, the average slope of the least squares fit is -2.3 min/hr and an average deviation of 166 sec. This is due to several factors. The primary factor affecting the ETAs of the turboprops is the fact that the aircraft are seen on radar early on in their flight.

For example, BTA2398 is seen at a distance of approximately 200 n.mi. from the airport. The aircraft is at 7500 feet and is climbing out to its cruise altitude. It is quite evident that the ETA is sensitive to the fact that the aircraft is not initially seen in a "steady-state" condition. Three flights in the above table are first seen while in cruise (ASH7654, BTA2209, BTA2296). It is no real surprise that these three flights are more accurate in terms of the long term change in ETA over the entire flight.

A comparison of the groundspeed time histories during cruise for flights BTA2398 and BTA2296 shows that BTA2296's groundspeed does not vary as significantly as that of BTA2398 (Figures 12 and 13). Recall that BTA2296 is picked up on the Center radar while it is in cruise; however, BTA2398 is ascending to its cruise altitude. Note that the groundspeed of BTA2296 after the initial transient is nearly constant until the aircraft begins its descent. On the other hand, BTA2398 has a groundspeed that varies widely throughout its entire flight profile. The ETAs for these aircraft are unsuprisingly very different. The long term and the short term changes in ETA are larger for BTA2398. This implies that the large variations in groundspeed, due to the different phases of the flight, are having a negative impact on the ETA of the aircraft. Particularly important is the ascent portion of the flight. This part of the flight seems to have the worst impact on the ETA (Figures B1 and B2). For further comparison, the trajectory plots for these two aircraft are located in Appendix B.

Although the groundspeeds of the three flights that are picked up in the cruise condition are fairly smooth, they are still not as well behaved as those for the jet aircraft. This is probably due to the fact that turboprop aircraft are sensitive to wind variations and turbulence due to their lower weight. This is a characteristic that is generally applicible to all the turboprop flight paths.

4 Conclusions

Analysis of a sample of aircraft that were in operation during a light traffic period shows that the modelling capabilities in CTAS appear to be fairly accurate under most circumstances. The problem areas that were identified above are the need for a more accurate modelling of the climb-out and level off of the turboprop aircraft. Large fluctuations in groundspeed during this portion of flight seem to be responsible for the large long term variations of the ETAs. Short term variations of the ETAs of the turboprops are attributed primarily to winds. The jet aircraft as a whole had much smaller long-term and short-term variations as compared to the turboprop aircraft. Although jet aircraft are almost always in cruise when they are picked up by radar, there is usually a large groundspeed transient at the beginning of the data that seems to affect the long term ETAs. This transient more than likely occurs as a direct result of the filtering algorithm. Also, it was shown above that the radar position data has a margin of error. The effects of such an error are heading errors as well as ground speed errors that translate into errors in the ETA. As a follow on study, it is suggested that ETAs for a different filtering algorithm be studied (for aircraft under the conditions above) in order to see if there are any improvements in the ETAs as they evolve over time.

