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COTS Fusion Tracker Evaluation

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16. Abstract

Lincoln Laboratory was tasked by the FAA to measure the performance of a representative sample of current commercial off-the-shelf (COTS) fusion trackers. This effort included cataloging the companies that have available ATC fusion trackers, acquiring executable tracker images from as many as possible of these trackers, running the commercial tracker code on the test sets, and evaluating the performance achieved.

This report presents an overall review of the state-of-the-art of fusion trackers as applied to the FAA surveillance problem. Average statistics of performance, as well as performance in special situations, are included. In each case, the performance of fusion is compared against the performance of single sensor and mosaiced tracking. Thus, the advantages and disadvantages of fusion will be evident. The statistics may also permit the generation of a fusion tracker specification should the FAA decide to procure one as part of a future automation system.

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EXECUTIVE SUMMARY

Current FAA automation systems use reports from a single beacon sensor to determine an aircraft's position, altitude, and identification. In en-route automation, should reports exist from overlapping sensors, one sensor is chosen as the preferred sensor and the others are assigned backup supplementary roles; these assignments are pre-defined for each sector of a geographic grid termed "radar sort boxes". Data from supplemental sensors are only referenced when the preferred sensor reports are missing. This system of operation is named mosaicing. While mosaicing does accomplish integration of surveillance data from multiple sensors, it has significant limitations. For example, differences between position reports for the same aircraft from different sensors normally exist due to sensor errors, including biases. These errors produce significant "hops" or "stitching" in the aircraft positions when the preferred sensor changes or when the supplemental sensor is used. The presence of these phenomena cause controllers to employ increased separation standards in affected regions, significantly reducing the effective airspace capacity.

In recent years, with the advent of faster computers, new techniques for multi-sensor surveillance integration have been developed. While the techniques vary with the individual developer, they all combine surveillance reports from multiple sensors into a single track for each aircraft. These techniques are collectively referred to as multi-sensor "fusion".

Lincoln Laboratory was tasked by the FAA to measure the performance of a representative sample of current commercial off-the-shelf (COTS) fusion trackers. This effort included cataloging the companies that have available ATC fusion trackers, acquiring executable tracker images from as many as possible of these companies, preparing test data sets (recorded and simulated) to input to these trackers, running the commercial tracker code on the test sets, and evaluating the performance achieved.

The fusion evaluation effort described in this report made use of four COTS trackers:

1. Lockheed-Martin (Minnesota) - MicroEARTS
2. Telephonics - ATC tracker used abroad
3. Eurocontrol - operational ATC fusion tracker (ARTAS) used in Europe
4. Raytheon – STARS tracker

As expected, since adaptation to specific sensor characteristics is critical to proper fusion performance, all of the COTS trackers required preparation by the manufacturers before they could be applied to our ATC databases.

The position and velocity information contained in the tracker output reports were analyzed in this study. Some of the COTS products have additional fields internal to the tracker that may influence the information passed to automation safety functions.

Analysis of a fusion tracker measured its performance in the following categories:

1. General accuracy – position and velocity in straight flight
2. How quickly it responds to turns – and accuracy of turn data

3. How long it takes to initiate tracks – and number of false alarms
4. How quickly it recovers from erroneous correlations
5. Its ability to handle system biases

The analysis was made using both recorded and simulated inputs, and with both single sensor and multiple sensor databases for comparison. The recorded data runs indicate qualitatively, in an overall average sense, how well the trackers perform on real ATC data, and show how much benefit may accrue with their introduction. The simulation runs permit detailed quantitative measures of each aspect of tracker performance, since ground truth is known and specific situations can be generated.

The Lincoln simulation generates data from a superset of the sensors for which recorded data was collected, namely all enroute sensors currently in the New England region, plus all terminal sensors at New England airports, plus the production Mode S sensor operated at Lincoln Laboratory (hereafter denoted as SURVSEF). The characteristics of the simulated data were matched to those measured in the recorded data. For each sensor, both a non-Mode S CD2 format version and a Mode S advanced format version are defined, so that tests dependent upon report data accuracy can be performed.

The basic simulation data set has 200 aircraft, each starting with 200 seconds of straight constant speed flight, followed by 30 seconds of standard-rate turn 3°/sec turning right flight, followed by another 100 seconds of straight flight. This database has been used for absolute and comparison performance tests for straight and turning flight and the transitions between them.

This data set was run through each commercial fusion tracker for the following set of sensor cases:

1. SURVSEF only (4.8 second scan)
2. mosaicing using all enroute sensors (each 12.0 second scan)
3. fusion using all enroute sensors

Each case was run for both CD2 and Mode S quality reports as subcases to test the effects of data quality. The input data in each case was unbiased; the effects of data biases were addressed separately.

For each case run, the analysis program was used to generate the absolute track angle, ground speed, and position errors for each tracked output report. The following characteristics were then observed:

1. The minimum time needed to initiate tracks.
2. The time required for the tracker to settle down for straight flight.
3. The performance during a turn – especially how long it took for the turn to be detected.
4. The time required for the tracker to re-establish straight flight steady state after the completion of the turn.

Since system biases play a key role in a multi-sensor fusion system, each COTS tracker was tested to determine its ability to compute and adapt in real time to their existence. The method of testing this performance characteristic was to play a data scenario in which sensor biases were present through the trackers twice: once at the beginning of the run, and then again after an hour of high-density aircraft data. The results indicate that all but one of the COTS trackers have algorithms that permit the tracker to adjust over time for the existence of biases. We have been informed that the other COTS tracker has a bias algorithm that is not yet part of the automated system.

A random scenario that mixes straight, accelerating, turning, and combination flight segments for each track was also used to test each COTS tracker. The analysis computed the track angle, ground speed, and positional errors for each segment type as a function of time in the segment, as well as the time required to recover from each type of maneuver and return to normal error conditions. This test also included as a benchmark of comparison a Lincoln developed non-Kalman routine that estimates velocity, but not position, for each output report when fed multi-sensor data, and thus can serve as an adjunct to a full tracker.

During the various fusion tests, it became clear that the performance in all cases was significantly improved when Mode S data quality (such as with ASTERIX) was assumed, as opposed to the CD2 data format and accuracy. A particularly important consequence of this improvement was that the significant number of track drops noted in aircraft turns with CD2 data was virtually completely eliminated when Mode S/MSSR quality data was input instead to the trackers.

The principal conclusion of this study is that technology is on the shelf (COTS) to achieve some, but not all, of the surveillance improvements that have been promised with sensor fusion algorithms.

The COTS products are able to receive inputs from typical FAA radars and produce output tracks that are as good as or better than those produced by existing FAA automation systems. In particular, the COTS products eliminate the track data "hops" and "stitching" that are characteristic of existing mosaic systems. This could produce substantial benefits by opening up the prospect of allowing controllers to use the same separation standard permitted for single sensor operation when multiple sensors are in use in a given sector. The COTS products are also robust to the presence of "outlier" data and the failure of a single sensor. In addition, it may be true that the use of a Kalman filter by itself in these COTS products in either mosaic or fusion systems may lead to significant surveillance improvements over the current alpha-beta smoothing (which was not tested).

The results indicated that the COTS products do not produce significantly better estimates of position and velocity in the fusion mode than in the mosaic mode, either in straight line or turning flight. Intuitively, one would have expected the additional data and the associated higher update rate would have contributed to improved performance in these areas. Improved state estimation might produce benefits by allowing decision support tools (e.g., CTAS, etc.) to better predict aircraft trajectories. At the present time, however, FAA requirements for aircraft state estimation in this context are not well developed. Therefore it is difficult to assess the impact of the current set of COTS products. An adjunct velocity tracker may provide improved performance should that prove to be necessary.

Our recommendation is that the FAA develop a set of quantitative performance criteria that it desires from a fusion tracker. If reliability, robustness, and smooth transitions among sensors are the principal criteria, the current COTS products tested are suitable, given appropriate tuning and adaptation. However, if the desire is significant improvement in aircraft position and velocity estimation, additional development may be required.

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1. FUSION TRACKING OVERVIEW

1.1 INTRODUCTION

Current FAA automation systems use reports from a single beacon sensor to determine an aircraft's position, altitude, and identification. In en-route automation, should reports exist from overlapping sensors, one sensor is chosen as the preferred sensor and the others are assigned backup supplementary roles; these assignments are pre-defined for each sector of a geographic grid termed "radar sort boxes". Data from supplemental sensors are only referenced when the preferred sensor reports are missing. This system of operation is named "mosaicing." While mosaicing does accomplish integration of surveillance data from multiple sensors, it has significant limitations. For example, differences between position reports for the same aircraft from different sensors normally exist due to sensor errors, including biases. These errors produce significant "hops" or "stitching" in the aircraft positions when the preferred sensor changes or when the supplemental sensor is used. The presence of these phenomena cause controllers to employ increased separation standards in affected regions, significantly reducing the effective airspace capacity.

In recent years, with the advent of faster computers, new techniques for multi-sensor surveillance integration have been developed. While the techniques vary with the individual developer, they have in common the property that surveillance reports from multiple sensors are combined into a single track for each aircraft. These techniques are collectively referred to as multi-sensor "fusion". Like mosaicing, fusion provides an automatic backup in the event of a single sensor failure or missing data. The fact that fusion algorithms make use of all sensor data to form a single track is often cited by fusion developers as the source of significant surveillance improvements such as more rapid track initiation, higher update rate, and more accurate position and velocity estimates. An additional potential improvement is the elimination of discontinuities at sensor boundaries. To the extent that separation standards are defined by surveillance performance, improvement in that performance will increase the effective capacity of the affected airspace. The fundamental technical question is: what quantitative surveillance improvements are possible, given the current state of industry skill in multi-sensor fusion trackers?

Lincoln Laboratory was tasked by the FAA to measure the performance of a representative sample of current commercial off-the-shelf (COTS) fusion trackers. This effort included cataloging the companies that have available ATC fusion trackers, acquiring executable tracker images from as many as possible of these companies, preparing test data sets (real and simulated) to input to these trackers, running the commercial tracker code on the test sets, and evaluating the performance achieved.

This report presents an overall review of the state-of-the-art of fusion trackers as applied to the FAA surveillance problem. Average statistics of performance, as well as performance in special situations, are included. In each case, the performance of fusion is compared against the performance of single sensor and mosaiced tracking. Thus the advantages and disadvantages of fusion will be evident. The statistics may also permit the generation of a fusion tracker specification should the FAA decide to procure one as part of a future automation system.

The intent of this study is to provide the FAA with the "state of the shelf" of fusion trackers. Therefore, there is no need to specifically identify a particular performance result with a given manufacturer in this report. In exchange for their participation, Lincoln Laboratory agreed to provide each manufacturer with specific performance data on its own tracker while reporting here data that is not identified by manufacturer.

There were two major classes of fusion trackers represented in the industry sample. The first formulates tracks from each individual sensor and then combines the tracks into a single track (track-to-track fusion). The second combines the reports from all sensors directly into a single track (report-to-track fusion). A comparison of the two techniques, as implemented by the manufacturers, is provided when appropriate.

All of the COTS trackers were Kalman filters. Although a Kalman filter is the theoretical optimum tracker, this statement is true only if the aircraft trajectories are modeled correctly and enough states exist in the filter to match the model. The usual linear Kalman filter, therefore, will have problems with aircraft maneuvers. Also least-mean-square error, the measure optimized by a Kalman filter, is not necessarily the best indicator of performance. For a simple counter-example, consider the tracker options of Figure 1. Although tracker 1 is "optimum", tracker 2 would be preferred for ATC applications, where maximum error is more important for determining separation standards than is average error. In conclusion, non-Kalman filter trackers could possibly be superior for this application, even though none were offered.

1.2 TRACKER FUNCTIONS

A tracker in a surveillance and automation system performs several functions, of which the most important are:

1. Position estimation
2. Velocity (track angle and ground speed) estimation
3. False alarm rejection.

The first two functions depend upon the ability of the tracker to smooth noisy position measurements made by the surveillance sensor, while the third function depends upon the ability of the tracker to correlate reports corresponding to the same aircraft and distinguish them from other, nearby reports. A tracker can have as inputs either single sensor reports or reports from multiple sensors; the latter type is a fusion tracker.

In theory, a fusion tracker should provide improved position and velocity estimates because it has more reports (measurements) available to it. The higher data input rate can also be used to produce a higher track update rate. False alarm rejection should be improved with fusion because a potential false aircraft report from one sensor can be checked against the data from other sensors viewing the same airspace - if none of them see the aircraft, the report can be dropped with greater certainty.

Surveillance attributes that complicate the job of a fusion tracker include aircraft turns, false alarm reports, garbled report information, split and merged reports, and system biases and registration errors. Although registration errors can be reduced by careful calibration, many of the dozens of other bias sources are difficult if not impossible to compute and remove. A previous Lincoln project [1] attempted to use recorded data to estimate these residual biases, but the interrelations between them prevented complete success. More recent proprietary algorithms exist for removal of biases, and testing of the COTS trackers included detecting their presence. Because of the existence of biases, a poorly designed fusion tracker can perform worse than a single-sensor tracker on the same input data.

Normally, the generation of an aircraft track is a two-step process. First, individual reports must be associated with a track (report-to-track association). Then the reports are assembled into a track (tracking). As discussed below, report-to-track association is not always perfect and can introduce errors whose impact must be addressed in the tracker implementation. Clearly, the performance of a tracker is dependent upon the quality of the data received from the sensor. At present, the constraints of the NAS communication protocols (CD2) used to disseminate surveillance data to NAS automation cause significant data to be eliminated – both significant bits in the measurements (4 for terminal sensor range and 5 for enroute sensor range, 4 for azimuth, and 2 for altitude), and data fields that would greatly aid the report-to-track correlation process. Since this loss handicaps the tracker in the NAS automation system, it is important that the impact of these performance constraints be measured as part of this evaluation. Also, due to performance coupling, the performance of the report-to-track association process and the tracker must be evaluated in combination. The focus of the remainder of this paper is on the tracker subsystem.

It is important to note that the tracking done in the NAS automation system has a relatively long prediction time horizon (30-60 seconds) compared to the scan-to-scan processing (often also called tracking) performed in the sensor itself. Sensor tracking is used to clean up uncertainty in the data and to significantly reduce the false alarms sent to automation. The automation tracking discussed here follows the sensor tracking but is in no way intended to replace it.

1.3 TRACKER ANALYSIS METHODOLOGY

Analysis of a fusion tracker should measure its performance in several categories, of which the most important are:

1. General accuracy – position and velocity in straight flight
2. How quickly it responds to turns – and accuracy of turn data
3. How long it takes to initiate tracks – and number of false alarms
4. How quickly it recovers from erroneous correlations
5. Its ability to handle system biases
6. Altitude and altitude rate estimation

The analysis should be made on both recorded and simulated inputs, and with both single sensor and multiple sensor databases for comparison. The recorded data runs indicate qualitatively, in an overall average sense, how well the trackers perform on real ATC data, and show how much benefit may accrue with their introduction. The simulation runs permit detailed quantitative measures of each aspect of tracker performance, since ground truth is known and specific situations can be generated.

The most important feature of a tracker is its ability to provide track angle and ground speed information on an aircraft. It does this by smoothing the raw measured positions of reports in a filter (usually a Kalman filter). Since aircraft tend to spend most of their time in straight-line flight, the key filter performance characteristic is the accuracy of position and velocity state vectors during straight-line flight.

With recorded real data, scan-to-scan changes in track angle and ground speed can be computed to measure track stability as well as time to settle down at initiation. Multi-sensor fusion tracking will have more reports available for smoothing (higher data rate). This would seem to be an advantage, especially for altitude tracking during climbs and descents, but system biases can actually cause fusion tracking to degrade below mosaic tracking if not accounted for by adjustment algorithms. For example, the mathematical foundation for a Kalman filter ensures optimal performance for inputs with zero-mean Gaussian noise. If the true noise in the input measurements is non-zero mean (contains biases) and/or non-Gaussian, the output of the Kalman filter is no longer optimal and may be noisier than the input data. Thus, tracking comparison of fusion against single sensor data was included in the test plan.

With known inputs – such as simulated data with typical sensor measurement noise – performance in straight flight can be isolated and measured. Thus, the average and variance of position and velocity errors can be determined. Both types of tests were performed.

Although turns are less frequent, they cannot be ignored. Safety algorithms such as Conflict Alert depend upon knowing when a turn is in progress to detect possible future reductions in separation below acceptable levels. Thus, the ability of a filter to note the onset and end of a turn as soon as possible is important. In particular, its time to recover stability after a turn is an important tracker characteristic. In the worst case, loss of positional accuracy in a turn due to an undershoot of the ground track angle estimate can cause the tracker to drop the track, removing the aircraft from the automation system (although reports will continue to appear on the display). Finally, accurate calculation of the rate of turn helps prediction algorithms make their decisions. To adequately perform these functions, the filter should ideally contain turn states, such as occurs in IMM (Interacting Multiple Model) Kalman filters.

Testing turn performance requires known inputs, so that delays in state changes and turn rate accuracy can be measured. Simulated single and multiple sensor data with typical noise, in which each aircraft flies straight for 200 seconds to establish steady state, then performs a 90-degree turn at a standard 3 deg/sec turn rate, followed by return to straight flight, were used to measure turn performance. Statistics including track angle error, ground speed error, and positional error versus time in turn were generated. Also, time to detect beginning and end of maneuvers with multi-sensor data was compared against single sensor performance.

Track initiation with multiple sensor tracking can be more complex than that for single sensor tracking. The potential for false alarm tracks is also increased due to the large number of "cross-sensor" report pairings. A properly designed fusion tracker should initiate tracks at least as fast as the single sensor case, and hopefully faster, with no additional false alarm tracks.

The test for this performance requirement was to compare the single and multi-sensor results for time to initiate tracks. Both recorded and simulated data were used; the recorded data indicated "real-life" performance while the simulated data permitted tests on specially constructed situations. Examples of such situations include number of sensors and percent of coast scans. No false alarm performance was tested in this study due to the complexity of the required tests and analysis routines, especially with the number of trial tracks used by each manufacturer (which mimic false tracks).

No tracker can attain perfect correlation – it will on occasion select for the track a report that does not correspond to the actual aircraft position. This report can correspond to another nearby aircraft, it can be a false alarm, or it can have a bad position due to errors in the report generation algorithm. Such a report has the potential to significantly deviate the track position or velocity. A well-designed tracker should have the ability to detect such an event when good data next occurs, and recover from the errors caused by the bad point. A particularly desirable implementation is to check each suspect report on the next scan when hindsight is available; if it is verified as a correlation error, the tracker should revert to its previous values prior to the error, and update correctly with the new good report.

A method of testing this performance characteristic with simulated inputs was to create a set of reports representing straight-line flight. Then, the position of one report at a known time was significantly altered, and the resulting data fed through the tracker. The errors in the predictions recorded after the bad report, compared to those prior to the outlier, indicate the tracker's resilience to correlation errors.

System biases will always exist in a multi-sensor fusion system. The fusion tracker must be able to deal with them, either by containing bias-resistant algorithms or by computing in real time the biases and then subtracting them from the input reports. Since bias-resistant algorithms are more difficult to design, and often have inferior performance, most contractors that deal with biases do so by computing them.

A method of testing this performance characteristic was to play a biased data scenario through the trackers twice: once at the beginning of the run, and then again after an hour of general aircraft data. If the output data and predictions are more accurate the second time than the first time, bias calculation and adjustment algorithms were employed by the tracker. Of course, one hour of delay is generally not enough time for the tracker to complete its bias adjustments, so the final accuracies that would be achieved are not known. The comparison of unbiased to biased results indicate how important careful location and calibration of FAA sensors is to a fusion tracker

Bias performance was also tested to see if the track "hops" discussed earlier that are encountered with mosaic systems were reduced with fusion. The method of testing employed was to input straight flight biased data into each tracker, such that the preferred sensor reports for each aircraft were curtailed at a known time. Then comparing the results of fusion tracking to that of mosaiced tracking indicated the improvement attained with fusion.

Altitude and altitude rate estimation are important requirements of a tracker, as safety functions such as Conflict Alert and MSAW depend upon these quantities. This report did not study altitude tracking, as the altitude algorithms are usually separate from the x,y Kalman filter and are not significantly impacted by fusion versus mosaic considerations.

2. FUSION TRACKER ACQUISITION

Lincoln was able to contact seven companies that have fusion trackers suitable for ATC surveillance applications. These companies, their available trackers, and the result of Lincoln's request to obtain a test version are as follows:

1. Lockheed-Martin (Minnesota) - MicroEARTS tracker - executable image running at Lincoln
2. Telephonics - ATC tracker used abroad - executable image running at Lincoln
3. Eurocontrol - operational ATC fusion tracker (ARTAS) in Europe - executable image running at Lincoln
4. Raytheon – STARS tracker – executable image running at Lincoln
5. Sensis - ATC tracker – company declined request to supply tracker
6. Lockheed-Martin (Owego) - best-of-breed AWACS tracker - no tracker supplied
7. Alenia - operational ATC fusion tracker in Italy - no tracker supplied

The fusion evaluation effort described in this report has made use of the first four COTS trackers. As per Lincoln's agreement with the companies, no name appears on any of the result figures. Instead, the letters A,B,C,D were employed. To prevent inferences on a letter-to-company match, the order of the companies was varied from section to section.

2.1 COTS TRACKER PREPARATION

As expected, all of the COTS trackers required extensive preparation by the manufacturers before they could be applied to our ATC databases. The first step, which we expected, was that each tracker had to be told of the characteristics of each sensor in our ensemble: location, scan rate, and data accuracy. Further steps, some of which came as a surprise, included modification of tracker parameters to be able to handle the scenarios, real and simulated, that we used for the tests. Also, we had to modify our data inputs to match the peculiarities of some of the trackers, and matching stereographic projections was a challenge for trackers that did not use lat/long coordinates.

In summary, none of the trackers could be used without some modifications by the companies or us. One of the trackers required several new builds to operate properly, while two others required numerous back and forth dialogs between Lincoln and the companies to reach an operational state after modifications were implemented.

2.2 COTS TRACKER TYPES

All the COTS trackers employed a Kalman filter implementation, although the details varied from company to company. One company chose a track-to-track system, in which each sensor's data is tracked separately in its own Kalman filter. These filter outputs are then weighted averaged to produce the final output provided to the user. The other three companies selected report-to-track fusion, in which all reports from all sensors are fed to the same Kalman filter. There was however a divergence in the filter states defined in these filters, in that one of the companies introduced turn rate as a state while the other two adopted a linear filter.

The filter differences also affected the types of data runs we could attempt in two ways. First, the track-to-track filter could not be fed mosaic data, as data from a new sensor requires many scans to re-initialize the output stream. Second, one of the other trackers had input format restrictions that did not permit the definition of a long-range terminal sensor, which barred the use of SURVSEF (the production Mode S sensor operated at Lincoln Laboratory) as a testable sensor.

The position and velocity information contained in the tracker output reports were analyzed in this study. Some of the COTS products have additional fields internal to the tracker that may influence the information passed to automation safety functions.

3. RECORDED DATA BASE GENERATION

Last year, Lincoln obtained, with the assistance of FAA personnel, a collection of report data from many of the beacon sensors in the New England region, including the Mode S sensor operated by Lincoln (operated at a 250-nm range), terminal sensors at regional airports, and enroute sensors reporting to the New England center. Figure 2 presents the location of the sensors employed; their specifications are listed below as part of the complete list in the simulation section. Figure 3 plots 8 sample minutes of the recorded data reports. These data have been reduced and converted to a form that can be input to the COTS algorithms.

Since the non-Mode S sensors had no time included in the reports, Lincoln was required to develop a time-alignment program to assign a common time to all reports. This was accomplished by including a Lincoln aircraft in the database, which performed several high rate climbs and descents. By slotting reports based on reported altitude - for example, a sensor 7 report at 12,500 feet must have occurred between sensor 1 reports at 12,400 feet and 12,600 feet - and by iterating over subsets of sensors to find a global solution, the time offset of each sensor relative to sensor 1 was determined. Then using the offset, and assuming a constant antenna rotation rate to convert azimuth to time-in-scan, time was added to all reports.

Initial examination of the recorded data indicated the presence of significant inter-sensor registration errors. For example, Figure 4 plots a sample segment of data from 3 sensors, in which positional offsets are obvious. Simple analysis revealed that azimuth bias (incorrect northmark calibration) was the overriding culprit producing these errors. Correcting the azimuth biases of each sensor by aligning the data in the best mean-square sense removed most of the errors; Figure 5 illustrates the new plot. Since we assume that accurate azimuth calibration will be made by the FAA for all sensors before fusion trackers are operated, the recorded data points were adjusted by the amount of the computed azimuth biases before the fusion tests were performed.

Residual biases still existed in the sensor data. An attempt was made by Lincoln to estimate these biases for a subset of the sensors assuming that azimuth bias and sensor location were the main contributing factors. The results are presented in Figure 6. These numbers are not "correct" since, as explained above, attempts to compute actual biases have not succeeded to date, but they provide an indication of the magnitude of the biases existing in the recorded data. GPS truth was used to help in the bias estimation effort. Unfortunately, GPS was only available for a single aircraft; GPS data from several aircraft located around the surveillance region would provide more reliable results.

3.1 TRACKER SMOOTHING OF RECORDED DATA

The recorded data set was used to generate statistics on typical performance for “real” scenarios. Since truth is known for only one aircraft (the GPS aircraft, analyzed below), scan-to-scan variations of track angle and ground speed replaced average errors as a measure of the tracker's smoothing capabilities.

Multiple sensor inputs provide an increased number of reports available to the tracker. Although this is assumed to be a positive factor, it can challenge a Kalman filter type of tracker. In particular, the variable update rate can introduce apparent velocity variations. The closer together in time are successive reports, the greater will be the effect of measurement noise and biases.

Figures 7 and 8 present for CD2 enroute data and Mode S terminal data respectively the noisiness of the velocity vectors of successive report pairs as a function of the smaller of the two time intervals. (That is, 3 successive reports are joined in a "connect the dots" manner, and the two vectors are compared). It is clear that the smaller the interval, the greater the variation. Note in addition the significantly smaller values for a full sensor scan (12 seconds for enroute, 5 seconds for terminal), in which the successive reports have come from the same sensor. This illustrates that a single sensor data stream is smoother because of the absence of inter-sensor biases. Finally note the significant improvement of the data with Mode S accuracy over that of CD2.

It is these inter-sensor biases that cause the "hops" in the current enroute mosaic system. To investigate the velocity hops that would occur with the recorded data under a mosaic regimen, the preferred reports for each track were culled from the data base. These reports were then fed to two of the three report-to-track COTS trackers (the third did not supply sensor identification of output reports). Finally, the times when a preferred sensor swap occurred were identified and analyzed.

Figure 9 presents the performance for each company of the track angle and ground speed estimates at these swap times as compared to the input data. The input data numbers were generated as above, while the tracker numbers were computed as the differences in tracker values before and after the swap. As seen, both trackers were capable of significantly smoothing the output data, nearly eliminating the hop problem in the velocity sphere. Position hops cannot be removed when transitioning from one sensor coordinate system to another, but these are much less bothersome to an automation system than are the velocity hops.

Next we studied the smoothing properties of the trackers in the general situation. Tests on the ability of the COTS trackers to smooth the recorded reports were made on various subsets of the sensor data to study the effects of number of sensors, sensor update rate, and data quality. Four cases were examined:

1. mosaicing of enroute CD2 sensors assuming the closest sensor to be the preferred,
2. fusion tracking of all enroute CD2 sensor data
3. tracking of single terminal sensor Mode S data (SURVSEF), and
4. fusion tracking of all terminal Mode S sensor data.

Figures 10 and 11 present the average scan-to-scan variation of the tracker's output velocity estimates for each case, the statistics selected to judge the smoothing properties of the COTS trackers.

It should be noted that none of the trackers had sufficient time in this test to fully execute any bias adjustment algorithms they may contain. Thus the performance may be better in an operational system that has had time to settle down. Bias adjustment performance is addressed in detail in the simulation section of this report.

3.2 TRACKER ACCURACY ON RECORDED DATA

As discussed above, one of the aircraft in the recorded data set had a GPS receiver onboard that permitted determination of its true position and velocity at each second. Analyzing the tracker outputs on this aircraft, velocity and position errors could be computed. All 4 sensor cases defined above were used to test the COTS tracker performances, although some cases could not be run for some of the companies (mosaic is not possible for the track-to-track Kalman filter, and SURVSEF could not be formatted to meet the requirements of another company). Unfortunately, the aircraft flew at a low altitude, so multiple sensor coverage was minimal. Thus the CD2 mosaic and CD2 enroute fused cases produced nearly similar results, as did the SURVSEF and Mode S terminal fused cases. Differences between single sensor and sensor fusion tracking performances are addressed in greater detail in the simulation section.

The section of the aircraft trajectory selected for analysis consisted of 2 turns separating 3 straight sections. Thus performance in a turn as well as recovery after its completion could be observed. The results are presented in Figures 12 through 23, where track angle, ground speed, and position error versus time are shown for each company.

COTS A, which could only be run on CD2 data, exhibited undershoot in track angle during turn initiations, followed by oscillatory recovery after its completion. In parallel, the ground speed estimates varied widely during this period, generally on the high side, although the aircraft was flying at a constant speed. Position errors also varied, although over a fairly small range.

COTS B exhibited similar behavior for the CD2 cases as COTS A, except that the positional variations were significantly greater (the 0.4 nm average error was due to differences in stereographic projection planes, and is not operationally relevant). The Mode S performance however was exceedingly accurate, with only minor track angle undershoot and virtually no ground speed or positional problems.

COTS C had major problems with CD2 quality data, indicating much tuning would be required before its operational use. The track angle correction during turns was so slow that the positional error grew to be as large as 2 miles (see the screen image below as well). The Mode S tuning was significantly better, and no major problems were encountered during the turns.

Finally, COTS D showed track angle undershoot in turns, followed by slow recovery, with CD2 errors more pronounced than Mode S. Its ground speed performance had no problems in the first turn, but the incomplete recovery of the track angle before the second turn initiation caused ground speed problems in that turn. The positional accuracy was acceptable in all cases.

To provide visual images of the performance just noted, FUS-RAP was used to peruse the results of tracking the recorded data. This is a graphical display program based on the 9PAC program PAC-RAP [2]. It permits placing input data, truth data (if present), and tracker output data together on the screen. By noting the tracker predicted velocity vectors, compared to the observed trajectories, performance can be inferred for ground speed and track angle errors.

Figures 24 through 27 illustrate for this maneuvering aircraft actual screen images of the tracker predictions for CD2 data processed by the various company fusion systems (COTS D outputs more frequently than once per scan). The undershoot and recovery properties of each tracker, noted in the last set of figures, are apparent during and after the turns. Statistics on velocity performance in turns is addressed in detail below for simulated trajectories, where truth is known for an ensemble of aircraft.

4. SIMULATION CAPABILITY

Lincoln Laboratory has developed a simulation capability that was used to generate a variety of realistic simulation data sets. These sets were used to test performance versus truth (truth in real data being unknown). For example, performance versus system biases was examined via the simulation. Also, special simulation data sets were prepared for tests of specialized statistics such as track angle error in turns. In this project, numerous analysis runs using simulated reports have been carried out.

4.1 SIMULATION SENSOR BASE

The Lincoln simulation generates data from all enroute sensors currently in the New England region, plus all terminal sensors at New England airports, plus the Lincoln production Mode S sensor that existed at SURVSEF. For each sensor, both a non-Mode S CD2 format version and a Mode S advanced format version are defined, so that tests dependent upon report data accuracy can be performed. The complete list of sensors, shown geographically by Figure 28, is as follows, where numbers 1 through 25 represent the actual current sensor type and assigned number, and the numbers 26 through 50 represent the alternate sensor version:

ID	Lat deg.	Lon deg.	Sensor	Format	Type	Name
LXM	+42.45661	-71.26644	1	Mode S	terminal	Lexington, MA
MAM	+42.95001	-71.29922	2	Mode S	terminal	Manchester, NH
NTC	+42.03417	-70.05417	4	CD2	enroute	North Truro, MA
SAC	+44.78171	-73.06566	5	CD2	enroute	St. Albans, VT
PRM	+41.72056	-71.59861	7	Mode S	terminal	Providence, RI
WLM	+41.93847	-72.68296	8	Mode S	terminal	Windsor Locks, CT
SAM	+44.78171	-73.06566	14	Mode S	enroute	St. Albans, VT
BEC	+41.35694	-76.29333	16	CD2	enroute	Benton. PA
DAC	+42.63917	-77.65944	17	CD2	enroute	Dansville. NY
CUC	+42.47472	-72.96805	18	CD2	enroute	Cummington. MA
RIC	+40.87833	-72.68722	19	CD2	enroute	Riverhead, NY
RC2	+40.87833	-72.68722	20	CD2	enroute	Riverhead, NY
UTC	+43.34556	-75.25000	21	CD2	enroute	Utica, NY
STC	+41.49036	-74.10597	22	CD2	enroute	Stewart, NY
BHC	+44.62963	-67.39549	23	CD2	enroute	Bucks Harbor, ME
SKC	+44.86139	-69.51111	24	CD2	enroute	Skowhwgan, ME
CAC	+46.88600	-67.97164	25	CD2	enroute	Caribou, ME
LXM	+42.45661	-71.26644	26	CD2	terminal	Lexington, MA
MAM	+42.95001	-71.29922	27	CD2	terminal	Manchester, NH
NTC	+42.03417	-70.05417	29	Mode S	enroute	North Truro, MA
SAC	+44.78171	-73.06566	30	Mode S	enroute	St. Albans, VT
PRM	+41.72056	-71.59861	32	CD2	terminal	Providence, RI
WLM	+41.93847	-72.68296	33	CD2	terminal	Windsor Locks, CT
SAM	+44.78171	-73.06566	39	CD2	enroute	St. Albans, VT
BEC	+41.35694	-76.29333	41	Mode S	enroute	Benton. PA
DAC	+42.63917	-77.65944	42	Mode S	enroute	Dansville. NY
CUC	+42.47472	-72.96805	43	Mode S	enroute	Cummington. MA
RIC	+40.87833	-72.68722	44	Mode S	enroute	Riverhead, NY
RC2	+40.87833	-72.68722	45	Mode S	enroute	Riverhead, NY
UTC	+43.34556	-75.25000	46	Mode S	enroute	Utica, NY
STC	+41.49036	-74.10597	47	Mode S	enroute	Stewart, NY
BHC	+44.62963	-67.39549	48	Mode S	enroute	Bucks Harbor, ME
SKC	+44.86139	-69.51111	49	Mode S	enroute	Skowhwgan, ME
CAC	+46.88600	-67.97164	50	Mode S	enroute	Caribou, ME

The assumed data characteristics for each sensor type are as follows:

type of sensor	range 1-sigma	range quantum	azimuth 1-sigma	azimuth quantum
enroute CD2	100'	1/8 nm	3 mrad	1 ACP
terminal CD2	100'	1/16 nm	3 mrad	1 ACP
enroute Mode S	25'	1/192 nm	1 mrad	1/16 ACP
terminal Mode S	25'	1/192 nm	1 mrad	1/16 ACP

Terminal sensors have a coverage range of 60 nautical miles, while SURVSEF and enroute sensors go out to 250 nautical miles.

4.2 SIMULATION DATA SETS

The basic simulation data set (denoted as BasicSim) has 200 aircraft, each starting with 200 seconds of straight constant speed flight, followed by 30 seconds of standard-rate turn 3°/sec turning right flight, followed by another 100 seconds of straight flight. All reports have standard sigma random noise depending upon sensor type. The initial ground speeds are randomly distributed between 60 and 600 knots, and the initial track angles are randomly distributed between 0 and 360 degrees, with the starting positions randomly selected within the sensor constellation. Figure 29 depicts these 200 trajectories.

The simulation generates reports for all of the sensors defined above. A culling program selects from this set of reports those corresponding to the set of sensors desired for the specific test (single sensor, mosaic, all CD2 enroute, etc.). When a mosaic test is desired, the culling program in addition determines the preferred (closest) and supplemental (next closest) sensors for each track at each scan; if the former sensor report is present, it is output, else the latter sensor report is used.

This database has been used for absolute and comparison performance tests for straight and turning flight and the transitions between them. The results achieved are presented later in this paper.

The second simulated data set, of one-hour duration, consists of random trajectories, with randomly occurring maneuvers (turns, accelerations, climbs, etc. all with standard airliner values), and a time-varying set of tracks. Data culling is performed as before. This set is labeled RandSim for random simulation, and has been used for the more comprehensive fusion tests detailed later.

Specialized simulation sets were generated as needed for specific tests; these are described in the test description sections. An example set is the one used to determine the effect of and recovery from bad data points. This involves introducing 10-sigma data error points at known times for each track.

5. ANALYSIS SOFTWARE

To permit the operation of the analysis effort, Lincoln has developed and coded a package of analysis software. Both graphical and statistical programs were produced.

The graphical tool permits observation of the performance of the fusion tracker. Input reports, truth (when simulation is employed), and tracker output estimates are all displayable. Thus the overall performance of the tracker is visible, as well as any and all instances of tracker problems. In particular, the display reveals performance areas where further testing and analysis are required, while the ability to locate problem cases helps direct the detailed tracker debugging effort.

The analysis programs are intended to generate statistical measures of tracker performance, both overall and in special situations. For example, the average track angle error of the tracker, as well as the error during turns, are both available.

5.1 DATA MERGING

Because each COTS tracker has a different output format, every analysis program had to be preceded by a re-formatting program. A set of these programs was created, one for each company. The most complex of these was the Merge routine, which was required to match every tracker output report with a corresponding simulation input report. Time variations and differences in available data fields complicated these programs.

Examples of tracker-specific problems Merge had to overcome were different time references and coordinate systems from the simulation, reports output at different times from the input reports, and plots and tracks output in different files. Thus, some Merges worked with 3 files instead of 2, and one had to interpolate the simulation input reports to the time of the tracker output. Also, one company had its output times expanded by 2.5% relative to the simulation report times (that is, if 2 simulation reports differed by 100 seconds, the corresponding tracker output times differed by 102.5 seconds). As a result, every Merge program was quite different from every other one.

The output data from each fusion run had first to be prepared for the analysis programs. The preparation depended upon the type of output provided by each company; some output the raw input reports separately from the smoothed output tracked reports, while others presented combined output reports. In the former case, preparation consisted of separating output reports and output tracks into separate lists, then merging the reports and tracks into pairings (the output tracked report with the input report that was used in its generation), and finally merging each pair with the simulated input report that was used to create it. In the latter case, the merge was performed directly. A separate merge program was required for each company due to the lack of uniformity in the fields provided in the output tracked reports.

For each company, the final output of the merge was a file of all merged entities in a common fusion format recognized by the analysis programs. The positions in this format are either in stereographic x-y or in lat-long depending upon the company choice of coordinates. A sample section of a merge file is shown in Figure 30. Note that in this case, as occurred for all COTS trackers, an output report is not produced for each simulation input.

5.2 SIMULATION ANALYSIS

The major statistical analysis program for the simulation runs computes the positional, ground speed, and track angle error for each merged entity. These errors were then averaged for each combination of flight maneuver, aircraft ground speed, range from closest sensor, and most importantly time into the maneuver. This program permits graphs of such statistics as time to settle down upon track initiation, track angle error versus time in turn, ground speed error versus time in acceleration, and time to recover when transitioning from one type of maneuver to another.

6. SIMULATION RESULTS

The simulation capability was employed to test a variety of COTS tracker characteristics. For each, a tailored data set was generated, whose reports produced the effect to be analyzed. The characteristics tested included handling of turns, resistance to biases, resilience in the face of sensor loss or bad input reports, and time to initiate tracking and adapt to and recover from maneuvers.

Although the simulation data sets included aircraft whose ground speeds were in the interval 60-600 knots, the analysis was restricted to those aircraft having a minimum ground speed of 150 knots. This requirement was adopted after it became apparent that the trackers had significant problems with the slower aircraft, as at such speeds the data noise was comparable to the inter-report motion. Figures 31 and 32 illustrate the problem by plotting the track angle error for straight flight as a function of time-in-track for both CD2 and Mode S quality data for one of the COTS trackers. It is seen that the trackers on slow speed aircraft failed to settle down even after 200 seconds, as compared to settling times of less than 60 seconds for faster moving aircraft. Fortunately, most aircraft in enroute airspace exceed 150 knots, so the results presented below for the trackers are in fact representative of their ability to handle real situations.

6.1 BASICSIM ENSEMBLE RESULTS

The BasicSim data set described above was run through each commercial fusion tracker for the following set of sensor cases:

1. SURVSEF only (4.8 second scan)
2. mosaicing using all enroute sensors (each 12.0 second scan)
3. fusion using all enroute sensors

Two exceptions occurred for the cases run. First, the COTS C tracker as provided to us was incapable of running SURVSEF data, as long-range terminal sensor was not an input specification supported in the build. Second, the track-to-track filter of COTS B could not be run in a mosaic mode, as such a filter will terminate tracking for a full initiation time when the sensor supplying the reports is changed. Each remaining case was run for both CD2 and Mode S quality reports as subcases. The input data in each case was unbiased; the effects of data biases are addressed in the next section.

For each case run, the analysis program was used to generate the absolute track angle, ground speed, and position errors for each tracked output report. These errors were averaged over all tracks for each 5-second interval of the simulation. The results, presented in Figures 33 through 56, indicate how well each tracker performed in each situation. In particular, because of the nature of the BasicSim data set, the following characteristics are evident for each company in each case:

1. The minimum time needed to initiate tracks.
2. The time required for the tracker to settle down for straight flight.

4. The time required for the tracker to re-establish straight flight steady state after the completion of the turn.

Several general observations are possible from these plots concerning each manufacturer. COTS A appears to be tuned for straight flight, as its fusion velocity and position estimates during turns are worse than those for single sensor data. COTS B has improved fusion performance, but being a track-to-track filter it requires a much longer initiation period. COTS C has somewhat improved fusion performance throughout relative to mosaic. COTS D has by far the best performance during turning flight periods.