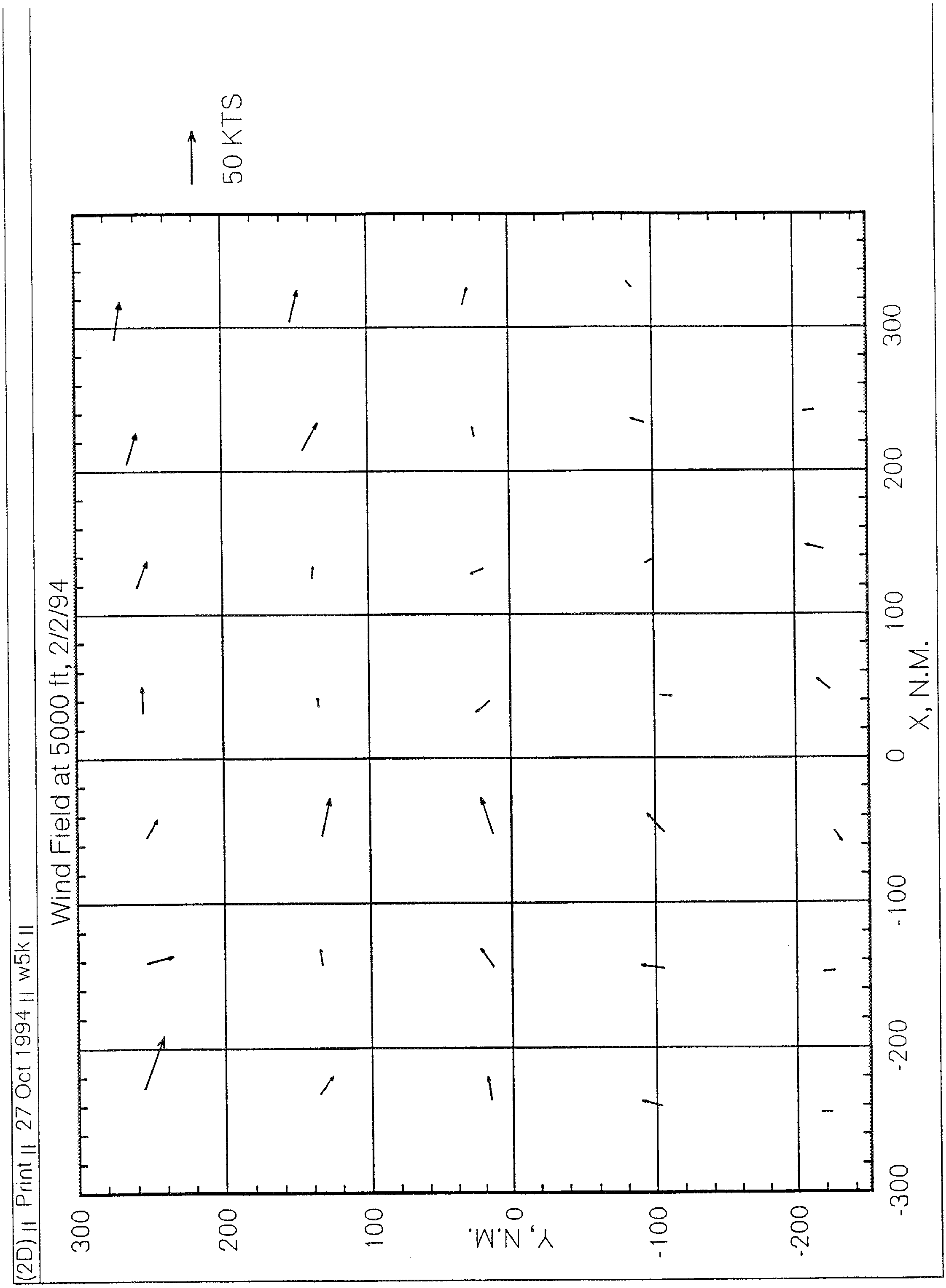


Figure 1: Winds on 2/2/94, 5,000 ft

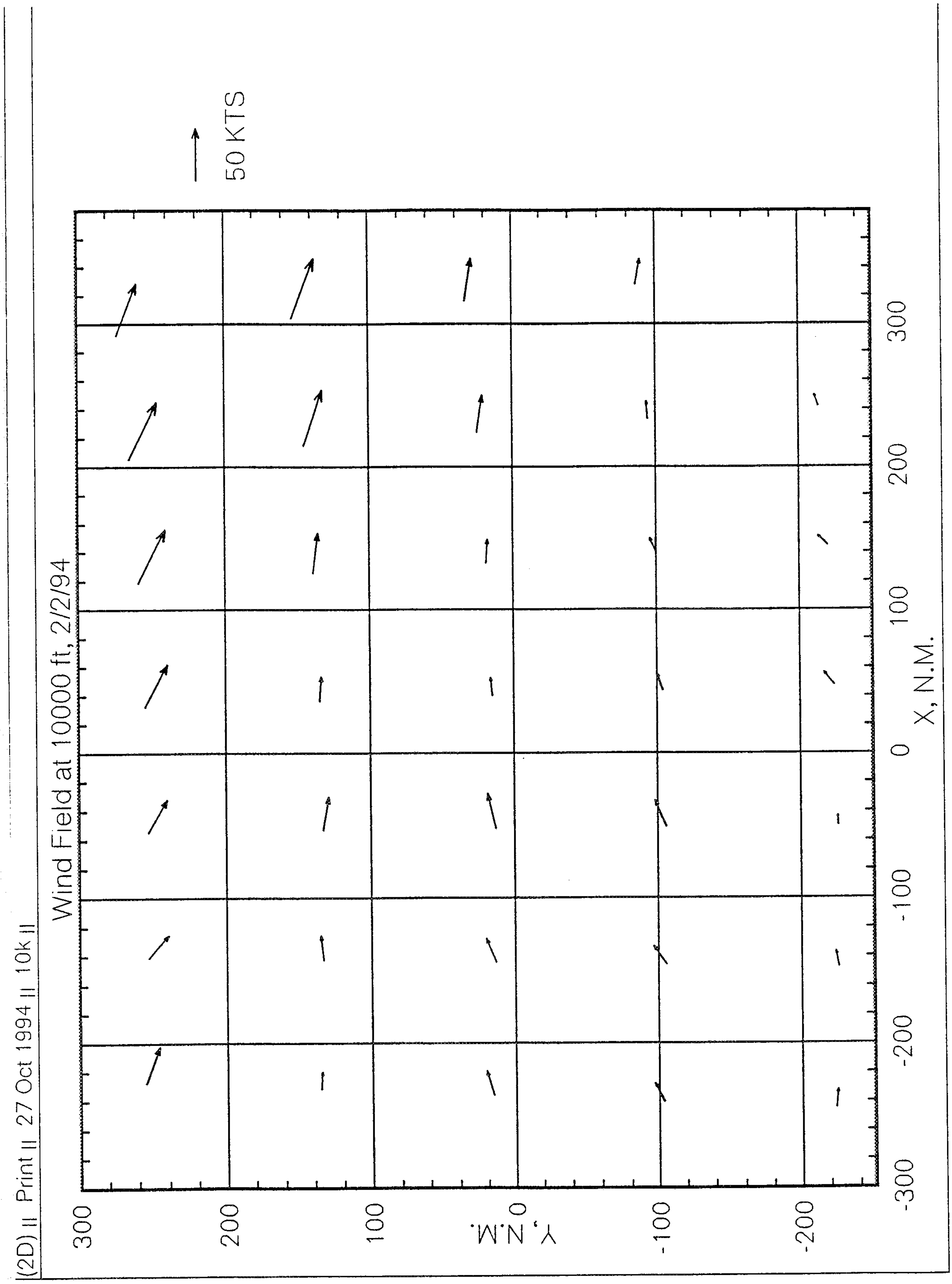


Figure 2: Winds on 2/2/94, 10,000 ft

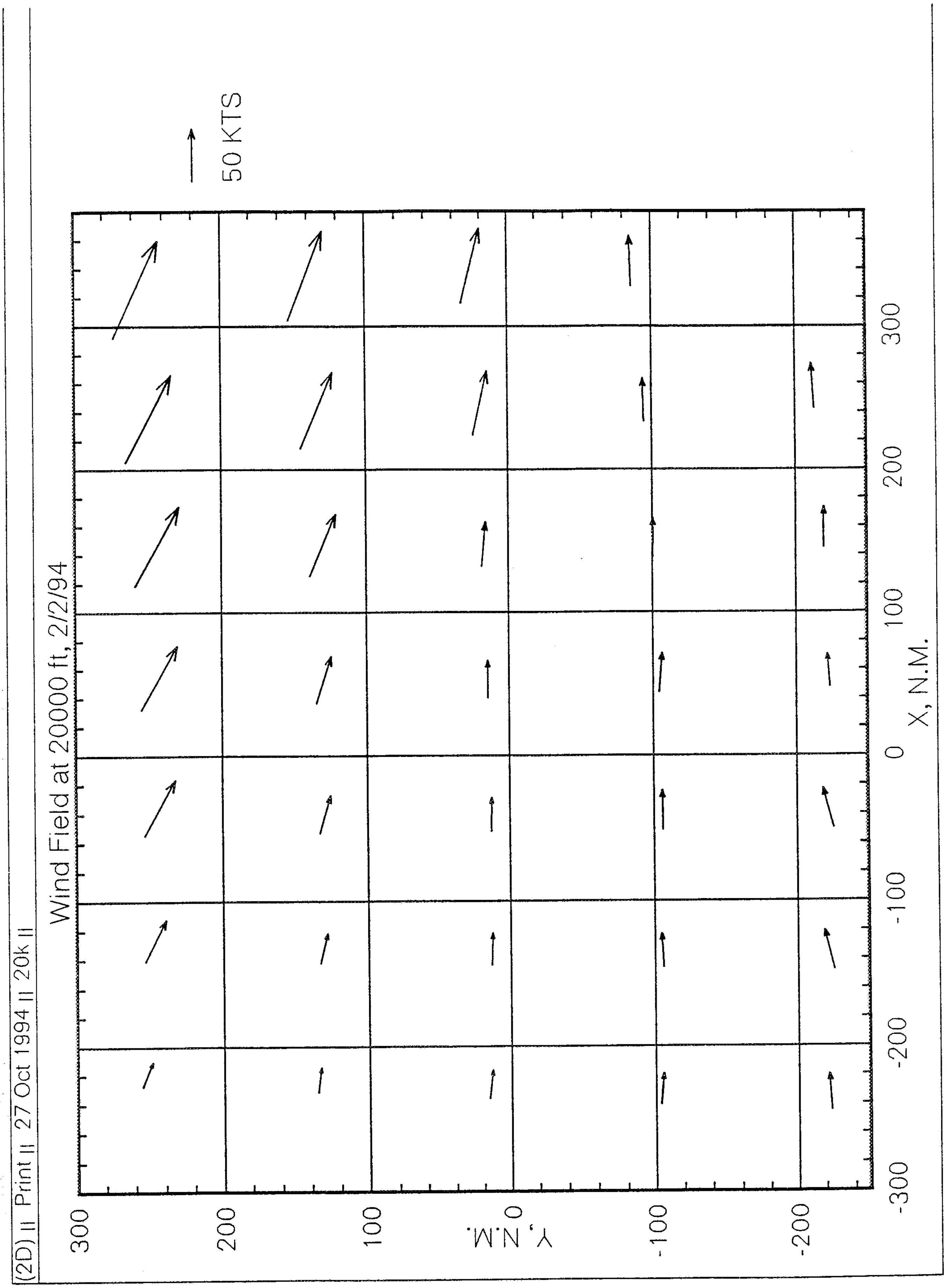


Figure 3: Winds on 2/2/94, 20,000 ft

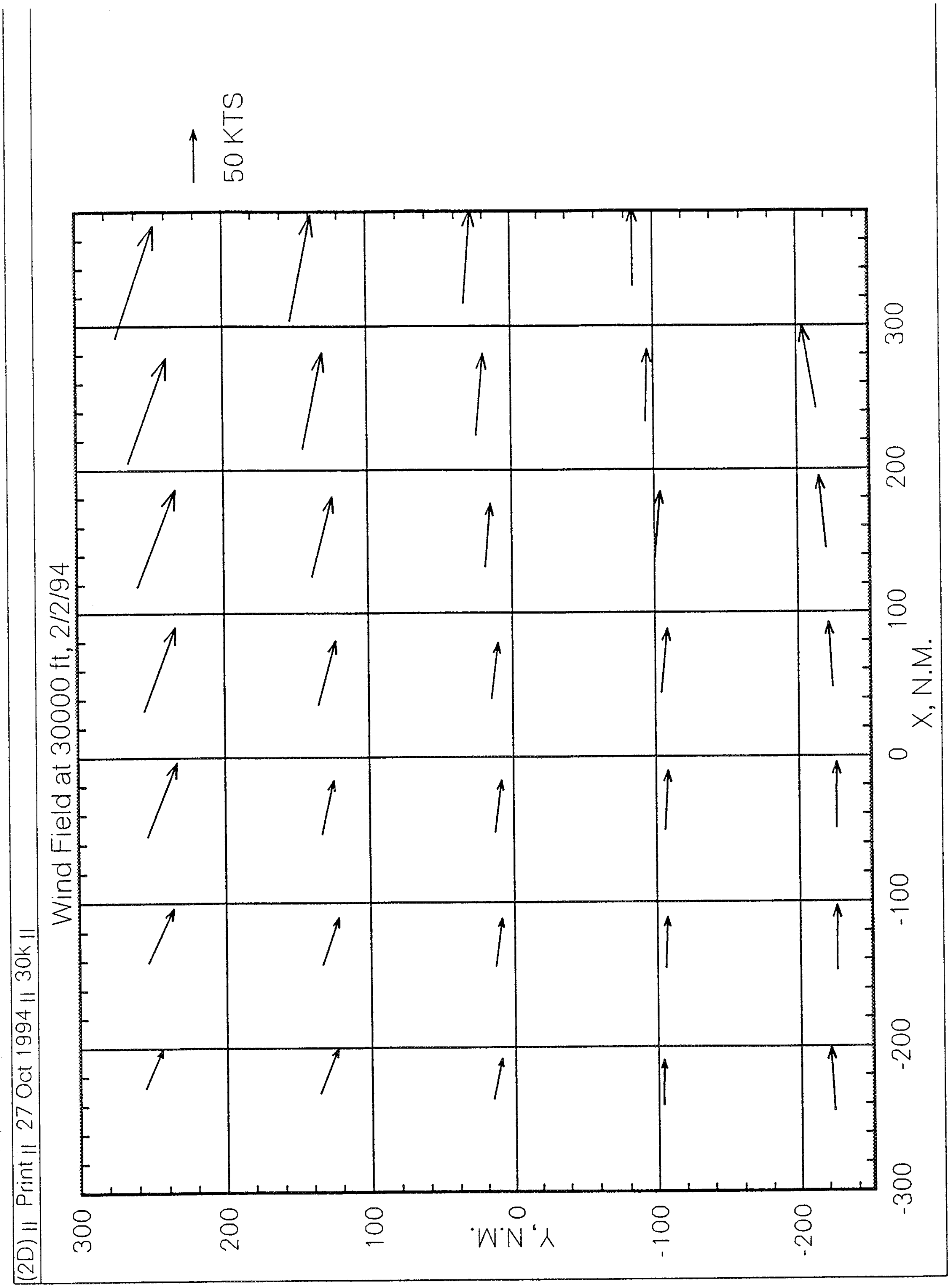


Figure 4: Winds on 2/2/94, 30,000 ft

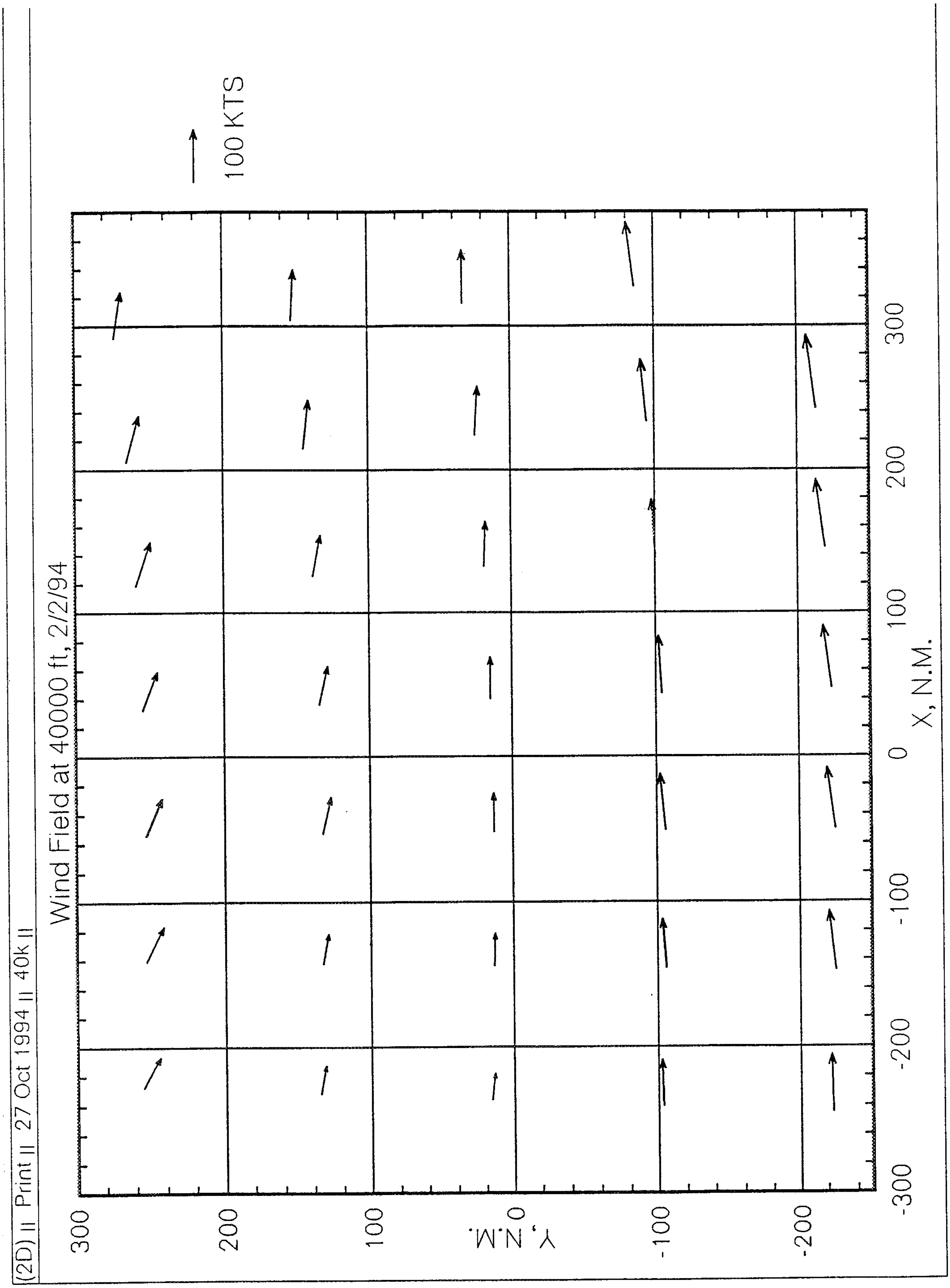


Figure 5: Winds on 2/2/94, 40,000 ft