Because these plots average absolute errors, they do not illustrate the possible oscillatory nature of the track angle and ground speed errors, particularly during the return to straight flight. To illustrate these effects, signed track error and signed ground speed error plots for each of the fusion cases are shown in Figures 57 through 72, where each dot represents an actual data point (no averaging over the tracks).

These figures show considerable difference between COTS trackers in the return to straight flight behavior of the track angle error. In particular, COTS A experiences significant overshoot corrections, COTS B and C decay back to truth, although COTS C is considerably quicker in its performance, and COTS D shows oscillation between overshoot and undershoot in its return behavior. In the ground speed realm, only COTS D maintains consistently accurate estimates during and after the turn.

The general conclusion reached with this test is that multi-sensor fusion does not appear to provide sufficient surveillance improvements over mosaiced sensor performance to permit algorithm improvements in automation safety functions, even when biases are not present to distort the tracker performance. In fact, it appears to actually degrade performance for some of the COTS trackers. Surprisingly, the performance for the high data rate SURVSEF sensor is much worse for some of the trackers; this appears to be due to improper setting of the tracker parameters for 4.8-second updates, as closer noisy data points can lead to more apparent velocity deviations.

Only COTS tracker D appears to have a turn state in the Kalman filter, with an estimate of the turn rate. For the other fusion trackers, the performance in turns consists only of slowly adjusting the heading when undershoot position errors are first detected. Thus, as seen the track angle reaches and maintains an approximately steady state error value throughout the turn period. Some of these trackers decay back toward true heading when the turn ends, while others tend to overshoot and oscillate back to truth. In all cases, steady state requires a significant time to re-achieve when straight flight is resumed.

The tracker D actually computes a turn rate and employs it in its smoothing and prediction routines. Figures 73 and 74 present, for all times and all tracks, the turn rate values in effect. During the actual 3 deg/sec turn period, these values appear to generally be within 2 deg/sec of reality, although outliers exist. Track initiation periods also appear to have turn rates error problems, and turn rates are computed for some tracks at all times. Thus although the existence of a turn rate has significantly improved turning performance, it does so at the occasional cost of degraded straight flight accuracy.

6.2 BIAS HANDLING AND PERFORMANCE

System biases can have a critical effect on the efficacy of fusion algorithms. In general, biases will always affect the positional accuracy of predictions. However, track angle and ground speed predictions are significantly greater compromised by inter-sensor biases in report-to-track fusion systems which enter all reports from all sensors into the same Kalman filter than in track-to-track fusion systems which track each sensor's reports separately and average the results. For any system, real-time algorithms that attempt to compute and eliminate biases in the input reports can reduce any bias degradation effects.

Each company fusion tracker was run three times against the BasicSim simulation data base with the following list of input specifications, where double nominal biases mean position and measurement biases set at random for each sensor and aircraft to double the amounts typically seen in the real data:

1. fused enroute unbiased sensors
2. fused enroute double nominally biased sensors and the initial bias file (i. e. no bias corrections yet determined)
3. fused enroute double nominally biased sensors after a 1-hour run to allow the bias file to adapt to the biases

Both CD2 and Mode S data accuracies were tested. In each case, the output reports were analyzed for track angle, ground speed, and position errors as a function of time during the run. The results are presented in Figures 75 through 98.

As seen by the results, all of the COTS tracker positions are significantly impacted by biases in their un-adapted state. As expected, all the report-to-track trackers in addition introduce significant velocity errors, while the track-to-track COTS D has its velocities essentially unaffected by biases. One interesting effect is seen in the COTS C velocity results: biases appear to have reduced the errors, especially in ground speed, during the turn. This paradox can be explained by assuming that the presence of biases has prevented the filter gains from closing down as far, so that the filter is better prepared to follow the turn.

Another test of bias performance is to see if the data "hops" noted in mosaic systems have been ameliorated by fusion. To this end, both mosaic and fusion runs were made with each COTS tracker (except no mosaic run for the track-to-track COTS D for the reasons expounded above) for the following simulation scenario:

1. straight flight for 100 seconds, where for each track the initial preferred sensor is maintained for all scans, and the same double system biases assumed above are present
2. removal of the preferred sensor reports for each track starting at time 100
3. further straight flight for another 100 seconds.

Figures 99 through 122 illustrate the effects of sensor switching in a biased system by presenting error statistics before and after the preferred sensor removal. Two points are clear from the plots. First, all the COTS trackers when run in mosaic mode suffered significant disruptions at the time of the preferred sensor loss, with both velocity and position errors suddenly jumping. These jumps ranged from modest for COTS A to larger for COTS B to very large for COTS C. Second, it is clear that the significant position and velocity hops seen for the mosaicing curves at time 100 do not appear with fusion for any of the trackers, including COTS D. Thus, the contention that fusion provides seamless sensor transition has been validated.

6.3 SENSOR OUTAGE

One of the main justifications for implementing fusion is that tracking can continue seamlessly if a sensor goes down, with other sensor reports covering for the lost sensor's output. To test the accuracy of tracking in such an eventuality, the BasicSim scenario was rerun under the assumption that, for each track, the preferred sensor was missing (the anti-mosaic case).

Figures 123 through 146 present the results for this sensor outage case compared to the previous cases of mosaic tracking and fusion tracking. The expected result was that the loss of the preferred sensor would degrade the fusion results, although not significantly, and hopefully that the remaining fusion would still be as good or better than mosaicing. In general, the results indicate that the velocity errors (track angle and ground speed) are affected to only a minor degree by the sensor loss and still remain superior to mosaicing, while the position error, especially with CD2 data, degrades more significantly. The position finding is not a surprise, as the preferred sensor will always have the least noisy azimuthal coordinate (azimuthal error is linear with range).

In any event, the contention that fusion can overcome sensor outages and still provide quality surveillance superior to mosaicing is supported by these results.

6.4 OUTLIER RECOVERY

Any tracker will on occasion experience outlier input reports, either due to noisy data or to erroneous correlations. Ideally, the tracker will identify the input to be an outlier, rather than the start of a maneuver, after the next input is received. If the tracker does not have outlier recognition algorithms, however, the tracker predictions may require several scans to recover.

To test each COTS tracker's outlier resilience, a simulation data set was created that consisted of the following segments for each of 200 aircraft:

1. 100 seconds of straight flight with unbiased reports, each with normal sigma noise
2. a single preferred sensor report with 10-sigma errors for both range and azimuth
3. 100 seconds of additional straight flight reports as in 1.

These tests were run for each company for both CD2 and Mode S data quality. In each case, both mosaiced and fusion runs were made for comparison purposes.

As before, the statistical analysis programs were used to generate the absolute average track angle, ground speed, and position errors for each 5 second interval of the run. Figures 147 through 170 present the results for each company for the various runs

The most important result observed in these figures is that although the outlier impacted positional and velocity accuracy at the time of its arrival in all cases, the fusion systems were far less affected, and produced in almost all cases far smaller errors. Thus another benefit of fusion over mosaic is seen to be significantly greater outlier resistance.

The CD2 runs experienced much greater outlier distortion, as expected, as 10-sigma errors are several times greater in magnitude for CD2 quality data than for Mode S data. In should be noted however that all trackers accepted the bad data points, indicating that their tracker correlation boxes were sized large enough to encompass the bad position. Thus error effects of the magnitude noted in the figures could occur when erroneous correlations are made.

Recovery was achieved after a few additional data points for all companies, indicating tracker resilience but no outlier detection algorithms. The level of distortion produced by outliers, however, varied significantly from the best company to the worst.

6.5 GENERAL TRACKING ACCURACY

As described earlier, a RandSim scenario was also used to test each COTS tracker. This scenario randomly mixed straight, accelerating, turning, and combination flight segments for each track. The analysis computed the track angle, ground speed, and positional errors for each segment type as a function of time in the segment. To reduce the number of possible plots to a manageable size, we present in Figures 171 through 202 the average absolute track angle and ground speed errors for several maneuver types for each COTS tracker for both CD2 and Mode S data qualities, assuming fusion of all enroute sensors. As is apparent, turning and accelerations create problems for all trackers, although the degree of difficulty varies widely.

The first 4 figures, 171-174, present performance in turns with CD2 data. These results confirm that only one of the COTS trackers, COTS C in Figure 173, has a turning state with turn rate as a variable. Such a state, when designed properly, correctly predicts the track angle after the turn is recognized, reducing the error for the remainder of the turn to a small value. The figures illustrate that for the other companies, errors in the turns never recover at any time during the turn, but experience significant undershoot throughout. In addition, only COTS C does not experience ground speed errors during the turn; the severe undershoot of the other trackers is coupled into speed errors as well.

The next 4 figures, 175-178, repeat the turning test for Mode S quality data. Although this data is several times more accurate, only COTS A experiences a significant improvement in performance over the CD2 case. Thus again, tuning issues are evident for this set of trackers.

Linear acceleration performance is examined next in Figures 179-186. All the trackers, as seen, experience ground speed errors that last throughout the acceleration period. Thus an acceleration state is not present in any of the Kalman filters; such a state is far less useful in general than a turning state. Note that no track angle errors are introduced in this case, as expected. Also, once again, only COTS A is significantly improved with Mode S data.

The next experiment combined turning and linear acceleration, such as might occur during takeoffs or landings. The results, in Figures 187-194, show significant errors in both track angle and ground speed. In fact, the track angle errors have been exacerbated by the linear acceleration, reaching values much higher than before. The turning state of COTS C has helped again to reduce the errors in this case, although the linear acceleration has reduced its effectiveness.

The final experiment tested the recovery patterns of the trackers after a maneuver terminated; the results are presented in Figures 195-202. As seen, with CD2 data, all trackers except for COTS C required the better part of a minute to return to normal error performance; with COTS C the errors had remained small during the maneuver, so recovery was minimal. With Mode S quality data, all trackers recovered significantly quicker.

6.6 TRACK INITIATION PERFORMANCE

A reasonable expectation of fusion is that by utilizing data from several sensors, tracking can commence earlier than is possible with single sensor reports. This would be particularly useful in enroute airspace, where sensor update rates are nominally 12 seconds. This expectation should usually be true for report-to-track fusion, where reports from all sensors are input to a common tracker. However, for report-to-track fusion trackers that initialize state vectors from single sensor reports, and for all track-to-track fusion trackers, the only possible gain occurs when a supplemental sensor track starts before the preferred sensor track.

Figure 203 presents the average time required for each COTS tracker (plus the Lincoln adjunct described below) to first output predictions for SURVSEF, mosaic, and fusion cases (same results assuming either CD2 or Mode S quality data inputs). As expected, the high data rate SURVSEF sensor produces the fastest track initiation. However, the gain with fusion over mosaic was not as dramatic as predicted for the report-to-track fusion trackers. The longer initiation for vendor B (track-to-track) appears to be an error in the tracker; it is being investigated by the company.

Of course some COTS trackers may first output velocity later than others to allow for settling of the estimates. Thus, Figure 204 re-plots the initiation times according to when the trackers first produce average track angle errors of less than 10 degrees in the BasicSim cases (initial straight flight) for CD2 quality input data. As seen, these times are significantly longer in many cases. For Mode S quality data, the initial track estimates were already within 10 degrees of truth.

6.7 TRACK NUMBER CONSISTENCY

The user of the tracker output data will wish to utilize the track number contained in the report to allocate the reports to the aircraft. Thus, any track number changes by the tracker will complicate its life. We observed numerous track number changes for the

COTS trackers during our testing program. However, the use of trial and parent/child tracking methods has obfuscated the actual number of such changes that would be apparent to the user.

Our only concrete result is that all COTS trackers dropped some tracks in the BasicSim tests, most often in the turning segment due to loss of positional prediction accuracy caused by undershoot in the track angle estimate. Thus, bad velocity estimates, besides leading to poor projections of aircraft positions, also lead to tracks disappearing from the safety logic algorithms. Figure 205 presents the percent of track drops for each COTS tracker for both CD2 and Mode S quality data for both mosaic and fusion runs.

This figure indicates that 5% track drop is typical in the CD2 fusion runs for all COTS trackers except for one with negligible drops. This is a disturbing result, which hopefully can be corrected by adjusting the tracking parameter settings (although such adjustments can degrade straight flight tracking). All the companies with CD2 tracking problems perform significantly better with fusion than with mosaicing, indicating that the higher data rate does indeed help prevent track drops. When Mode S data quality is assumed, all trackers but one no longer experience track drops with fusion, thus providing another reason for the FAA to adopt Mode S data accuracies through ASTERIX surveillance formats.

7. LINCOLN TRACKER ROUTINE

The above analysis has indicted minor surveillance improvements at best from data fusion. A likely rationale for this is that all the COTS fusion trackers analyzed in this study are in essence extensions of single sensor trackers. The report-to-track trackers input all reports as received into a common Kalman filter; there are just more reports with fusion. The track-to-track trackers use a single sensor Kalman filter for each sensor; the outputs are then weighted averaged.

When it became clear that the COTS fusion trackers did not provide significant improvements in the quality of aircraft state estimation, we wondered whether it would be possible to use unique attributes of multi-sensor data to design a tracker completely different from the standard Kalman filter. As an example, Lincoln developed a routine that estimates velocity, but not position, for each output report when fed multi-sensor data, and thus can serve as an adjunct to a full tracker. This tracker routine was also tested during the study to provide a benchmark against which to compare the COTS performances achieved.

The Lincoln filter adjunct has the following properties:

1. It only produces velocity estimates - track angle and ground speed - with no positional smoothing.
2. It includes estimates of both turn rate and linear acceleration.
3. It only operates on tracks seen by 2 or more sensors.
4. It is unaffected by system or transponder registration errors and biases.

This tracker routine was tested on the same RandSim simulation data sets as the COTS trackers, for both CD2 and Mode S fusion cases. Figures 206 through 213 present the track angle and ground speed errors for the set of maneuver classes considered above for the COTS trackers.

As seen in the results, this filter can cope with all types of maneuvers, with negligible track angle and ground speed errors after a short initial undershoot. It quickly matches both turn rates and linear accelerations, tracking the data throughout the maneuver duration in all cases. At maneuver termination, the filter experiences a short overshoot, with total recovery achieved in less than 30 seconds. Thus the superiority of the velocity estimates of this filter over those of most of the COTS trackers when multi-sensor data is present, especially in turns and accelerations, is quite evident. The only exception is COTS C, which was able to provide comparable velocity estimates for non-accelerating turns.

The accuracy of the turn rate calculations was also investigated by repeating the BasicSim test used to study the one COTS tracker's turn rate values. Figures 214 and 215 present these results for all tracks and all times for both CD2 and Mode S quality reports. As seen, the turn rate values proceed to a narrow band around the true 3 deg/sec rate early in the turn, and remain there until the turn ends, at which time they decay back to zero. False turn rates during straight flight are relatively rare. It is also clear that this routine is far more accurate for Mode S data, indicating its ability to be properly tuned to noise sigmas even in the presence of system biases.

To be useful as a stand-alone tracker, this adjunct must be expanded by the addition of a routine to estimate position and a procedure to handle single-sensor tracks, and outlier exception handlers must be developed.

8. CONCLUSIONS

The principal conclusion of this study is that technology is on the shelf (COTS) to achieve some, but not all, of the surveillance improvements that have been promised with sensor fusion algorithms.

The COTS products are able to receive inputs from typical FAA radars and produce output tracks that are as good as or better than those produced by existing FAA automation systems. In particular, the COTS products eliminate the track data "hops" and "stitching" that are characteristic of existing mosaic systems. This could produce substantial benefits by opening up the prospect of allowing controllers to use the same separation standard permitted for single sensor operation when multiple sensors are in use in a given sector. The COTS products are also robust to the presence of "outlier" data and the failure of a single sensor. In addition, it may be true that the use of a Kalman filter by itself in these COTS products in either mosaic or fusion systems may lead to significant surveillance improvements over the current alpha-beta smoothing (which was not tested).

The results indicated that the COTS products do not produce significantly better estimates of position and velocity in the fusion mode than in the mosaic mode, either in straight line or turning flight. Intuitively, one would have expected the additional data and the associated higher update rate would have contributed to improved performance in these areas. Improved state estimation might produce benefits by allowing decision support tools (e.g., CTAS, etc.) to better predict aircraft trajectories. At the present time, however, FAA requirements for aircraft state estimation in this context are not well developed. Therefore it is difficult to assess the impact of the current set of COTS products. An adjunct velocity tracker may provide improved performance should that prove to be necessary.

During the various fusion tests, it became clear that the performance in all cases was significantly improved when Mode S data quality (such as with ASTERIX) was assumed, as opposed to the CD2 data format and accuracy. A particularly important consequence of this improvement was that the significant number of track drops noted in aircraft turns with CD2 data was virtually completely eliminated when Mode S quality data was input instead to the trackers.

Our recommendation is that the FAA develop a set of quantitative performance criteria that it desires from a fusion tracker. If reliability, robustness, and smooth transitions among sensors are the principal criteria, the current COTS products tested are suitable, given appropriate tuning and adaptation. However, if the desire is significant improvement in aircraft position and velocity estimation, additional development may be required.

	Average Errors		
Tracker	Straight (95%)	Turning (5%)	Mean-Square Error
1	0.01 nm 1° heading	1.50 nm 30° heading	0.08 nm 2.5° heading
2	0.10 nm 3° heading	0.10 nm 3° heading	0.10 nm 3° heading

- Mean Square Error Winner: Tracker 1
- ATC Preference: Tracker 2

Figure 1. Example of Competing Tracker Solutions.

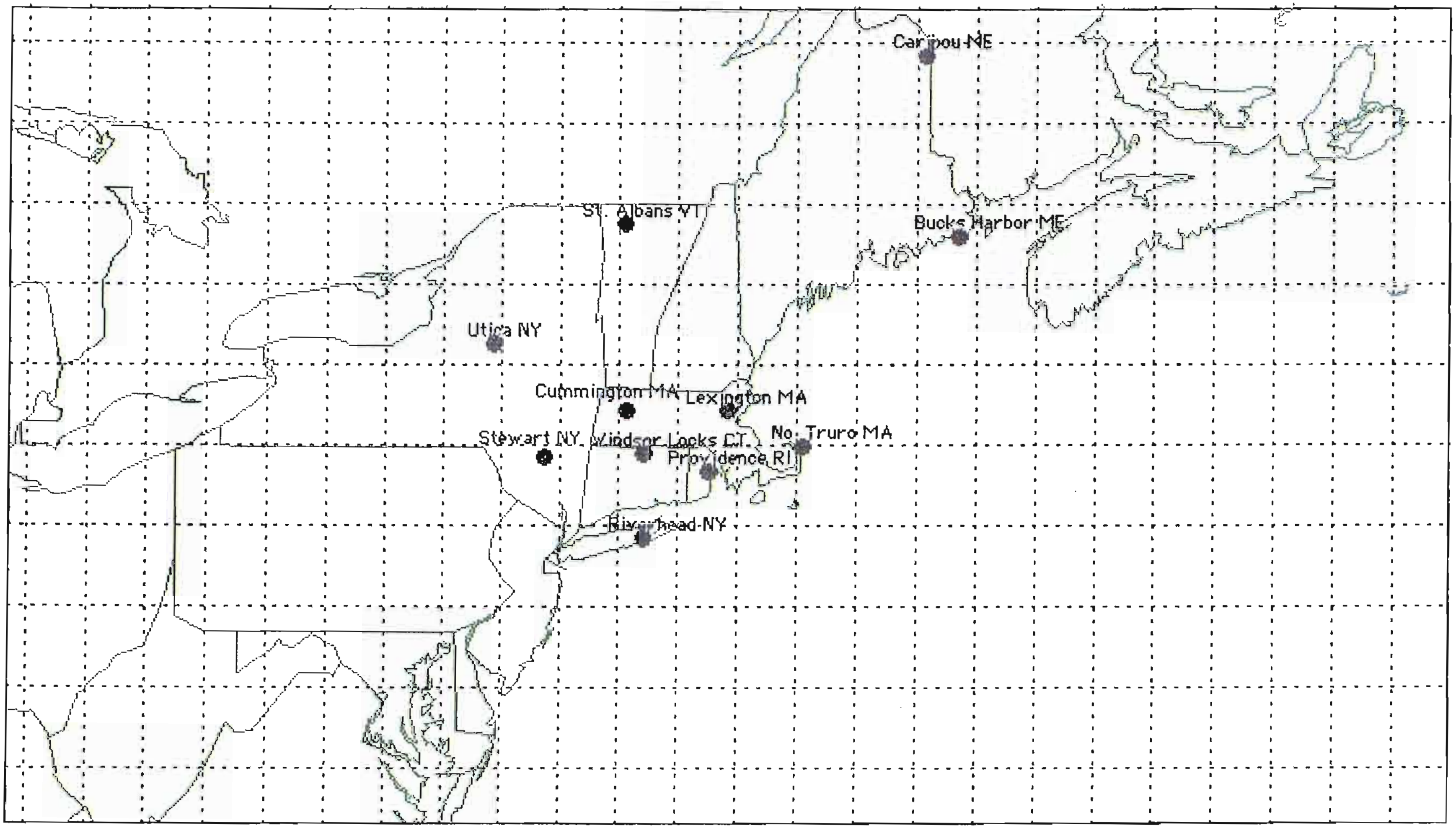


Figure 2. Real Data Sensor Ensemble.

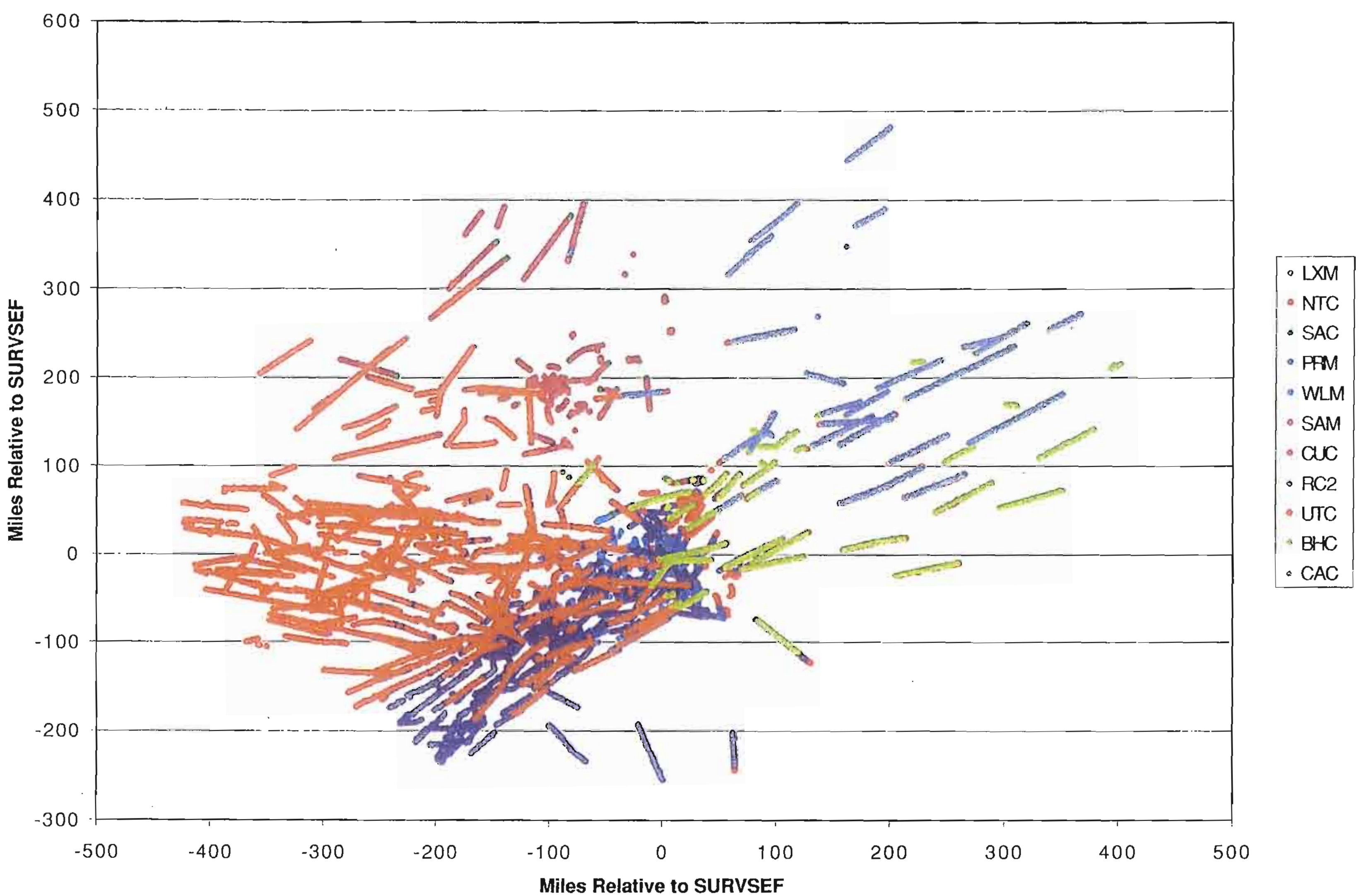


Figure 3. Sample 8 Minutes of Recorded Data.

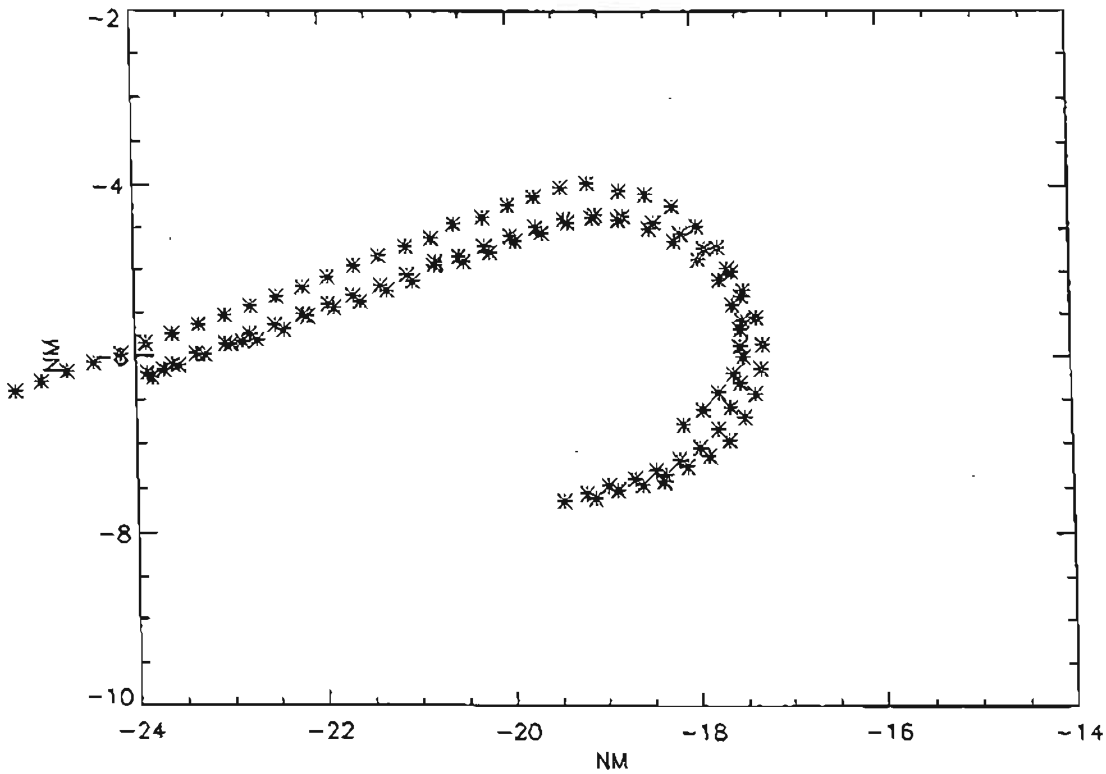


Figure 4. Sample Multisensor Input Reports - As Recorded.

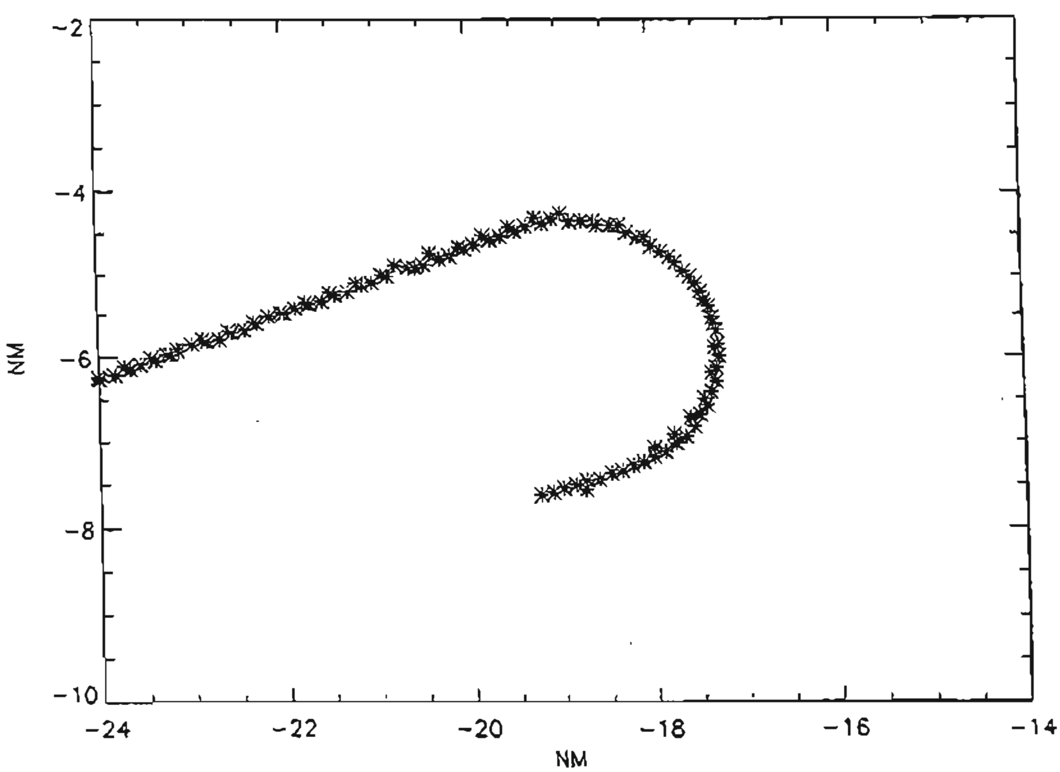


Figure 5. Sample Multisensor Input Reports - Azimuth Biases Removed.

ID	Sensor	Az Bias (deg)	Estimated Residual Biases		
			Az (deg)	Sensor X (nm)	Sensor Y (nm)
LXM	1	+0.00	-0.01	-0.02	+0.01
MAM	2	+0.00	-	-	-
NTC	4	+0.24	+0.05	-0.03	-0.01
SAC	5	+0.27	+0.13	+0.08	+0.10
PRM	7	+0.26	-0.04	-0.09	+0.01
WLM	8	+0.35	-0.04	-0.09	+0.05
SAM	14	+0.15	+0.05	0.08	+0.10
BEC	16	+0.00	-	-	-
DAC	17	+0.00	-	-	-
CUC	18	+0.00	-0.04	-0.05	+0.05
RIC	19	+0.18	-	-	-
RC2	20	+0.18	+0.05	-0.01	+0.04
UTC	21	+0.01	-0.02	-0.05	+0.08
STC	22	+0.31	-	-	-
BHC	23	+0.21	-0.02	+0.04	+0.05
SKC	24	+0.00	-	-	-
CAC	25	+0.09	-0.02	+0.01	+0.16

Figure 6. Biases Identified for Real Sensors.

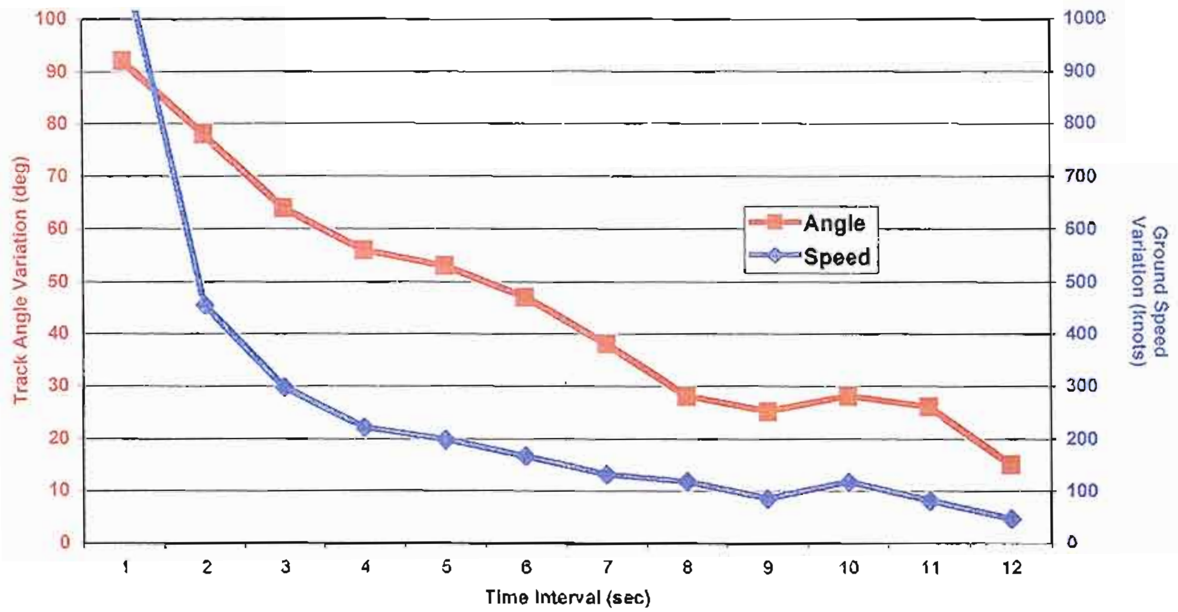


Figure 7. Effect of Inter-Report Interval on 2-pt Velocity Variation - CD2 Data.

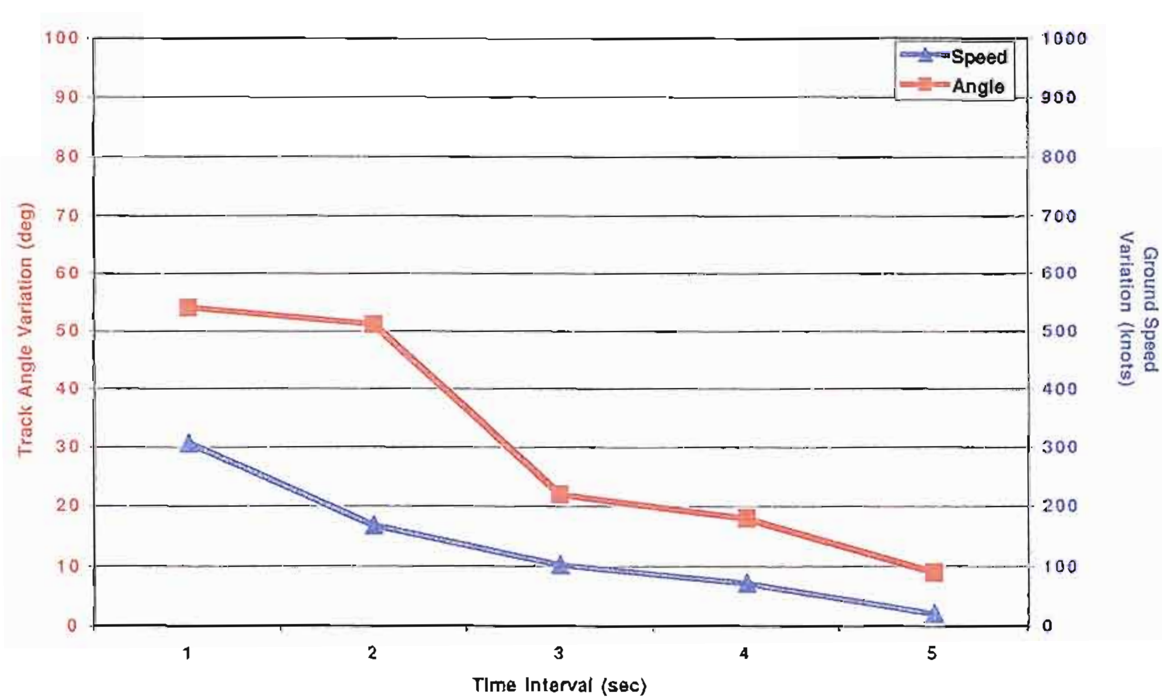


Figure 8. Effect of Inter-Report Interval on 2-pt Velocity Variation - Mode S Data.

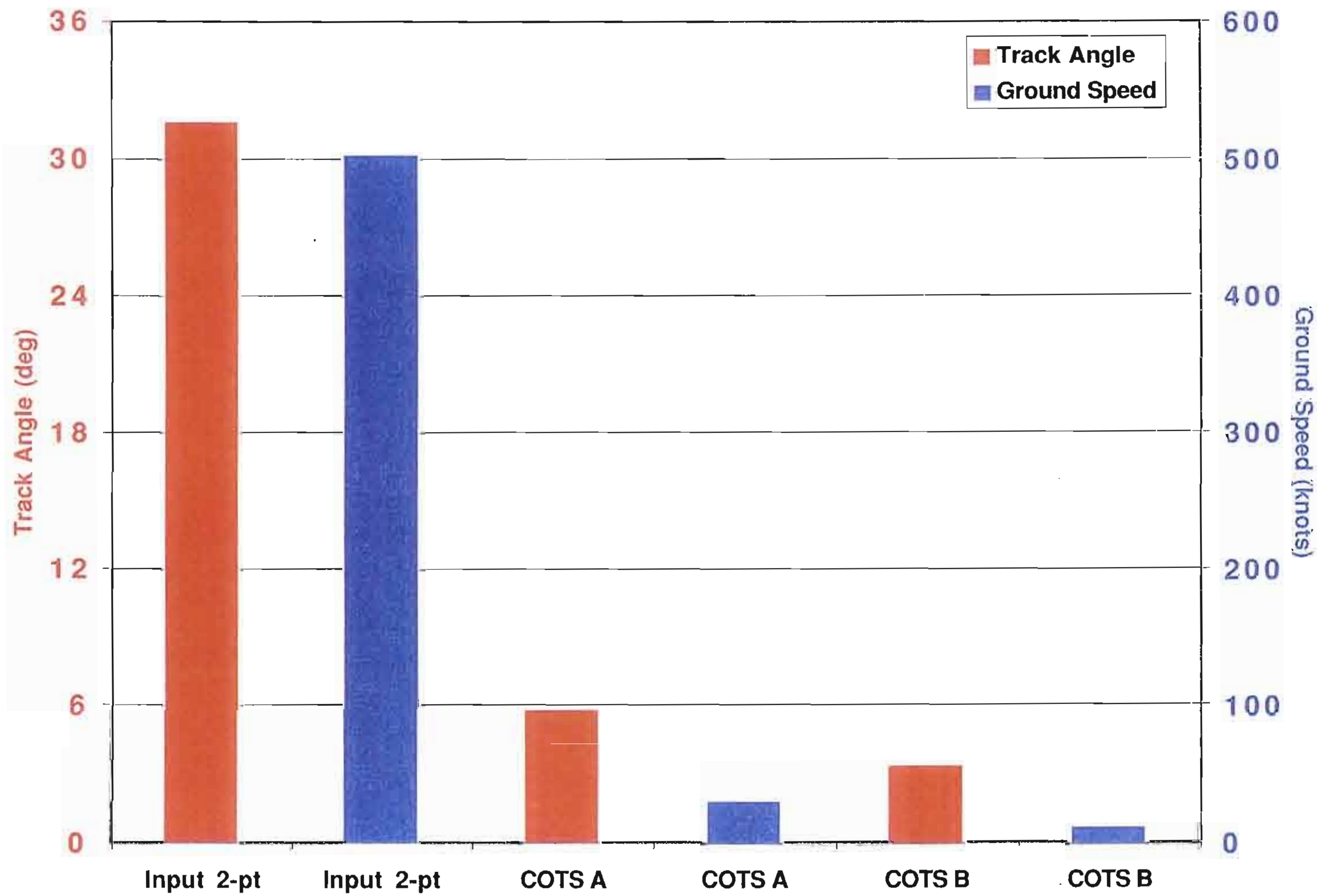


Figure 9. Mosaic "Hop" Smoothing - Tracker versus Input Data.