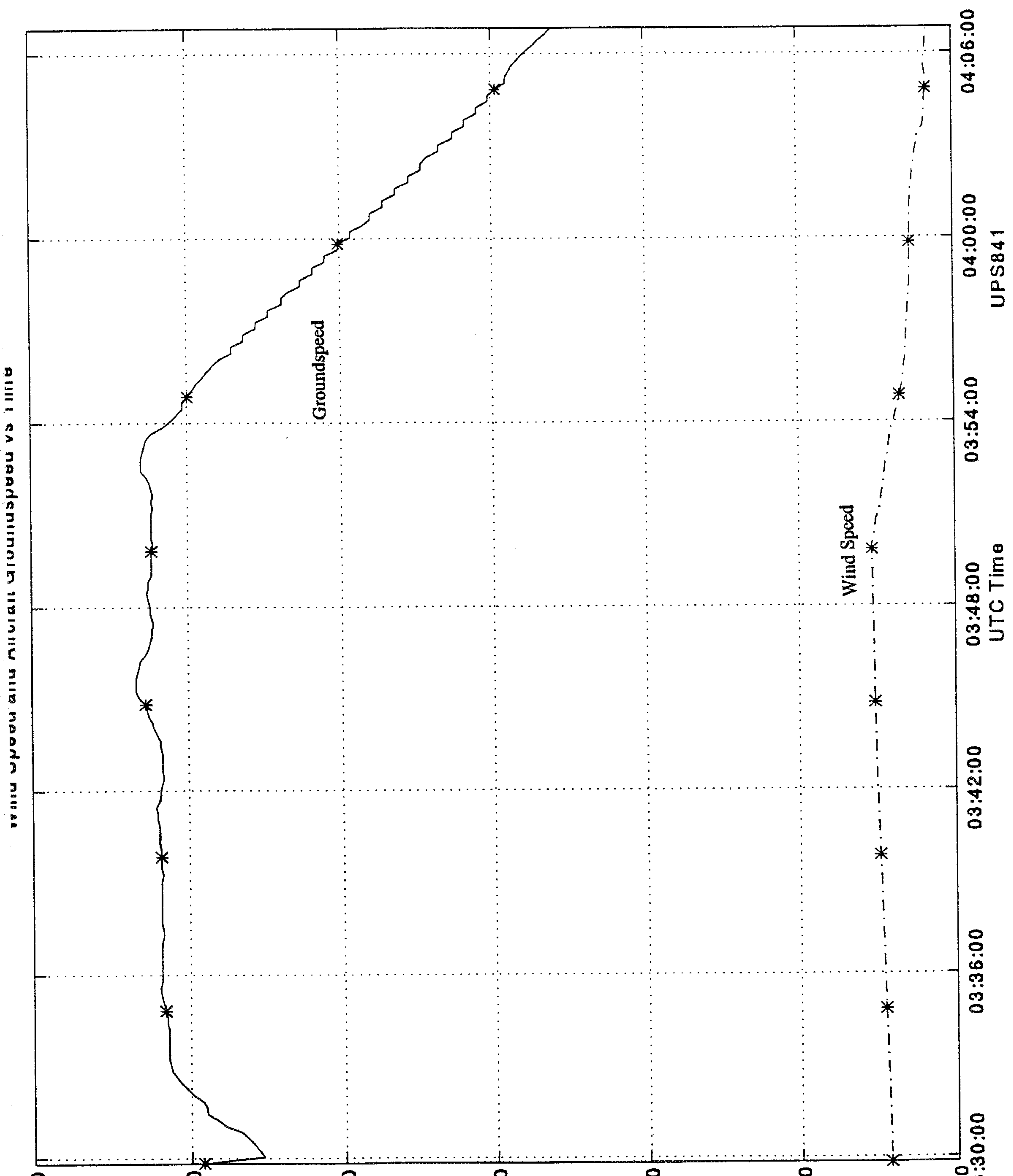


Figure 6: Groundspeed vs Time, UPS841

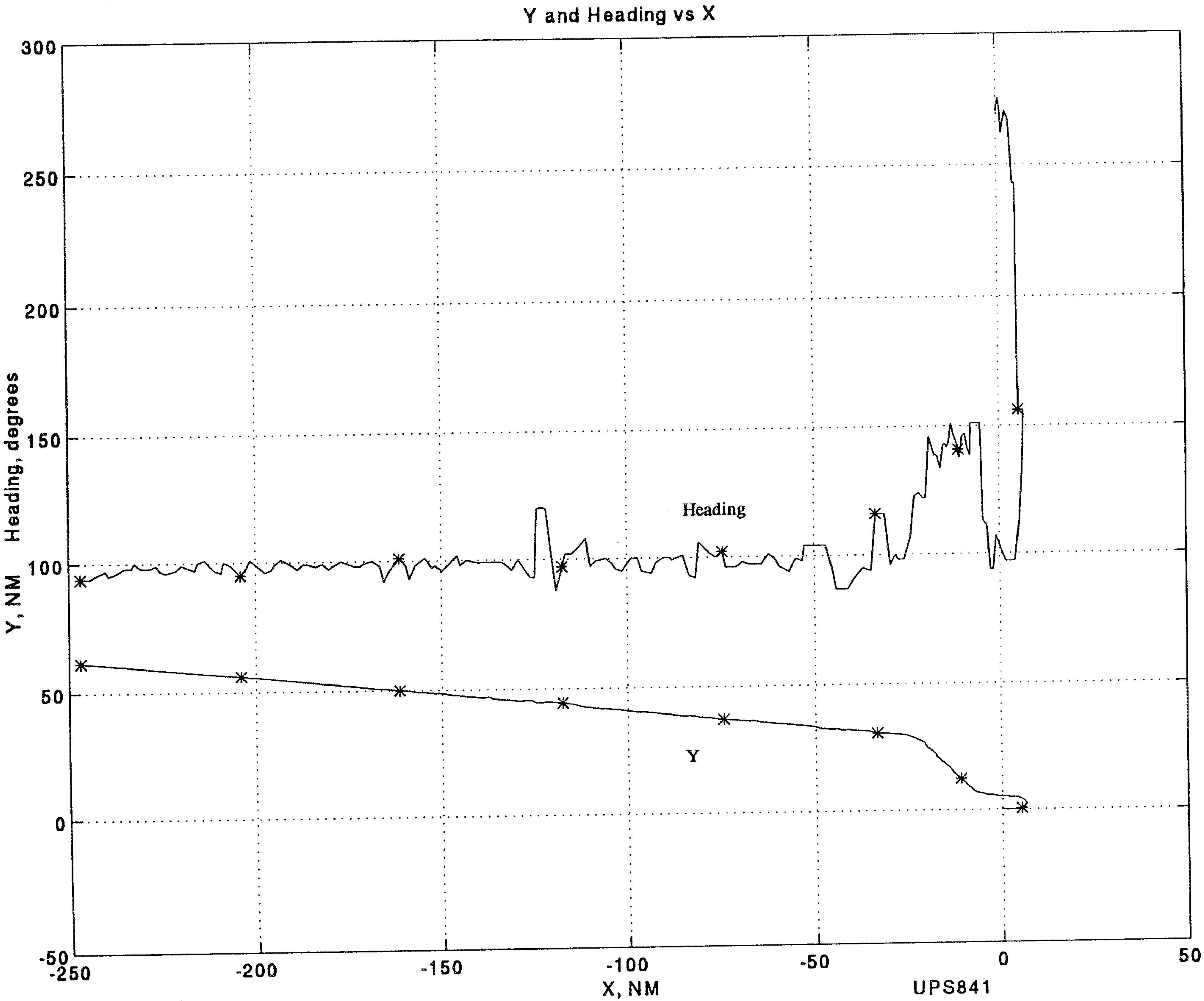


Figure 7: Y vs X and Heading vs X

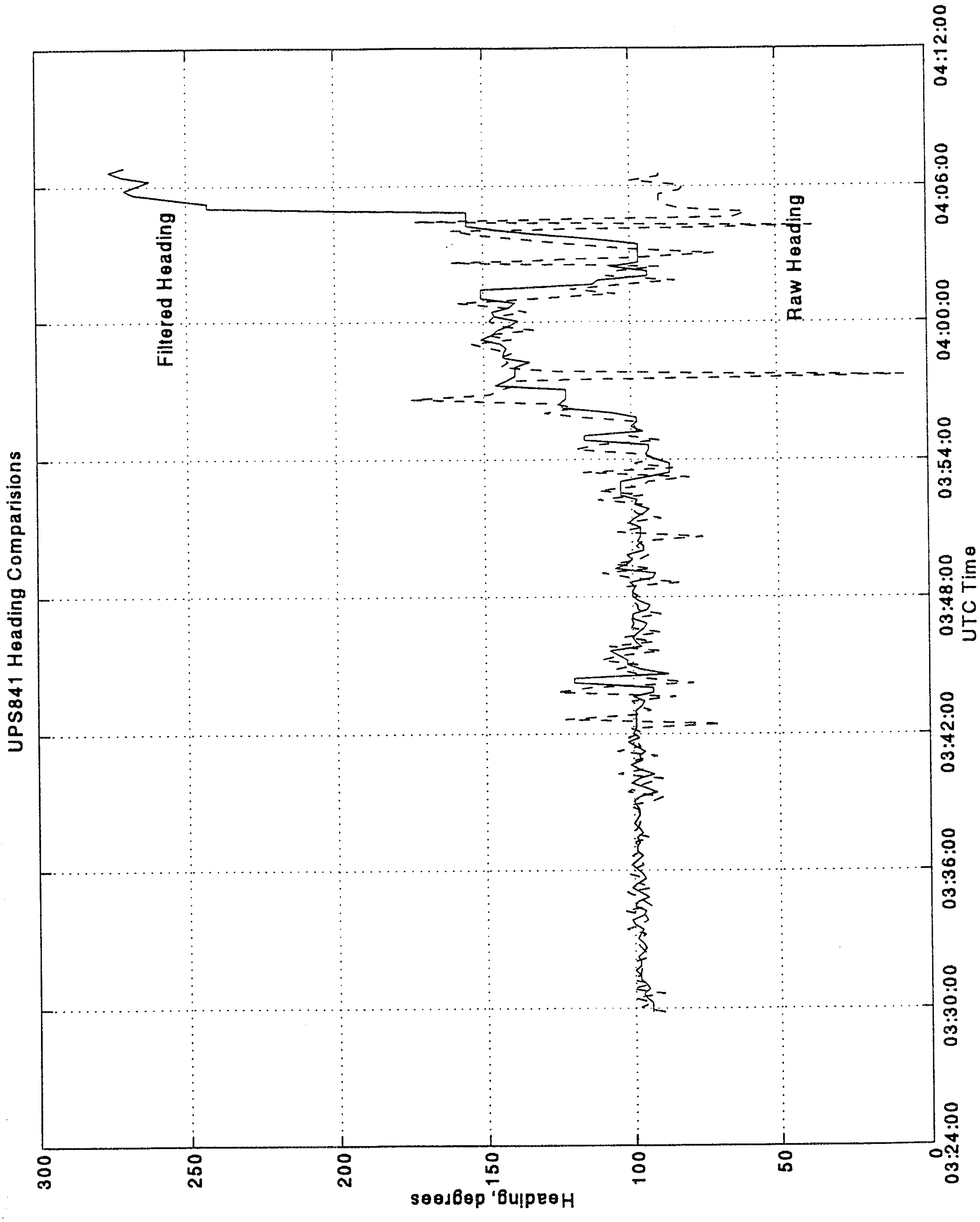


Figure 8: Comparison of Filtered and Raw Headings

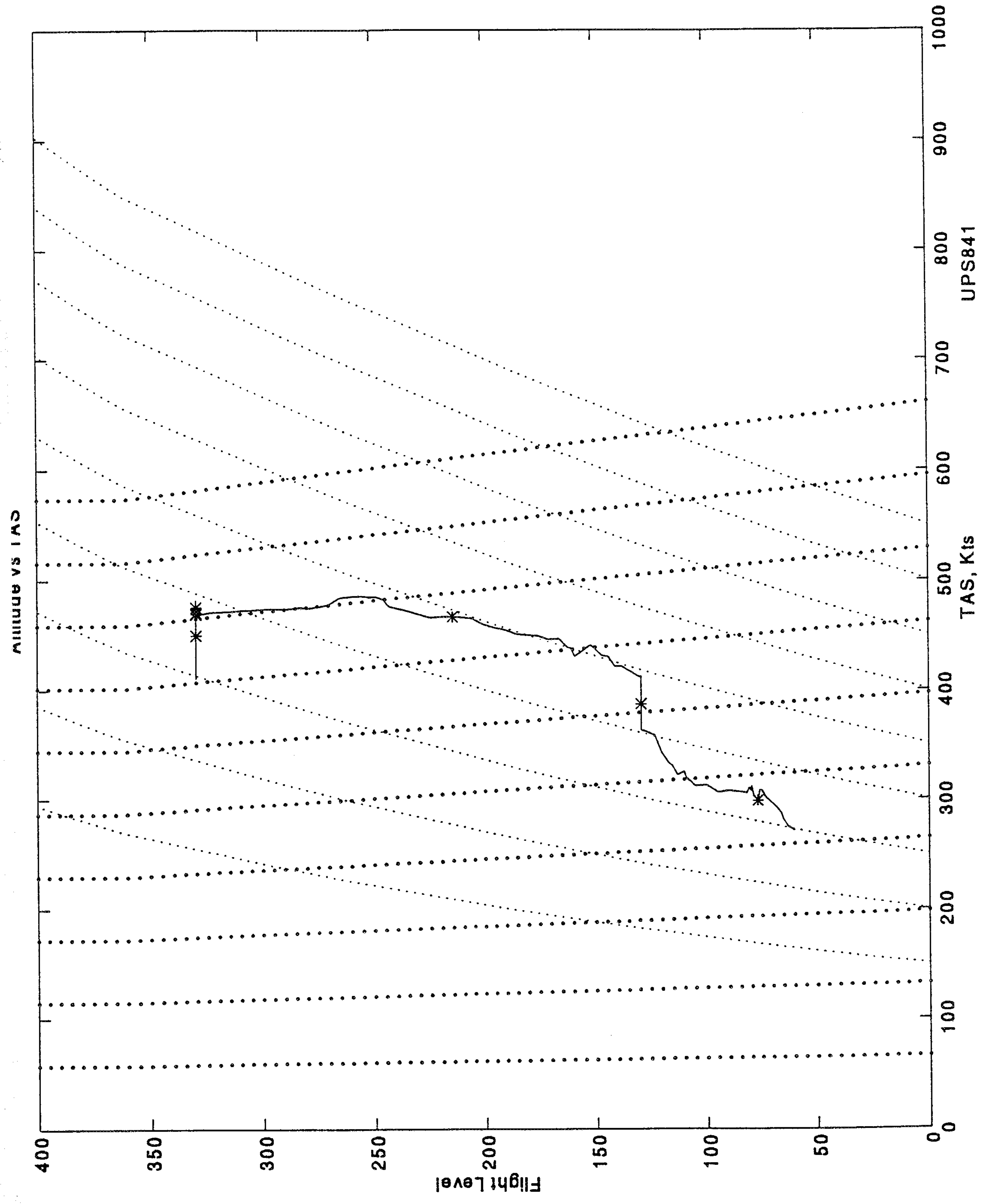


Figure 9: Altitude vs TAS for UPS841

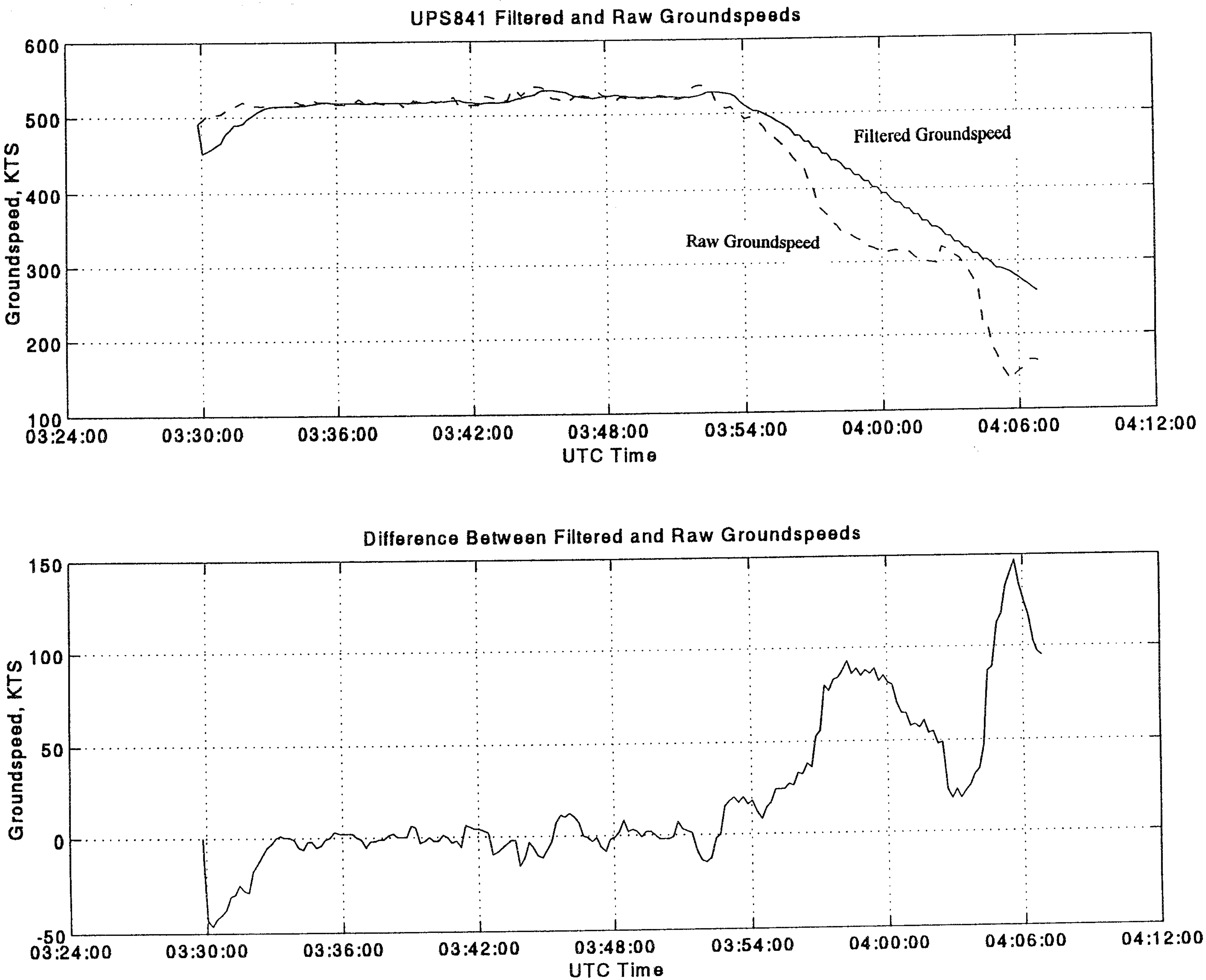


Figure 10: Comparison of Filtered and Raw Groundspeed for UPS841

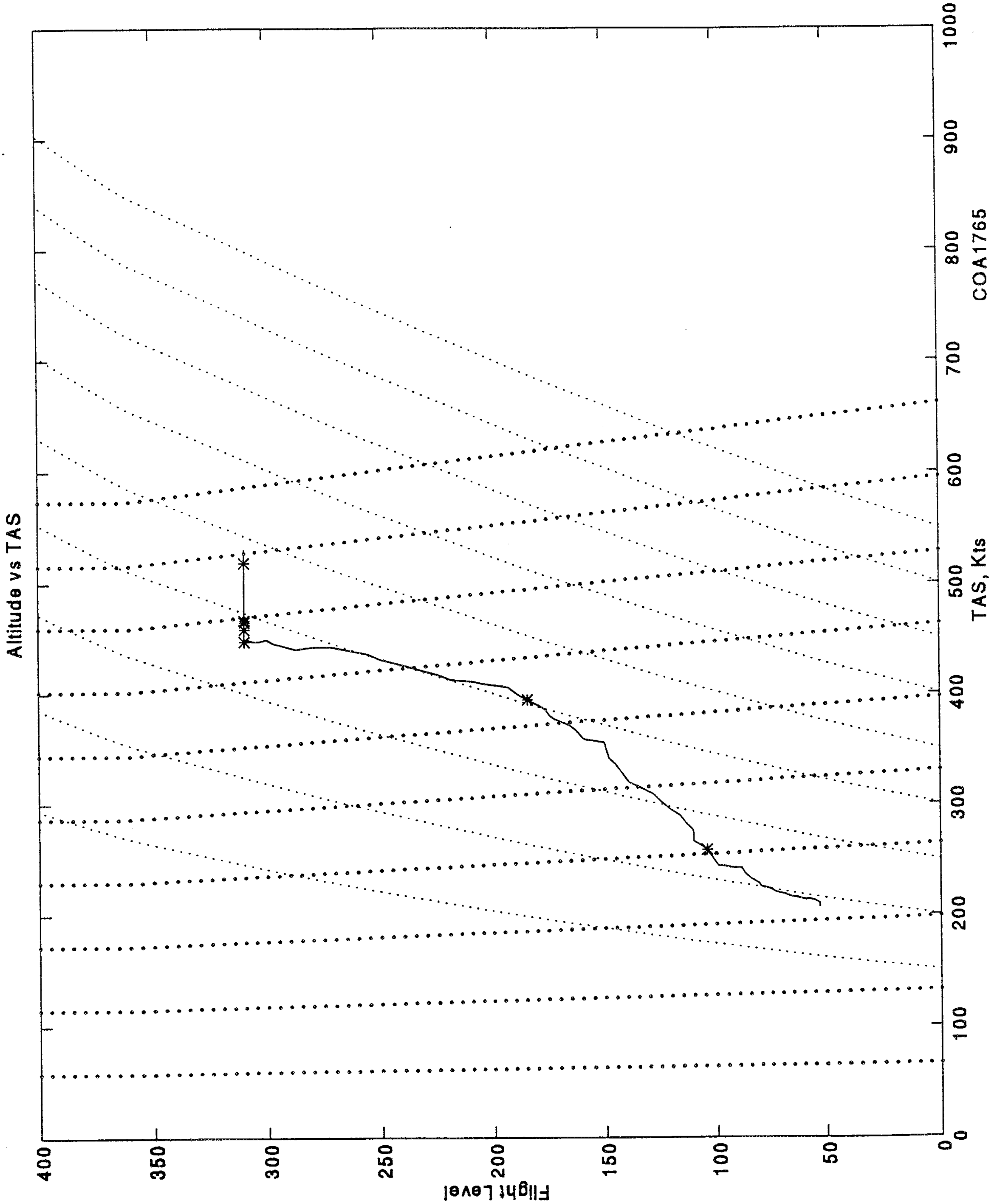


Figure 11: Altitude vs TAS for COA1765

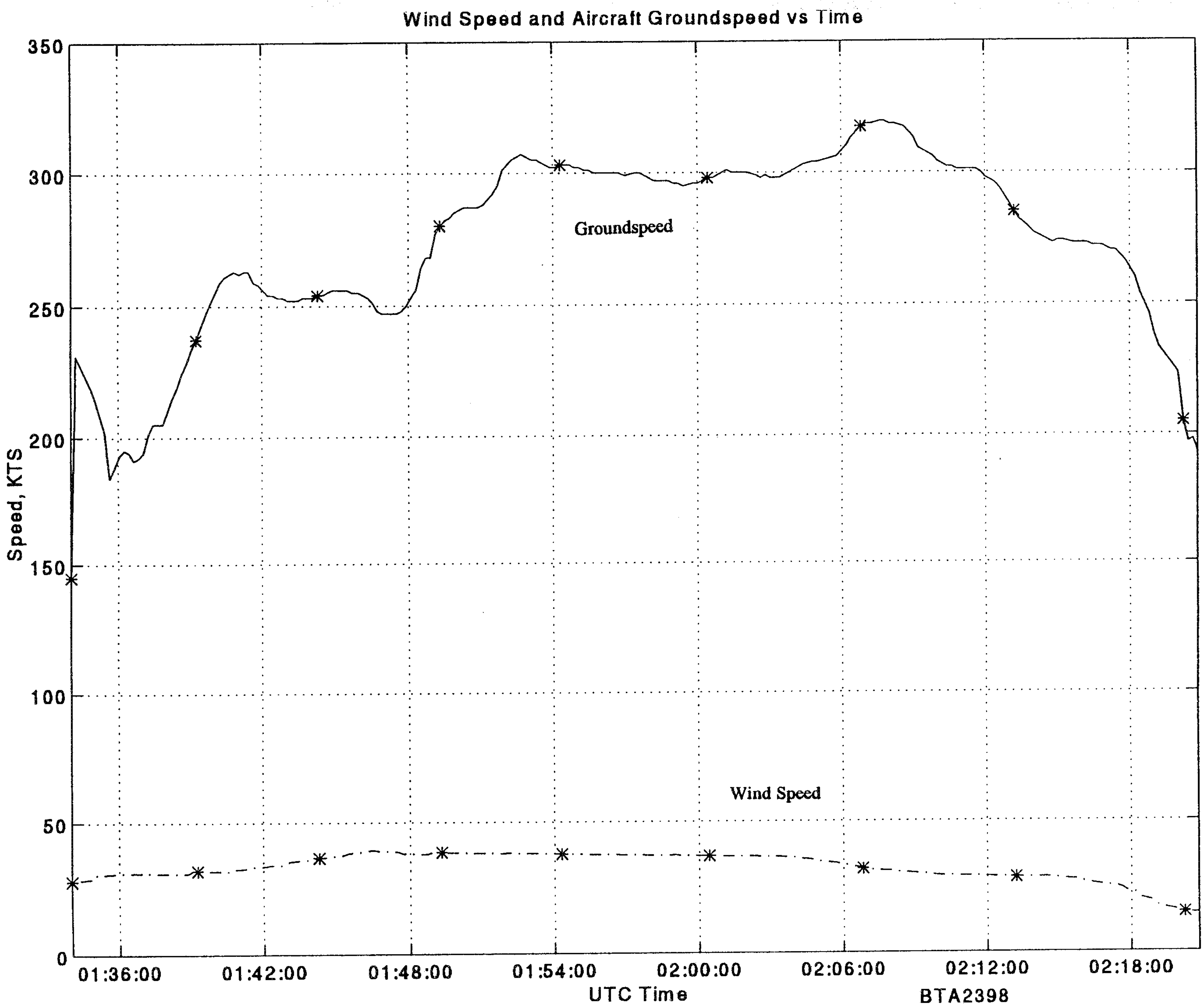


Figure 12: Groundspeed vs Time, BTA2398

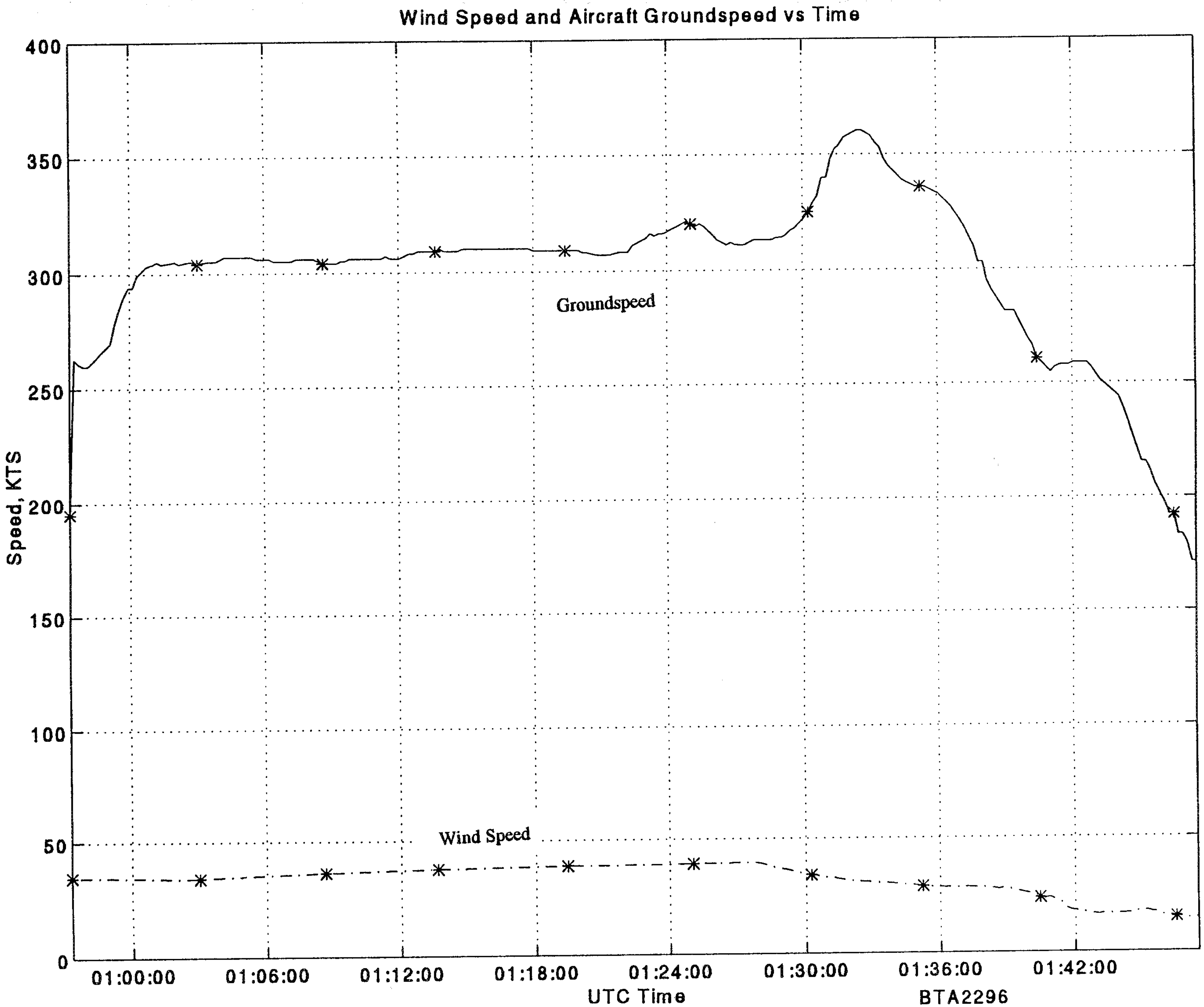


Figure 13: Groundspeed vs Time, BTA2296

Appendix A

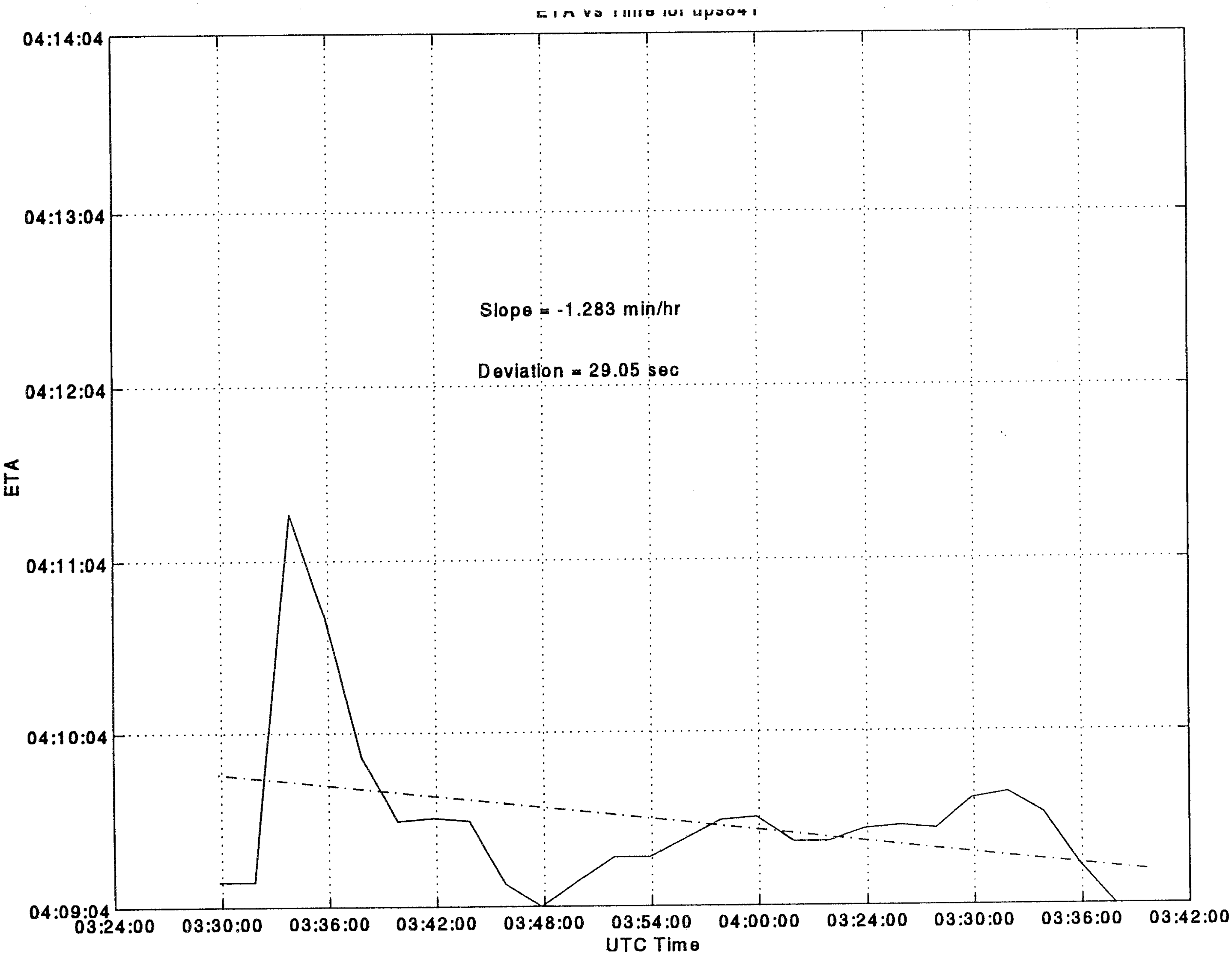


Figure A1: ETA vs Time, UPS841