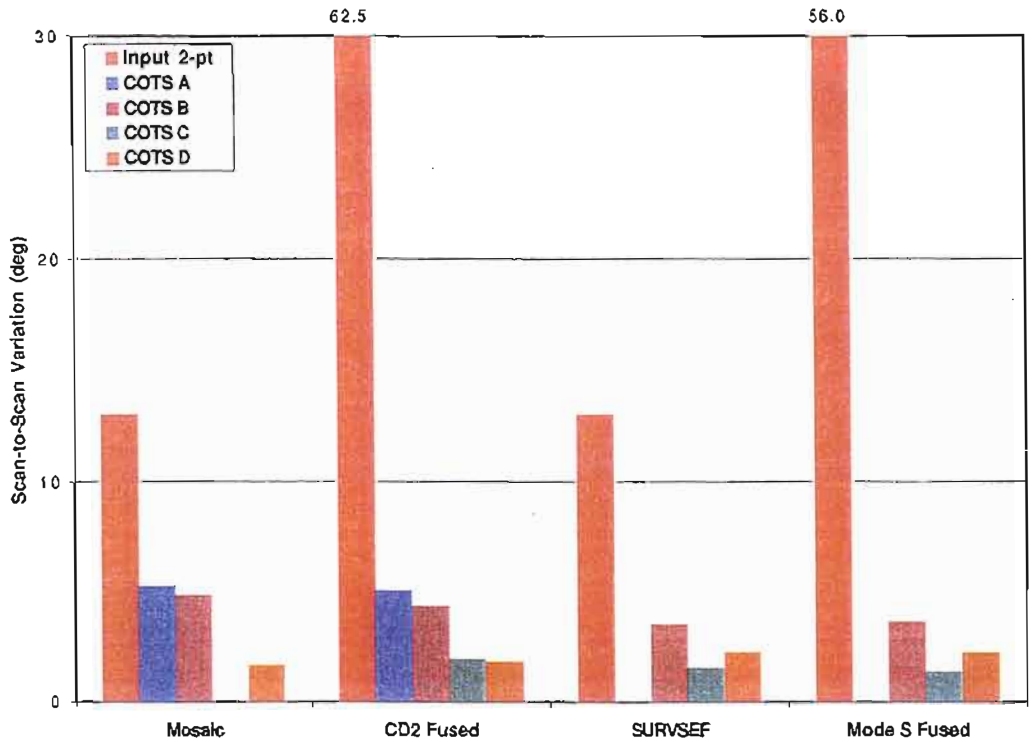


Figure 10. Tracker Track Angle Smoothness versus Type of Data.

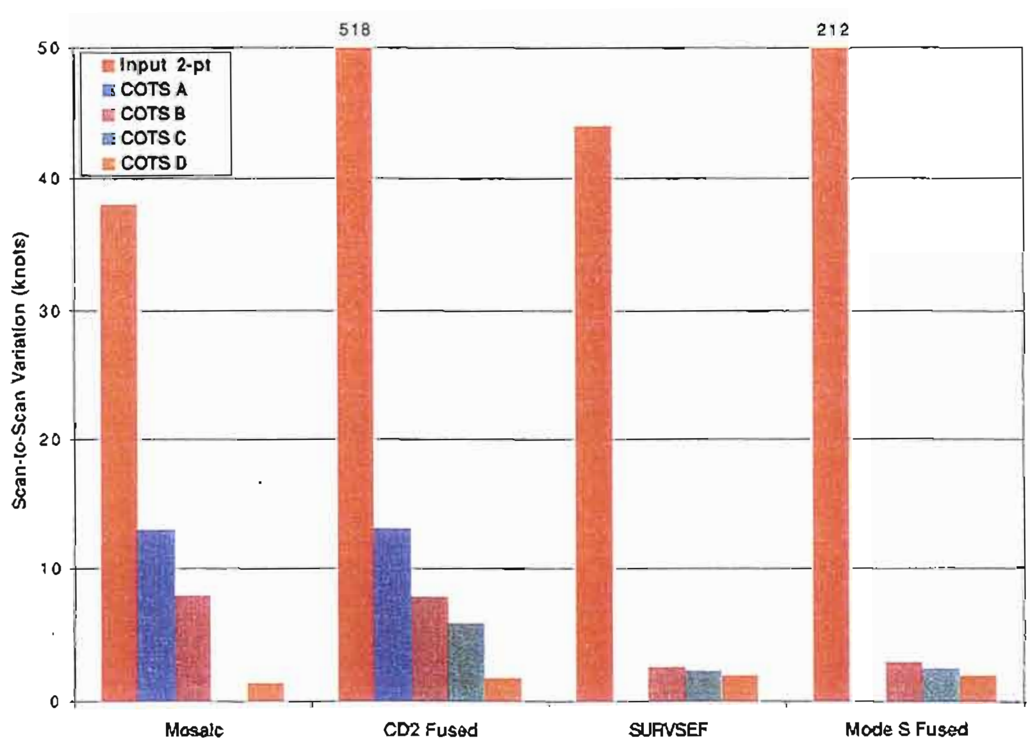


Figure 11. Tracker Ground Speed Smoothness versus Type of Data.

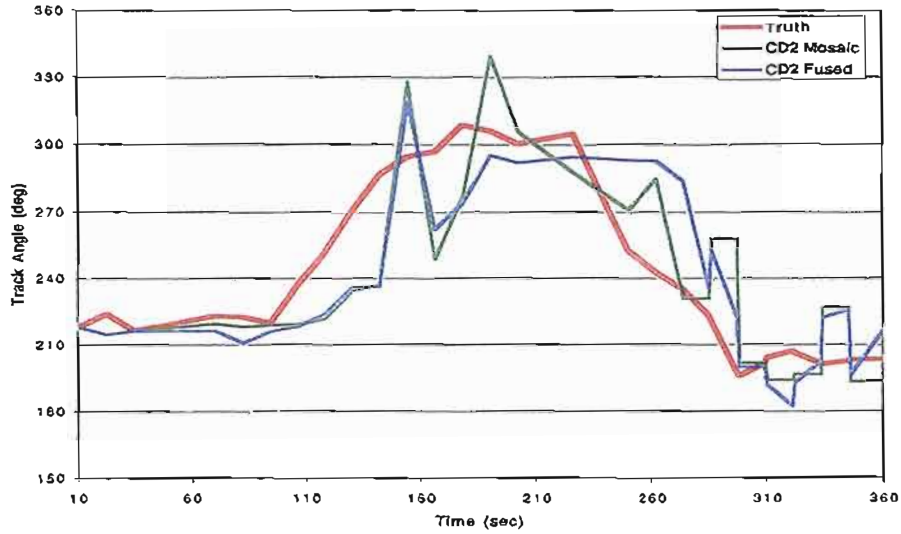


Figure 12. Tracked Recorded Data - Track Angle - COTS A.

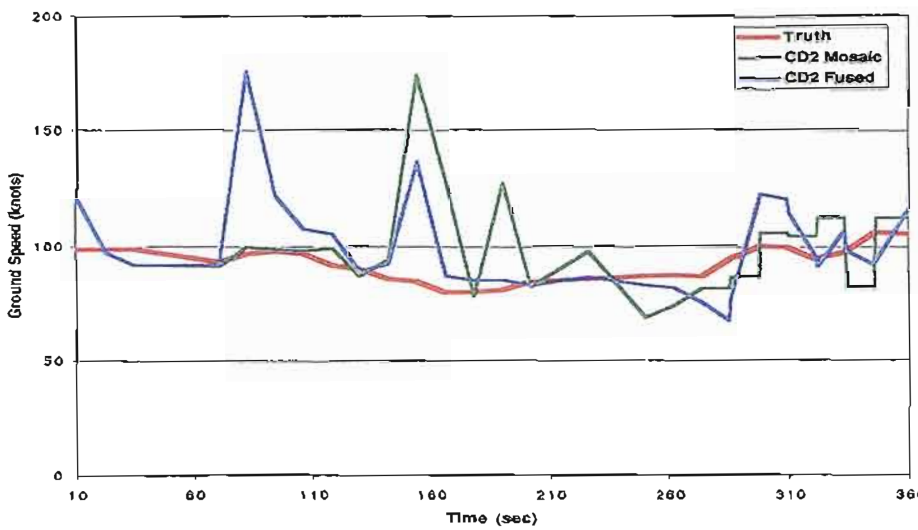


Figure 13. Tracked Recorded Data - Ground Speed - COTS A.

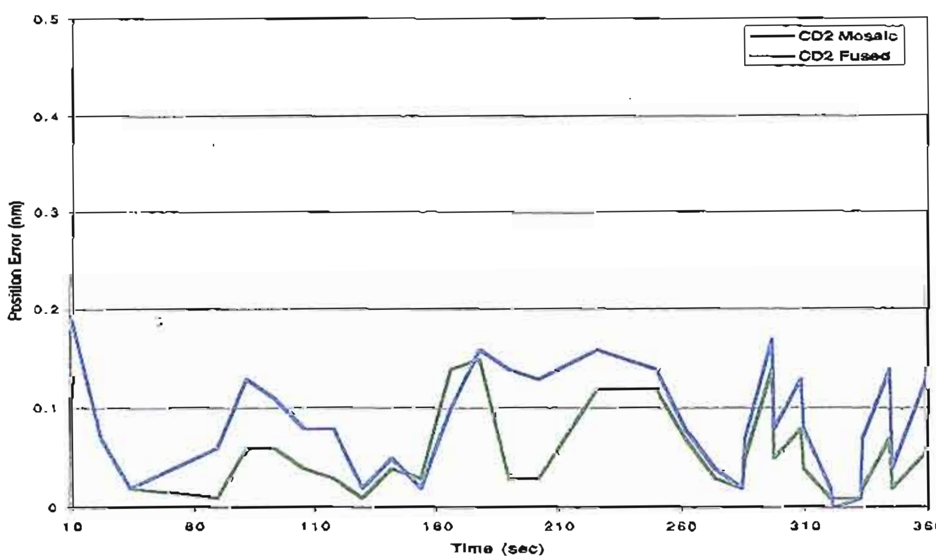


Figure 14. Tracked Recorded Data - Position Error - COTS A.

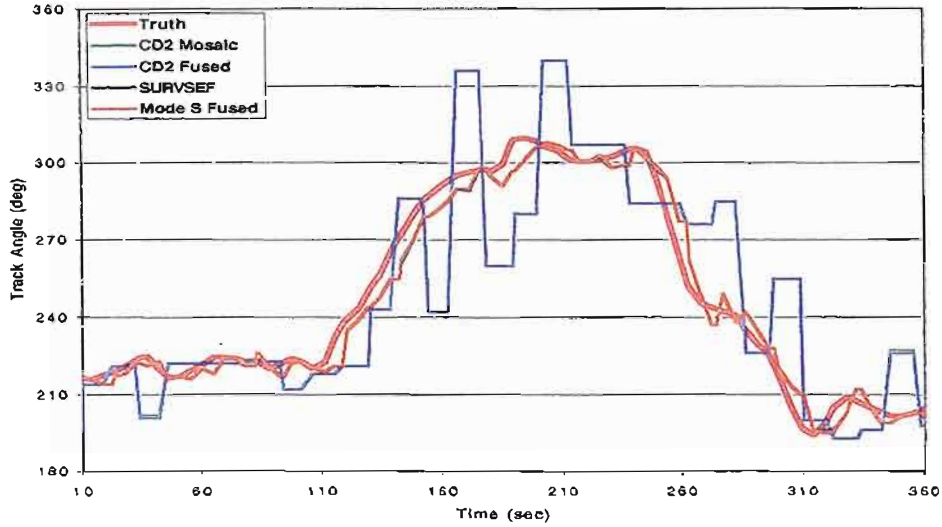


Figure 15. Tracked Recorded Data - Track Angle - COTS B.

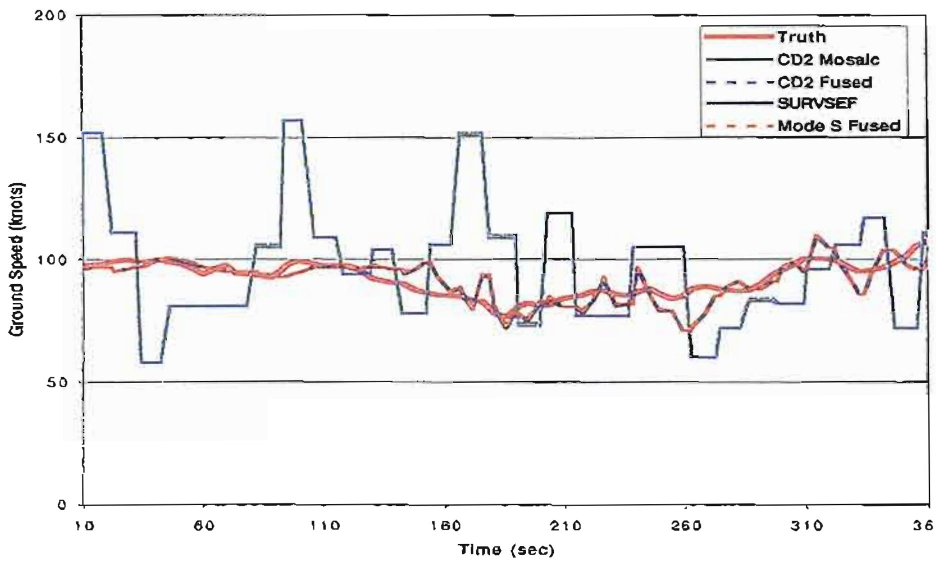


Figure 16. Tracked Recorded Data - Ground Speed - COTS B.

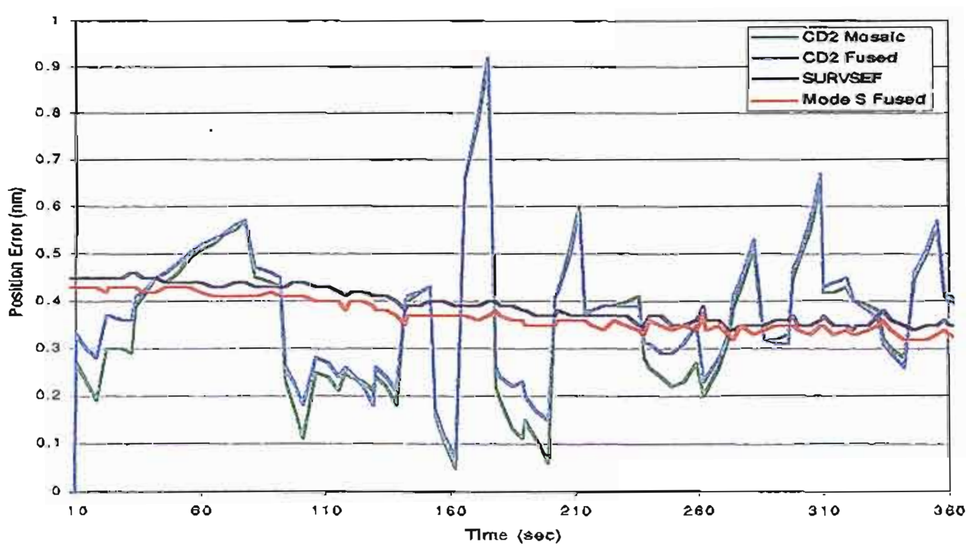


Figure 17. Tracked Recorded Data - Position Error - COTS B.

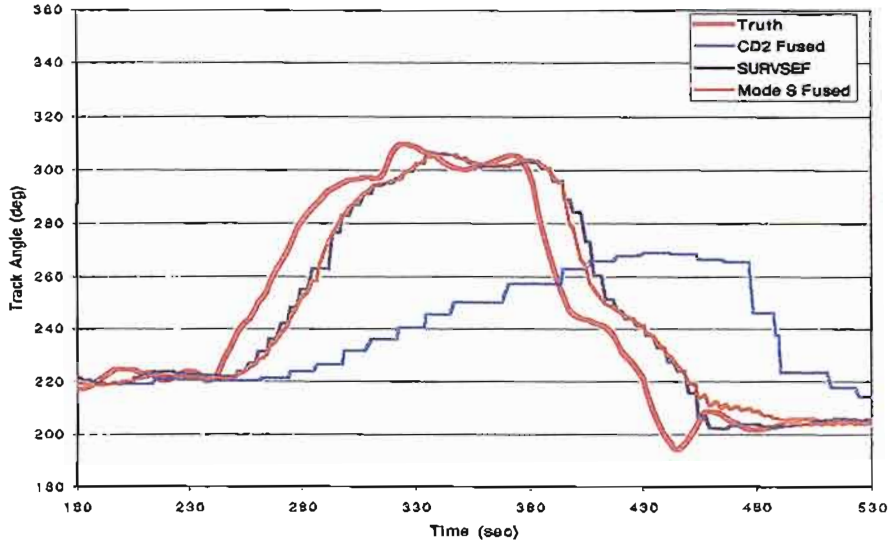


Figure 18. Tracked Recorded Data - Track Angle - COTS C.

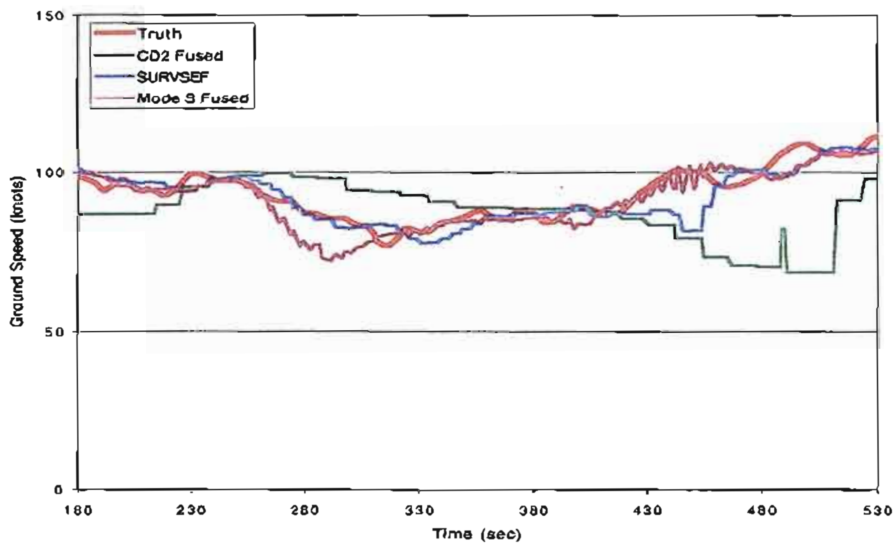


Figure 19. Tracked Recorded Data - Ground Speed - COTS C.

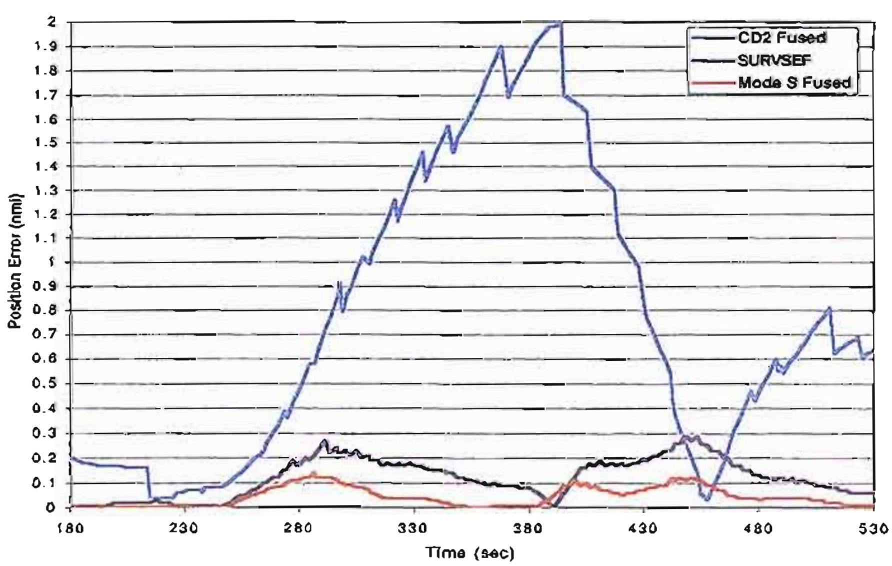


Figure 20. Tracked Recorded Data - Position Error - COTS C.

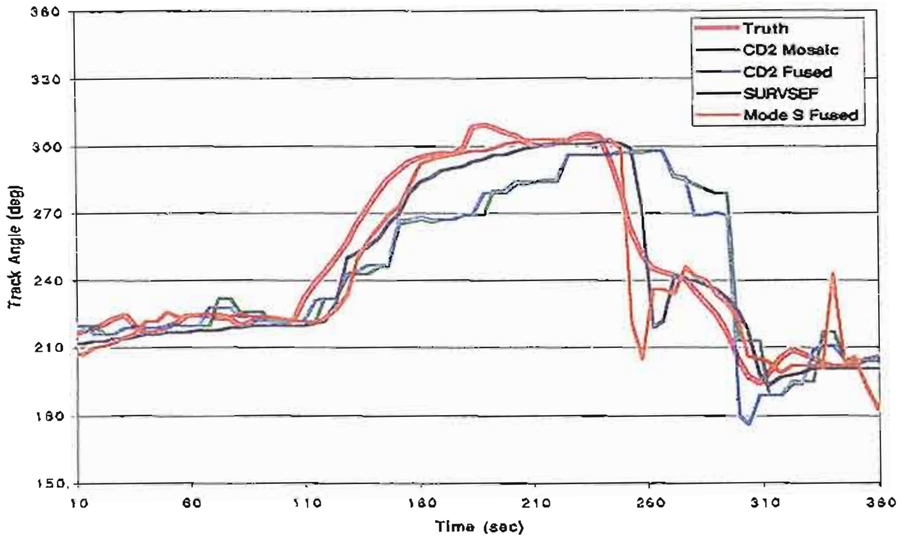


Figure 21. Tracked Recorded Data - Track Angle - COTS D.

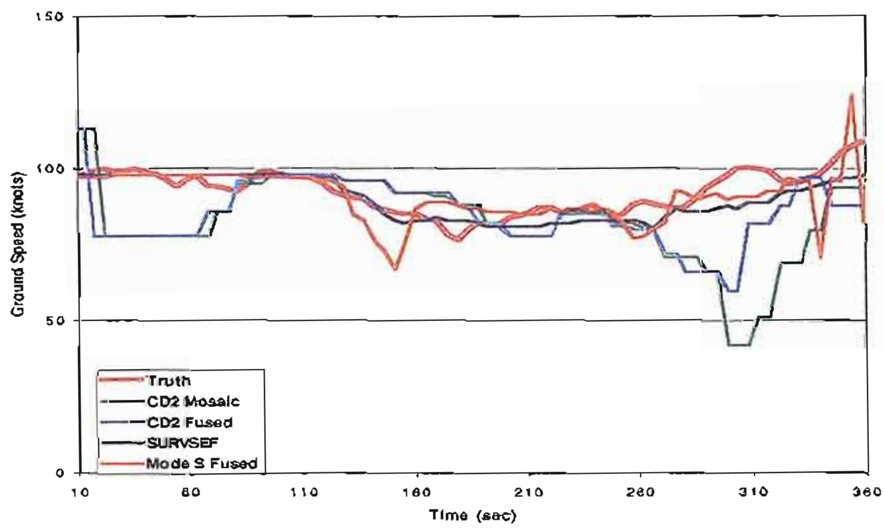


Figure 22. Tracked Recorded Data - Ground Speed - COTS D.

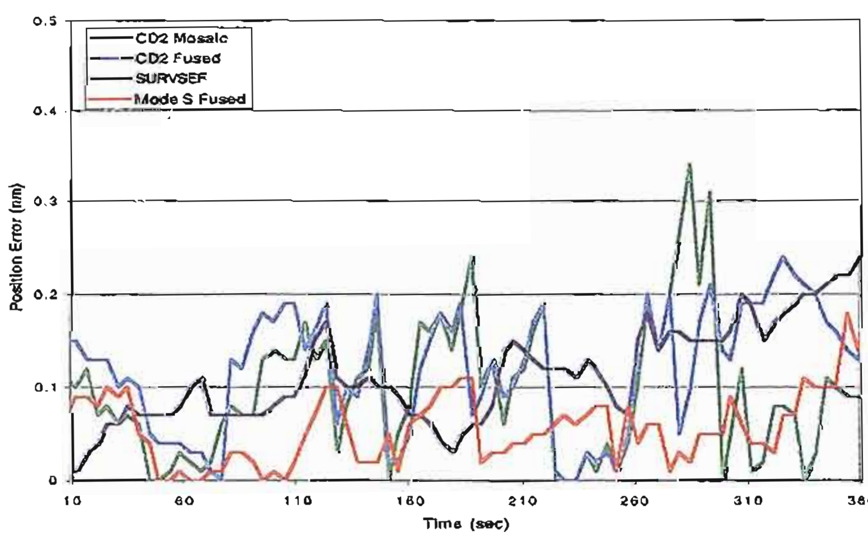


Figure 23. Tracked Recorded Data - Position Error - COTS D.

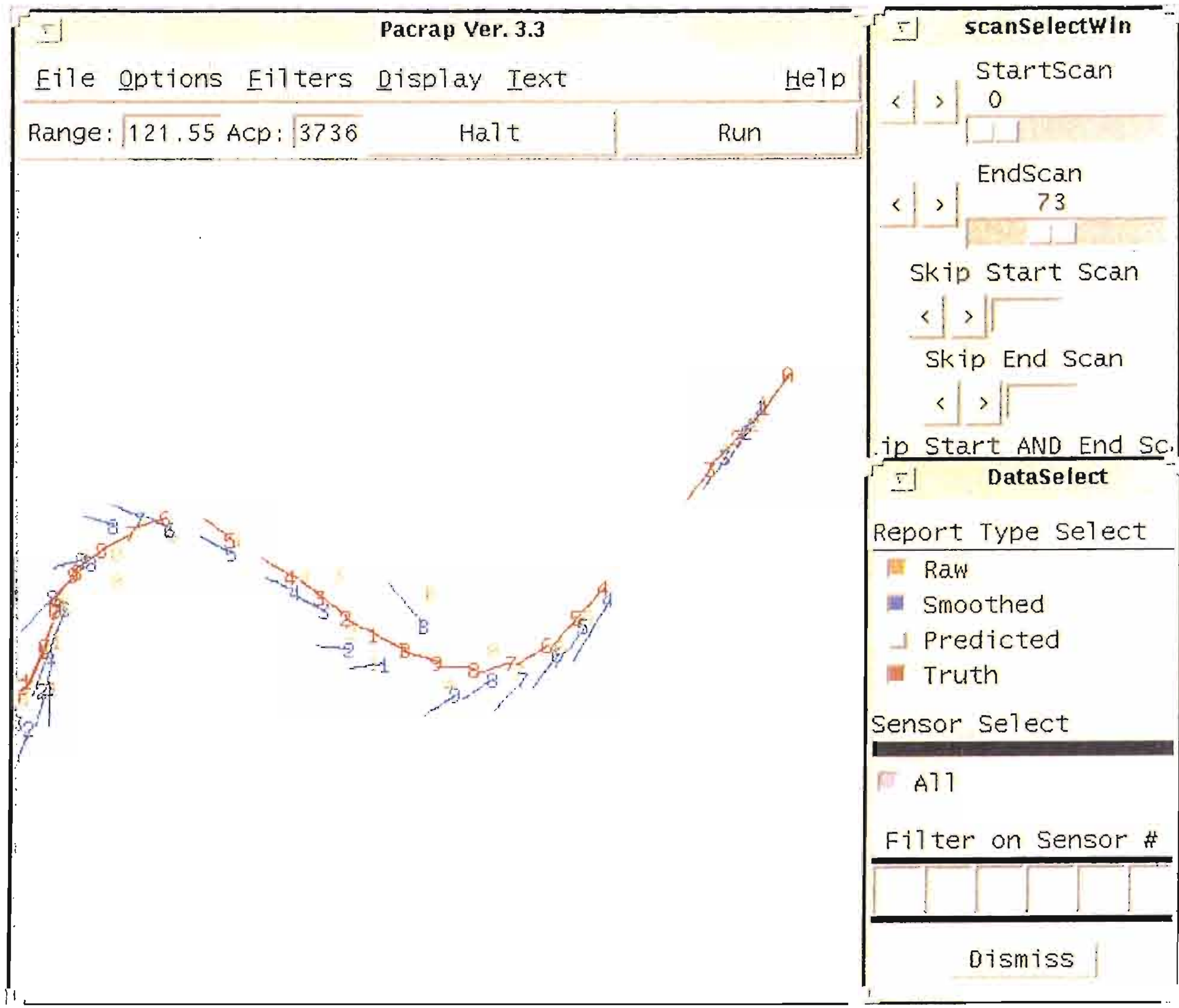


Figure 24. Sample Tracking Performance on Recorded Data During a Turning Segment - COTS A.

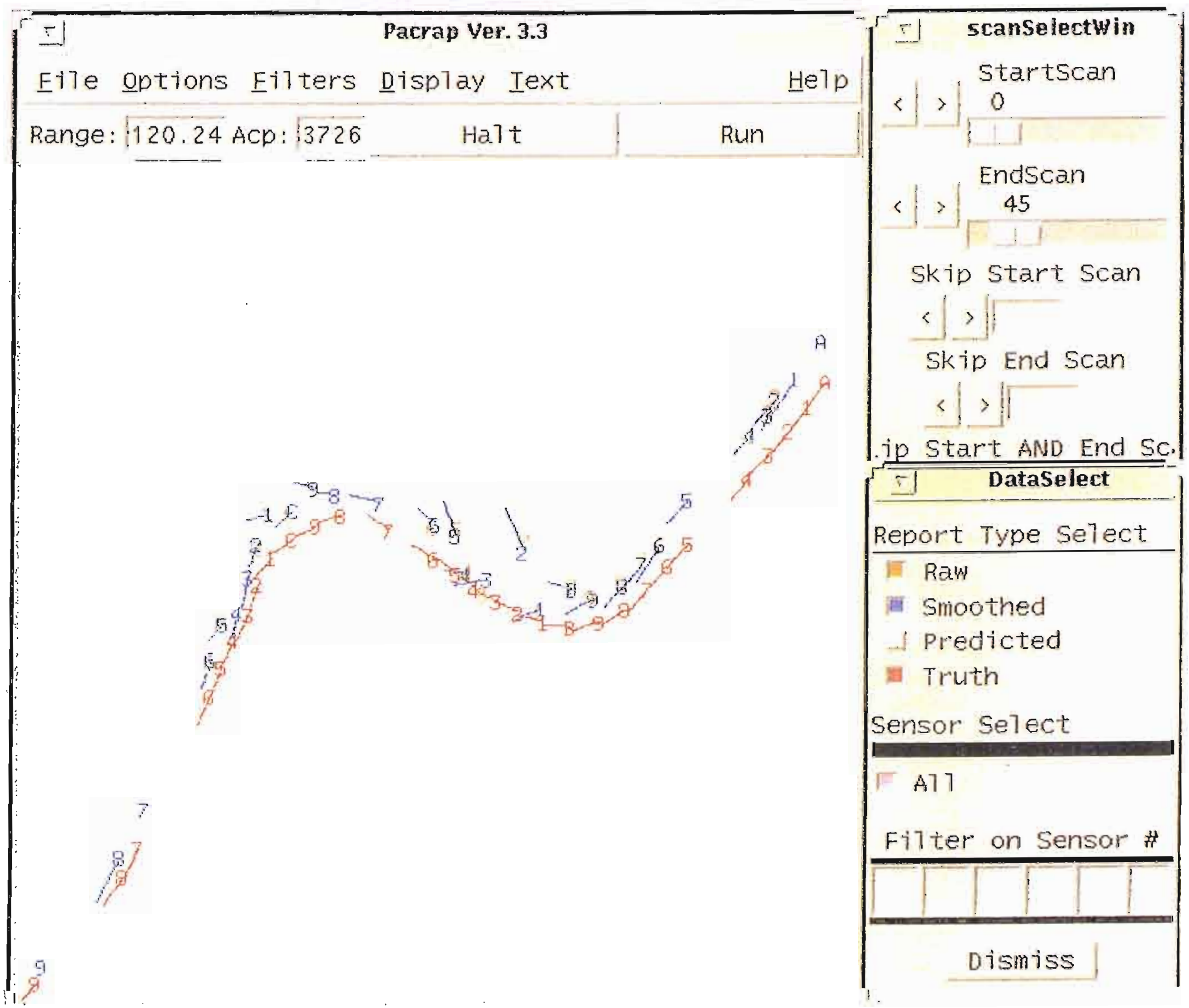


Figure 25. Sample Tracking Performance on Recorded Data During a Turning Segment - COTS B.

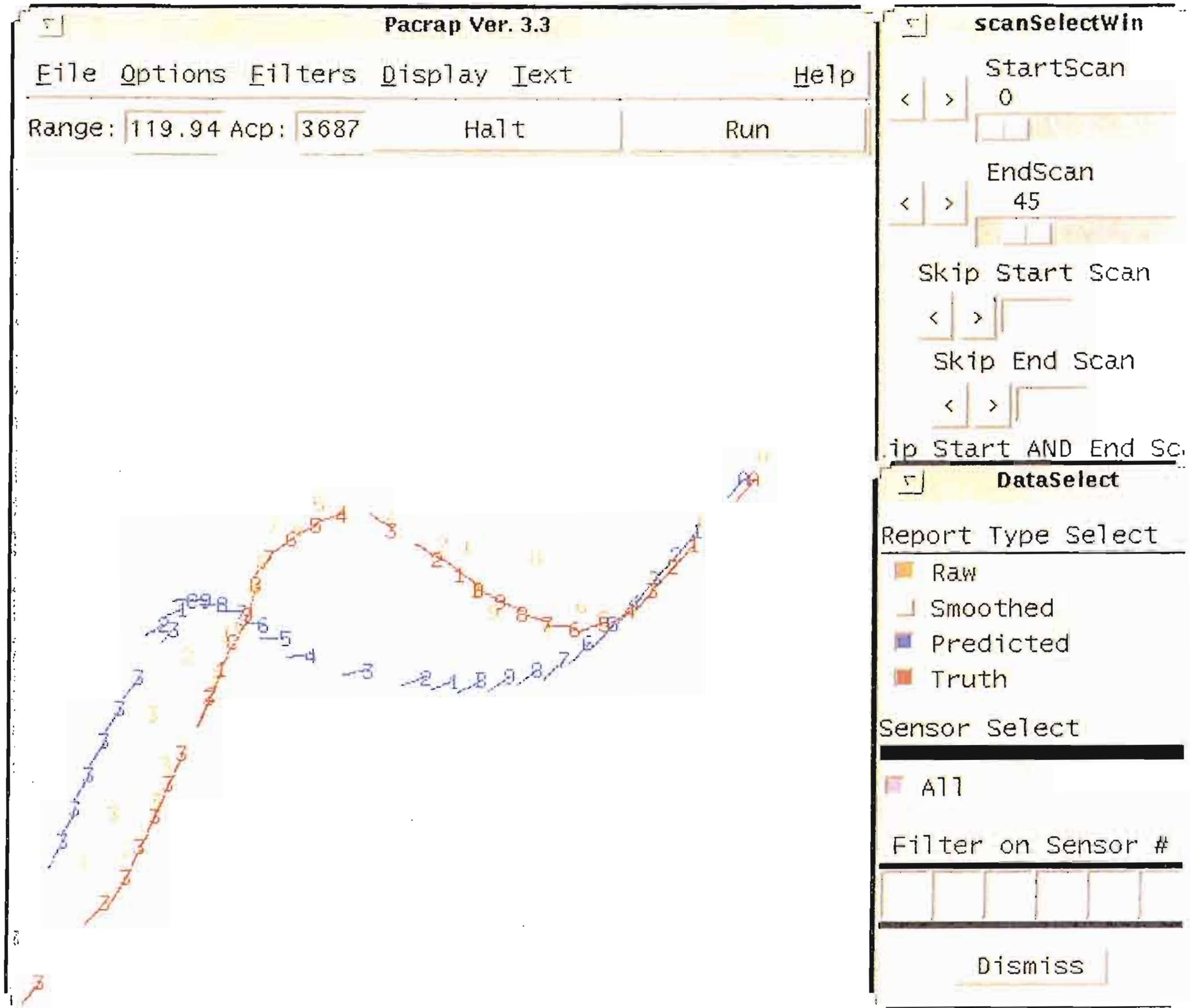


Figure 26. Sample Tracking Performance on Recorded Data During a Turning Segment - COTS C.

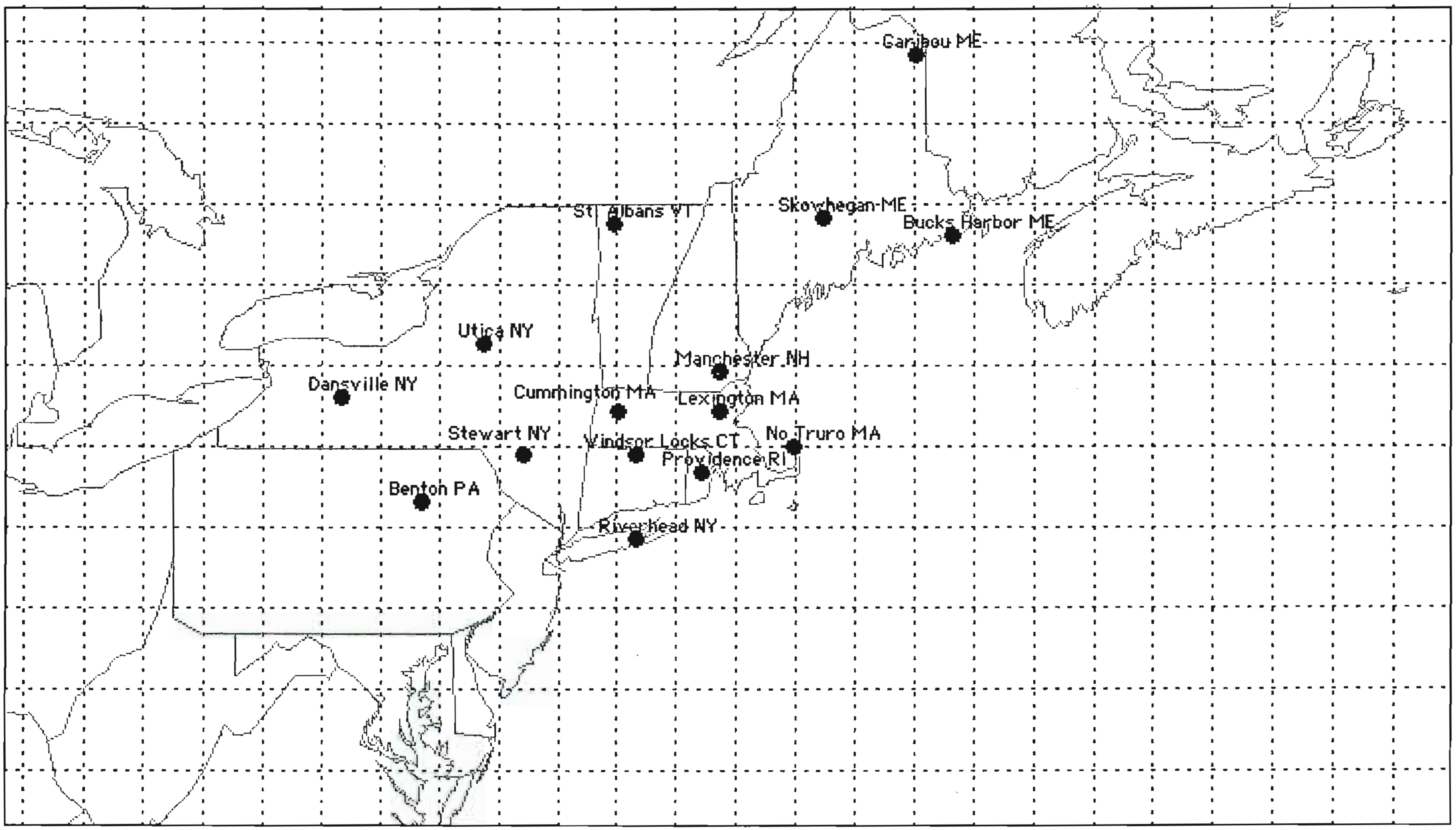
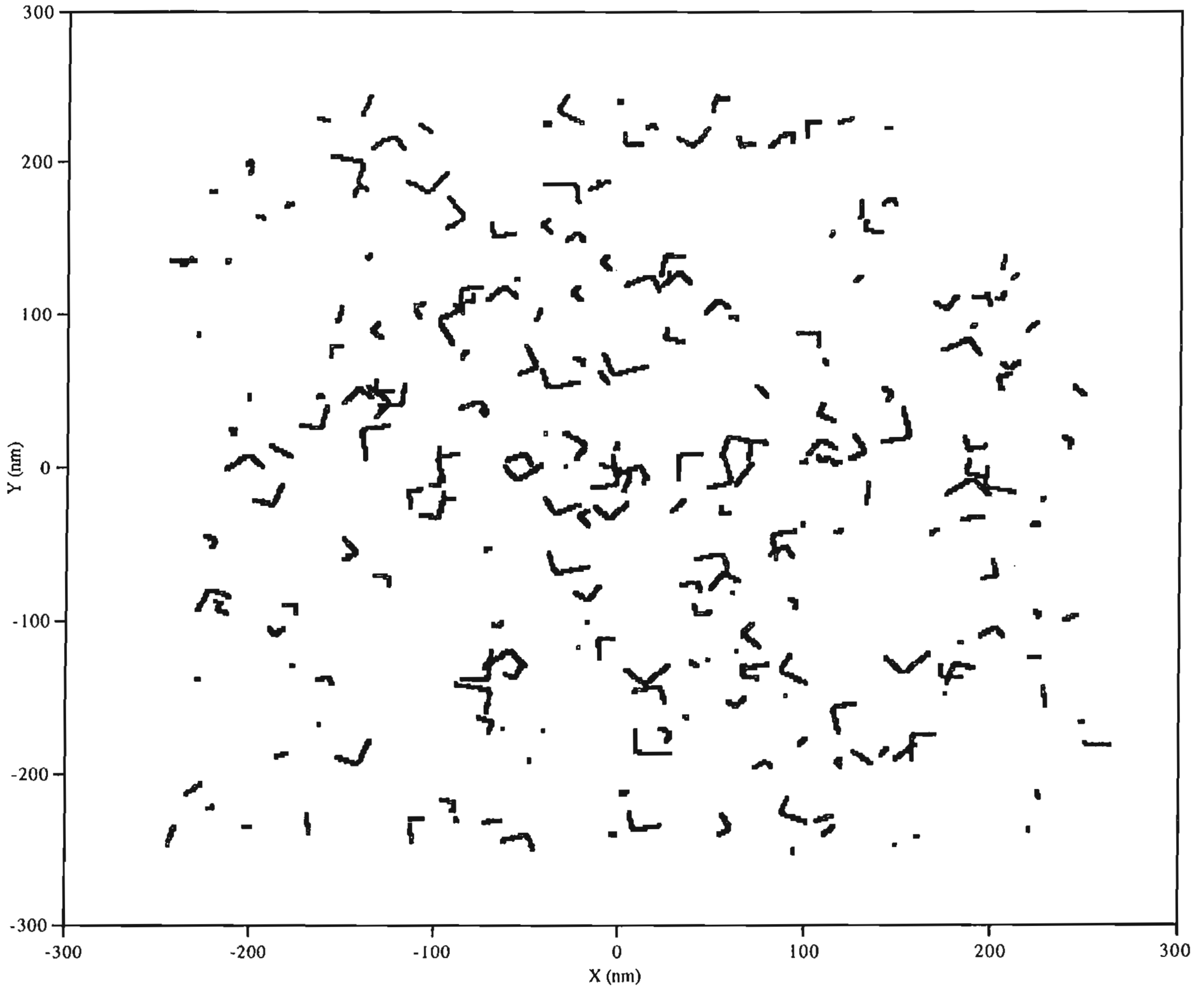


Figure 28. Simulation Sensor Ensemble.