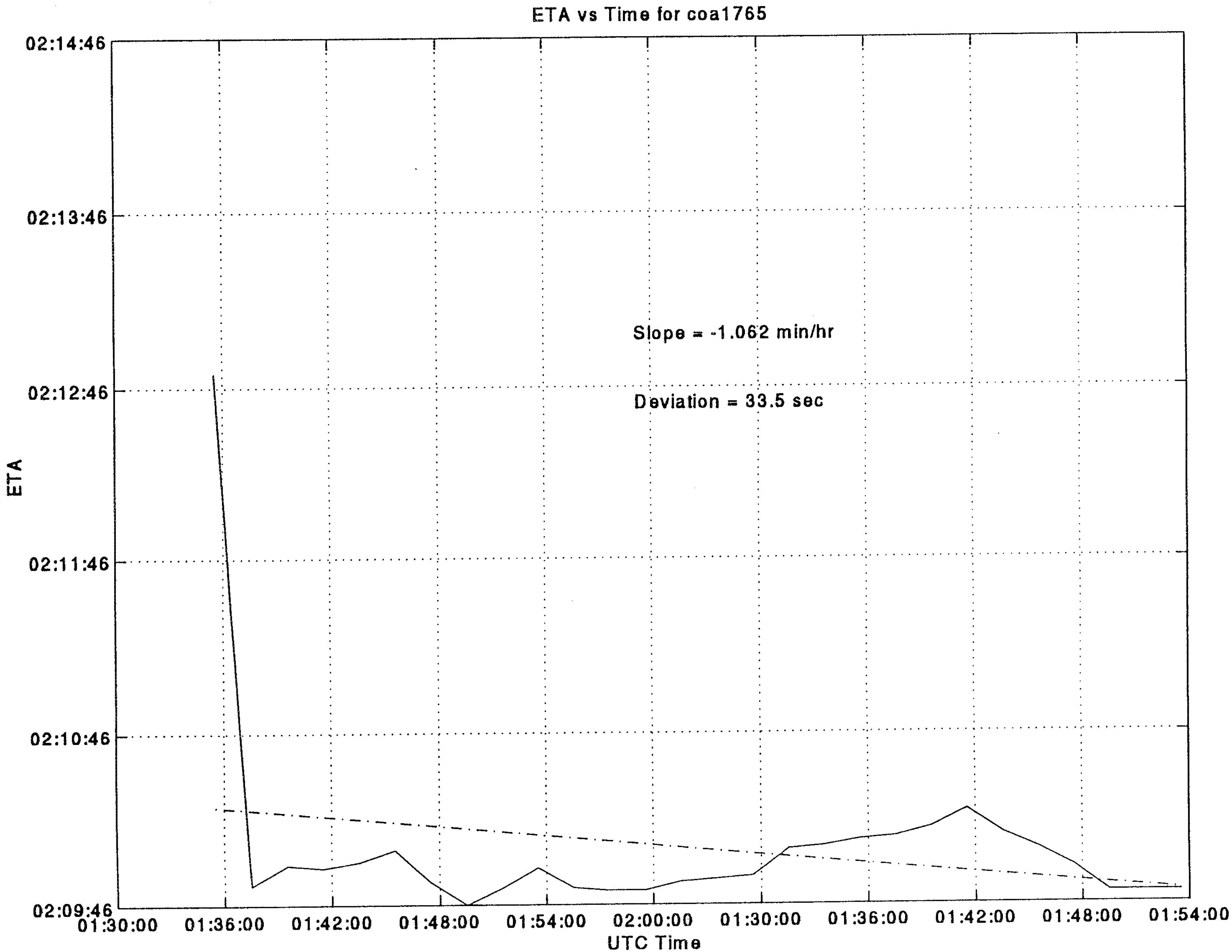


Figure A2: ETA vs Time, COA1765

Appendix B

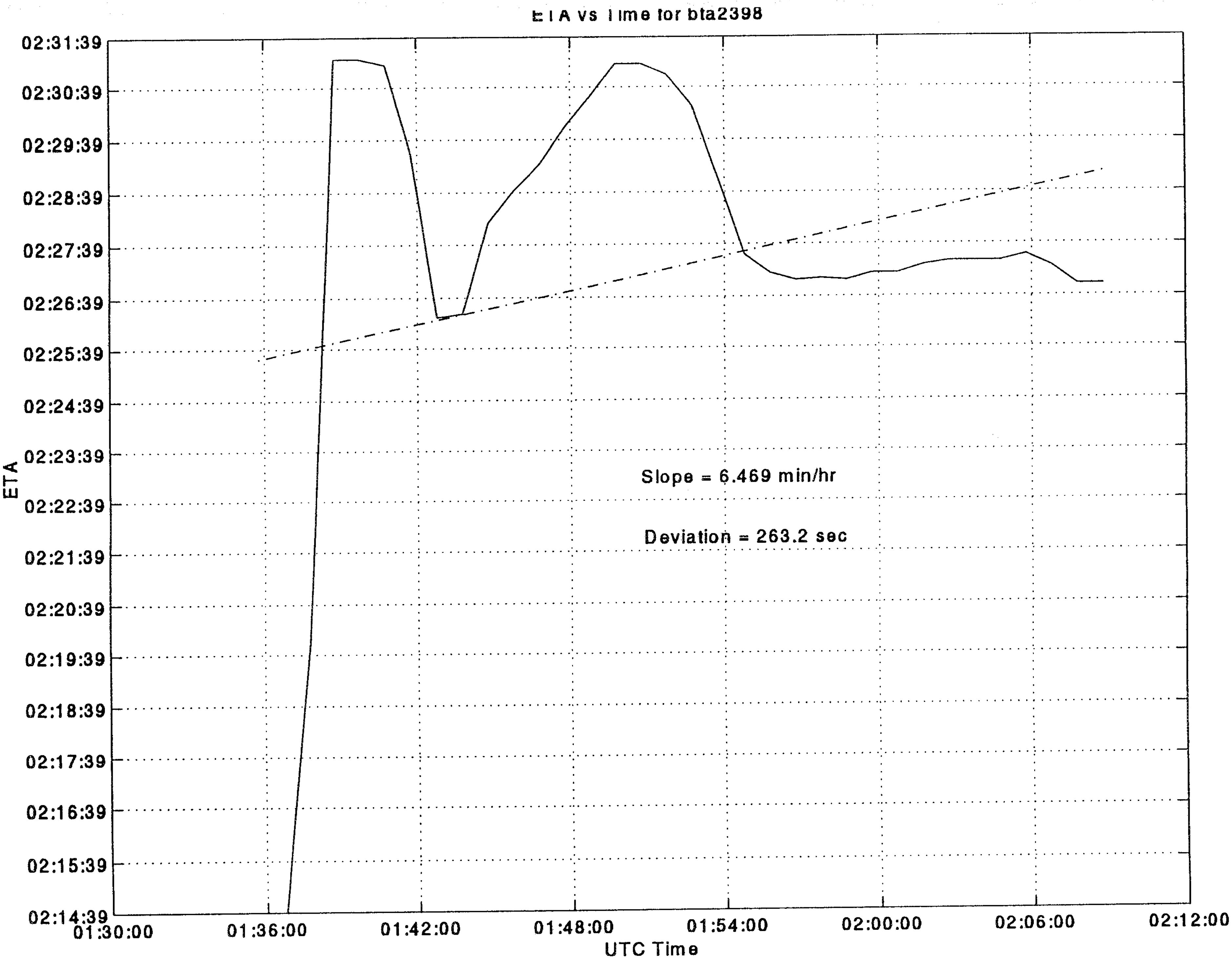


Figure B1: ETA vs Time, BTA2398

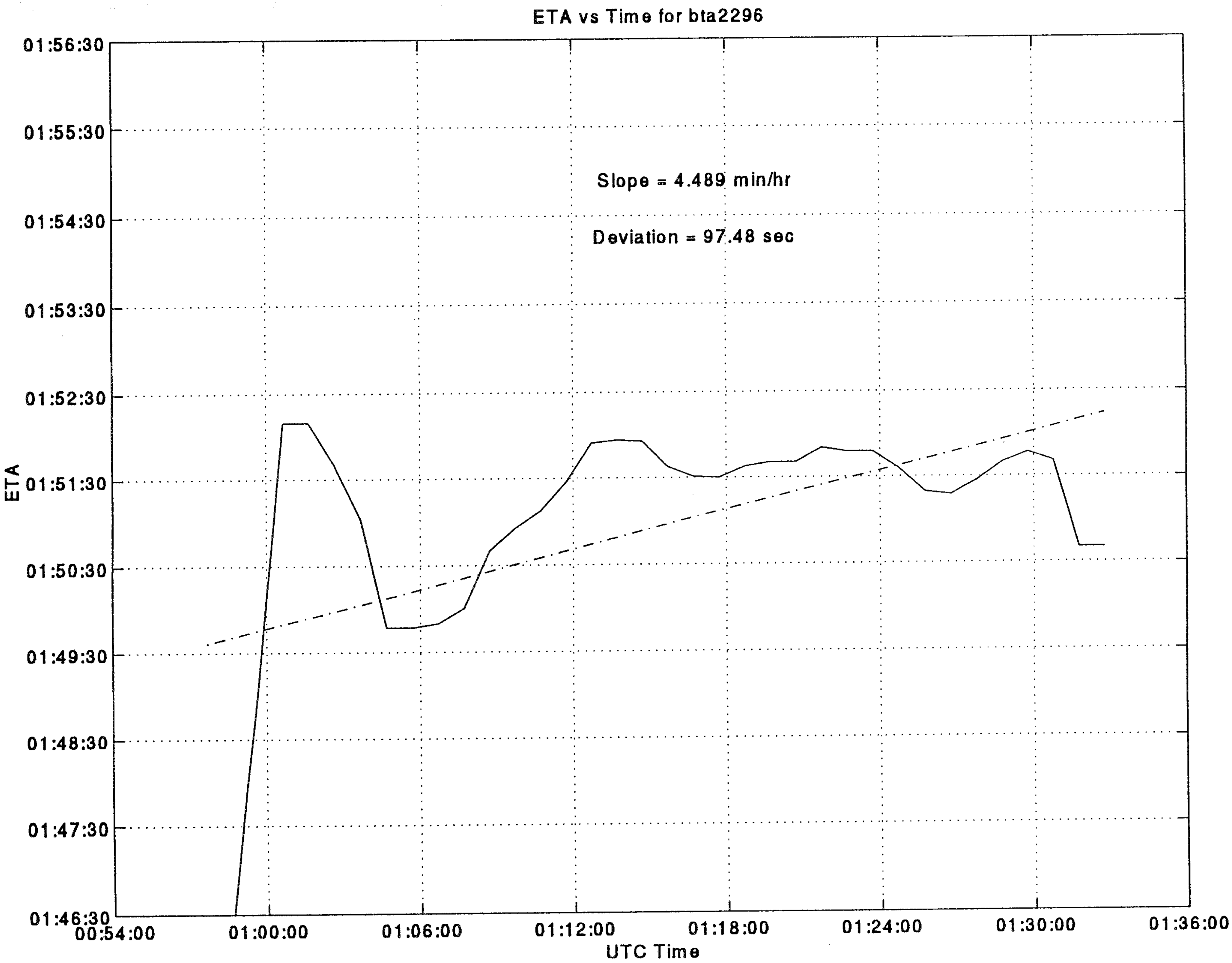


Figure B2: ETA vs Time, BTA2296

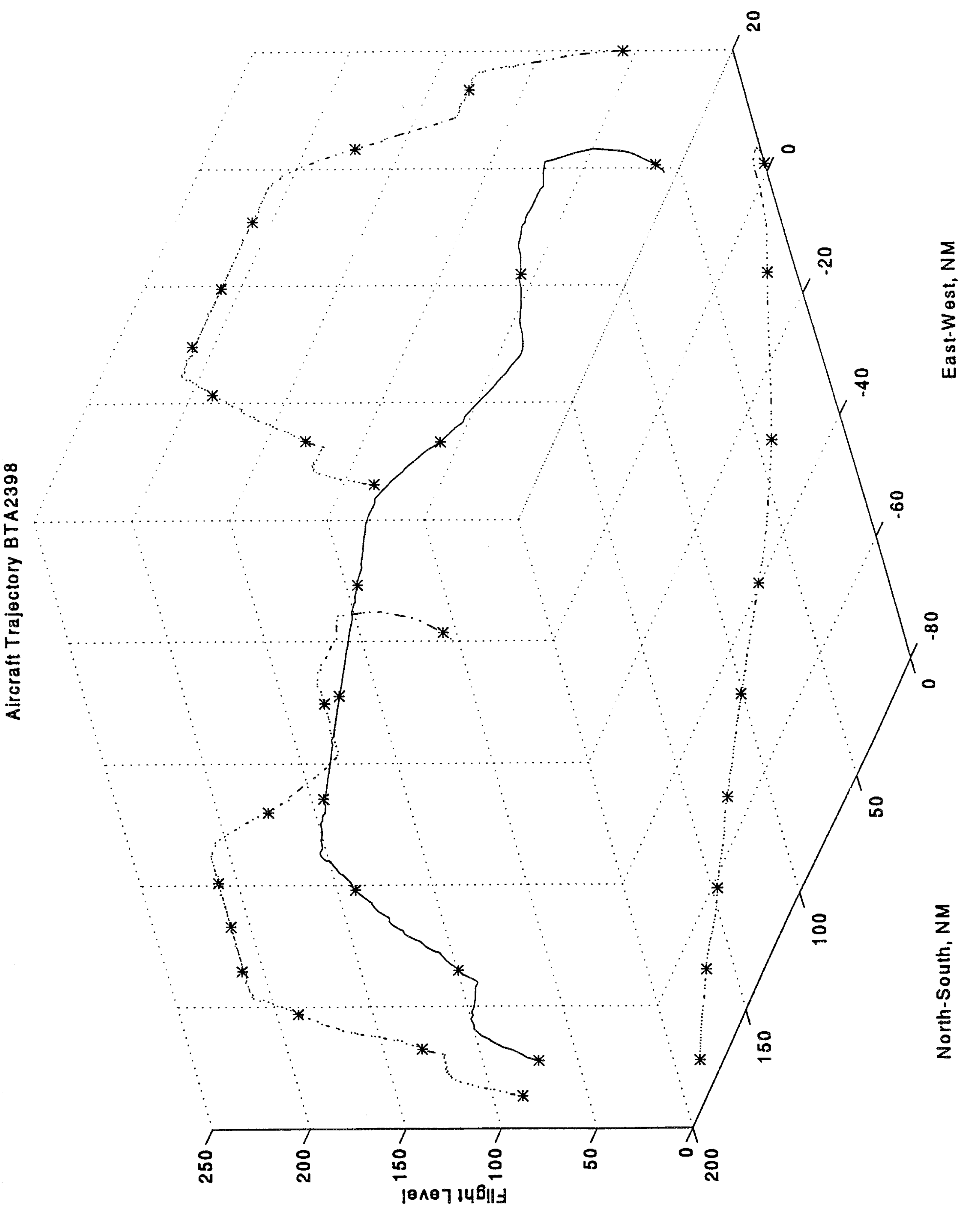


Figure B3: Trajectory for BTA2398

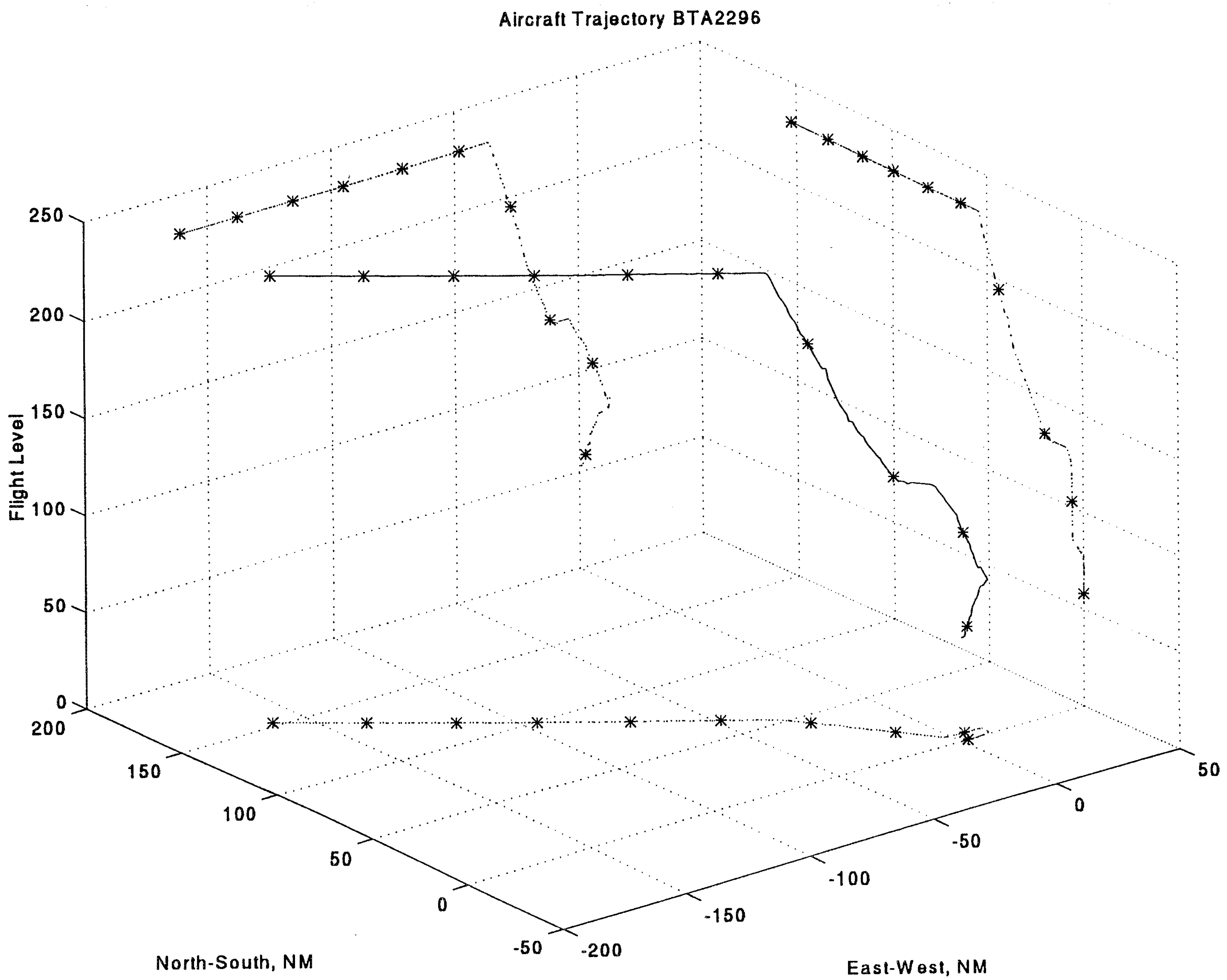


Figure B4: Trajectory for BTA2296