Each track has 90 degree turn @ standard turn rate

Figure 29. Trajectories Used for BasicSim Tests.

Sen	Code		Time	X	Y	Heading	Speed		Time	X	Y	Heading	
1	0233	true:	93.74	67.390	-110.570	309.000	375.000	smooth:	44747.40	542.800	341.970	309.000	3
2	0233	true:	94.00	67.370	-110.560	309.000	375.000	smooth:	0.00	0.000	0.000	0.000	
20	0233	true:	94.86	67.300	-110.500	309.000	375.000	smooth:	44744.80	543.060	341.740	308.000	3
7	0233	true:	95.57	67.240	-110.450	309.000	375.000	smooth:	0.00	0.000	0.000	0.000	
1	0233	true:	98.34	67.020	-110.270	309.000	375.000	smooth:	44752.00	542.420	342.290	309.000	3
2	0233	true:	98.61	67.000	-110.250	309.000	375.000	smooth:	0.00	0.000	0.000	0.000	
4	0233	true:	100.06	66.880	-110.160	309.000	375.000	smooth:	44750.05	542.640	342.090	308.000	3
7	0233	true:	100.16	66.870	-110.150	310.000	375.000	smooth:	0.00	0.000	0.000	0.000	
5	0233	true:	102.04	66.730	-110.020	315.000	375.000	smooth:	0.00	0.000	0.000	0.000	
16	0233	true:	102.60	66.680	-109.980	317.000	375.000	smooth:	0.00	0.000	0.000	0.000	
1	0233	true:	102.93	66.660	-109.950	318.000	375.000	smooth:	44756.50	542.090	342.660	317.000	3
2	0233	true:	103.21	66.640	-109.930	319.000	375.000	smooth:	0.00	0.000	0.000	0.000	
7	0233	true:	104.76	66.540	-109.810	323.000	375.000	smooth:	0.00	0.000	0.000	0.000	
18	0233	true:	104.97	66.530	-109.790	324.000	375.000	smooth:	44754.95	542.230	342.430	309.000	3
20	0233	true:	106.84	66.420	-109.630	330.000	375.000	smooth:	0.00	0.000	0.000	0.000	
1	0233	true:	107.52	66.390	-109.560	332.000	375.000	smooth:	44761.10	541.990	343.120	346.000	3

Figure 30. Sample Printout from Merge Routine - Truth from Simulation Input, Smooth from Tracker Output. (Note All Inputs do not Generate an Output.)

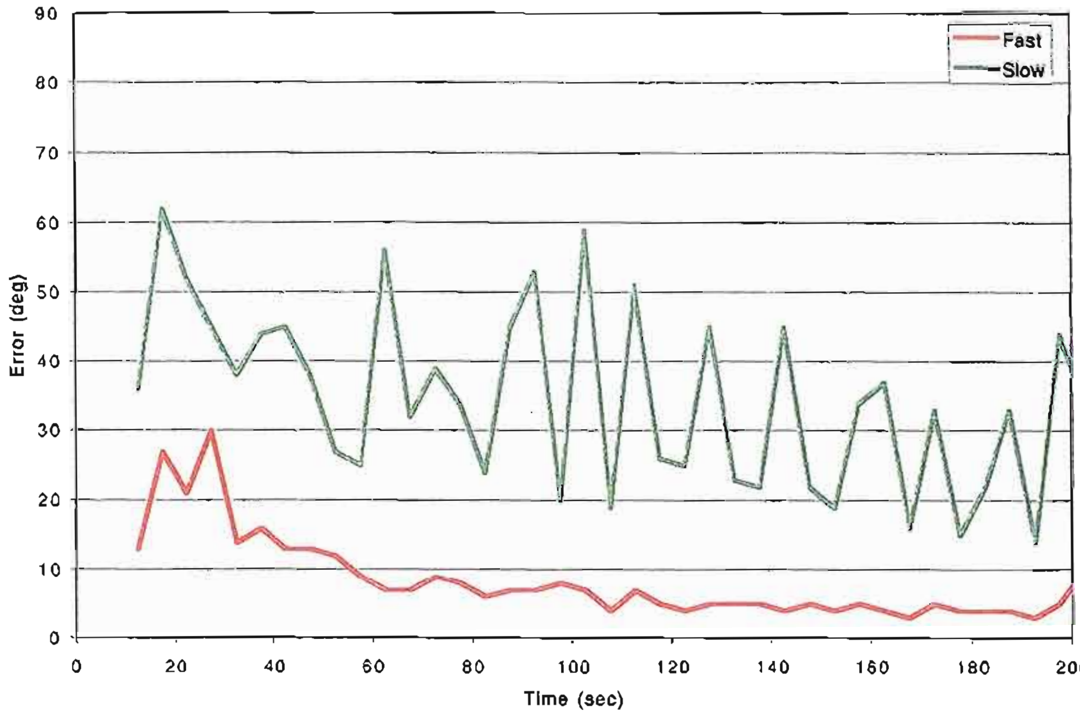


Figure 31. Track Angle Error in Straight Flight for Fast (>150 Knots) vs. Slow (<150 Knots) Aircraft - CD2 Data.

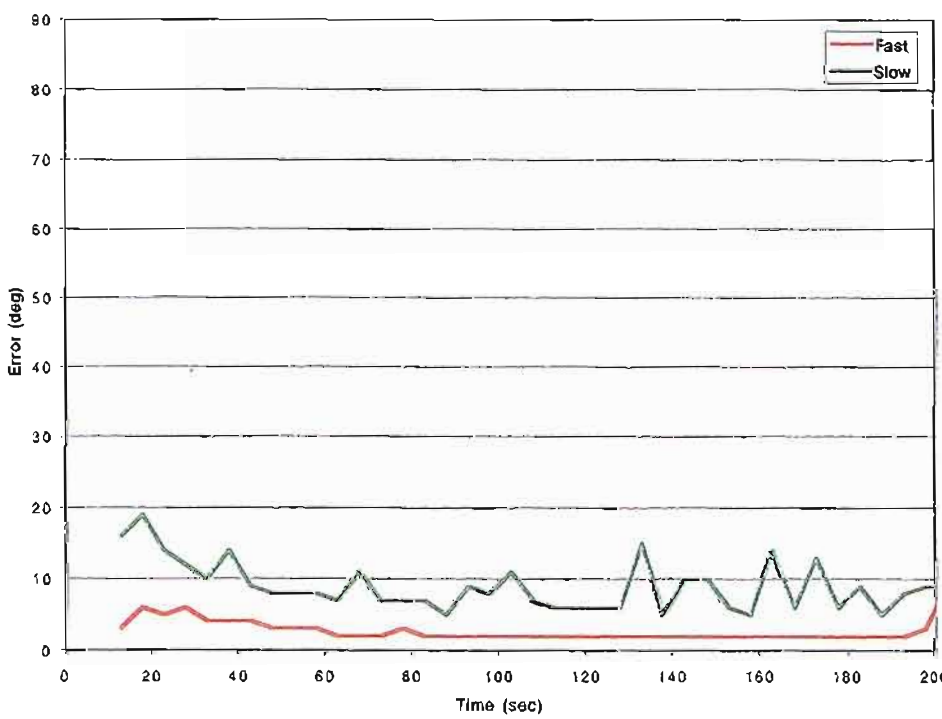


Figure 32. Track Angle Error in Straight Flight for Fast (>150 Knots) vs. Slow (<150 Knots) Aircraft - Mode S Data.

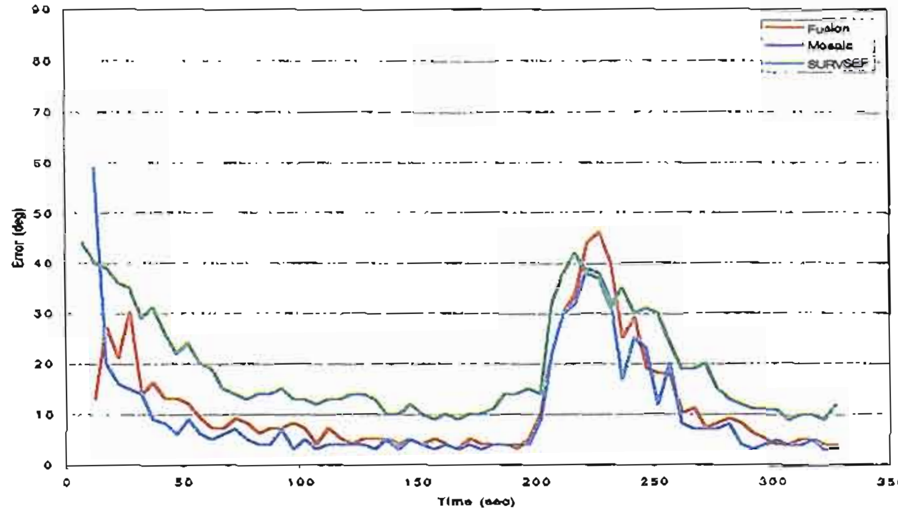


Figure 33. Turning Test (Turn 200-230 Seconds) - Track Angle Error - CD2 Data – COTS A.

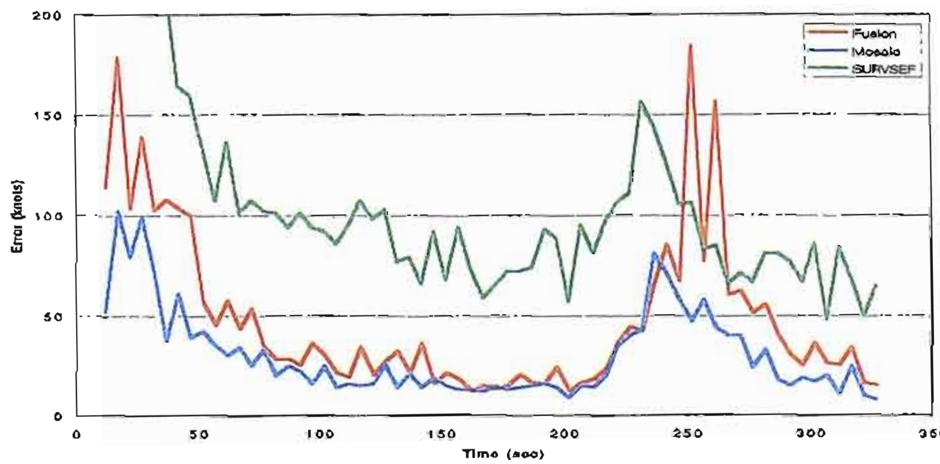


Figure 34. Turning Test (Turn 200-230 Seconds) - Ground Speed Error - CD2 Data – COTS A.

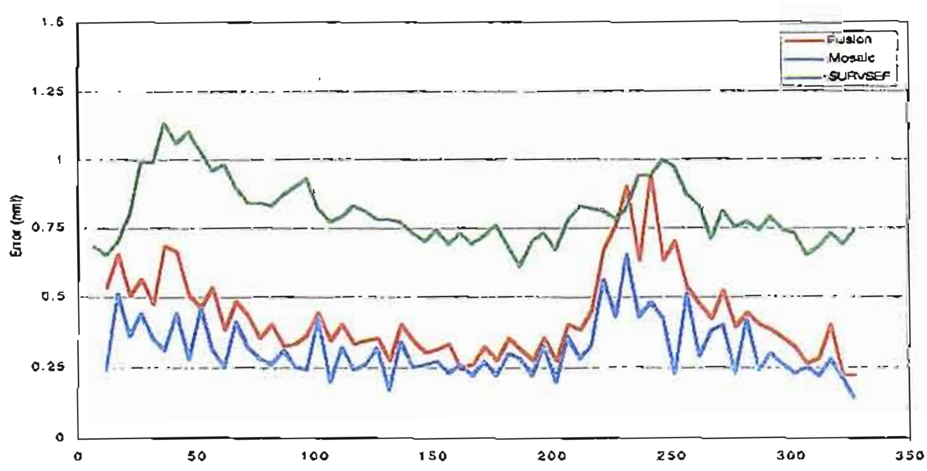


Figure 35. Turning Test (Turn 200-230 Seconds) - Position Error - CD2 Data – COTS A.

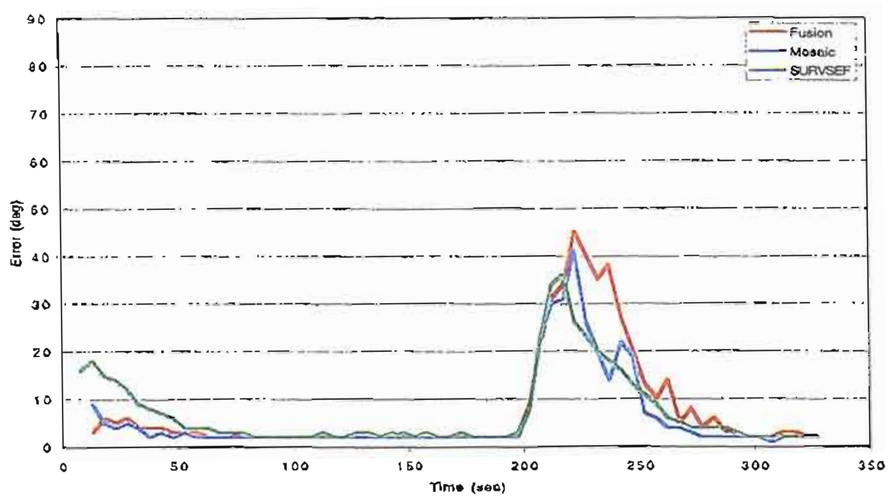


Figure 36. Turning Test (Turn 200-230 Seconds) - Track Angle Error - Mode S Data - COTS A.

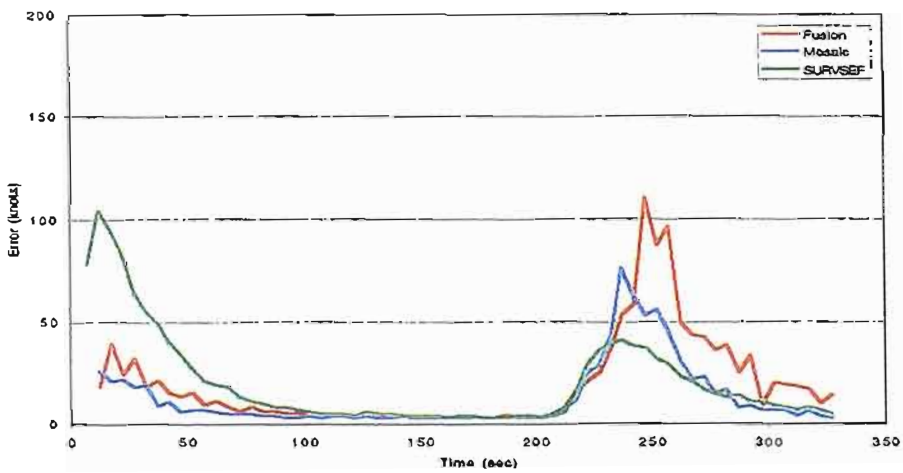


Figure 37. Turning Test (Turn 200-230 Seconds) - Ground Speed Error - Mode S Data – COTS A.

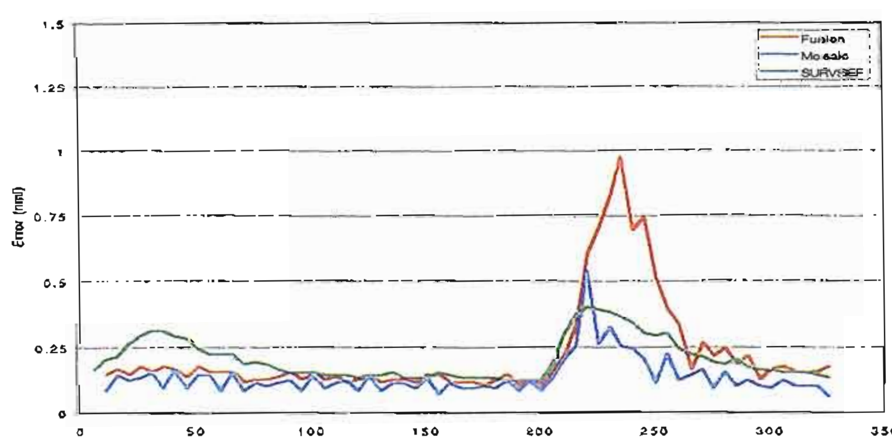


Figure 38. Turning Test (Turn 200-230 Seconds) - Position Error - Mode S Data - COTS A.

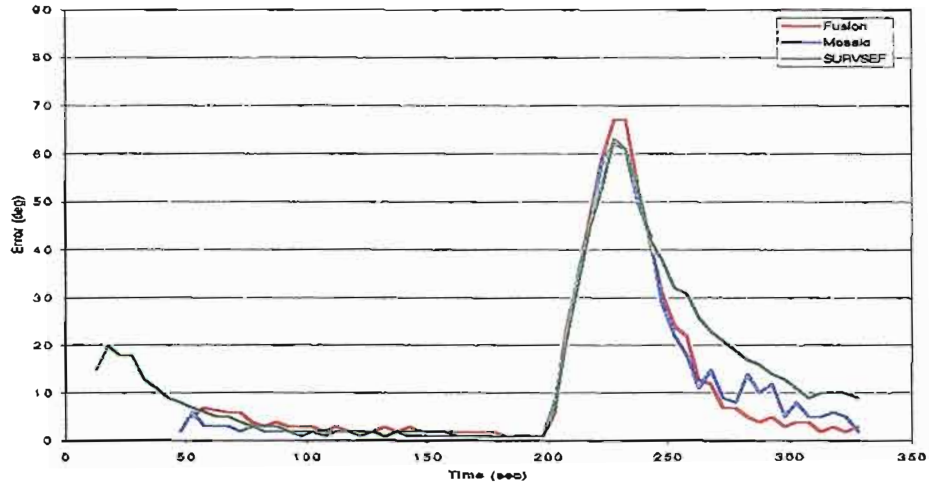


Figure 39. Turning Test (Turn 200-230 Seconds) - Track Angle Error - CD2 Data - COTS B.

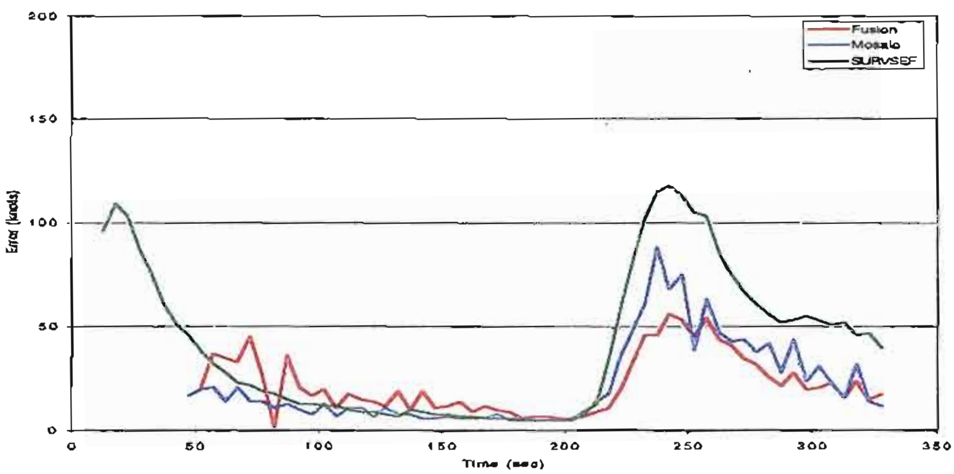


Figure 40. Turning Test (Turn 200-230 Seconds) - Ground Speed Error - CD2 Data - COTS B.

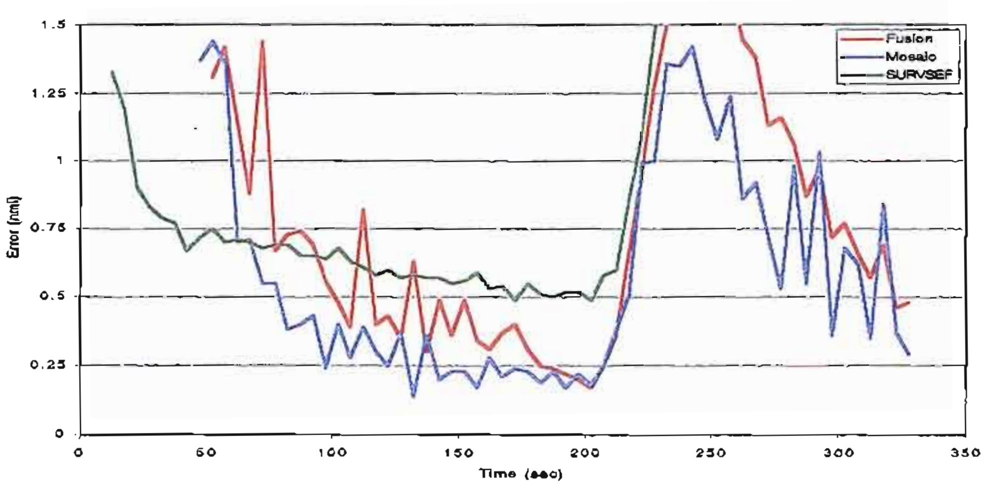


Figure 41. Turning Test (Turn 200-230 Seconds) - Position Error - CD2 Data - COTS B.

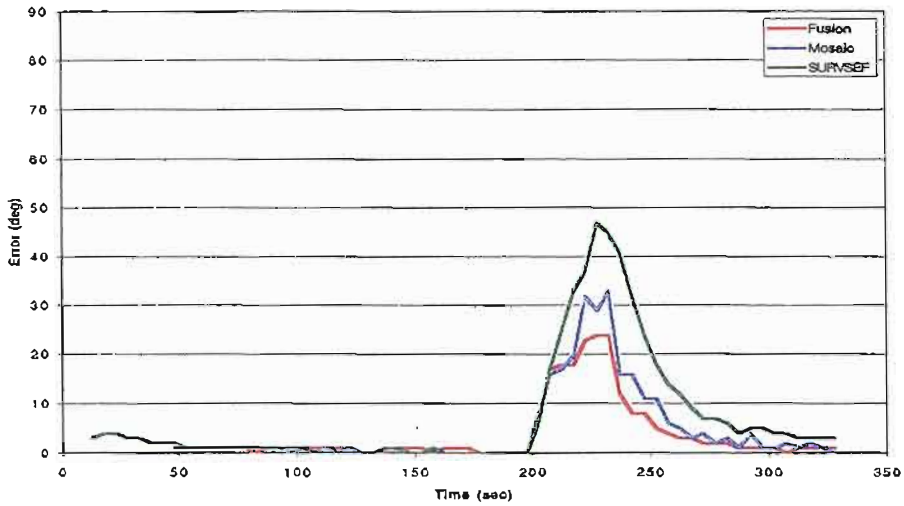


Figure 42. Turning Test (Turn 200-230 Seconds) - Track Angle Error - Mode S Data - COTS B.

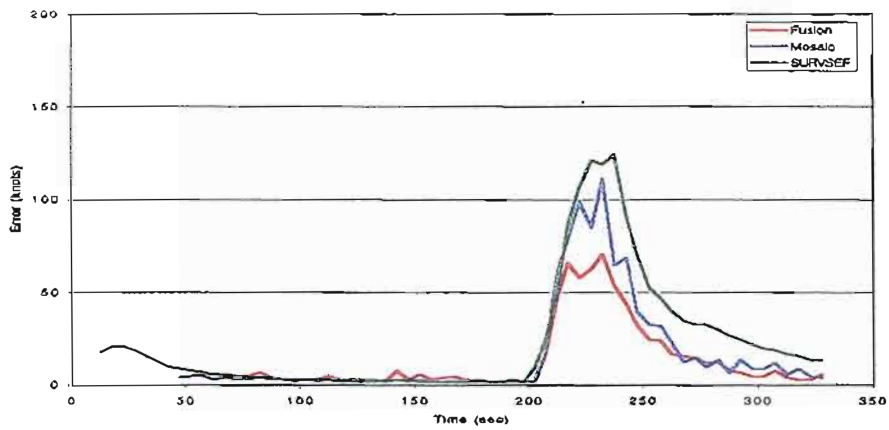


Figure 43. Turning Test (Turn 200-230 Seconds) - Ground Speed Error - Mode S Data - COTS B.

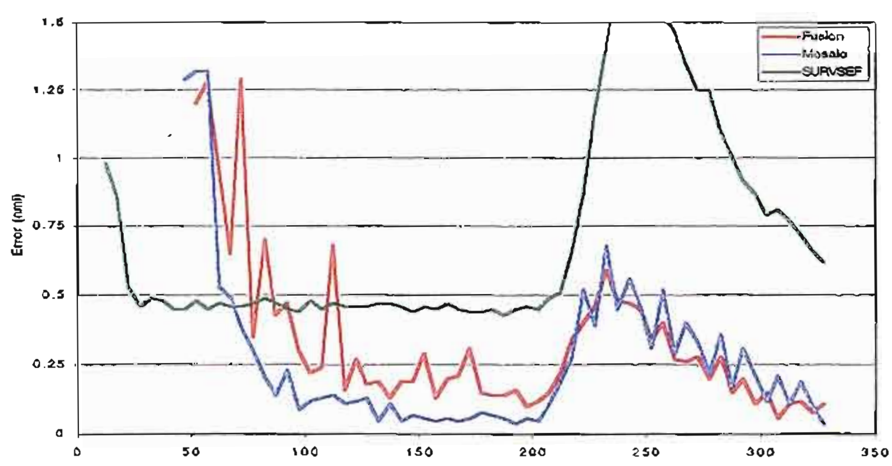


Figure 44. Turning Test (Turn 200-230 Seconds) - Position Error - Mode S Data - COTS B.

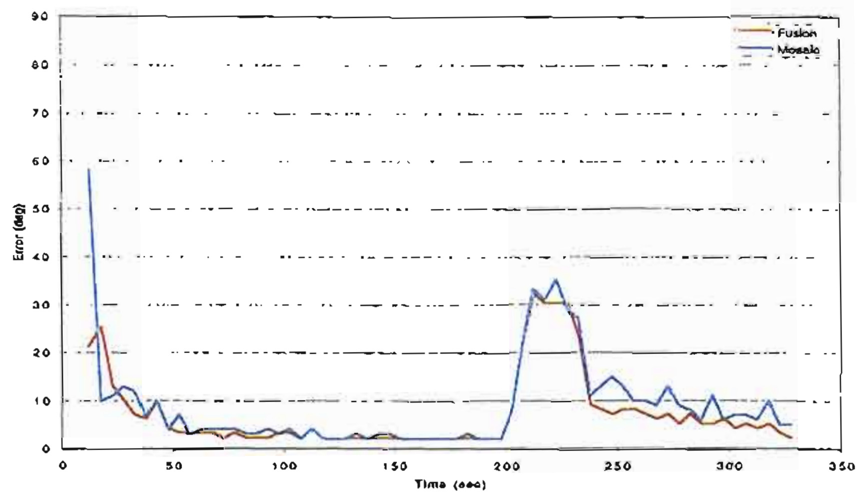


Figure 45. Turning Test (Turn 200-230 Seconds) - Track Angle Error - CD2 Data - COTS C.

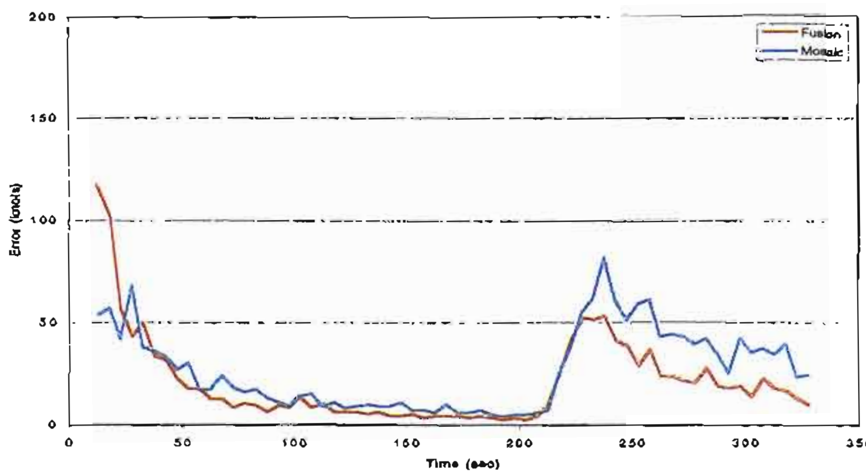


Figure 46. Turning Test (Turn 200-230 Seconds) - Ground Speed Error - CD2 Data - COTS C.

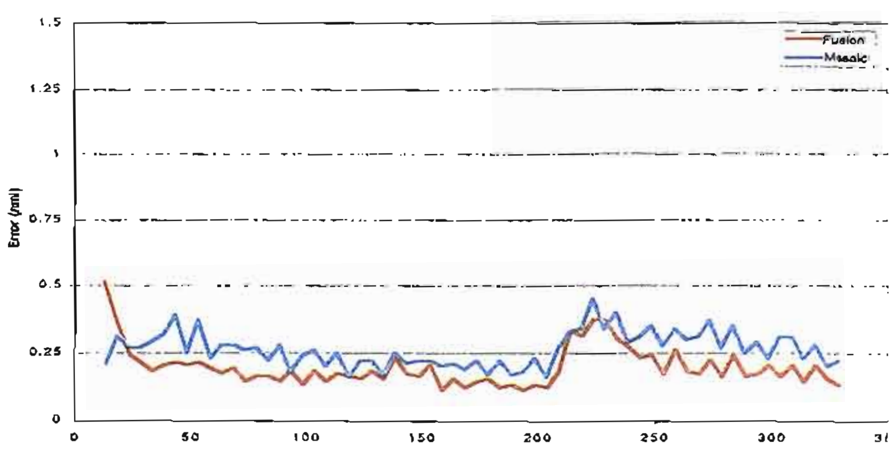


Figure 47. Turning Test (Turn 200-230 Seconds) - Position Error – C D2 Data - COTS C.

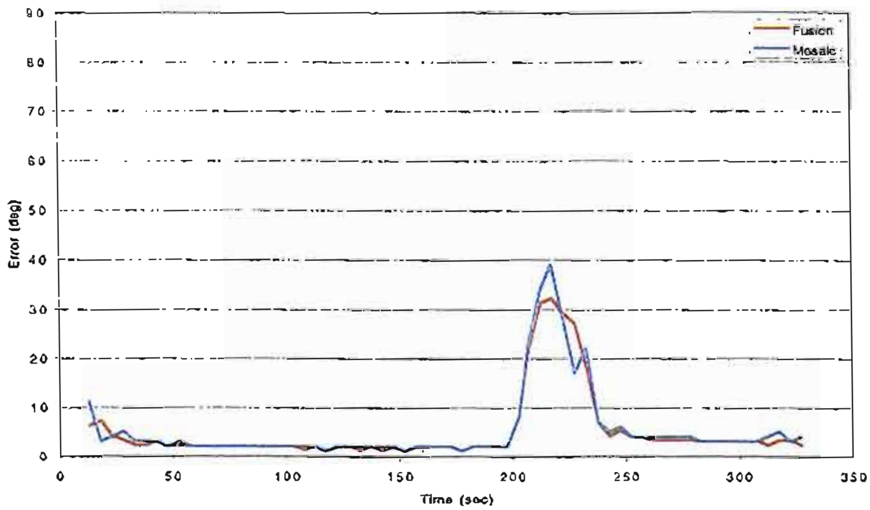


Figure 48. Turning Test (Turn 200-230 Seconds) - Track Angle Error - Mode S Data - COTS C.

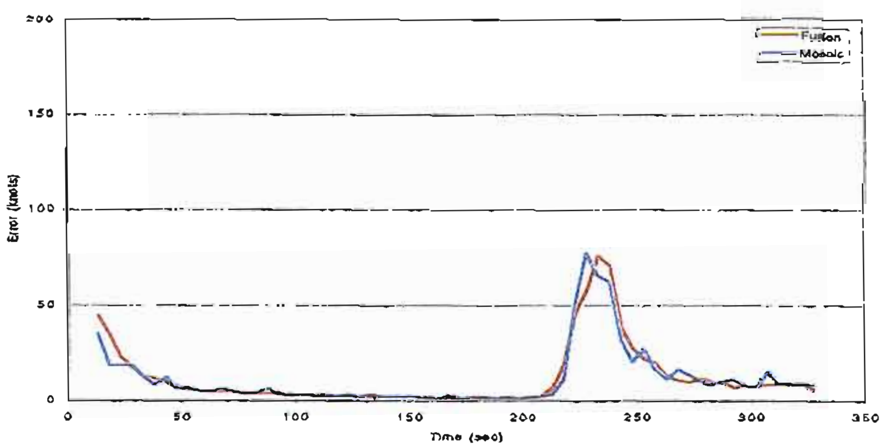


Figure 49. Turning Test (Turn 200-230 Seconds) - Ground Speed Error - Mode S Data - COTS C.

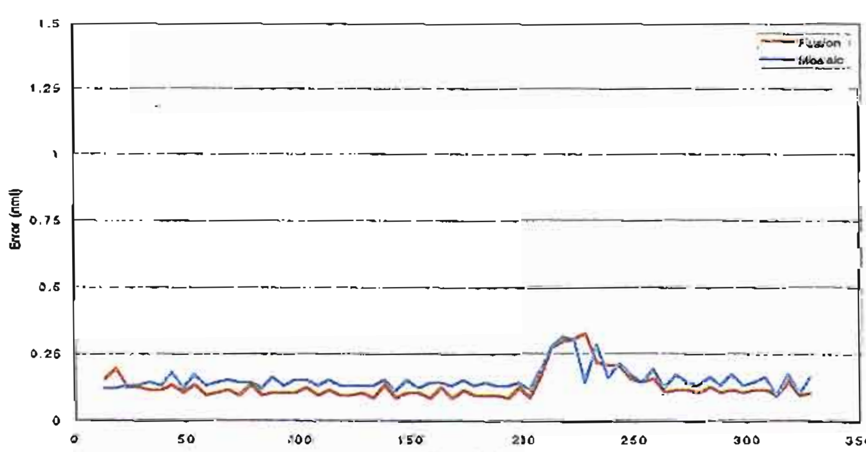


Figure 50. Turning Test (Turn 200-230 Seconds) - Position Error - Mode S Data - COTS C.

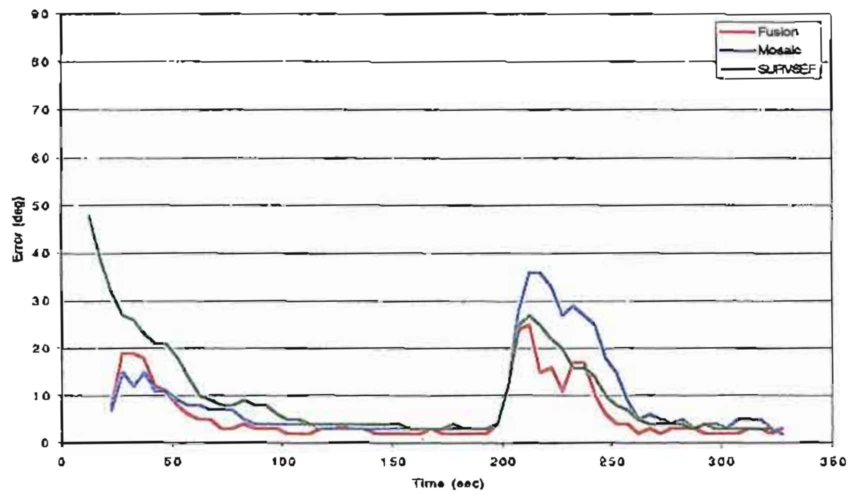


Figure 51. Turning Test (Turn 200-230 Seconds) - Track Angle Error - CD2 Data - COTS D.

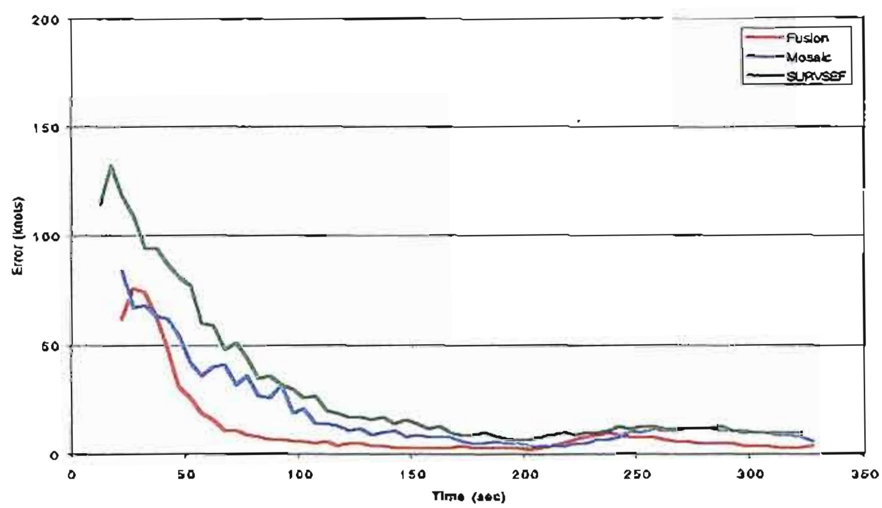


Figure 52. Turning Test (Turn 200-230 Seconds) - Ground Speed Error - CD2 Data - COTS D.

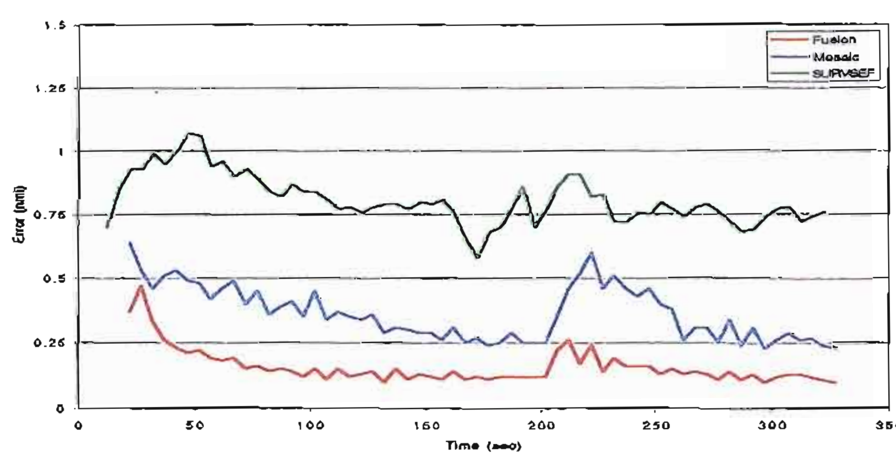


Figure 53. Turning Test (Turn 200-230 Seconds) - Position Error - CD2 Data - COTS D.

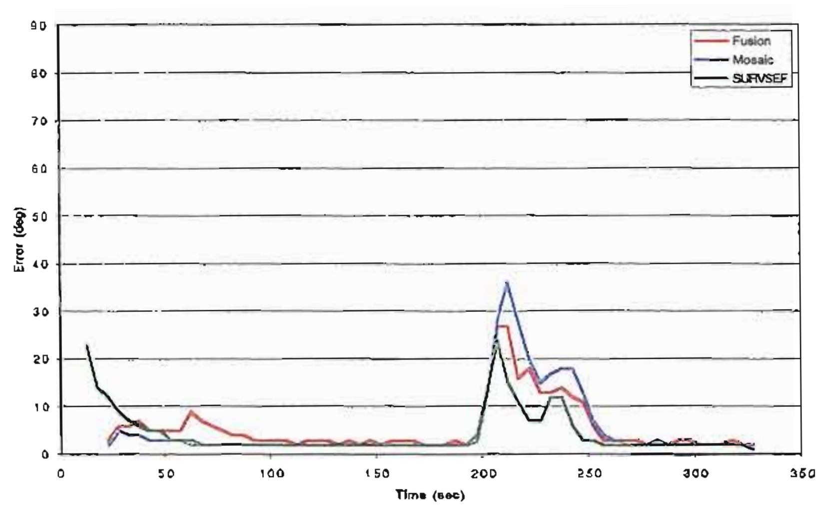


Figure 54. Turning Test (Turn 200-230 Seconds) - Track Angle Error - Mode S Data - COTS D.