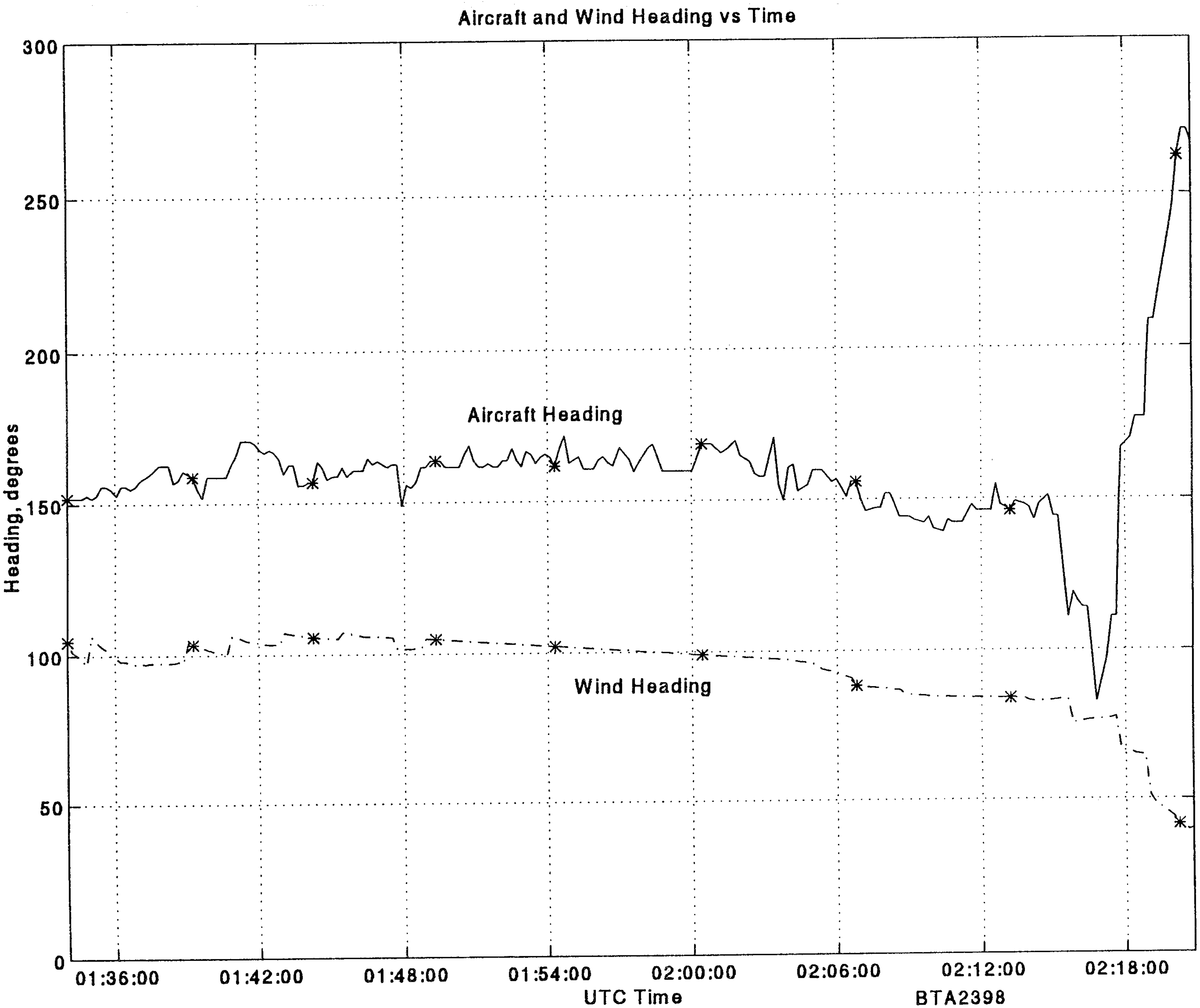


Figure B5: Aircraft Heading and Wind Heading vs Time, BTA2398

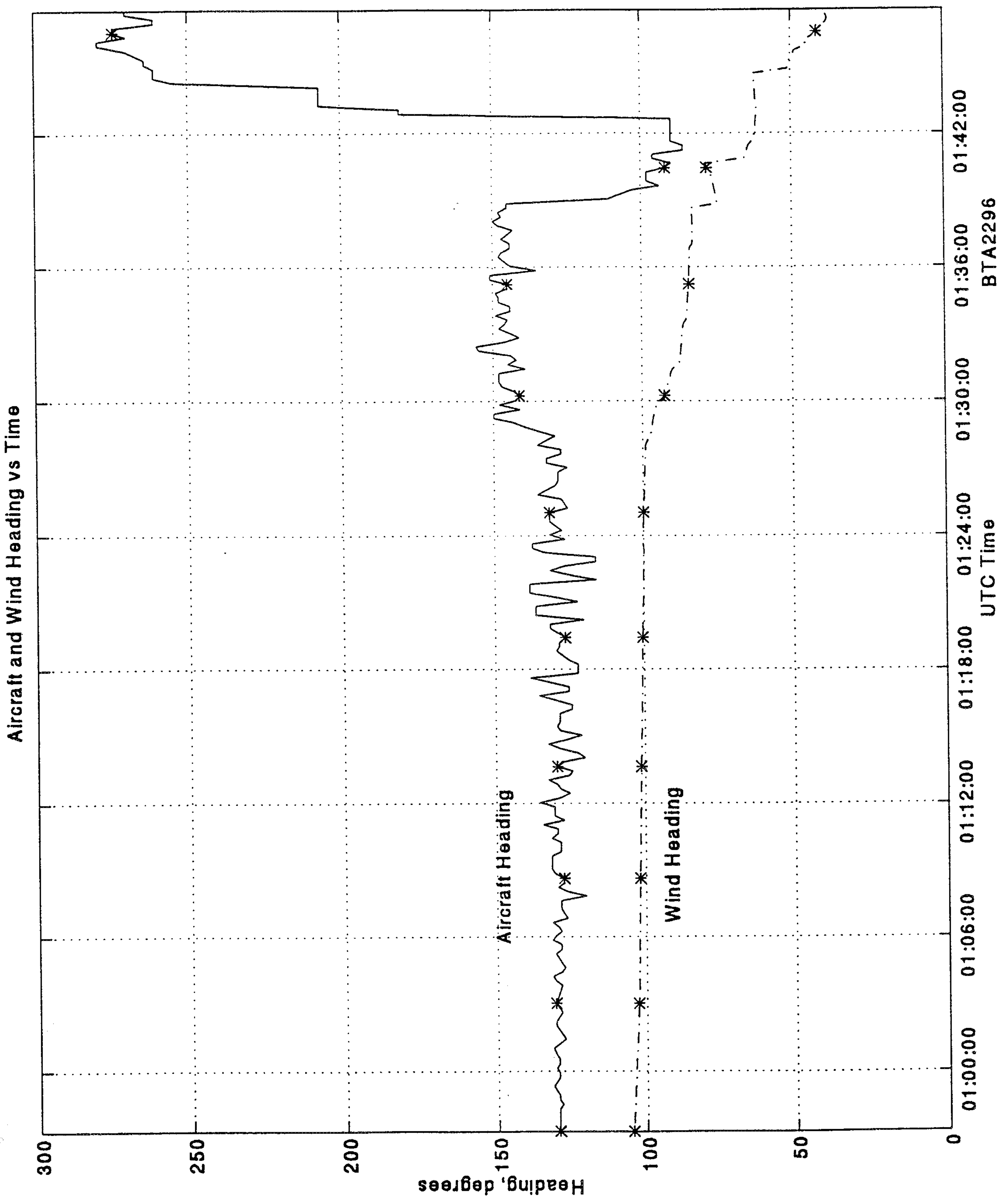


Figure B6: Aircraft Heading and Wind Heading vs Time, BTA2296

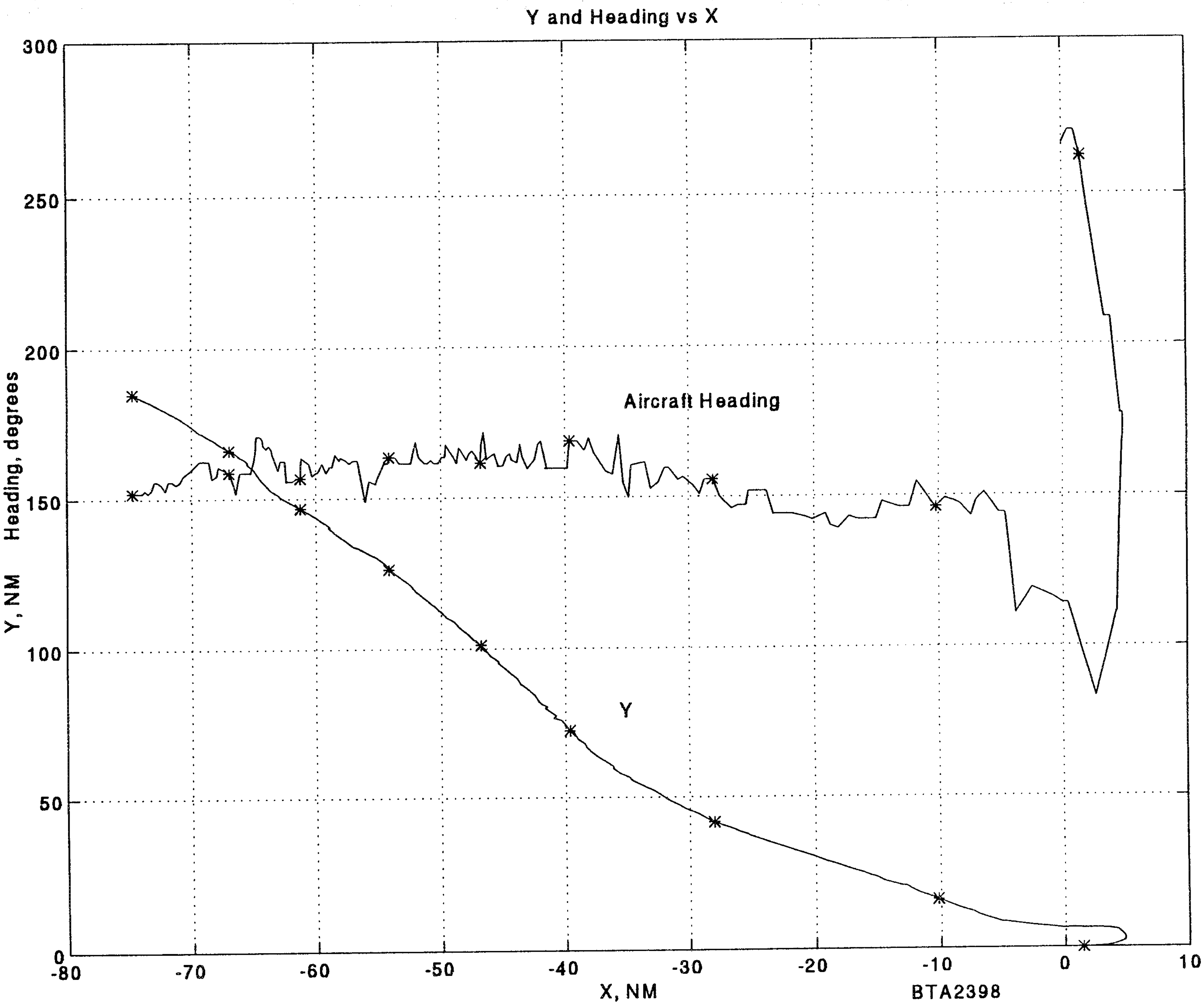


Figure B7: Y vs X and Aircraft Heading vs X, BTA2398

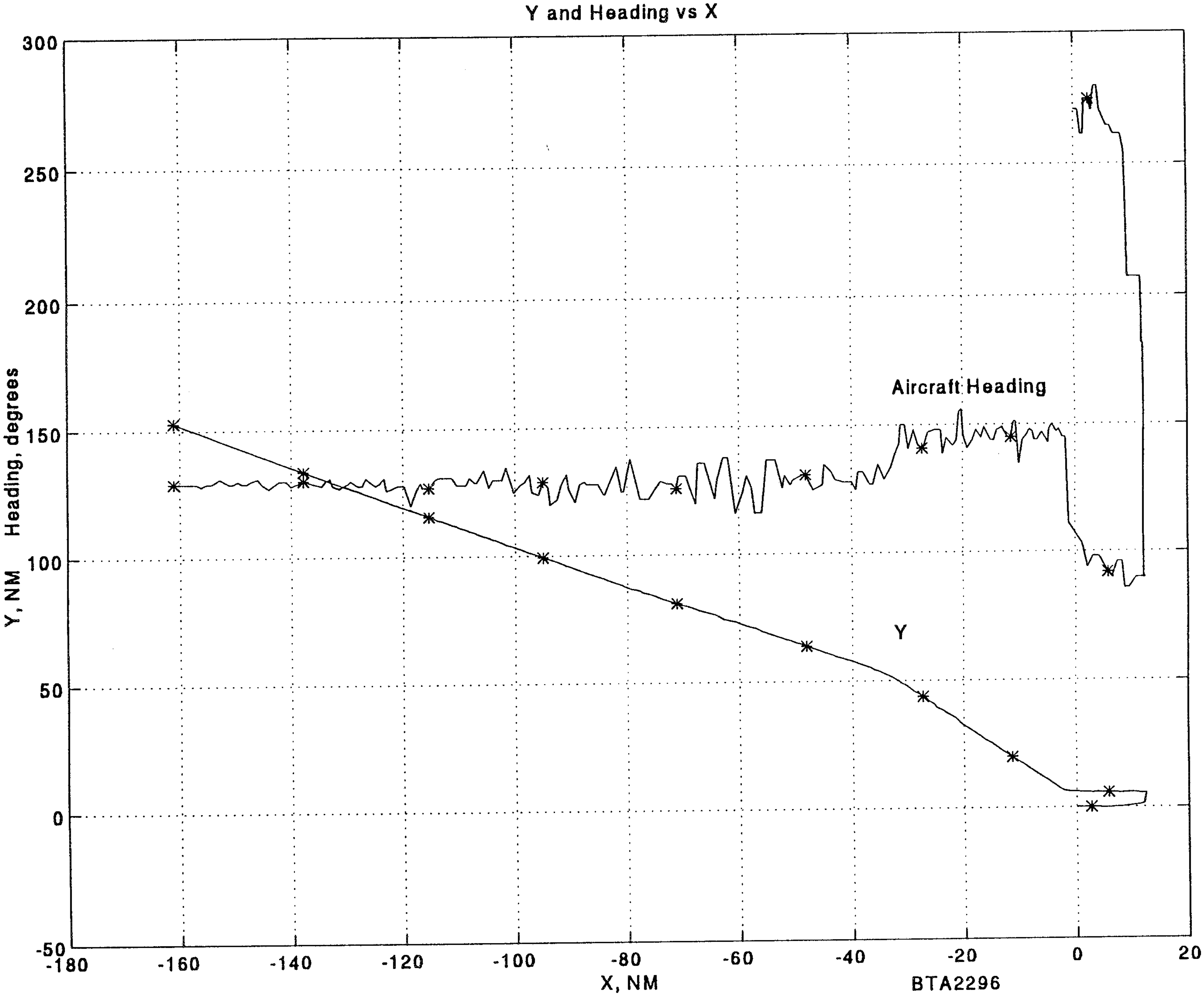


Figure B8: Y vs X and Aircraft Heading vs X, BTA2296