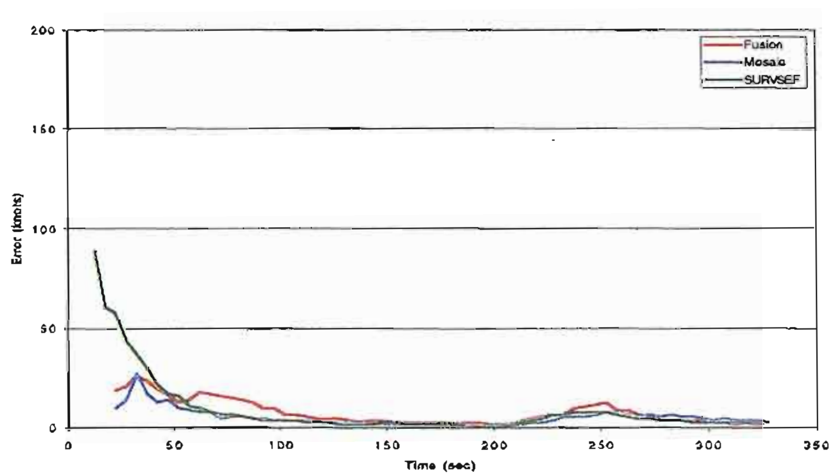


Figure 55. Turning Test (Turn 200-230 Seconds) - Ground Speed Error - Mode S Data - COTS D.

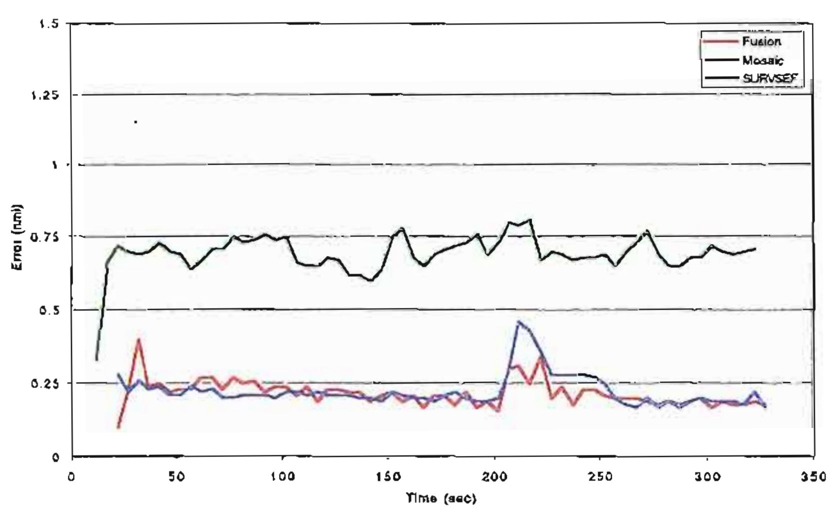


Figure 56. Turning Test (Turn 200-230 Seconds) - Position Error - Mode S Data - COTS D.

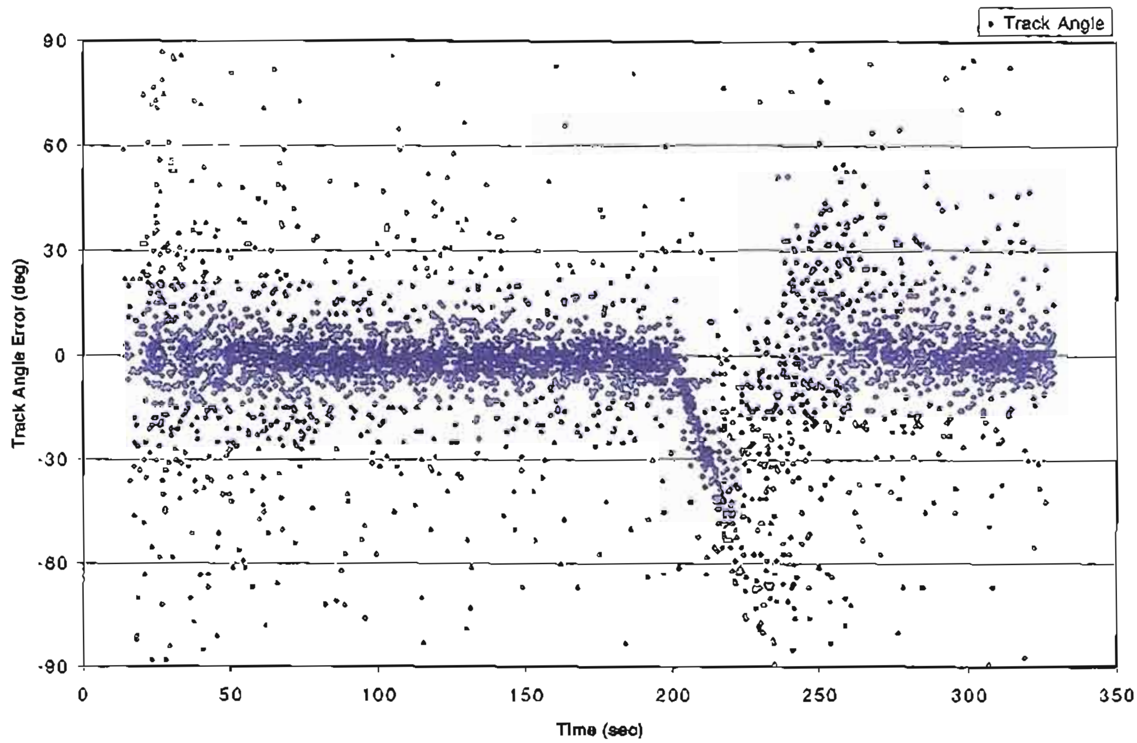


Figure 57. Turning Test (Turn 200-230 Seconds) - Track Angle Error - CD2 Data - COTS A.

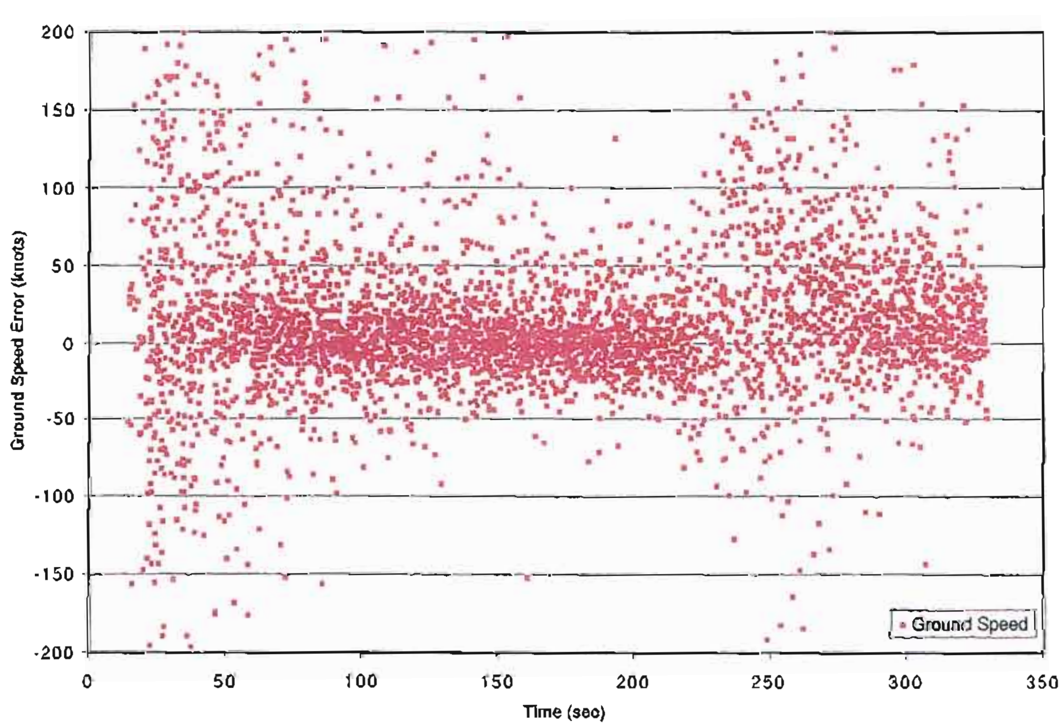


Figure 58. Turning Test (Turn 200-230 Seconds) - Ground Speed Error - CD2 Data - COTS A.

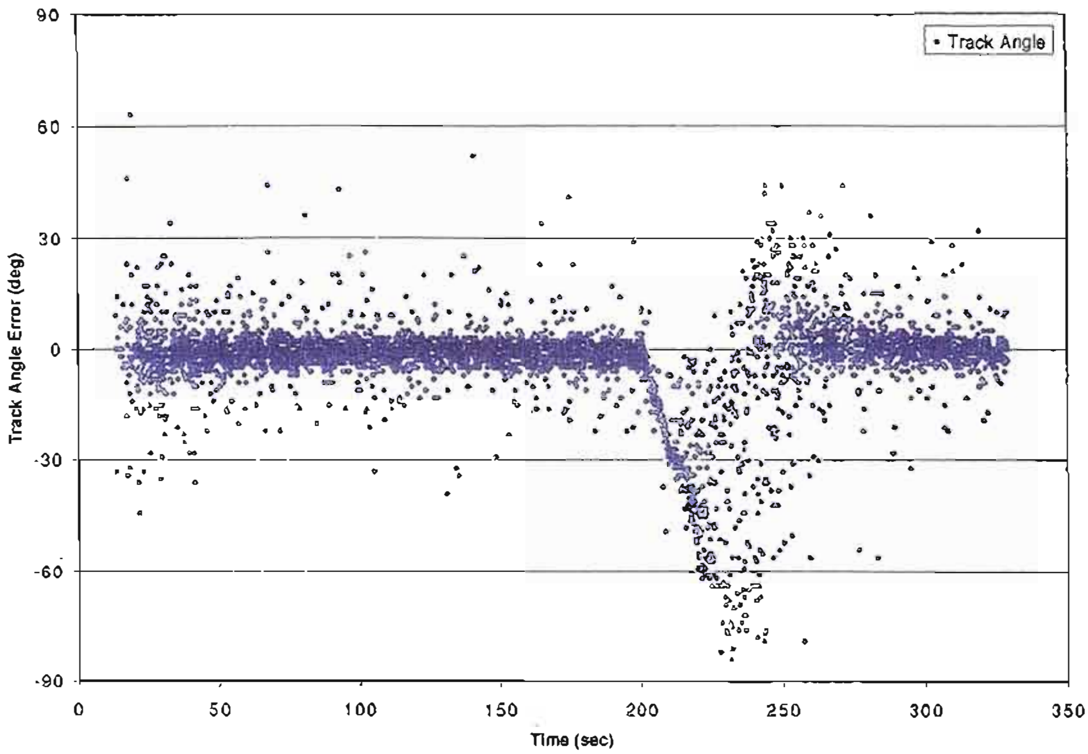


Figure 59. Turning Test (Turn 200-230 Seconds) - Track Angle Error - Mode S Data - COTS A.

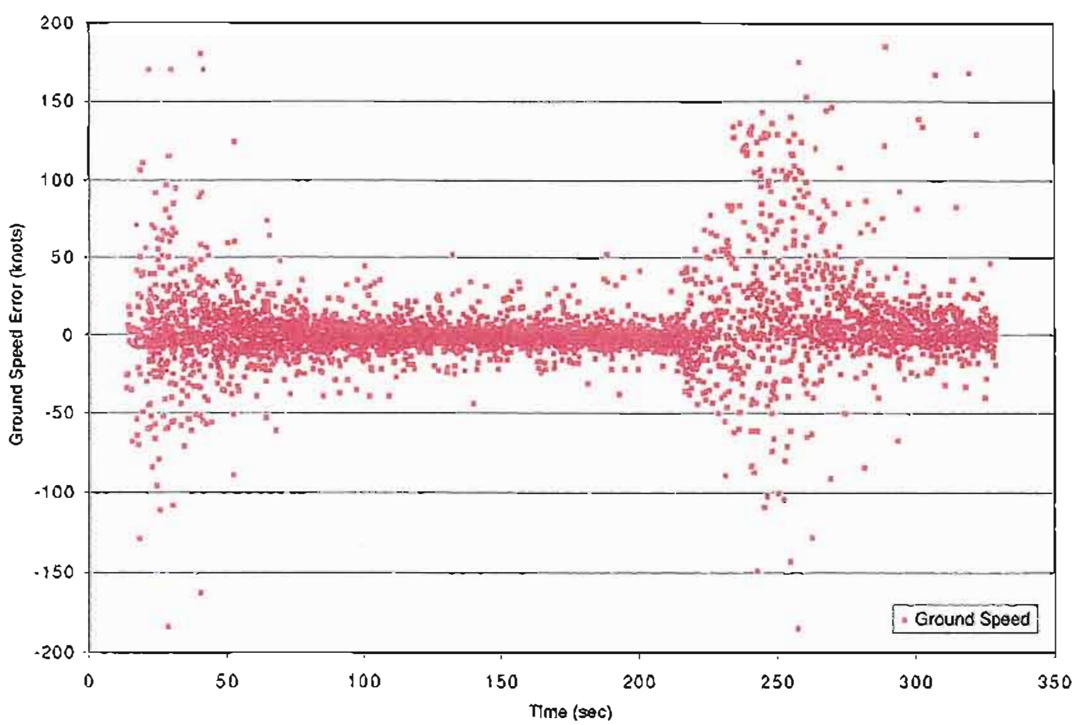


Figure 60. Turning Test (Turn 200-230 Seconds) - Ground Speed Error - Mode S Data - COTS A.

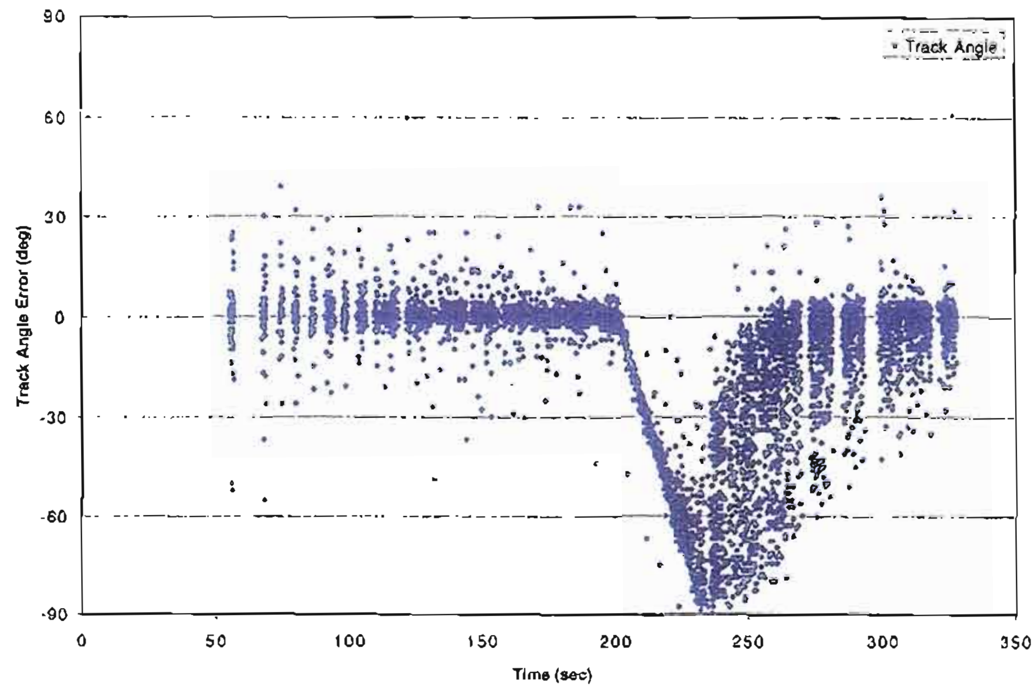


Figure 61. Turning Test (Turn 200-230 Seconds) - Track Angle Error - CD2 Data - COTS B.

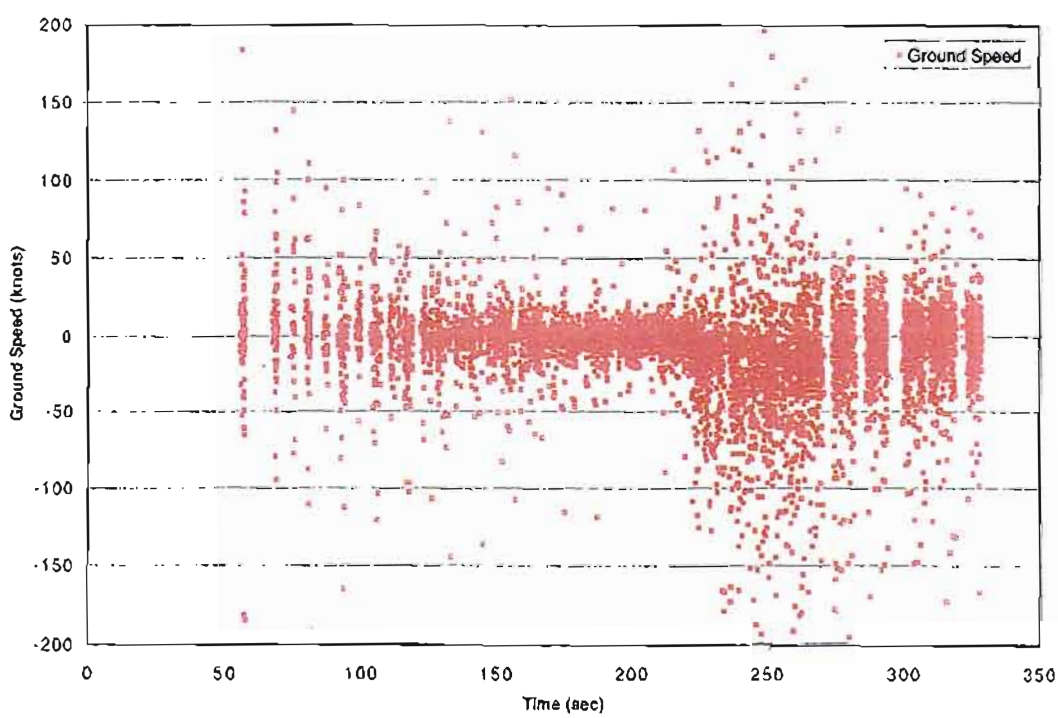


Figure 62. Turning Test (Turn 200-230 Seconds) - Ground Speed Error - CD2 Data - COTS B.

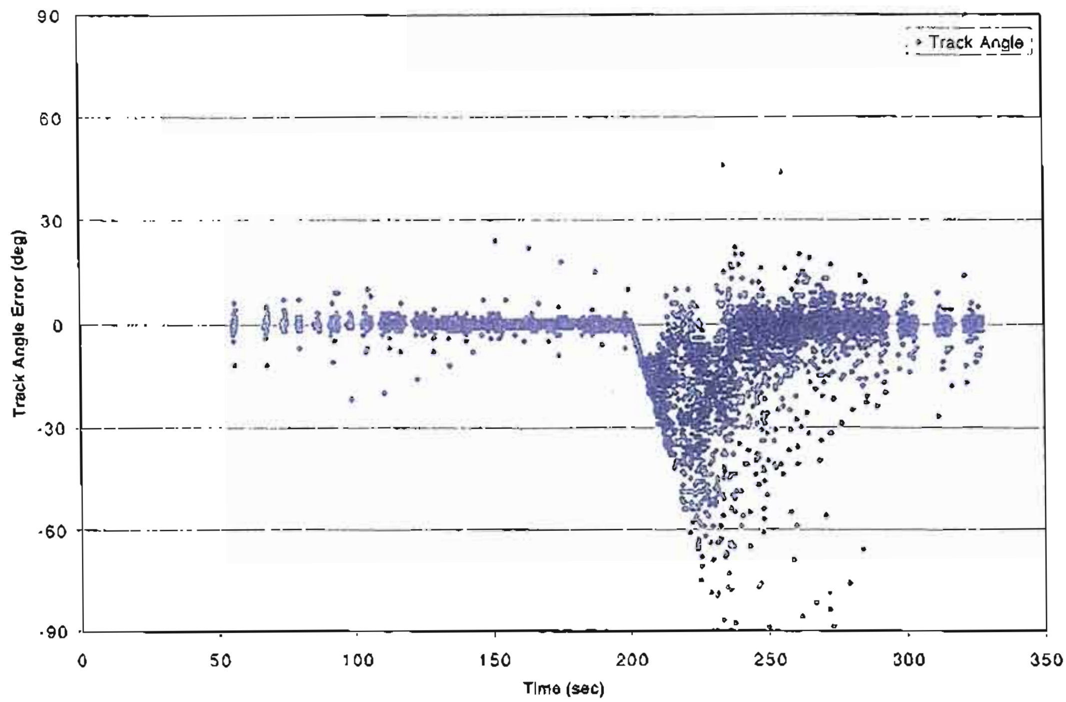


Figure 63. Turning Test (Turn 200-230 Seconds) - Track Angle Error - Mode S Data - COTS B.

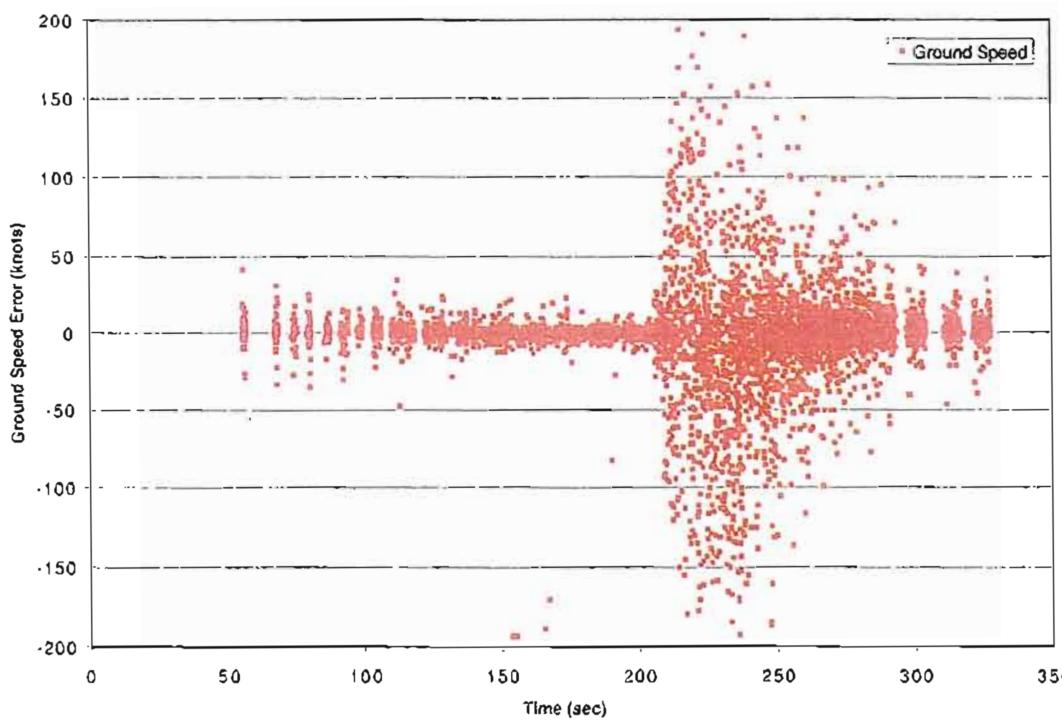


Figure 64. Turning Test (Turn 200-230 Seconds) - Ground Speed Error - Mode S Data - COTS B.

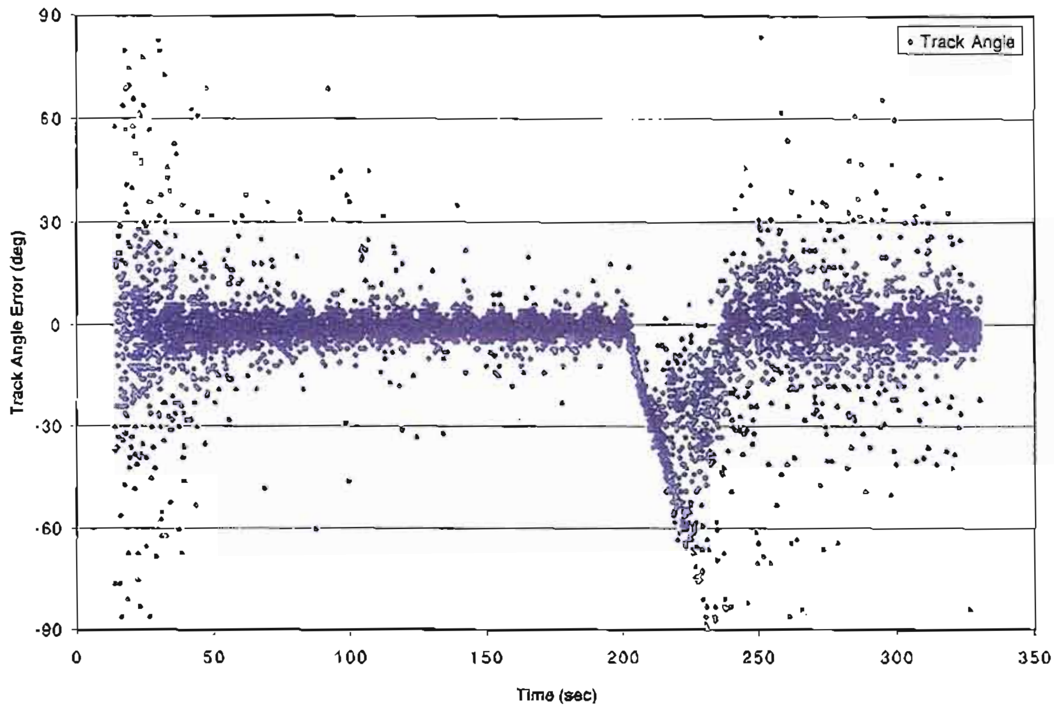


Figure 65. Turning Test (Turn 200-230 Seconds) - Track Angle Error - CD2 Data - COTS C.

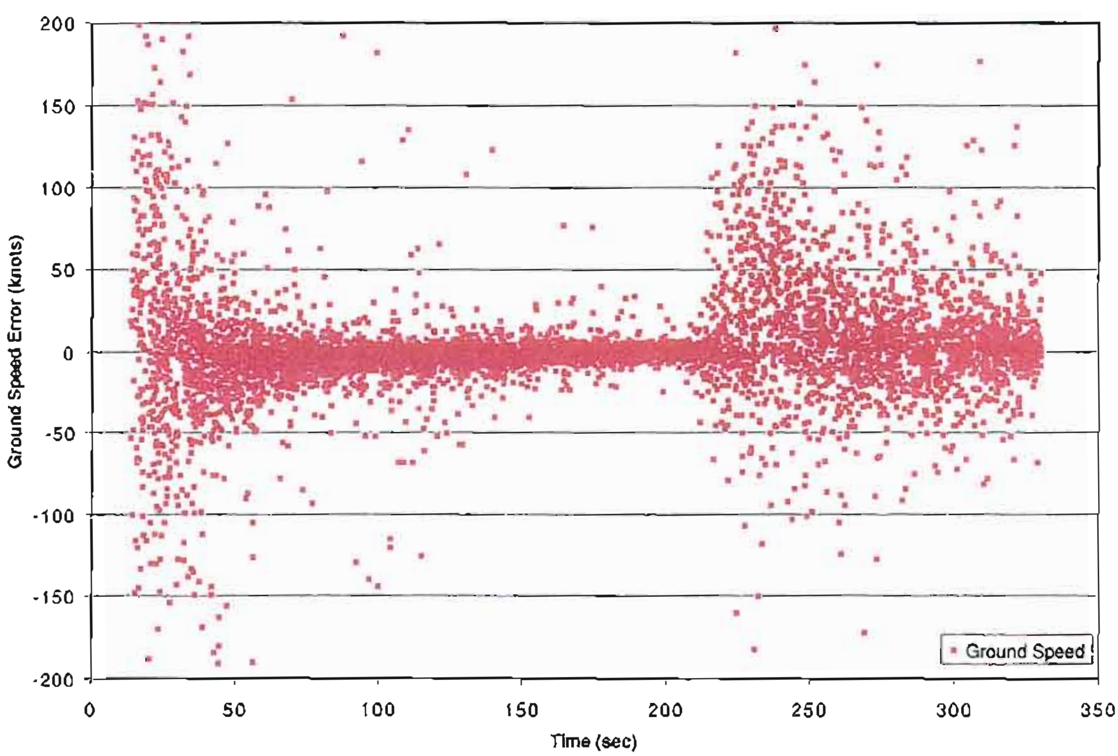


Figure 66. Turning Test (Turn 200-230 Seconds) - Ground Speed Error - CD2 Data - COTS C.

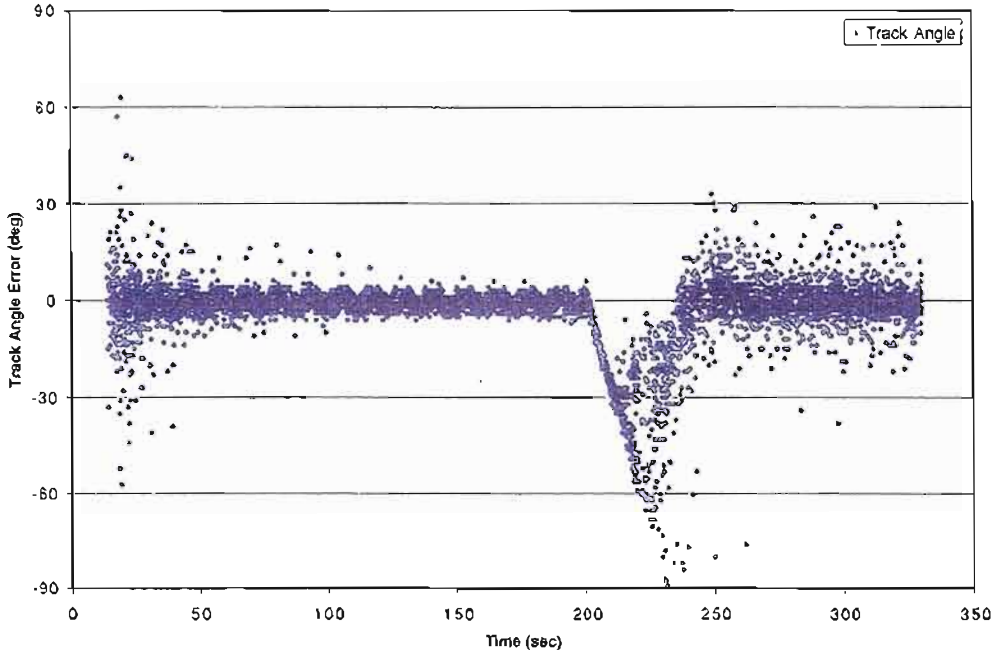


Figure 67. Turning Test (Turn 200-230 Seconds) - Track Angle Error - Mode S Data - COTS C.

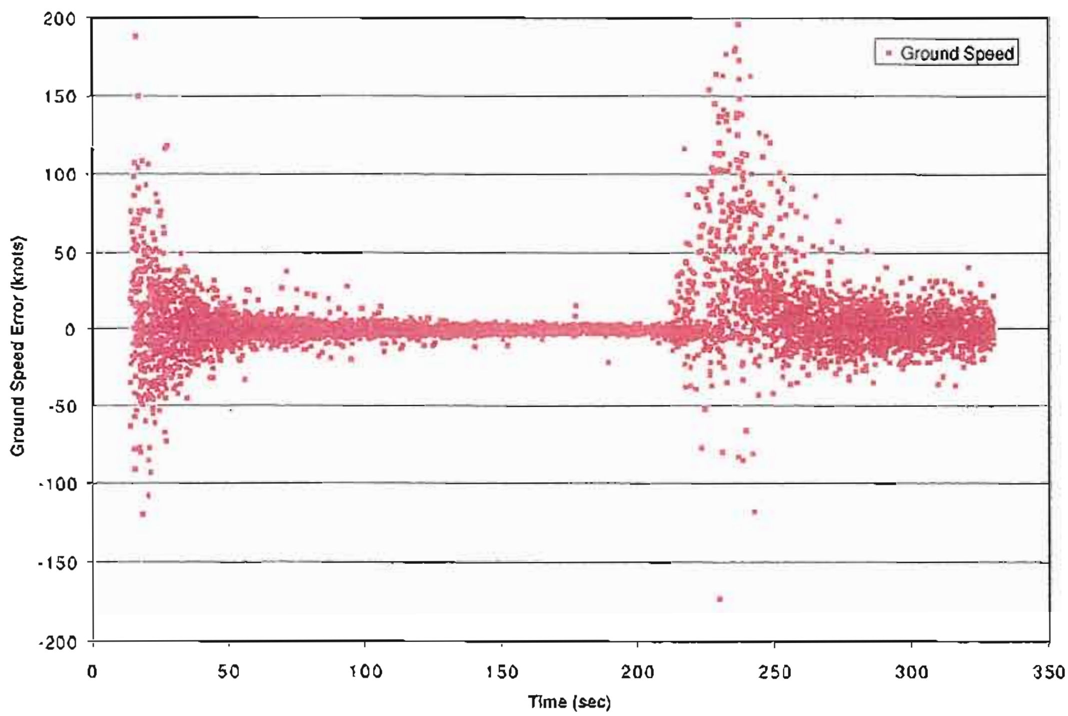


Figure 68. Turning Test (Turn 200-230 Seconds) - Ground Speed Error - Mode S Data - COTS C.

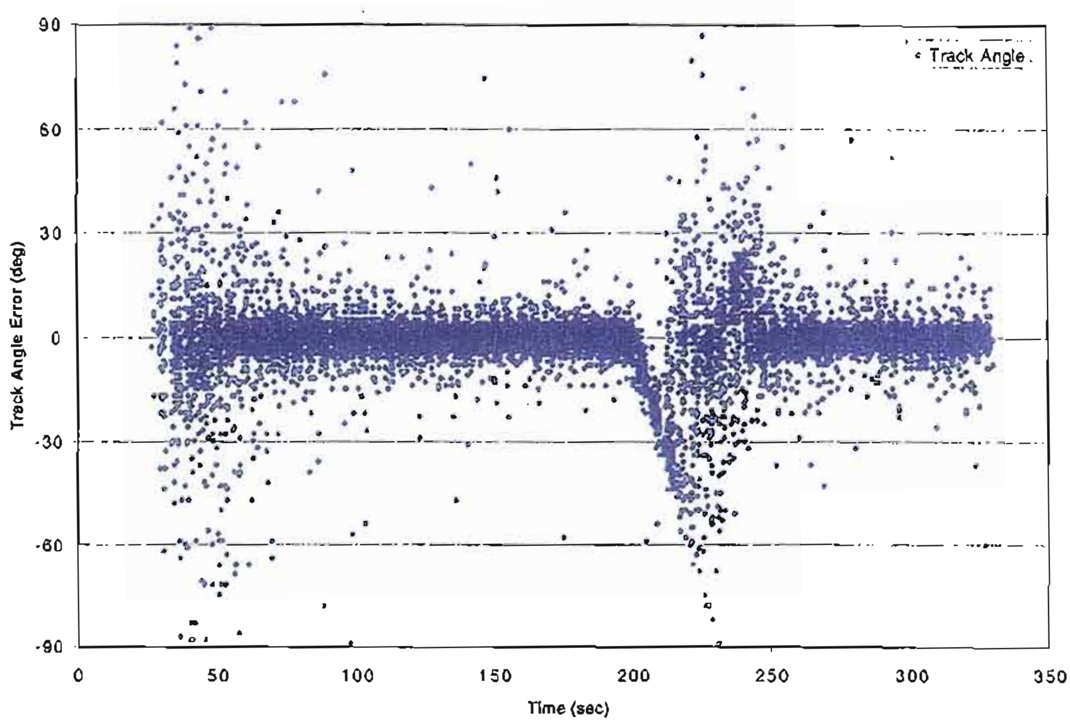


Figure 69. Turning Test (Turn 200-230 Seconds) - Track Angle Error - CD2 Data - COTS D.

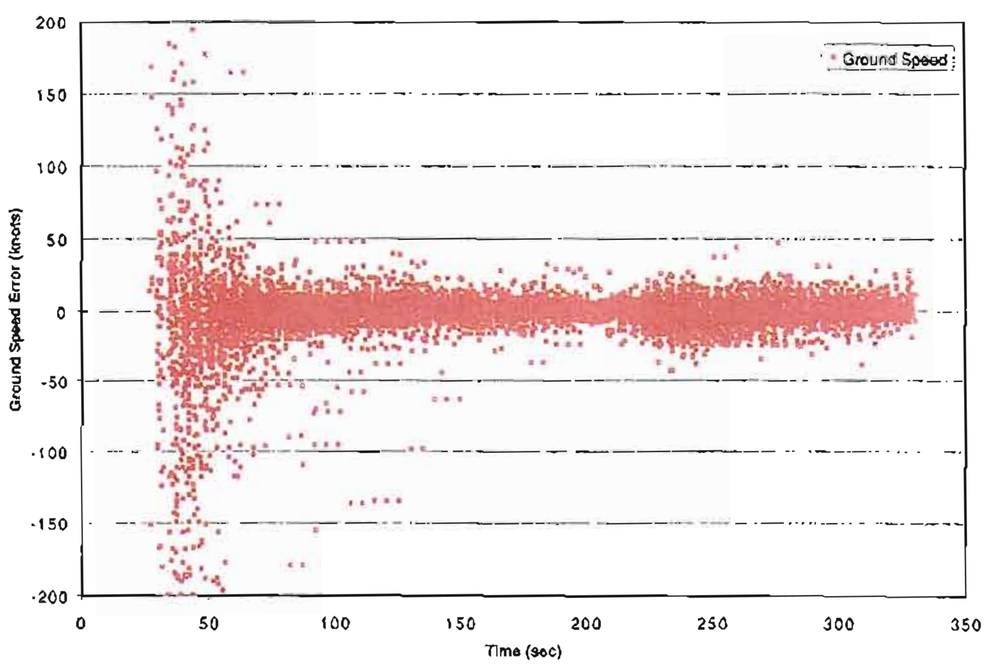


Figure 70. Turning Test (Turn 200-230 Seconds) - Ground Speed Error - CD2 Data - COTS D.

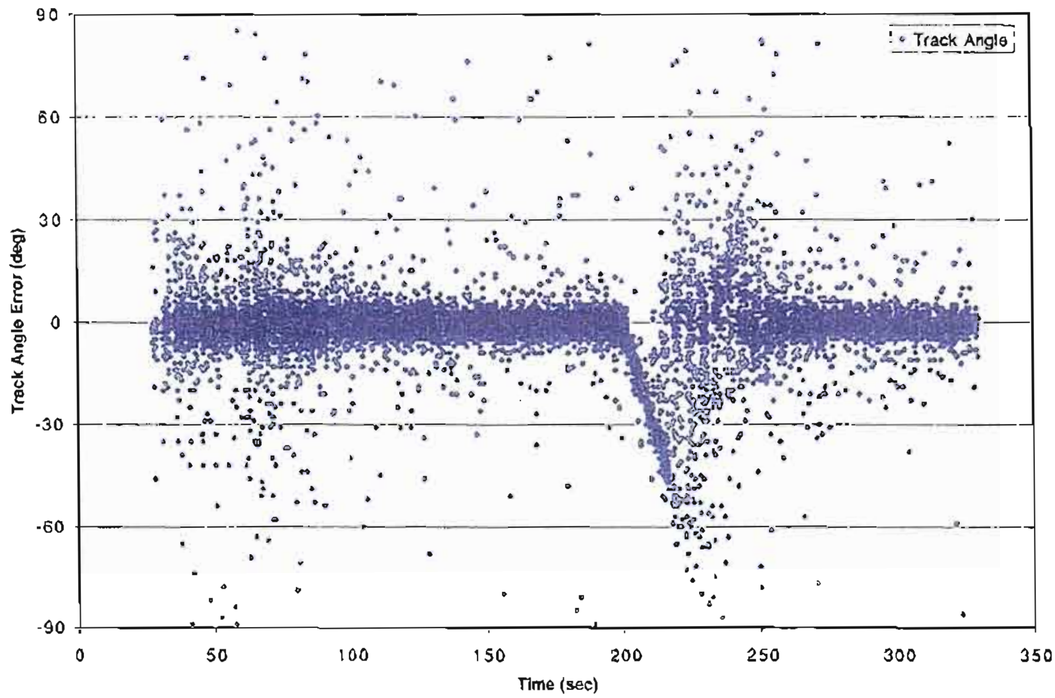


Figure 71. Turning Test (Turn 200-230 Seconds) - Track Angle Error - Mode S Data - COTS D.

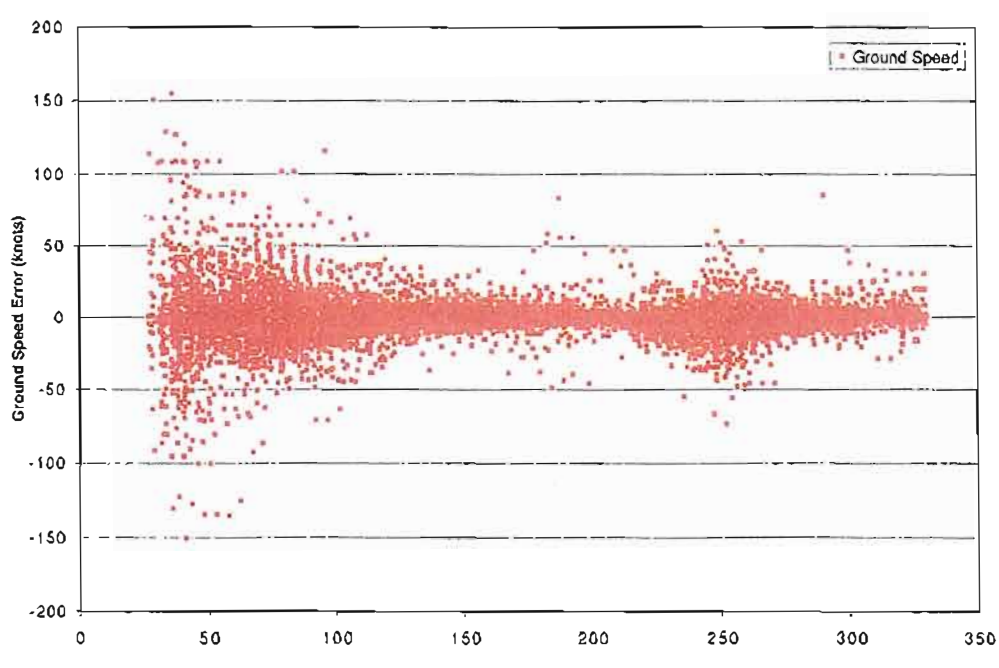


Figure 72. Turning Test (Turn 200-230 Seconds) - Ground Speed Error - Mode S Data - COTS D.

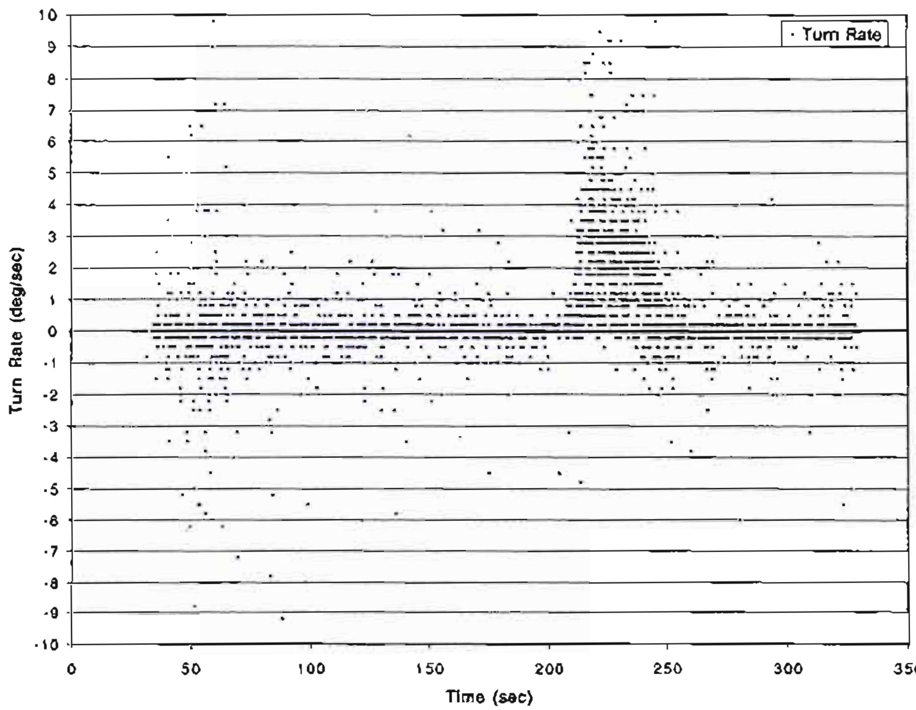


Figure 73. Computed Turn Rate Values - Turn 200-230 Seconds @ 3 Deg/Sec - CD2 Data - COTS D.

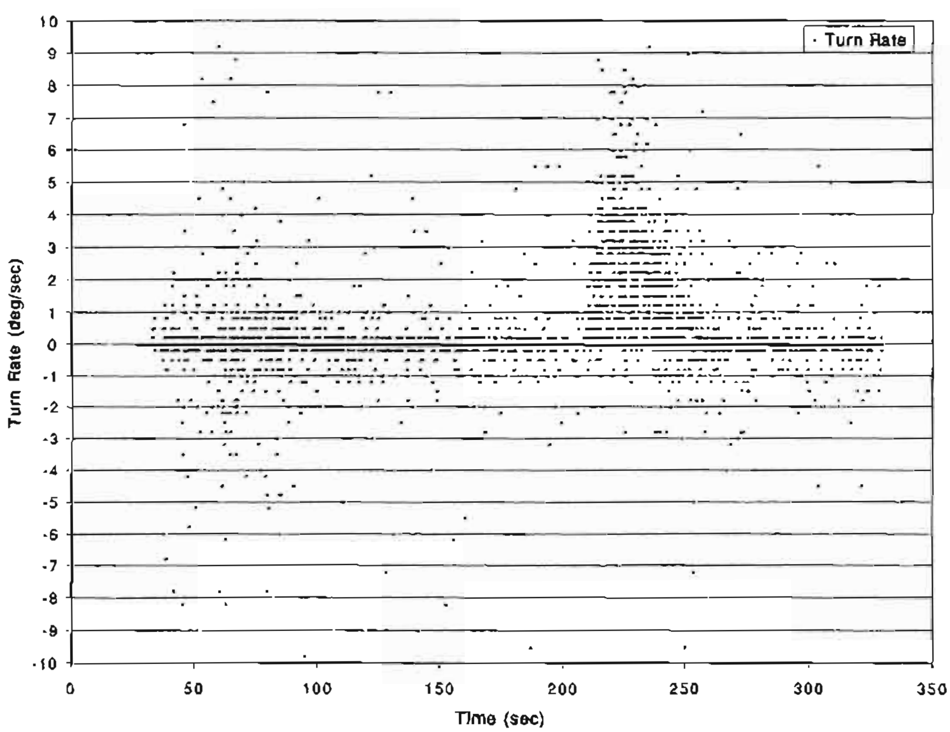


Figure 74. Computed Turn Rate Values - Turn 200-230 Seconds @ 3 Deg/Sec - Mode S Data - COTS D.

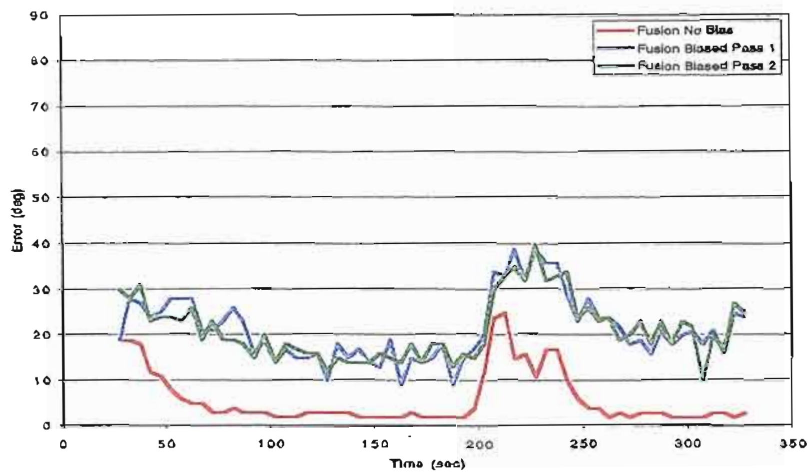


Figure 75. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds - Track Angle Error - CD2 Data - COTS A.

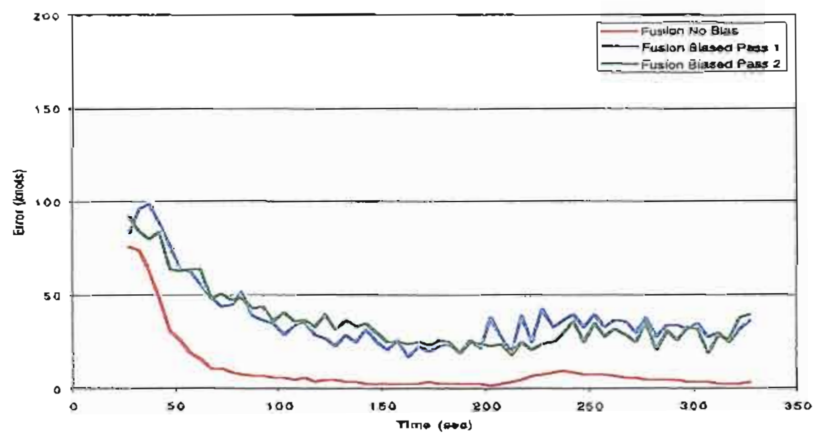


Figure 76. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds - Ground Speed Error - CD2 Data - COTS A.

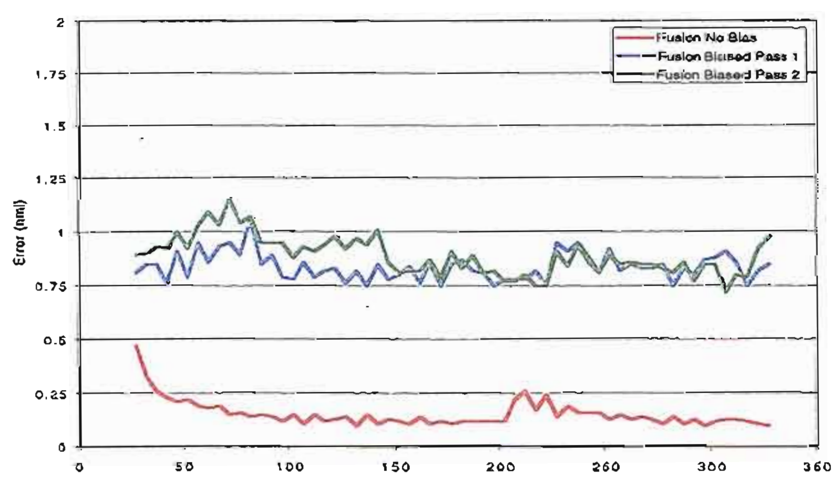


Figure 77. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds - Position Error - CD2 Data - COTS A.

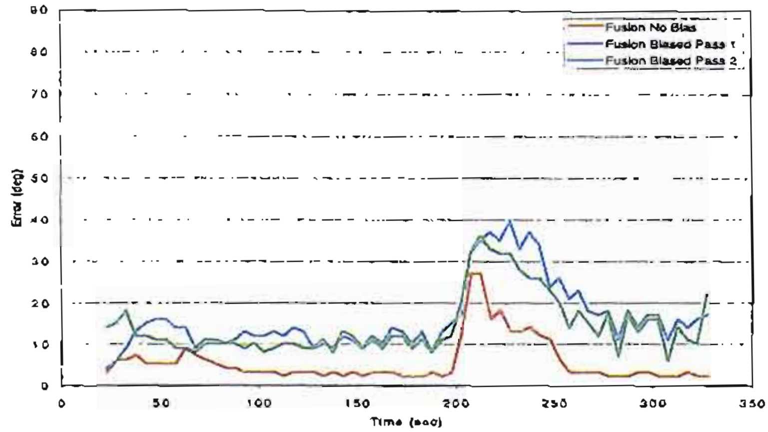


Figure 78. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds - Track Angle Error - Mode S Data - COTS A.

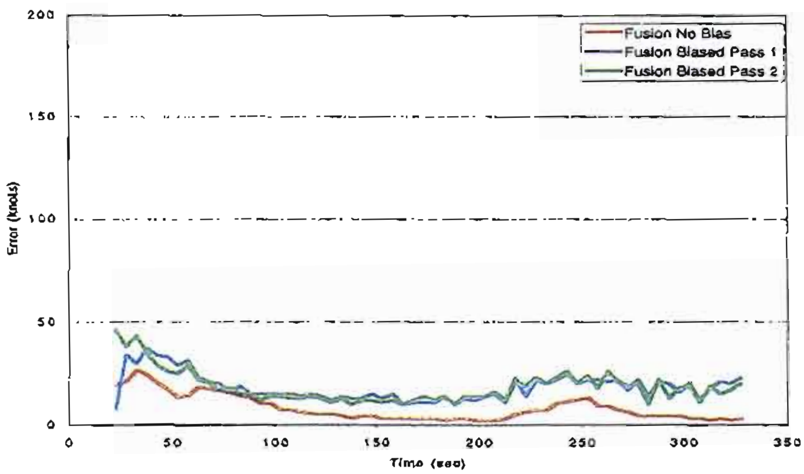


Figure 79. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds - Ground Speed Error - Mode S Data - COTS A.

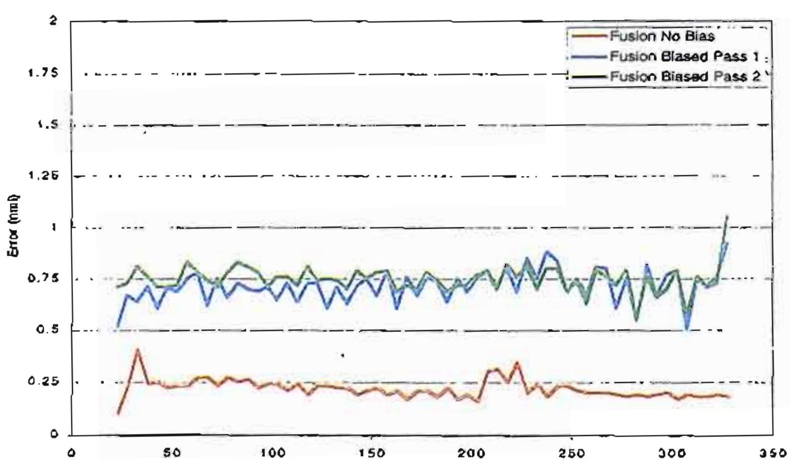


Figure 80. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds - Position Error - Mode S Data - COTS A.

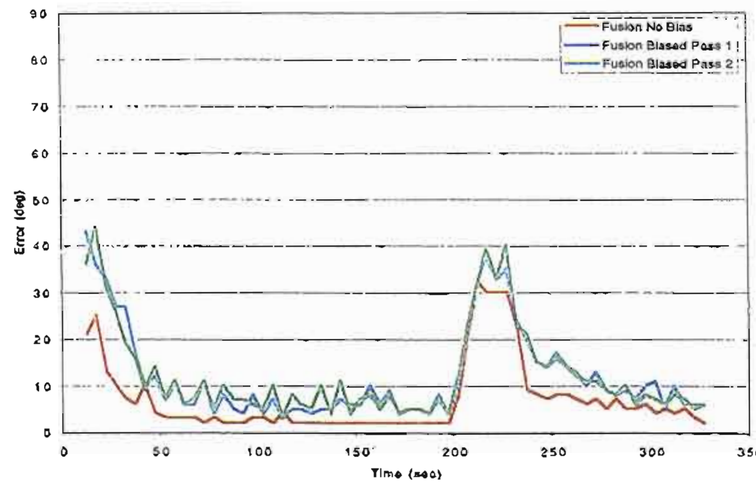


Figure 81. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds - Track Angle Error - CD2 Data - COTS B.

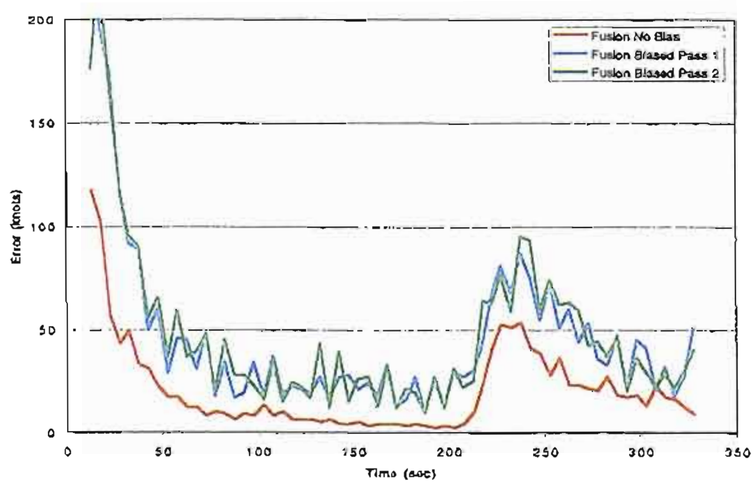


Figure 82. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds - Ground Speed Error - CD2 Data - COTS B.

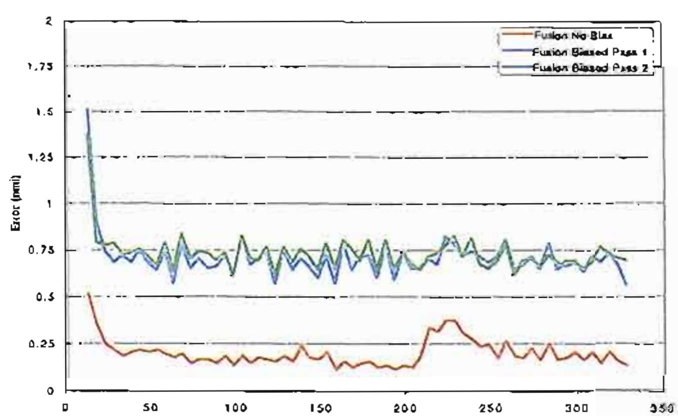


Figure 83. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds - Position Error - CD2 Data - COTS B.

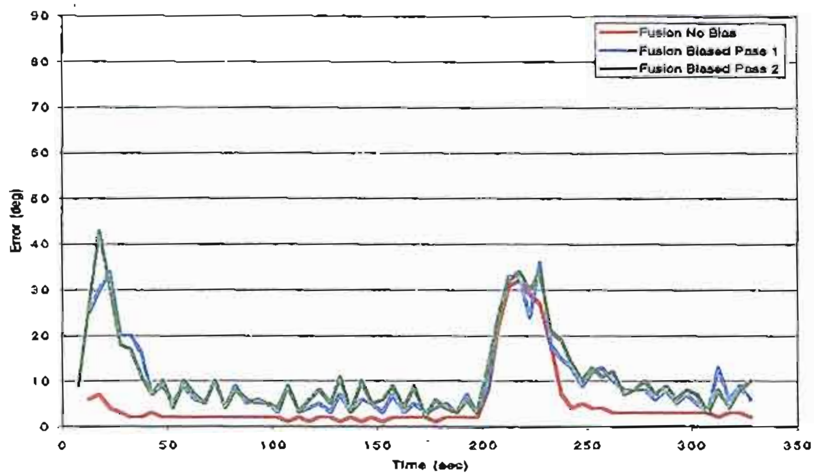


Figure 84. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds – Track Angle Error – Mode S Data - COTS B.

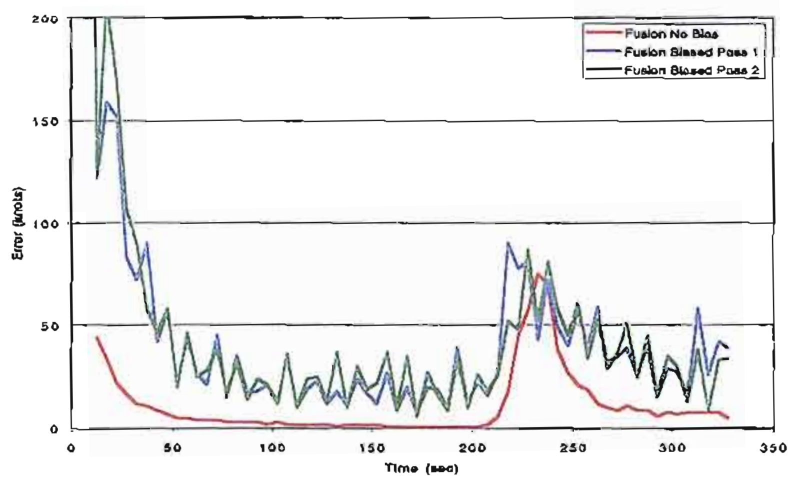


Figure 85. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds - Ground Speed Error - Mode S Data - COTS B.

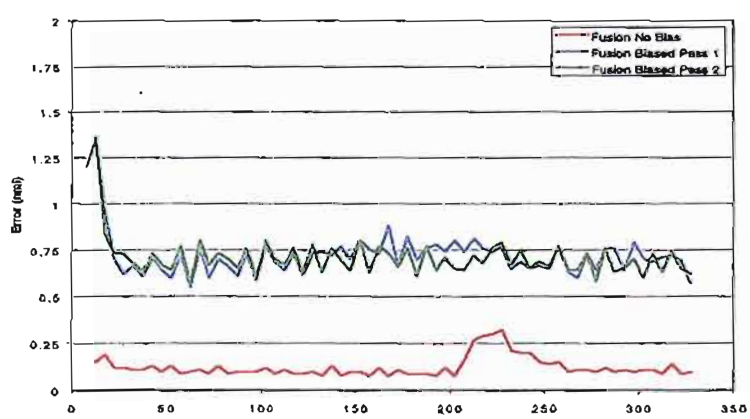


Figure 86. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds - Position Error - Mode S Data - COTS B.

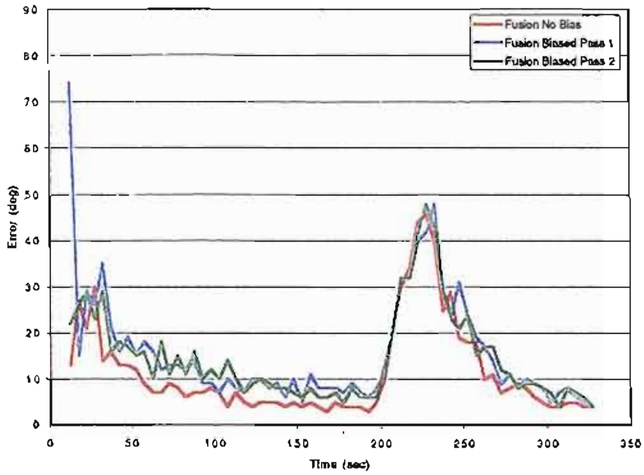


Figure 87. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds - Track Angle Error - CD2 Data - COTS C.

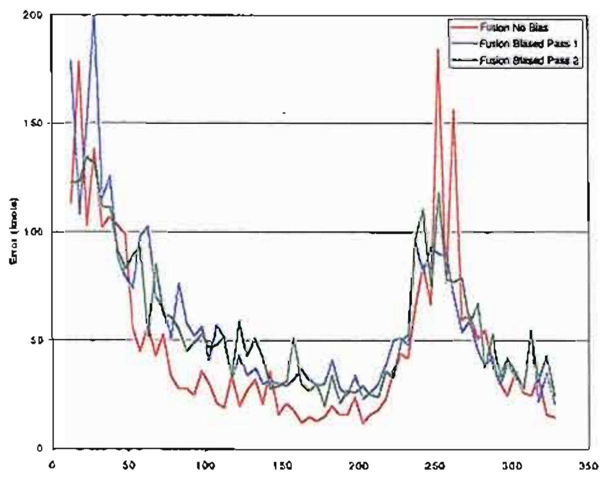


Figure 88. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds - Ground Speed Error - CD2 Data - COTS C.

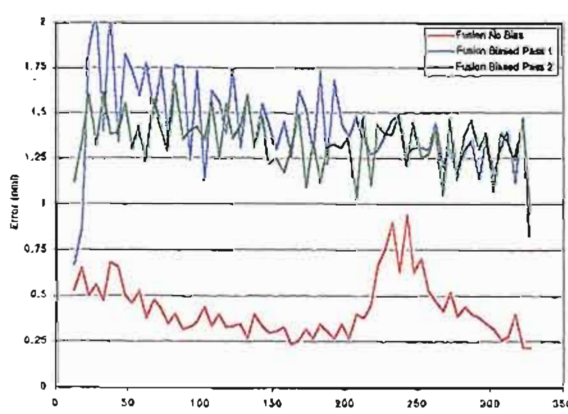


Figure 89. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds - Position Error - CD2 Data - COTS C.

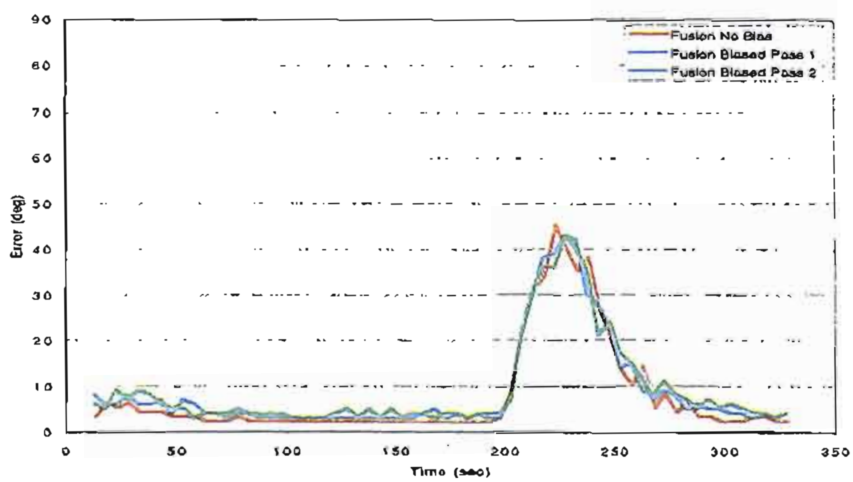


Figure 90. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds - Track Angle Error - Mode S Data -COTS C.

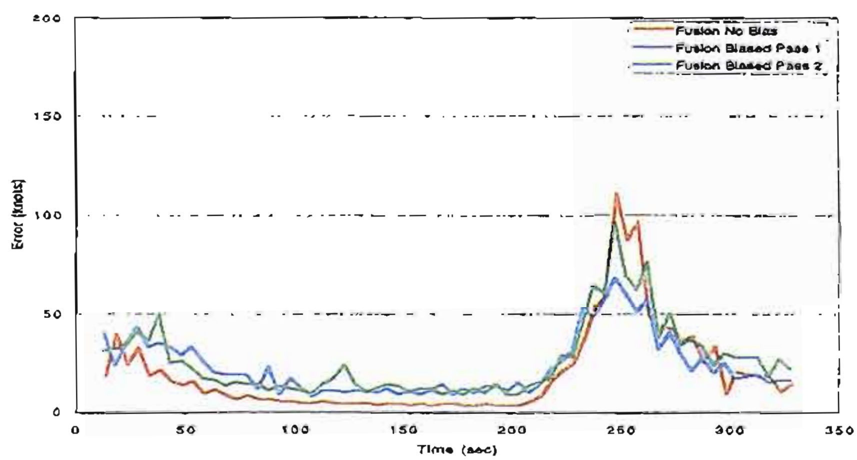


Figure 91. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds - Ground Speed Error - Mode S Data -COTS C.

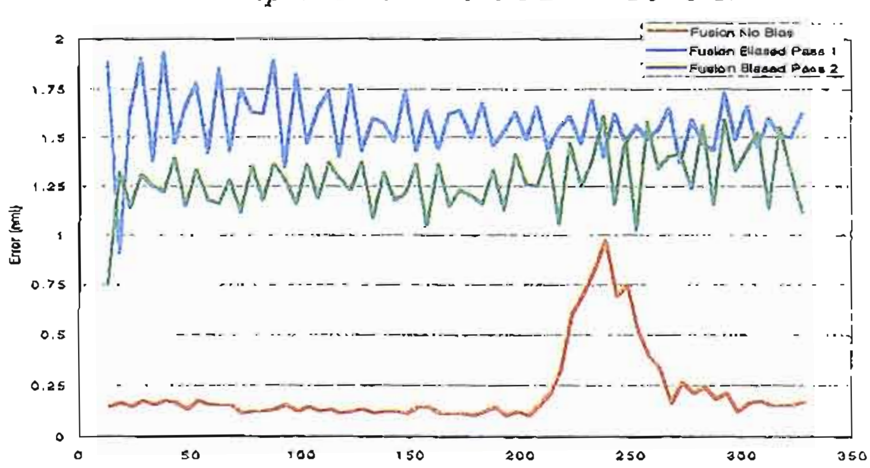


Figure 92. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds - Position Error - Mode S Data - COTS C.

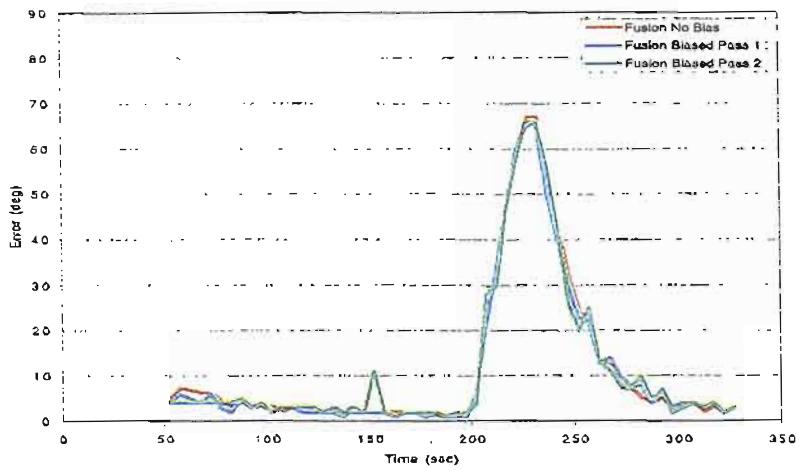


Figure 93. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds - Track Angle Error - CD2 Data - COTS D.

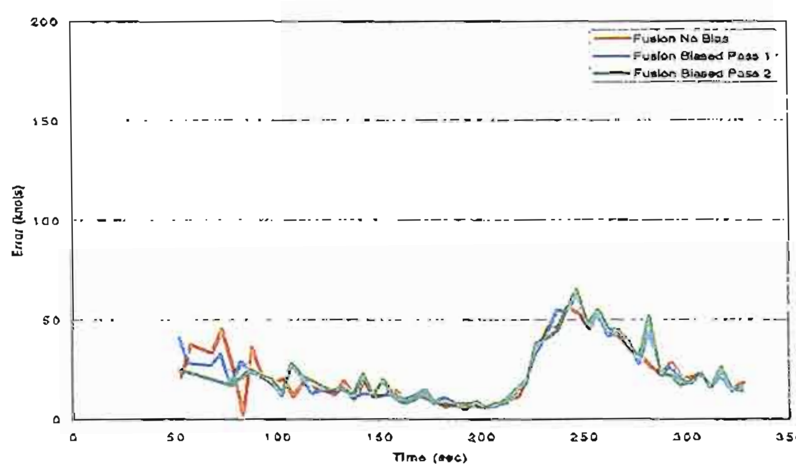


Figure 94. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds - Ground Speed Error - CD2 Data - COTS D.

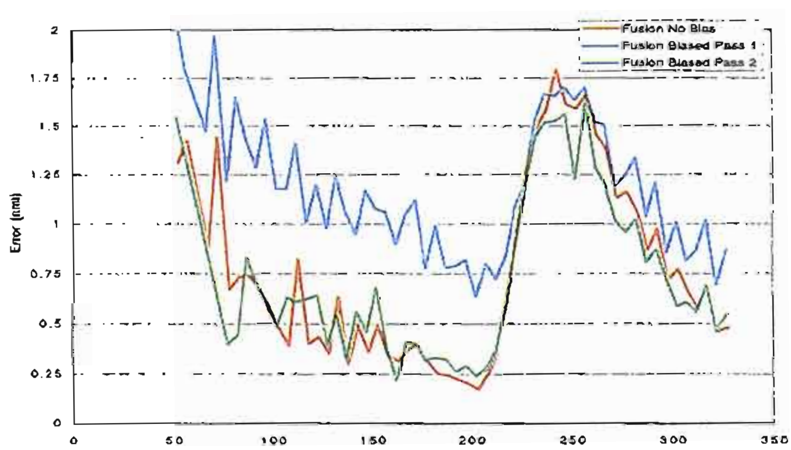


Figure 95. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds - Position Error - CD2 Data - COTS D.

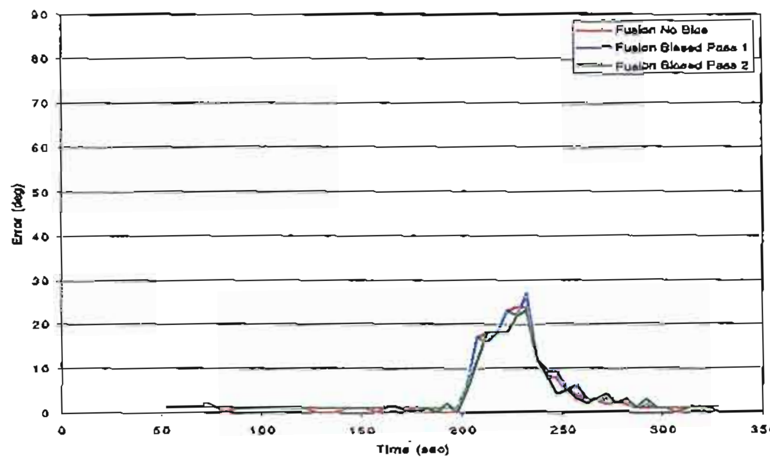


Figure 96. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds – Track Angle Error - Mode S Data - COTS D.

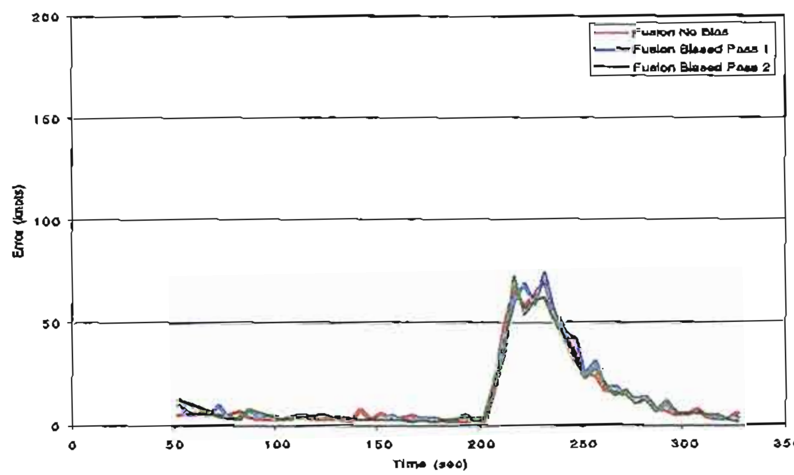


Figure 97. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds - Ground Speed Error - Mode S Data - COTS D.

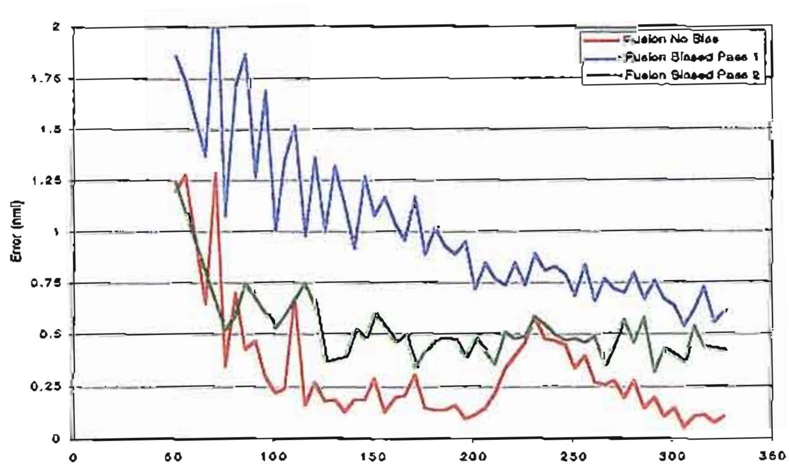


Figure 98. Bias Adaptation Test (1 Hour Adaptation Period) - Turn 200-230 Seconds - Position Error - Mode S Data - COTS D.

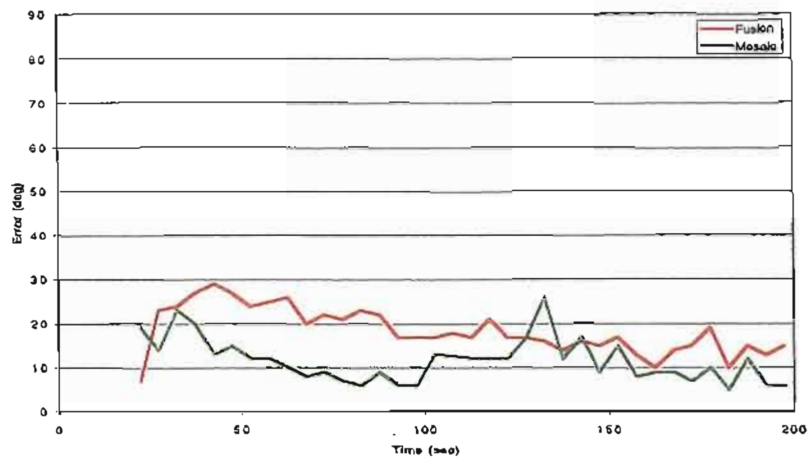


Figure 99. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Track Angle Error - CD2 Data - COTS A.

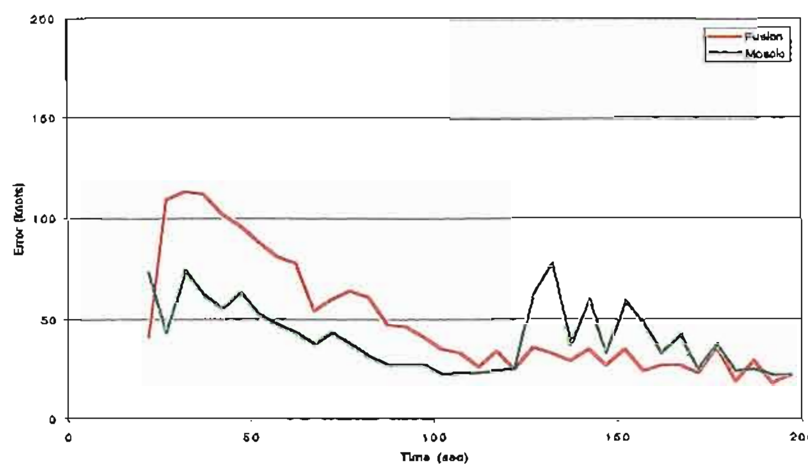


Figure 100. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Ground Speed Error - CD2 Data - COTS A.

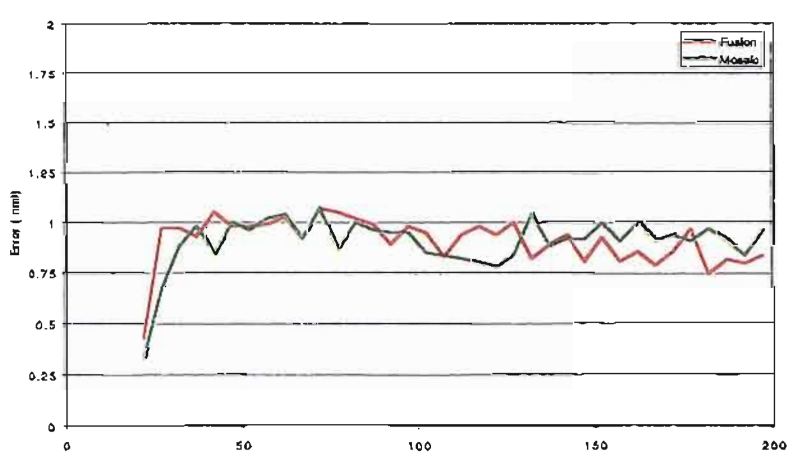


Figure 101. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Position Error - CD2 Data - COTS A.

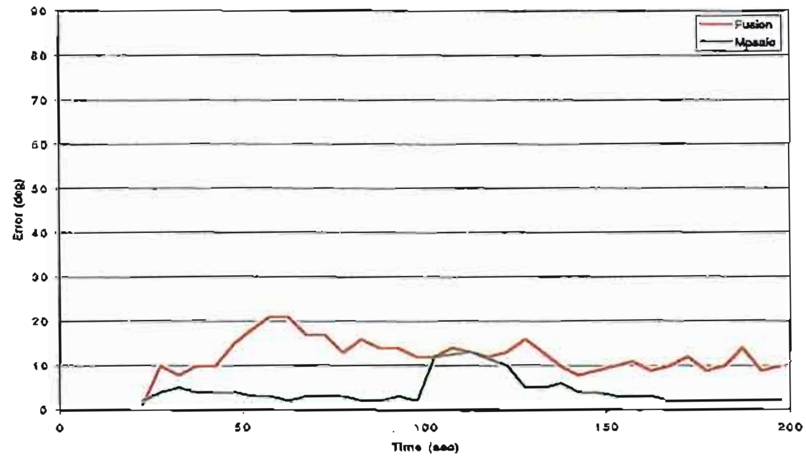


Figure 102. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Track Angle Error - Mode S Data - COTS A.

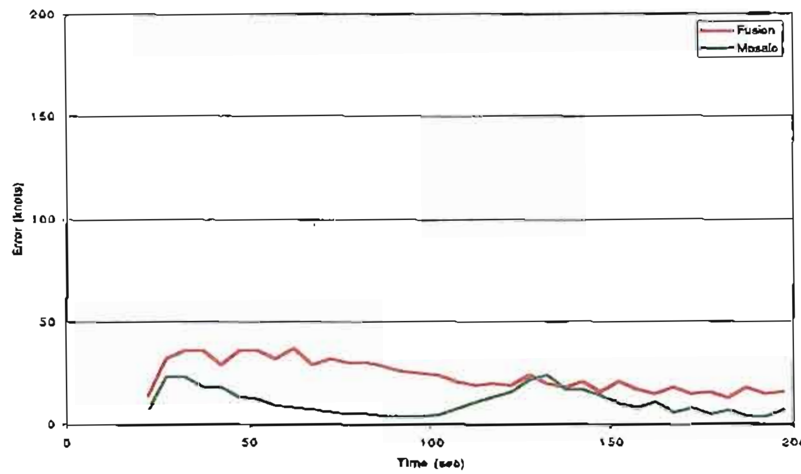


Figure 103. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Ground Speed Error - Mode S Data - COTS A.

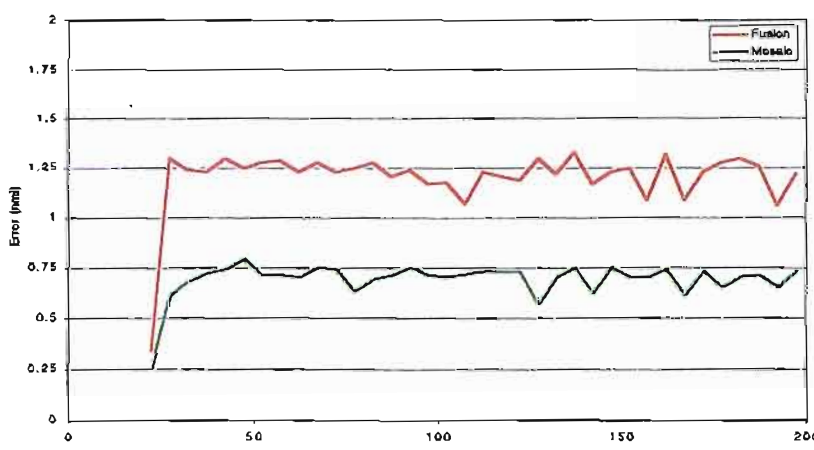


Figure 104. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Position Error - Mode S Data - COTS A.