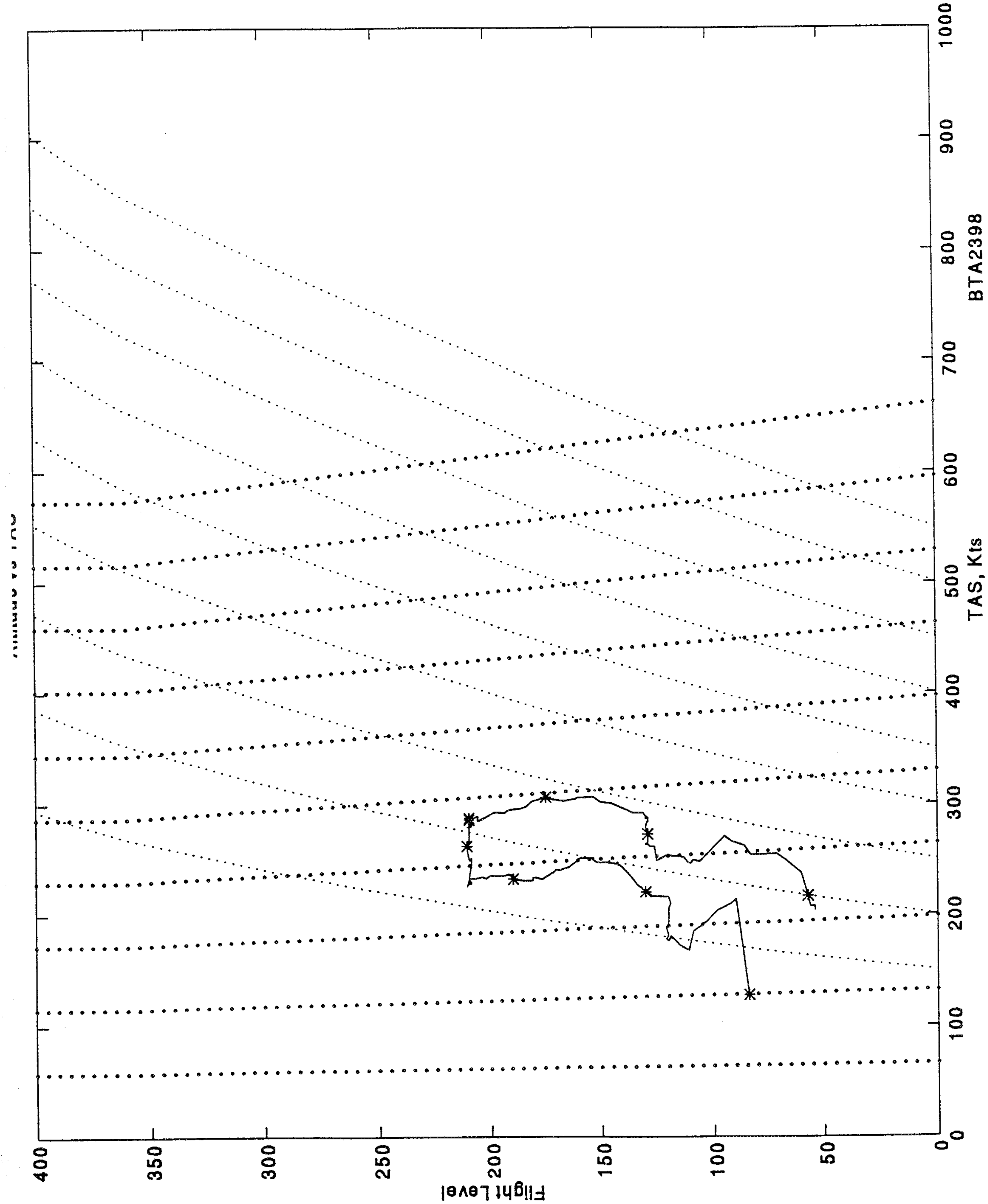


Figure B9: Altitude vs True Airspeed, BTA2398

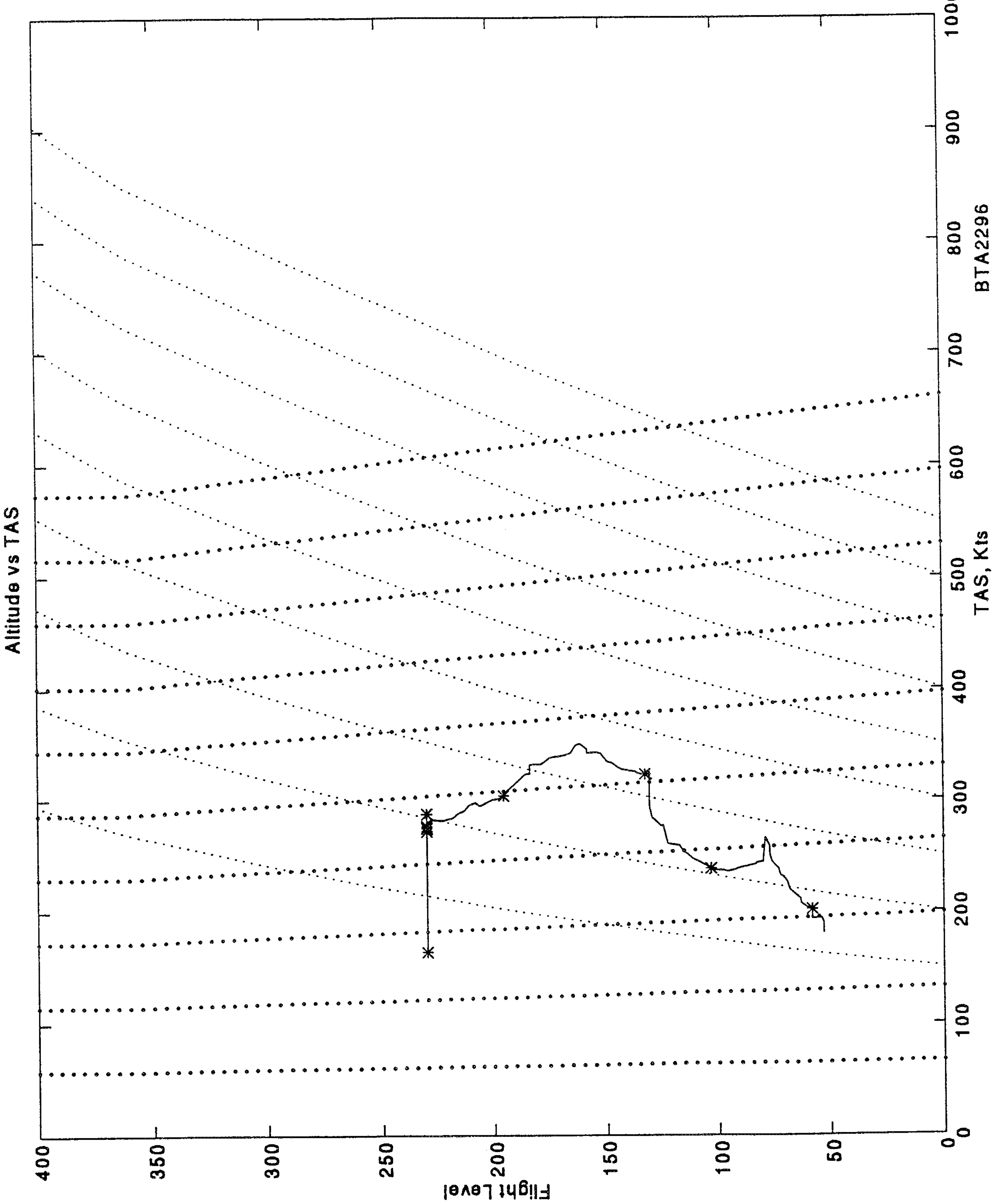
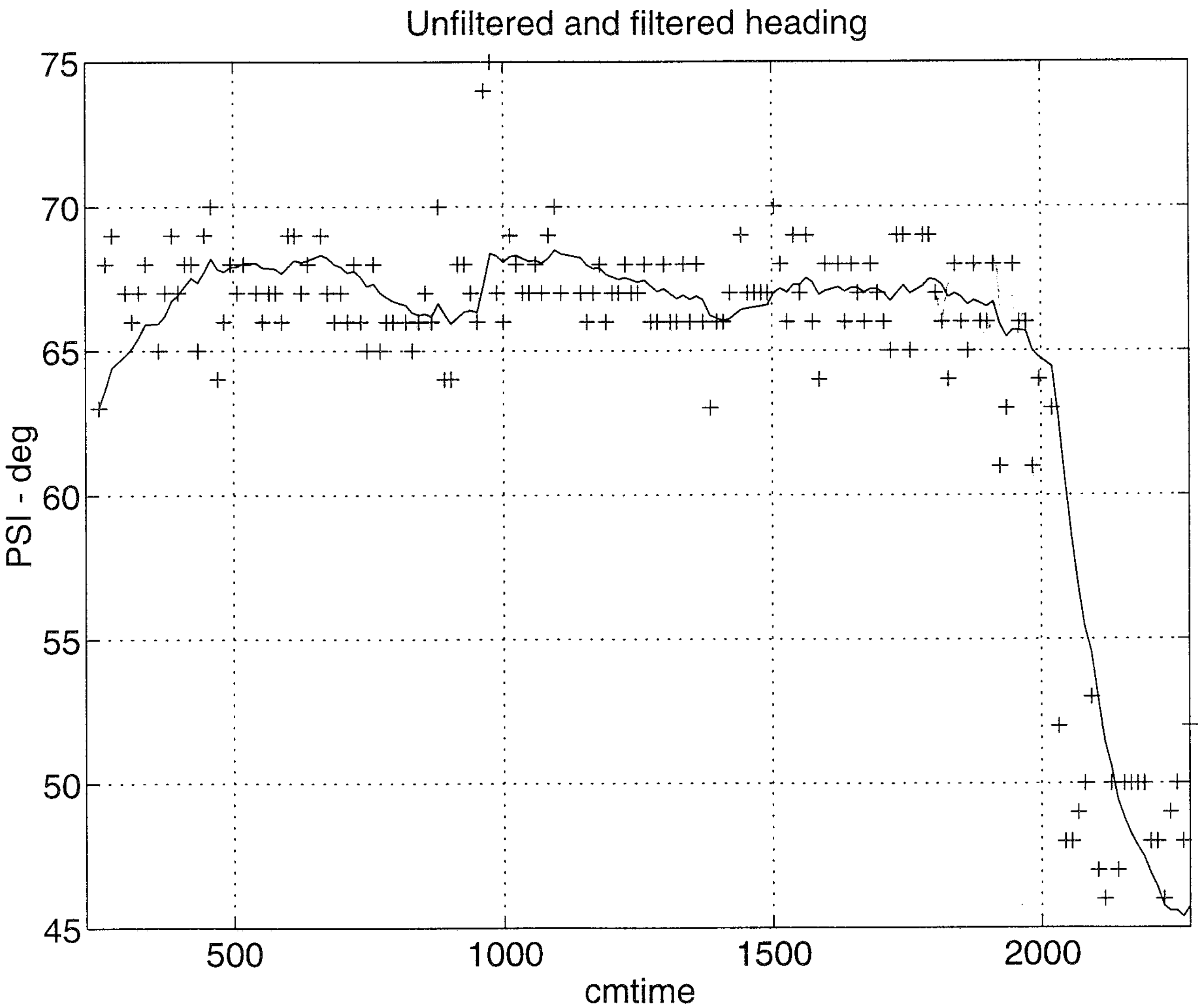
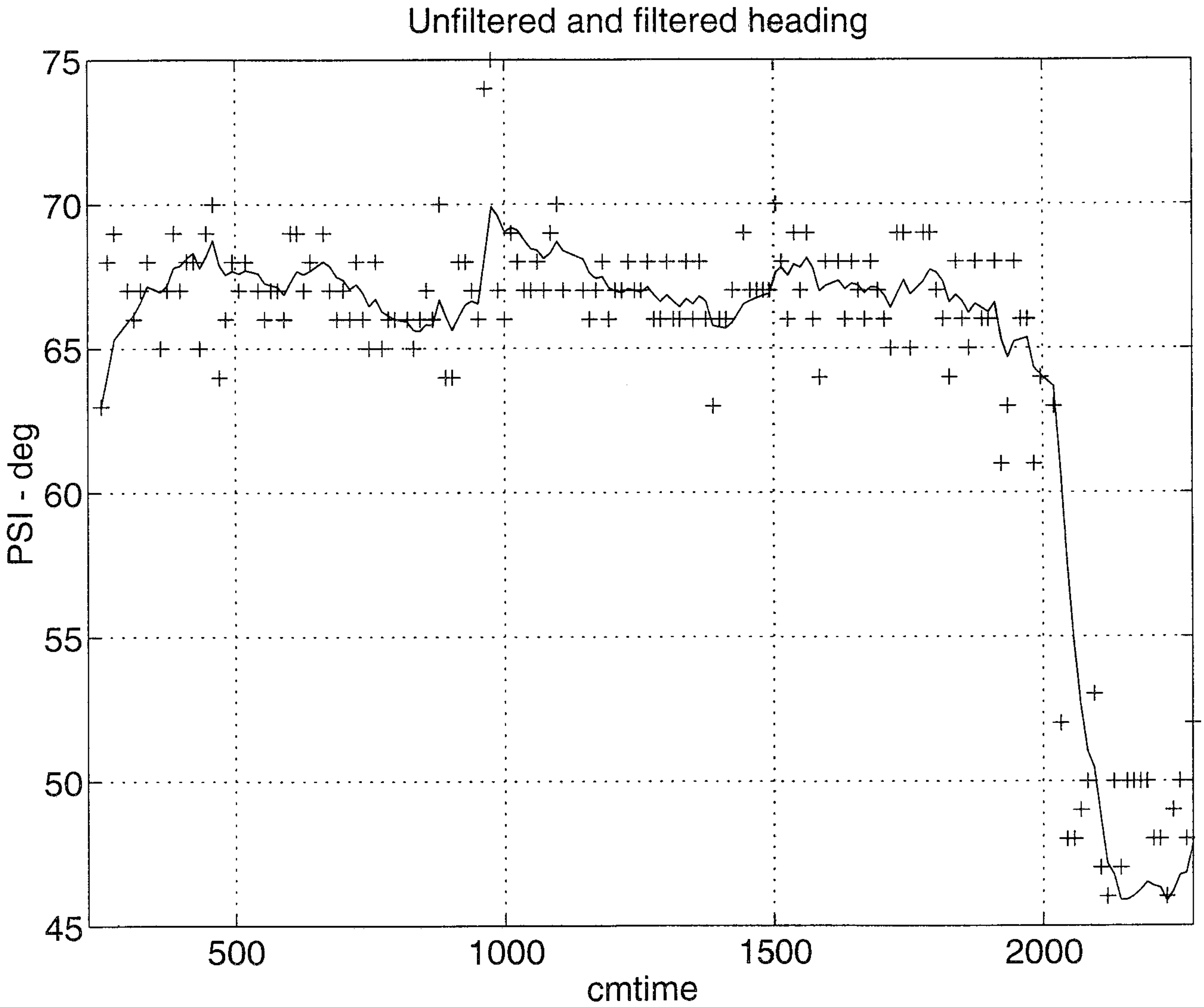


Figure B10: Altitude vs True Airspeed, BTA2296

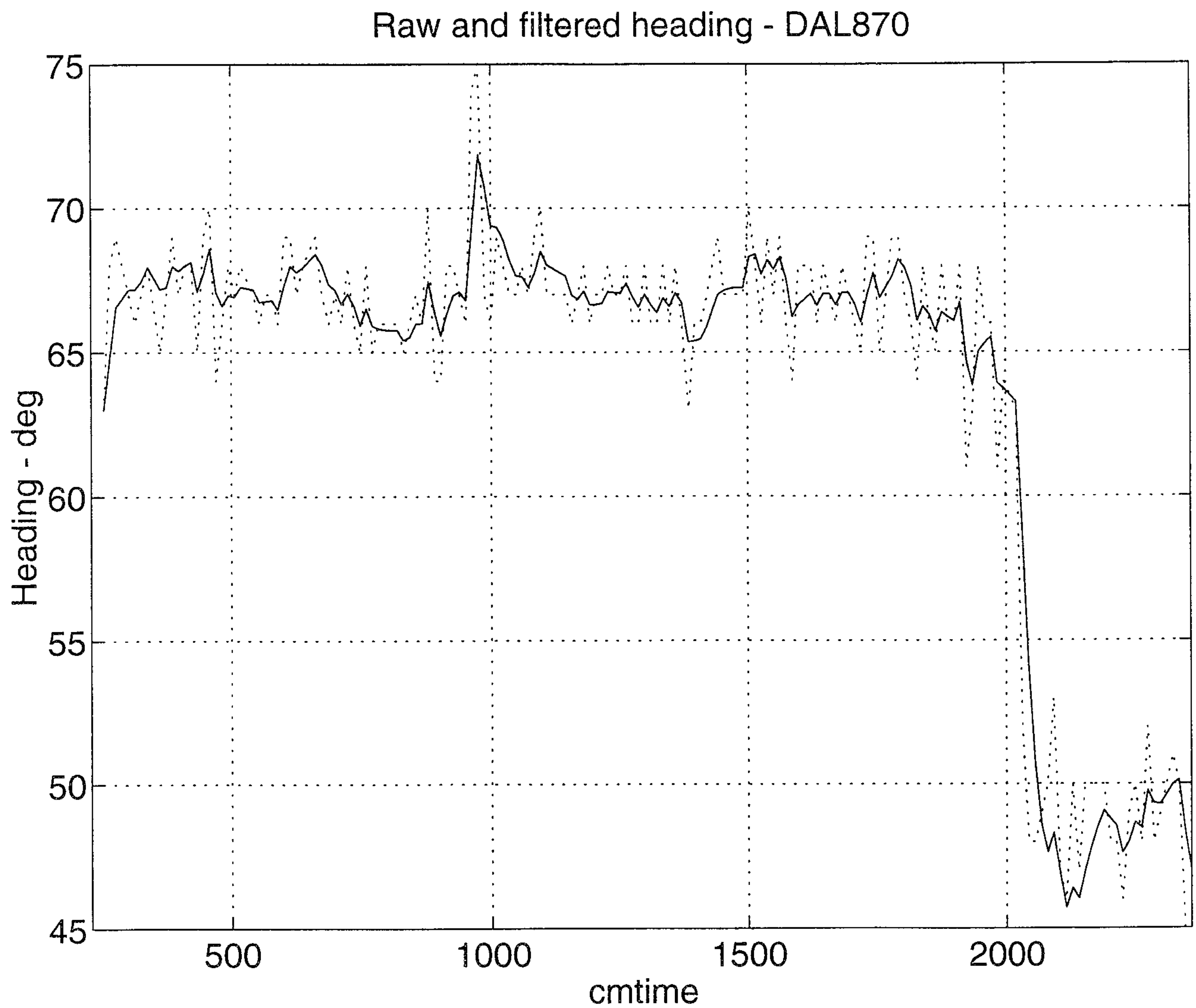

Unfiltered and filtered heading
PSI - deg
cmtime
75
70
65
60
55
50
45