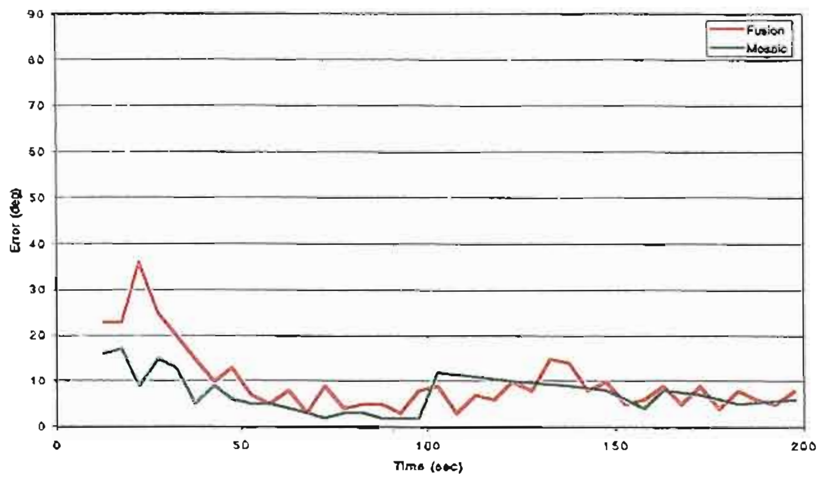


Figure 105. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Track Angle Error - CD2 Data - COTS B.

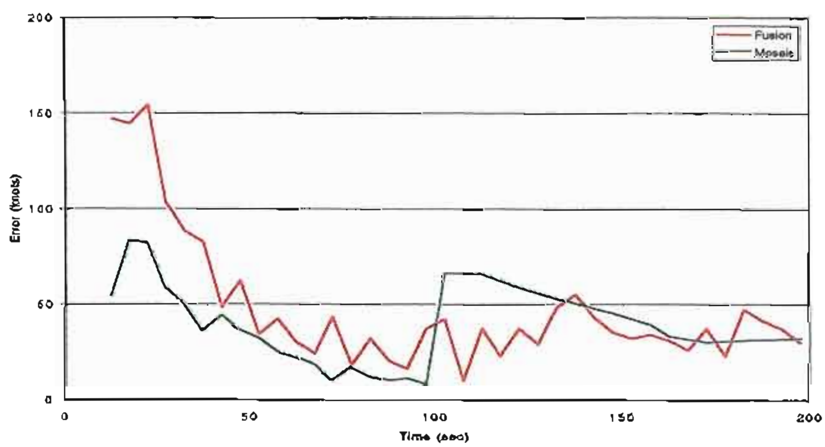


Figure 106. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Ground Speed Error - CD2 Data - COTS B.

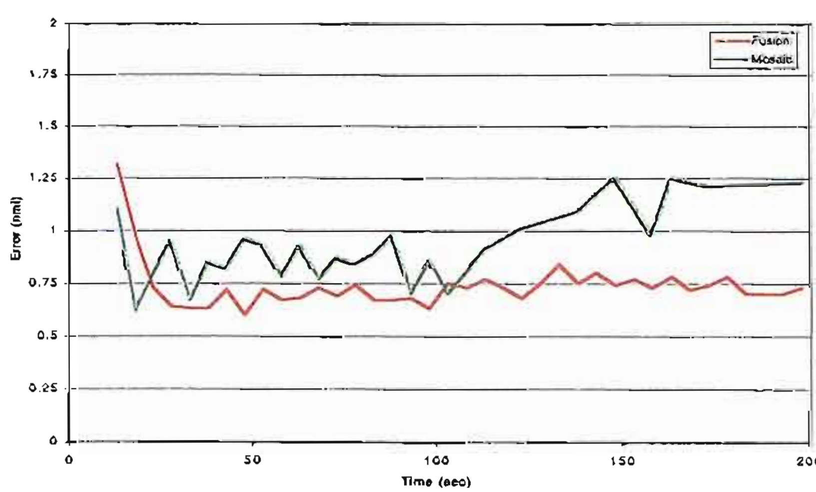


Figure 107. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Position Error - CD2 Data - COTS B.

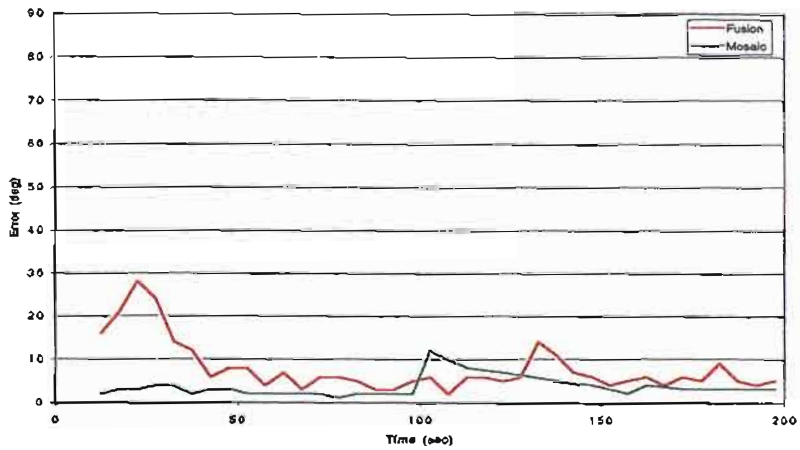


Figure 108. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Track Angle Error - Mode S Data - COTS B.

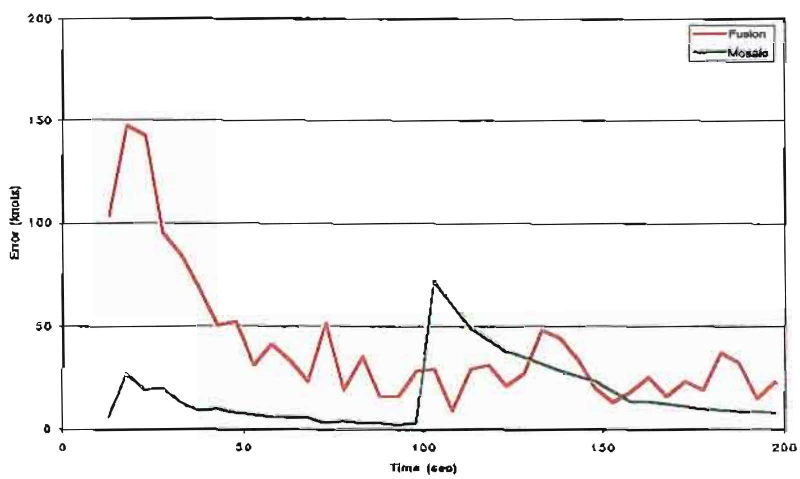


Figure 109. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Ground Speed Error - Mode S Data - COTS B.

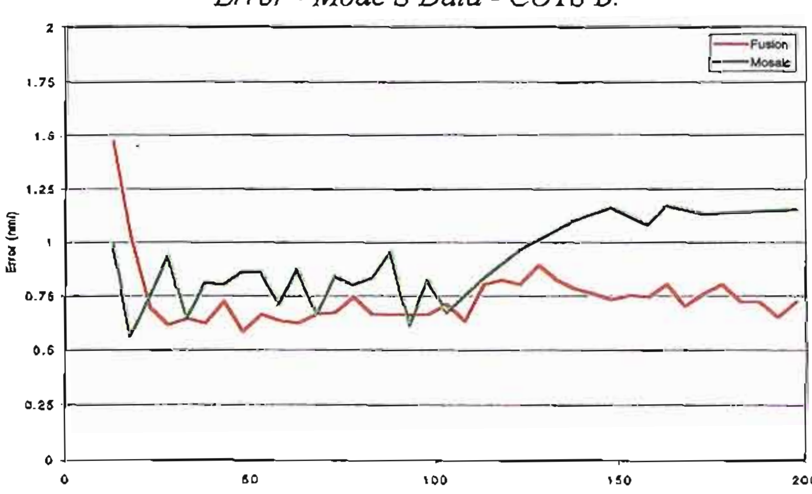


Figure 110. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Position Error - Mode S Data - COTS B.

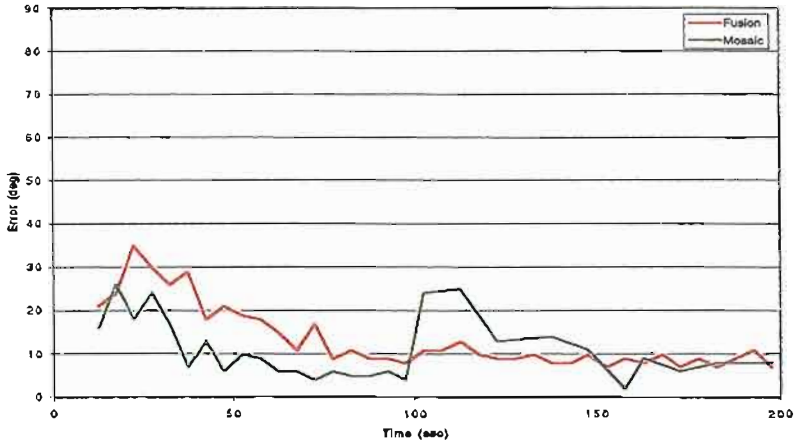


Figure 111. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Track Angle Error - CD2 Data - COTS C.

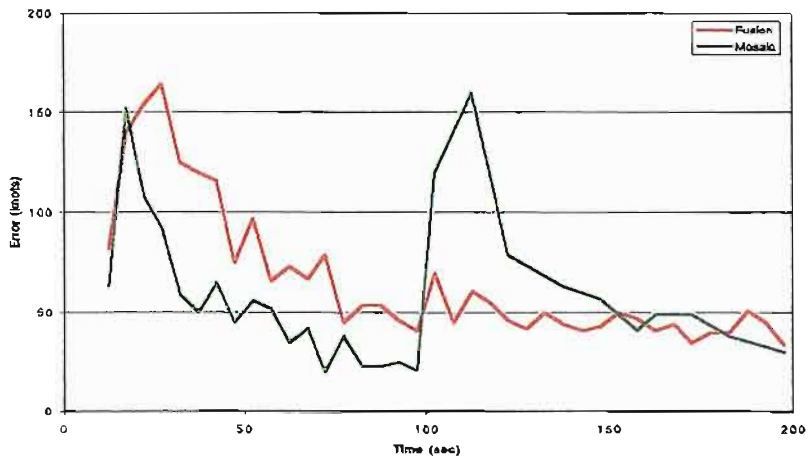


Figure 112. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Ground Speed Error - CD2 Data - COTS C.

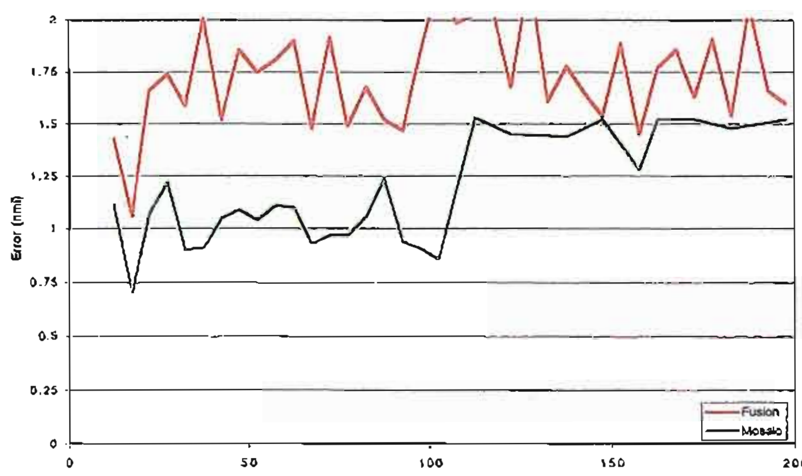


Figure 113. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Position Error - CD2 Data - COTS C.

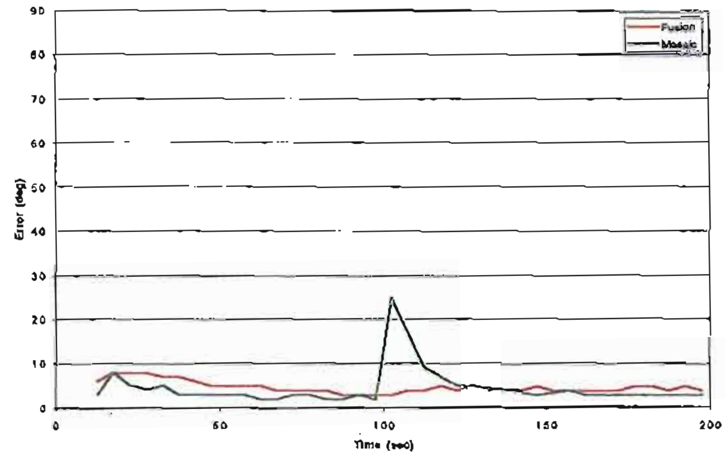


Figure 114. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Track Angle Error - Mode S Data - COTS C.

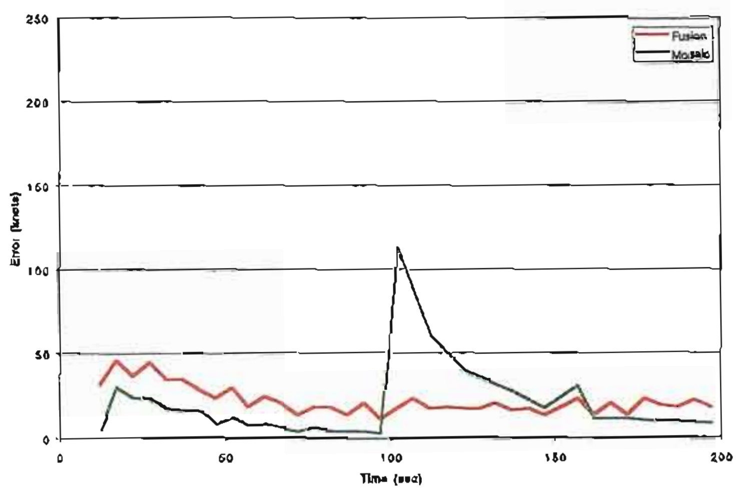


Figure 115. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Ground Speed Error - Mode S Data - COTS C.

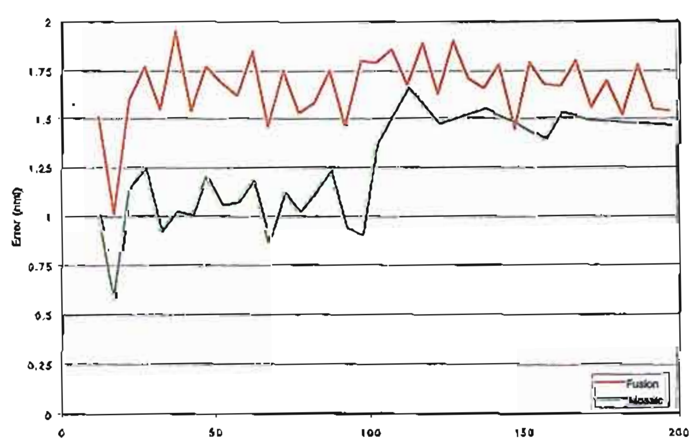


Figure 116. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Position Error - Mode S Data - COTS C.

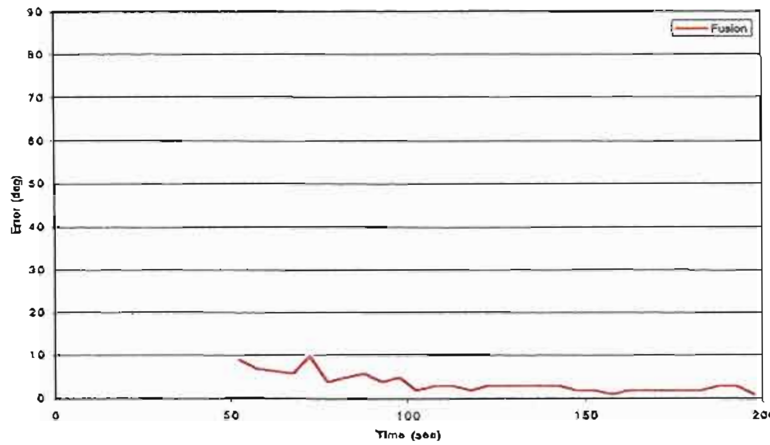


Figure 117. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Track Angle Error - CD2 Data - COTS D.

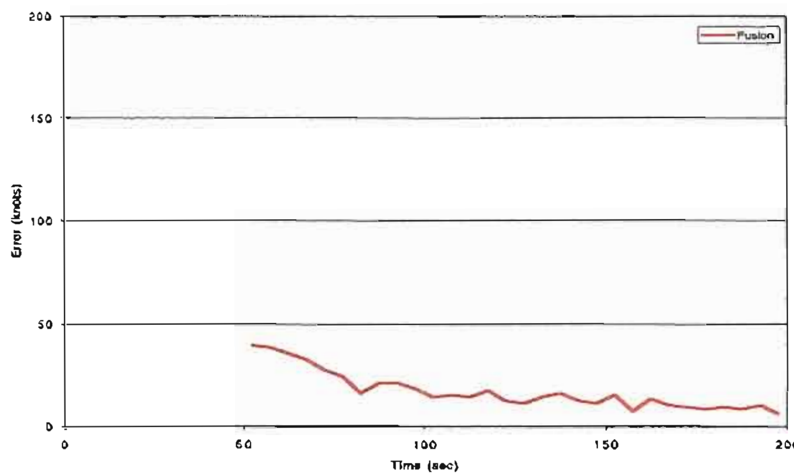


Figure 118. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Ground Speed Error - CD2 Data - COTS D.

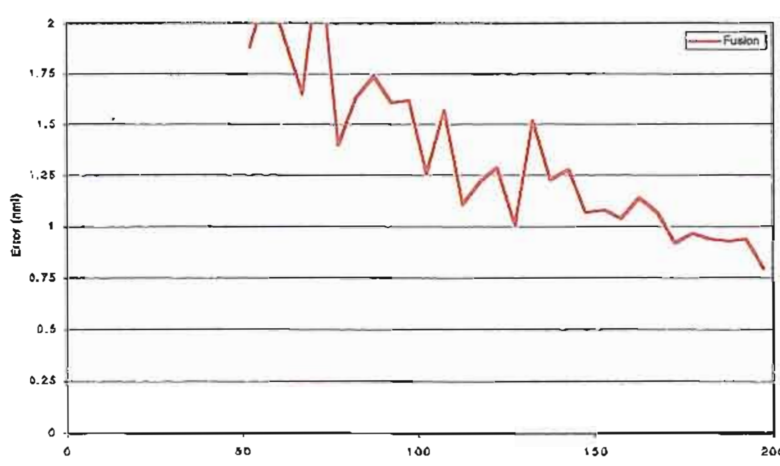


Figure 119. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Position Error - CD2 Data - COTS D.

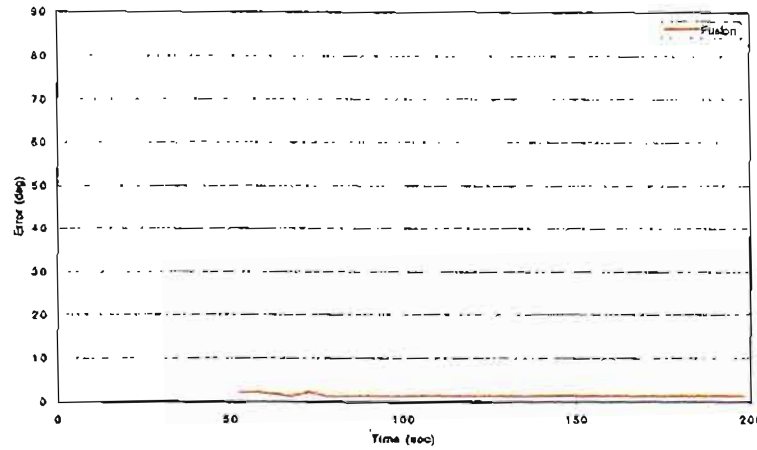


Figure 120. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Track Angle Error - Mode S Data - COTS D.

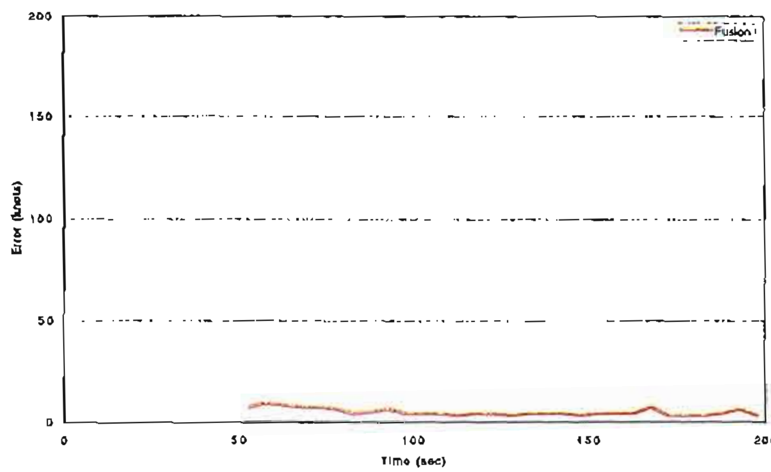


Figure 121. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Ground Speed Error - Mode S Data - COTS D.

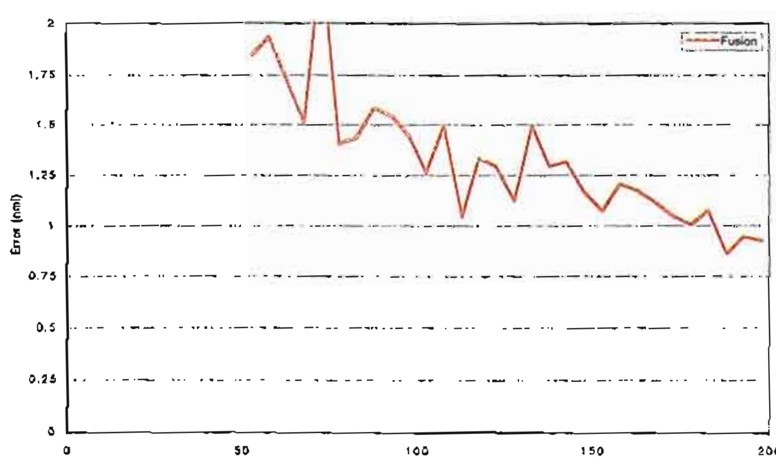


Figure 122. Sensor Hop Due to Biases Test - Sensor Change at 100 Seconds - Position Error - Mode S Data - COTS D.

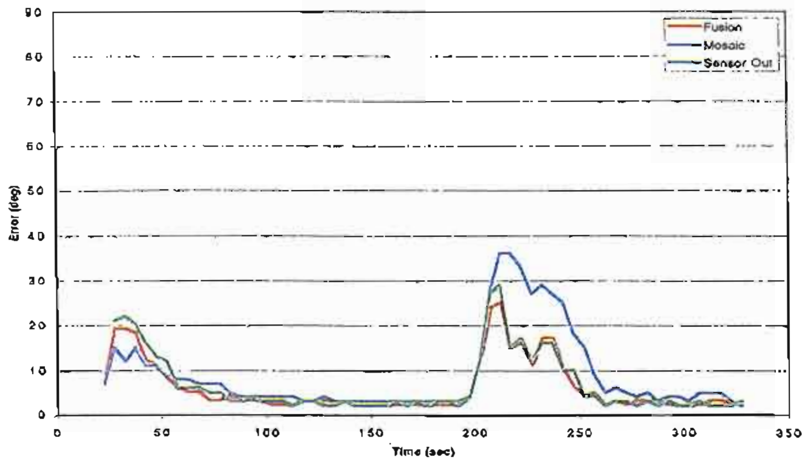


Figure 123. Preferred Sensor Outage Test - Turn 200-230 Seconds - Track Angle Error - CD2 Data - COTS A.

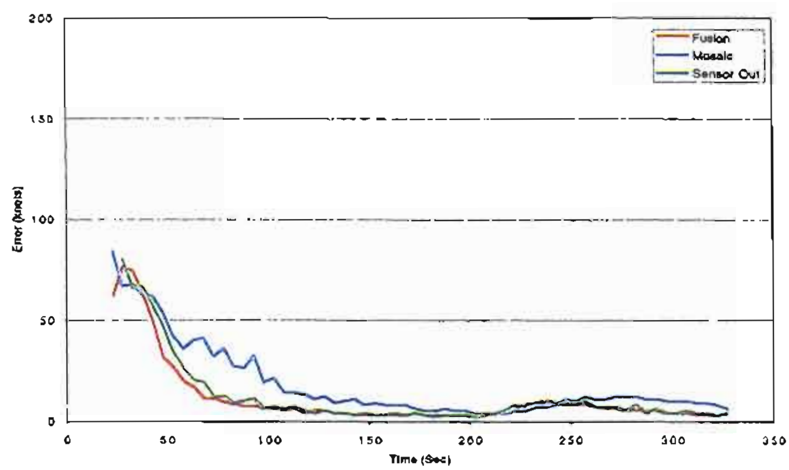


Figure 124. Preferred Sensor Outage Test - Turn 200-230 Seconds - Ground Speed Error - CD2 Data - COTS A.

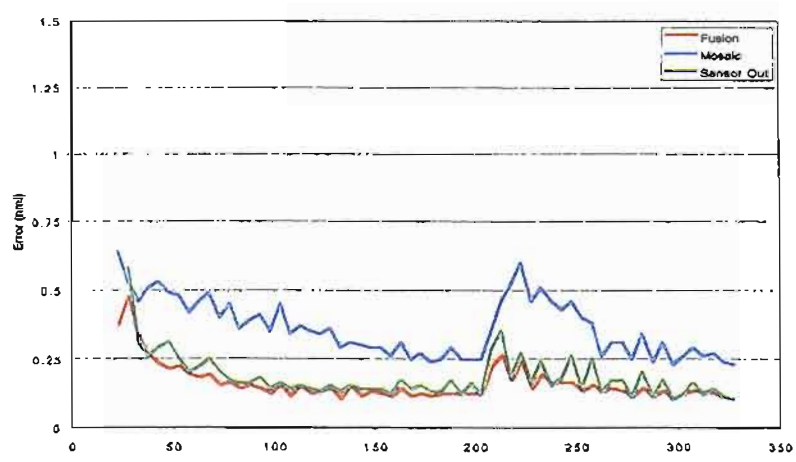


Figure 125. Preferred Sensor Outage Test - Turn 200-230 Seconds - Position Error - CD2 Data - COTS A.

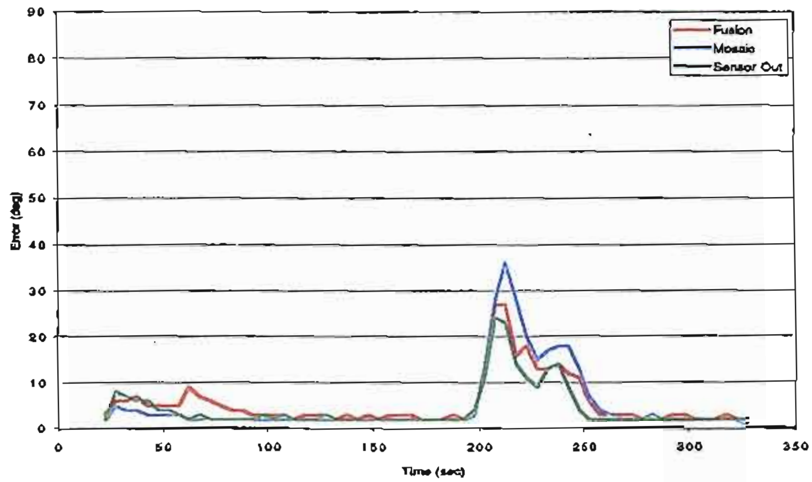


Figure 126. Preferred Sensor Outage Test - Turn 200-230 Seconds - Track Angle Error Mode S Data - COTS A.

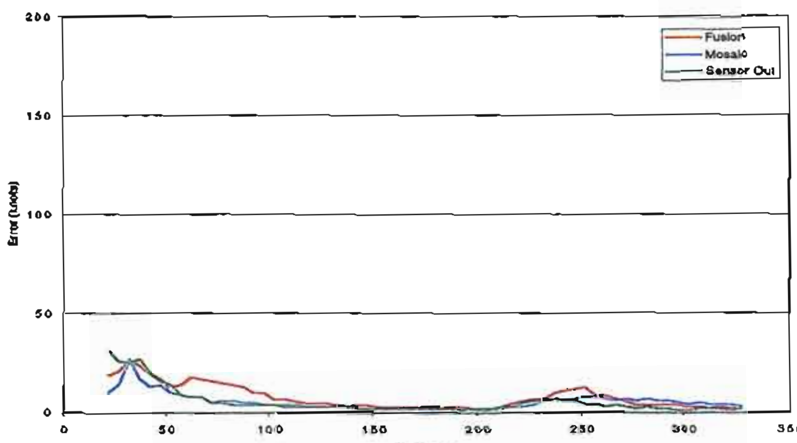


Figure 127. Preferred Sensor Outage Test - Turn 200-230 Seconds - Ground Speed Error - Mode S Data - COTS A.

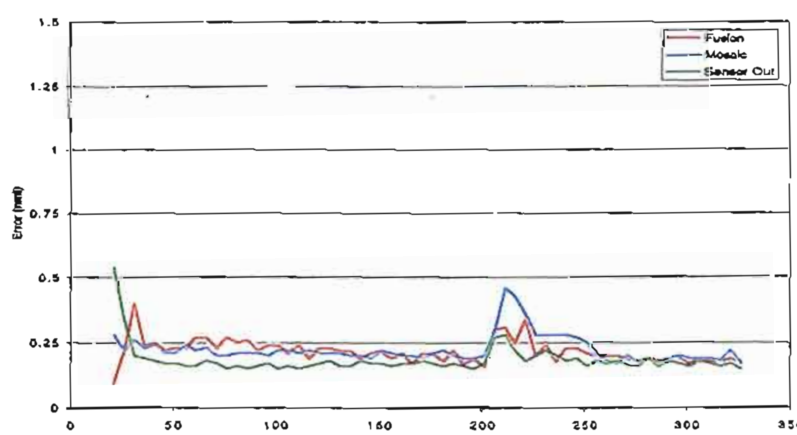


Figure 128. Preferred Sensor Outage Test - Turn 200-230 Seconds - Position Error - Mode S Data - COTS A.

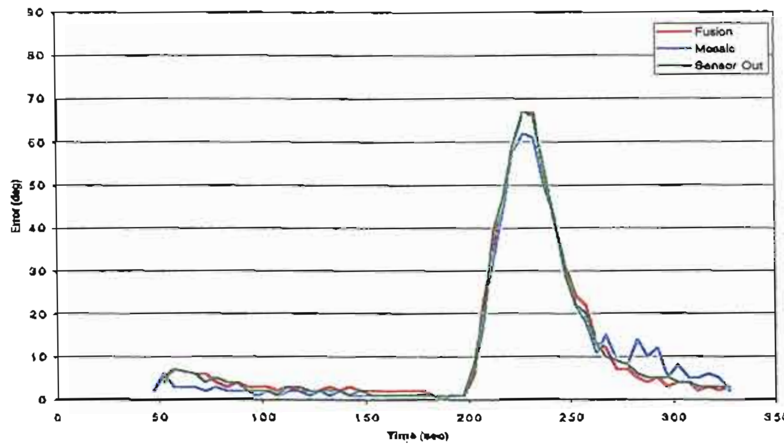


Figure 129. Preferred Sensor Outage Test - Turn 200-230 Seconds - Track Angle Error - CD2 Data - COTS B.

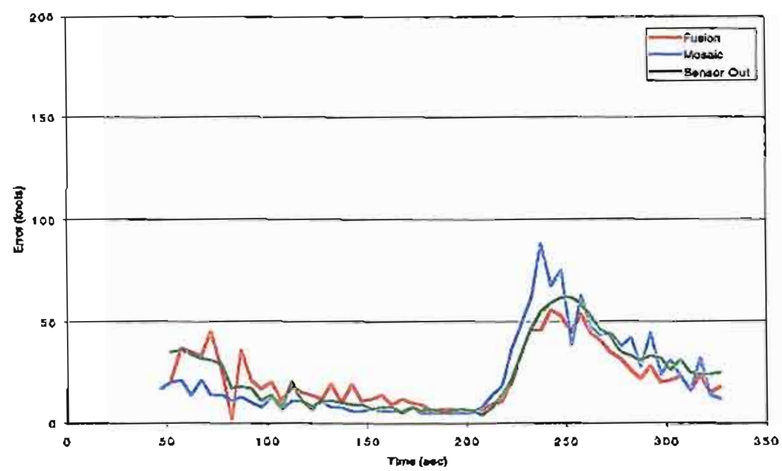


Figure 130. Preferred Sensor Outage Test - Turn 200-230 Seconds - Ground Speed Error - CD2 Data - COTS B.

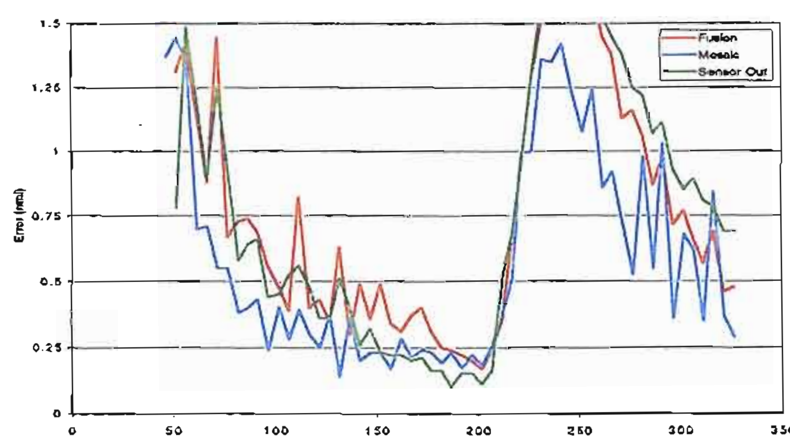


Figure 131. Preferred Sensor Outage Test - Turn 200-230 Seconds - Position Error - CD2 Data - COTS B.

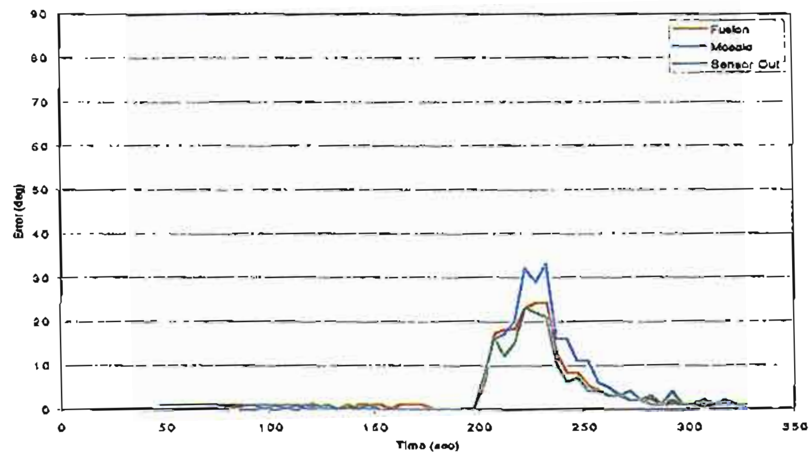


Figure 132. Preferred Sensor Outage Test - Turn 200-230 Seconds - Track Angle Error - Mode S Data - COTS B.

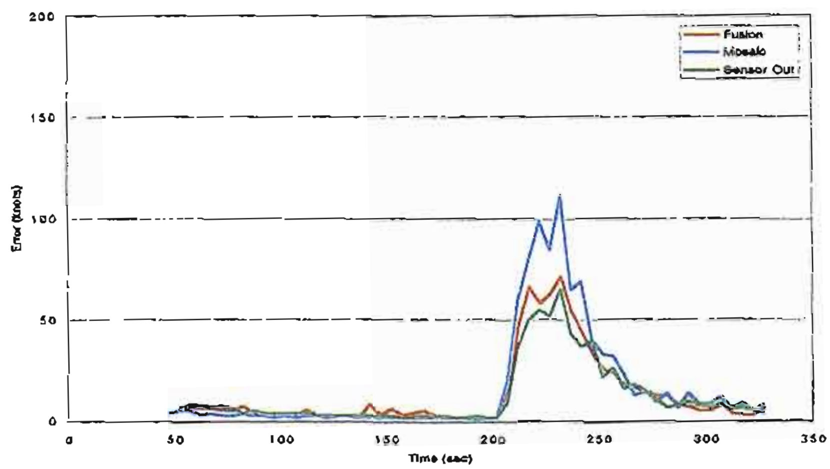


Figure 133. Preferred Sensor Outage Test - Turn 200-230 Seconds - Ground Speed Error - Mode S Data - COTS B.

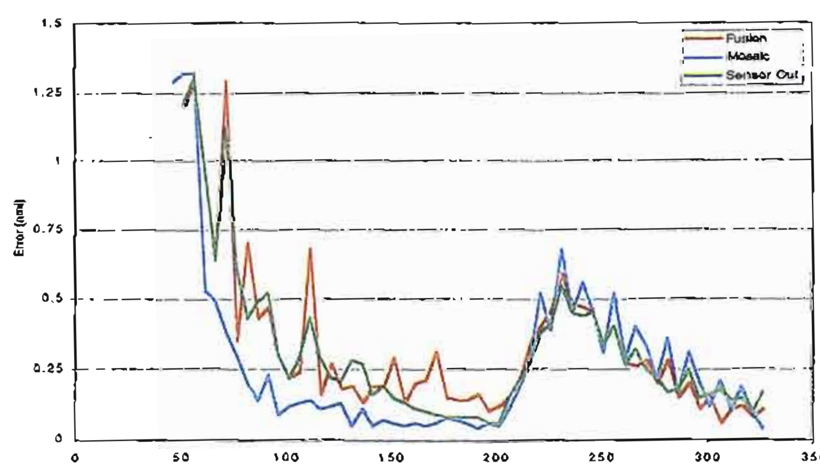


Figure 134. Preferred Sensor Outage Test - Turn 200-230 Seconds - Position Error - Mode S Data - COTS B.

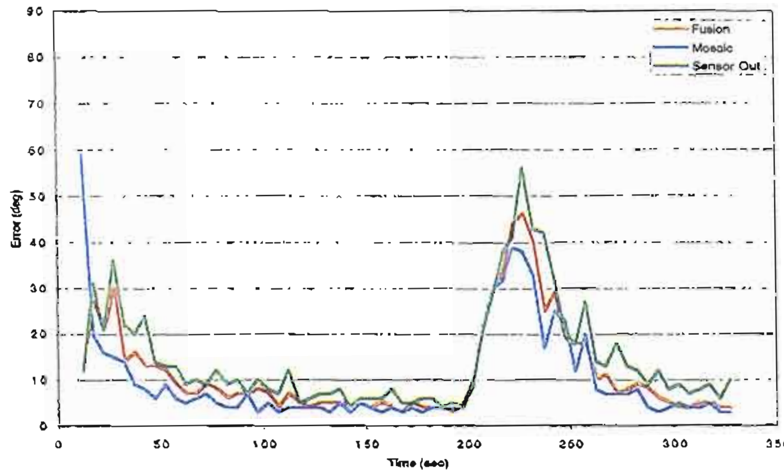


Figure 135. Preferred Sensor Outage Test - Turn 200-230 Seconds - Track Angle Error - CD2 Data - COTS C.

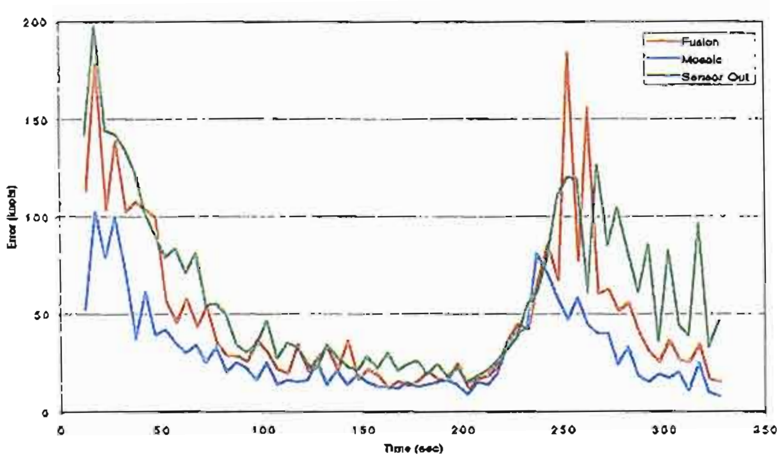


Figure 136. Preferred Sensor Outage Test - Turn 200-230 Seconds - Ground Speed Error - CD2 Data - COTS C.