500
1000
1500
2000

[q = .01
r = 10]

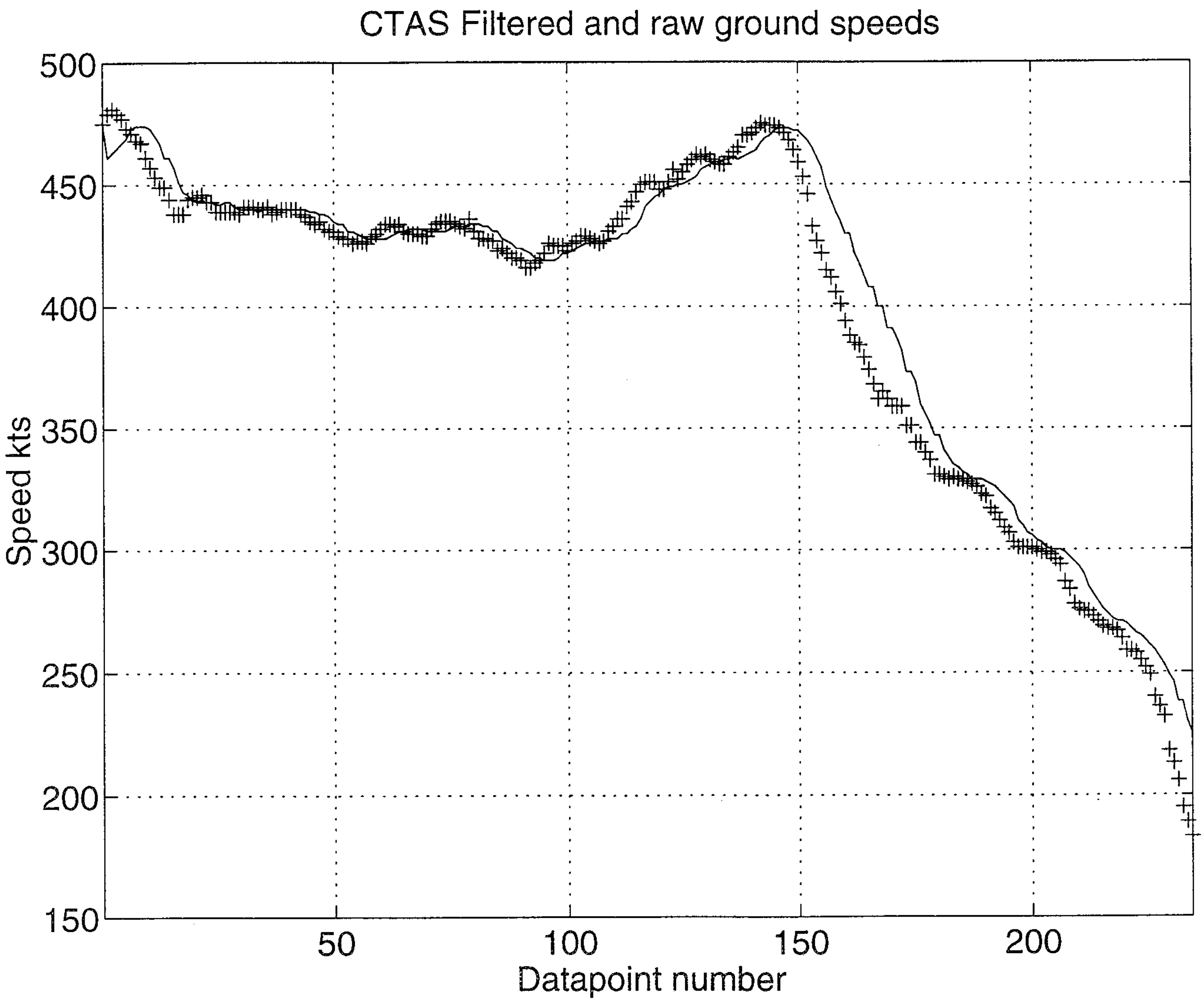


Unfiltered and filtered heading
PSI - deg
cmtime
75
70
65
60
55
50
45
500
1000
1500
2000

q = .01
r = 1



Raw and filtered heading - DAL870
75
70
65
60
55
50
45
Heading - deg
500
1000
1500
2000
cmtime


CTAS Filtered and raw ground speeds
Speed kts
Datapoint number
500
450
400
350
300
250
200
150
50
100
150
200