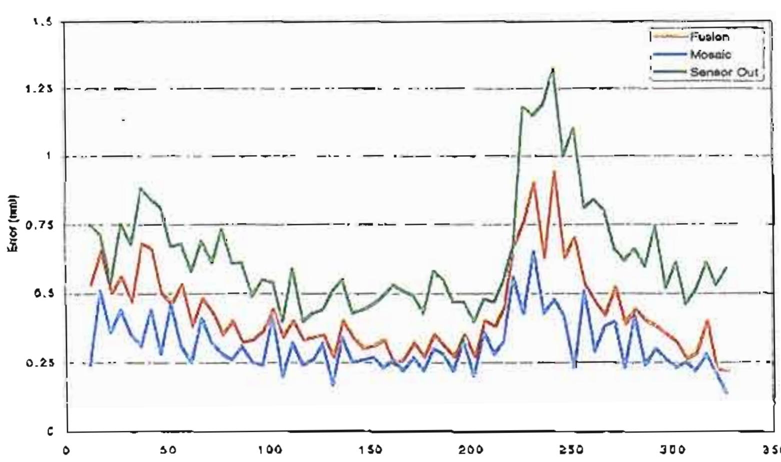


Figure 137. Preferred Sensor Outage Test - Turn 200-230 Seconds - Position Error - CD2 Data - COTS C.

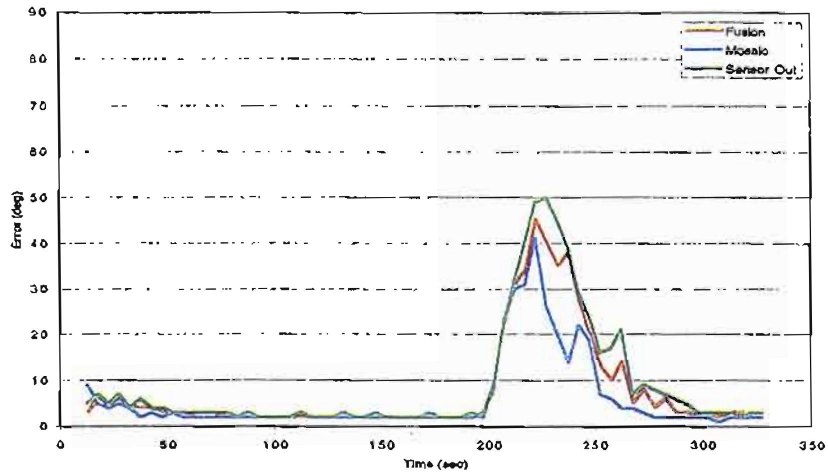


Figure 138. Preferred Sensor Outage Test - Turn 200-230 Seconds - Track Angle Error - Mode S Data - COTS C.

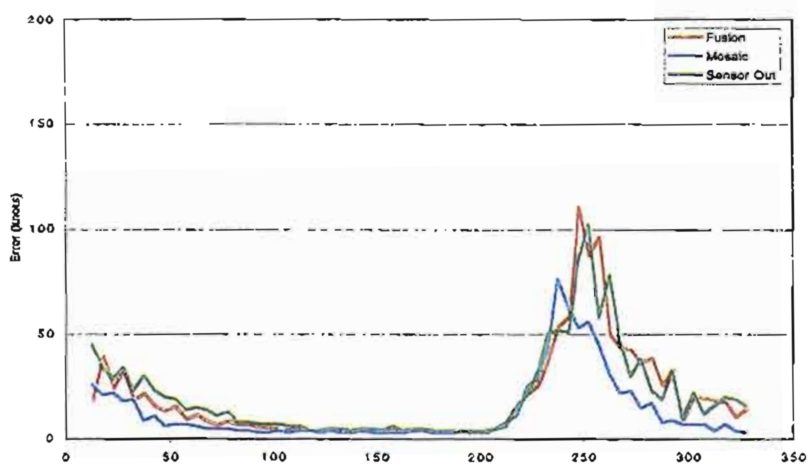


Figure 139. Preferred Sensor Outage Test - Turn 200-230 Seconds - Ground Speed Error - Mode S Data - COTS C.

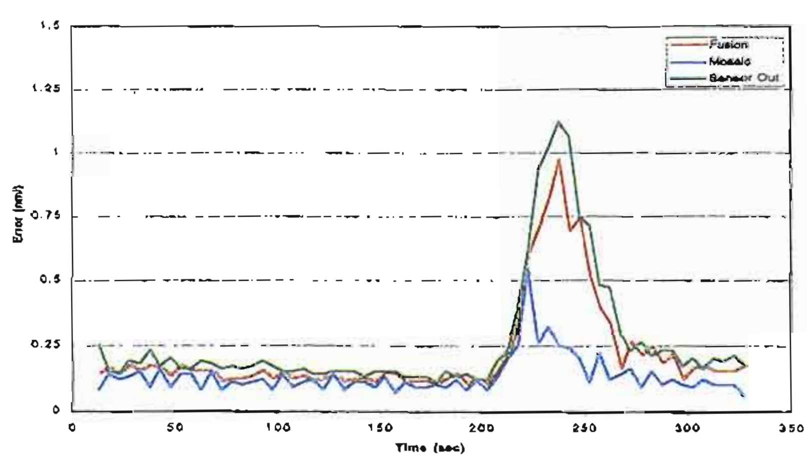


Figure 140. Preferred Sensor Outage Test - Turn 200-230 Seconds - Position Error - Mode S Data - COTS C.

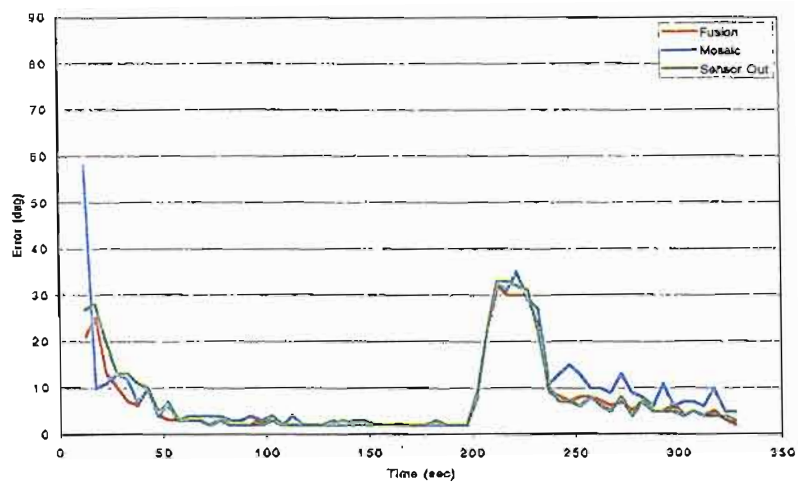


Figure 141. Preferred Sensor Outage Test - Turn 200-230 Seconds - Track Angle Error - CD2 Data - COTS D.

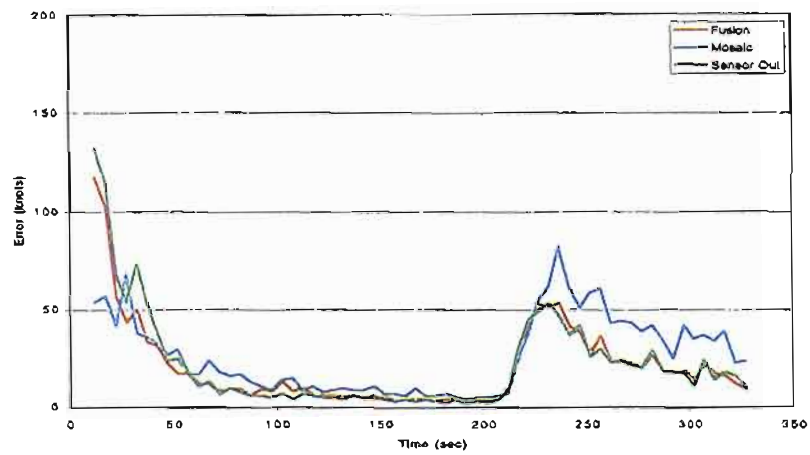


Figure 142. Preferred Sensor Outage Test - Turn 200-230 Seconds - Ground Speed Error - CD2 Data - COTS D.

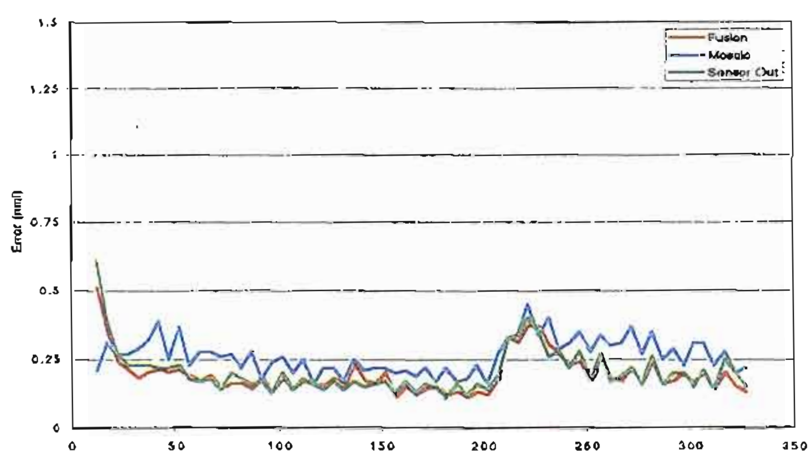


Figure 143. Preferred Sensor Outage Test - Turn 200-230 Seconds - Position Error - CD2 Data - COTS D.

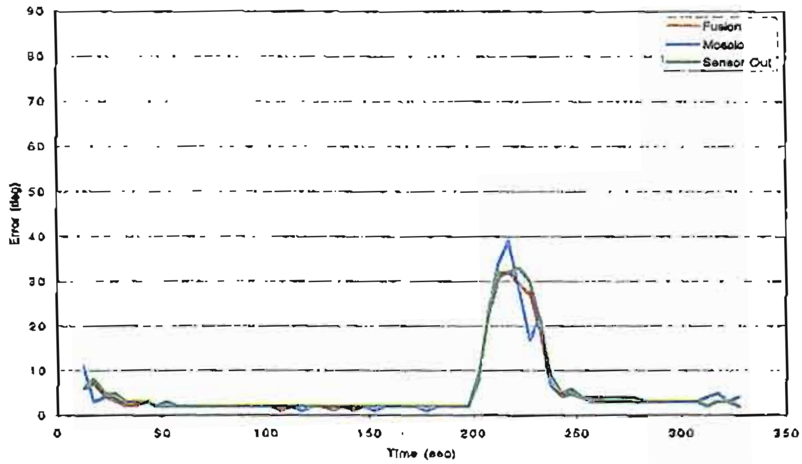


Figure 144. Preferred Sensor Outage Test - Turn 200-230 Seconds - Track Angle Error - Mode S Data - COTS D.

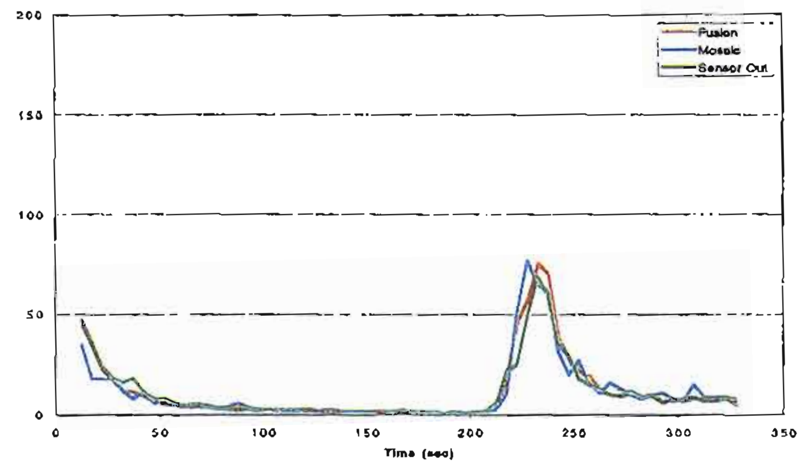


Figure 145. Preferred Sensor Outage Test - Turn 200-230 Seconds - Ground Speed Error - Mode S Data - COTS D.

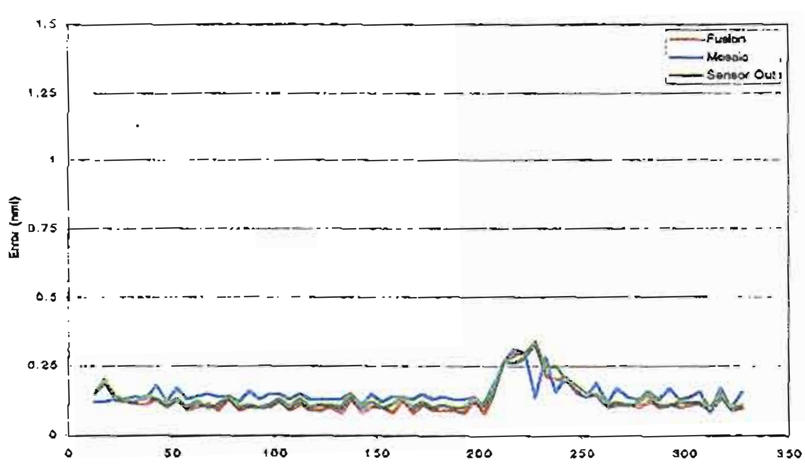


Figure 146. Preferred Sensor Outage Test - Turn 200-230 Seconds - Position Error - Mode S Data - COTS D.

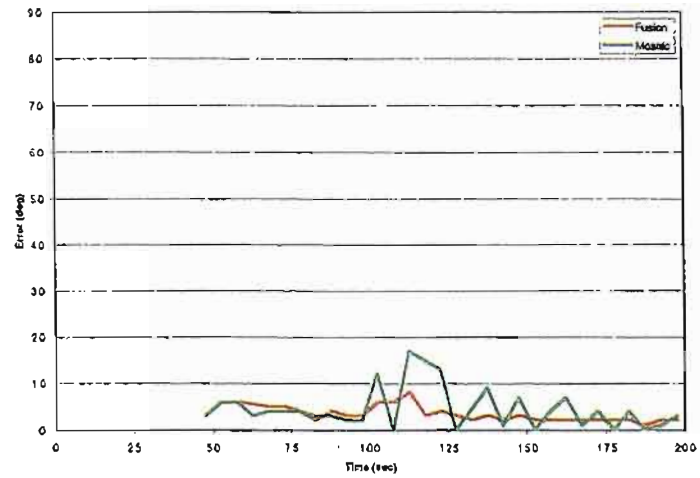


Figure 147. Outlier Test (Outlier at Time 100) - Track Angle Error - CD2 Data - COTS A.

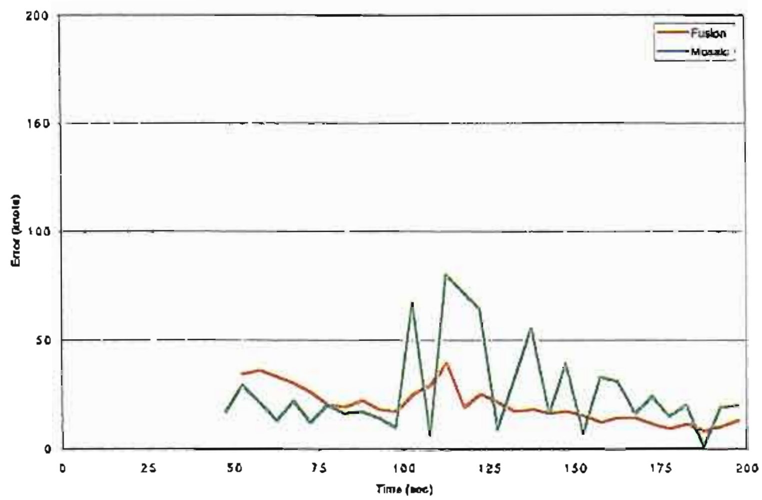


Figure 148. Outlier Test (Outlier at Time 100) - Ground Speed Error - CD2 Data - COTS A.

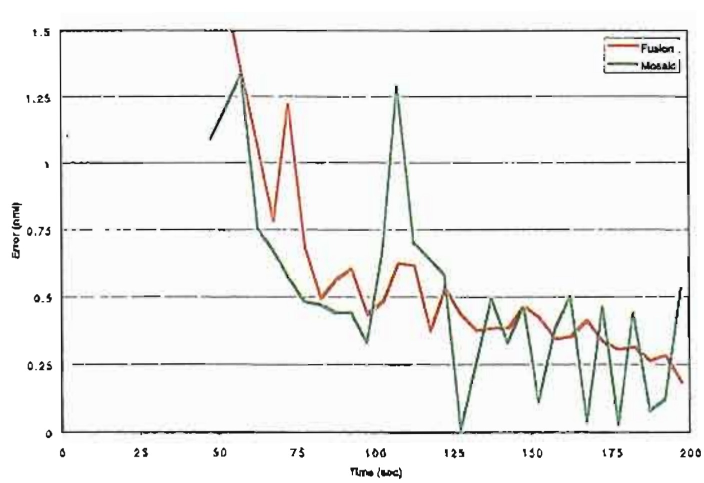


Figure 149. Outlier Test (Outlier at Time 100) - Position Error - CD2 Data - COTS A.

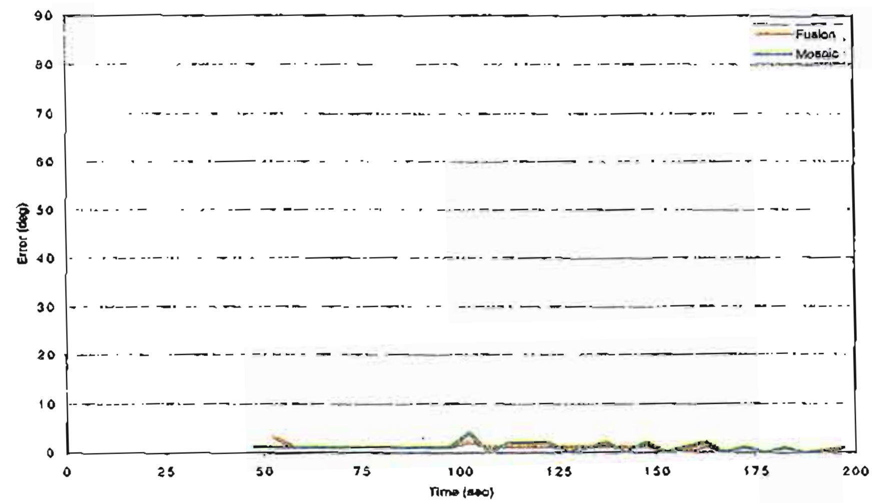


Figure 150. Outlier Test (Outlier at Time 100) - Track Angle Error - Mode S Data - COTS A.

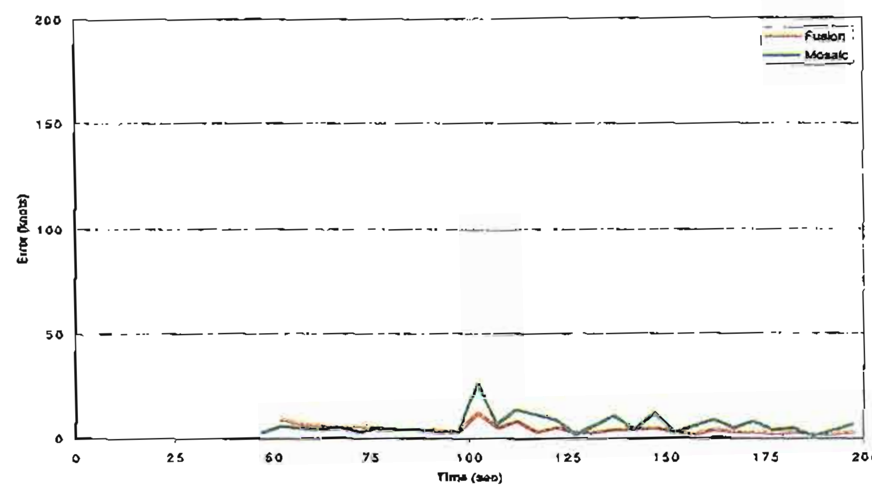


Figure 151. Outlier Test (Outlier at Time 100) - Ground Speed Error - Mode S Data - COTS A.

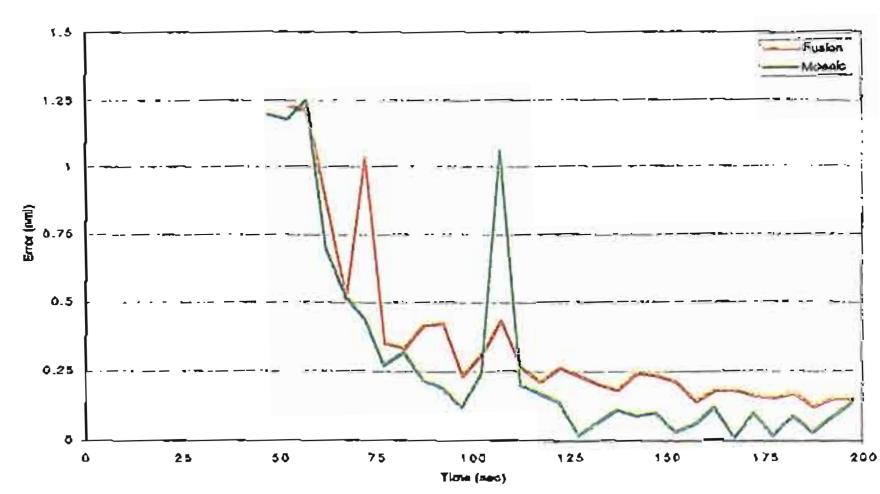


Figure 152. Outlier Test (Outlier at Time 100) - Position Error - Mode S Data - COTS A.

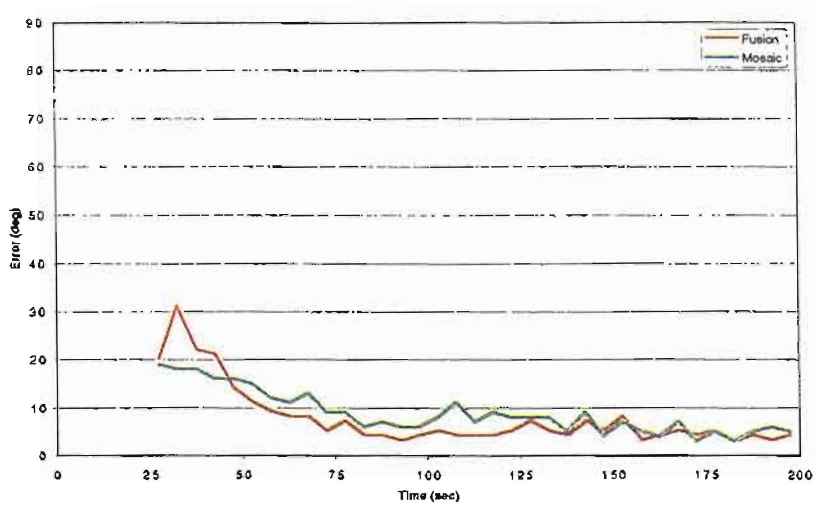


Figure 153. Outlier Test (Outlier at Time 100) - Track Angle Error - CD2 Data - COTS B.

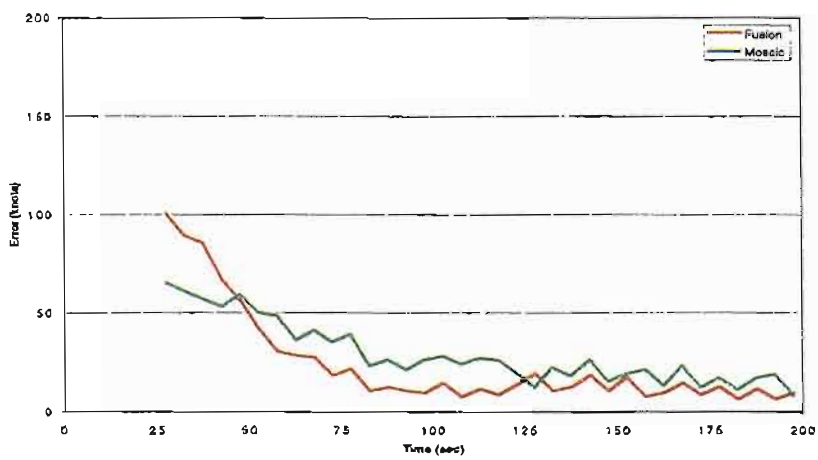


Figure 154. Outlier Test (Outlier at Time 100) - Ground Speed Error - CD2 Data - COTS B.

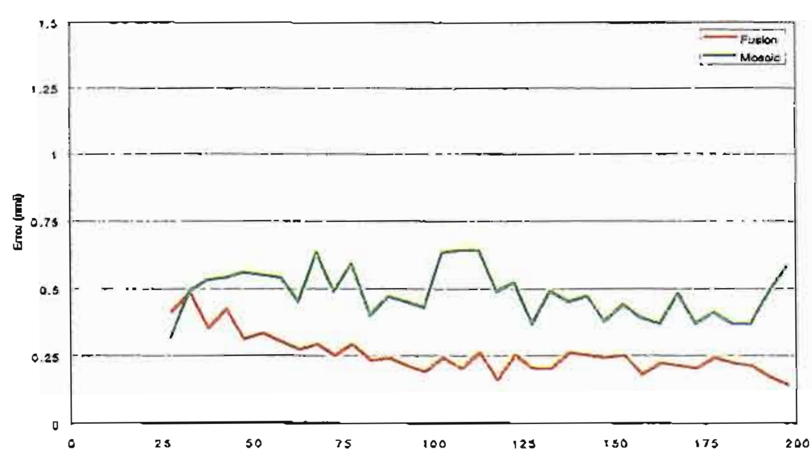


Figure 155. Outlier Test (Outlier at Time 100) - Position Error - CD2 Data - COTS B.

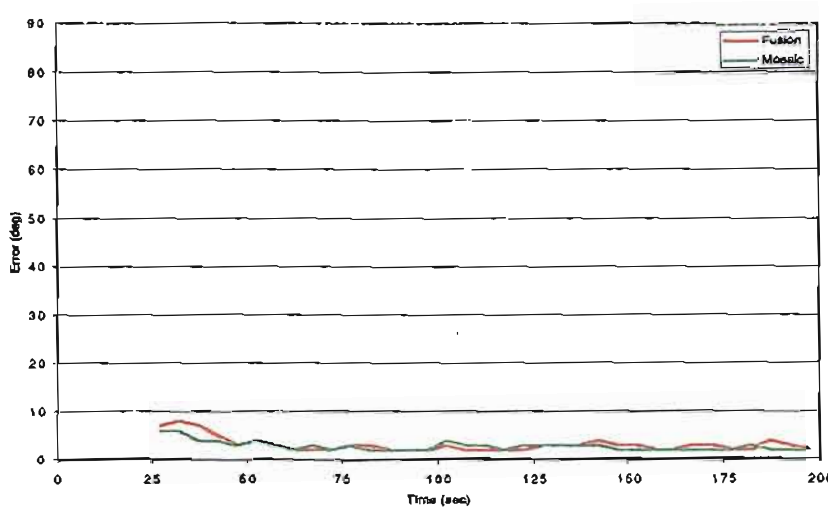


Figure 156. Outlier Test (Outlier at Time 100) - Track Angle Error - Mode S Data - COTS B.

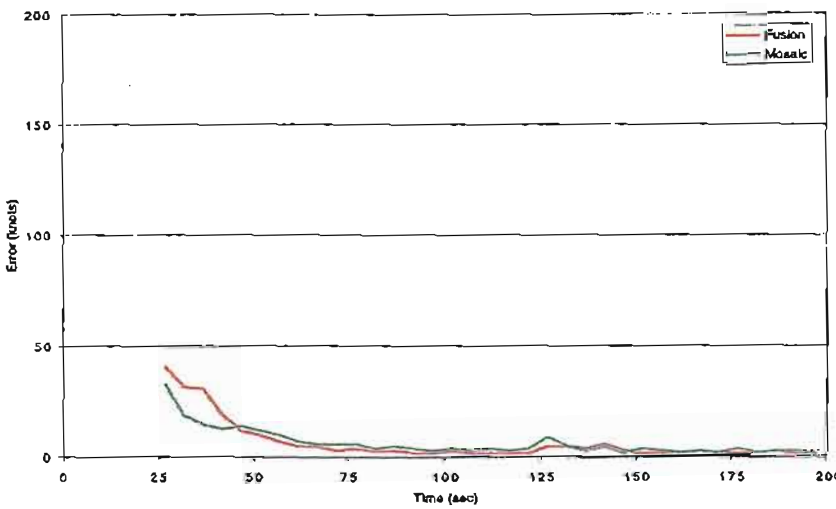


Figure 157. Outlier Test (Outlier at Time 100) - Ground Speed Error - Mode S Data - COTS B.

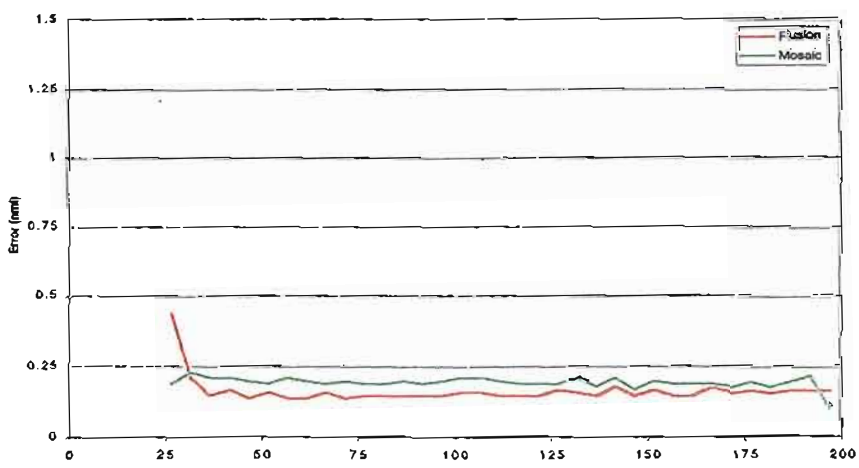


Figure 158. Outlier Test (Outlier at Time 100) - Position Error - Mode S Data - COTS B.

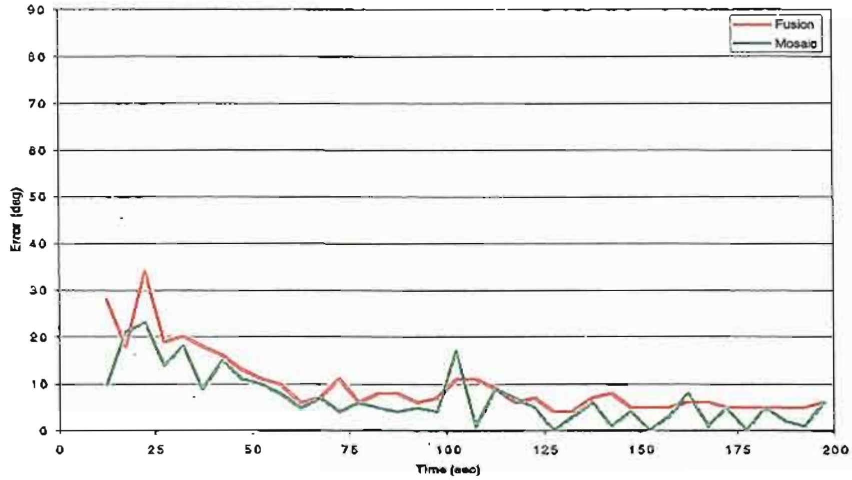


Figure 159. Outlier Test (Outlier at Time 100) - Track Angle Error - CD2 Data - COTS C.

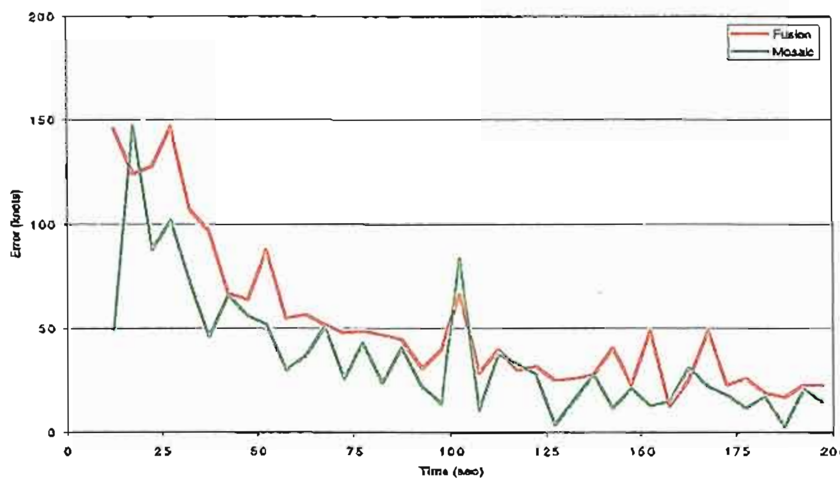


Figure 160. Outlier Test (Outlier at Time 100) - Ground Speed Error - CD2 Data - COTS C.

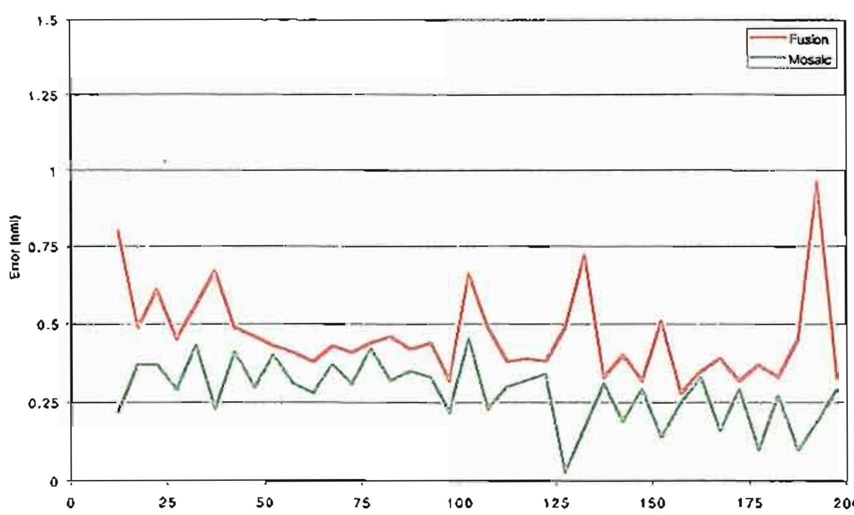


Figure 161. Outlier Test (Outlier at Time 100) - Position Error - CD2 Data - COTS C.

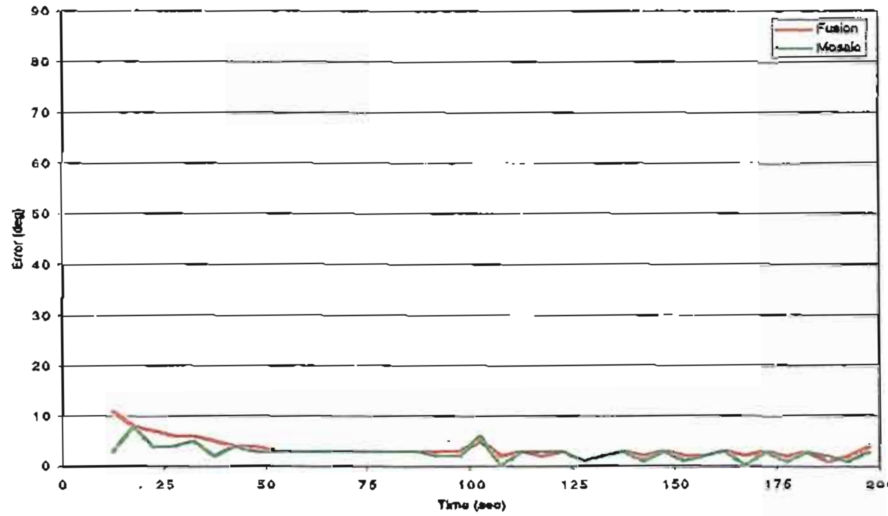


Figure 162. Outlier Test (Outlier at Time 100) - Track Angle Error - Mode S Data - COTS C.

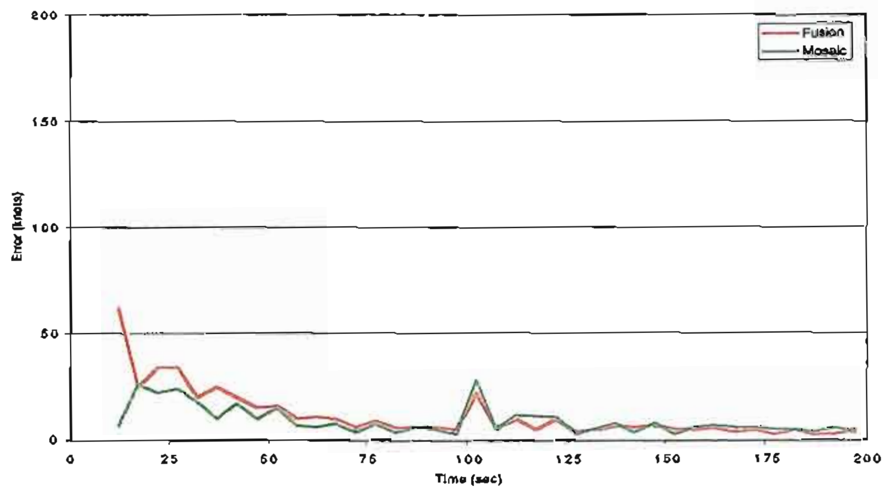


Figure 163. Outlier Test (Outlier at Time 100) - Ground Speed Error - Mode S Data - COTS C.

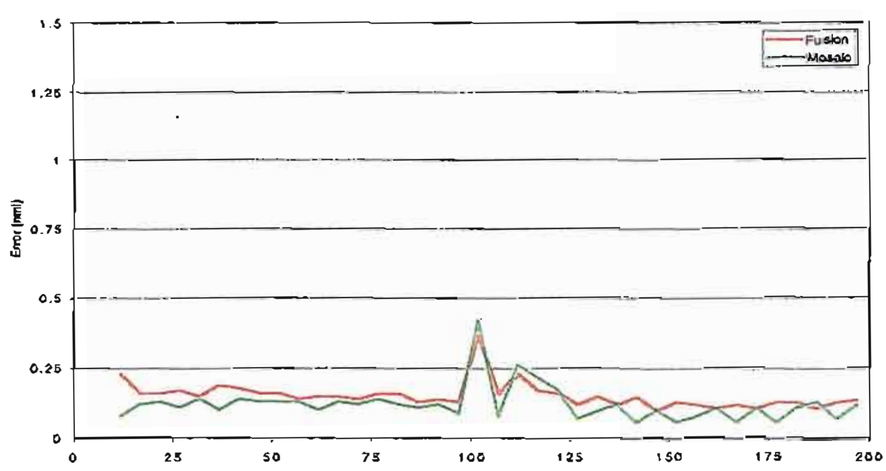


Figure 164. Outlier Test (Outlier at Time 100) - Position Error - Mode S Data - COTS C.

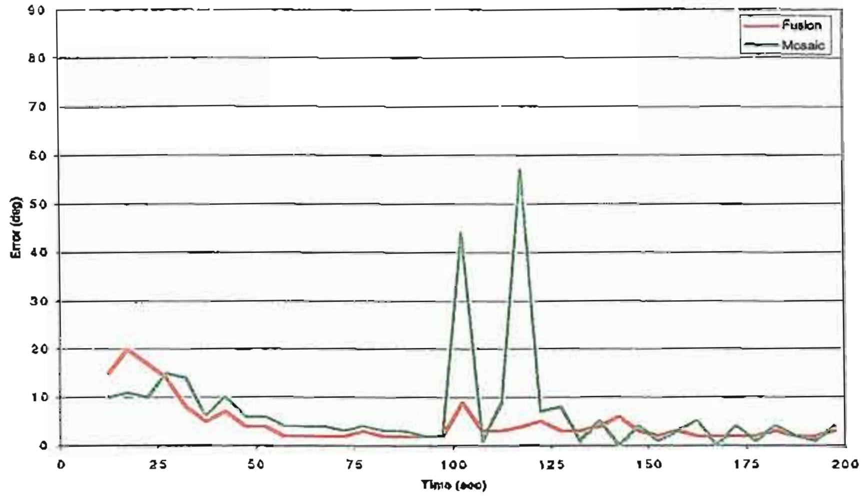


Figure 165. Outlier Test (Outlier at Time 100) - Track Angle Error - CD2 Data - COTS D.

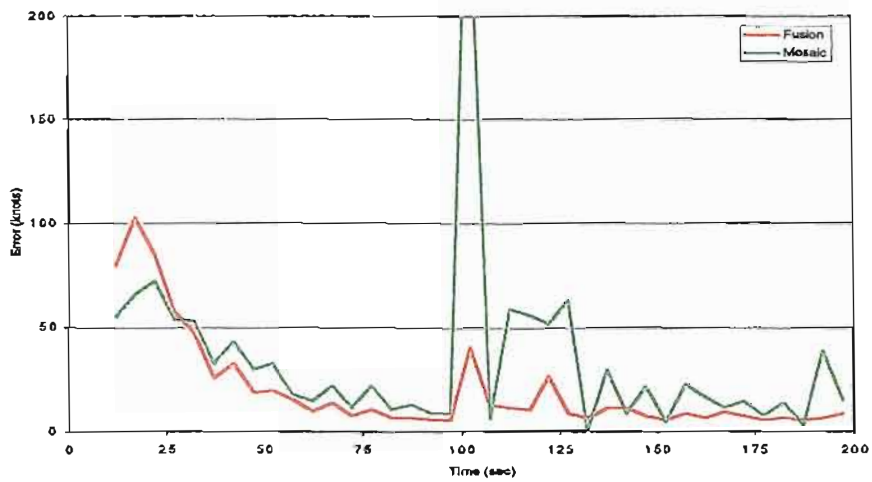


Figure 166. Outlier Test (Outlier at Time 100) - Ground Speed Error - CD2 Data - COTS D.

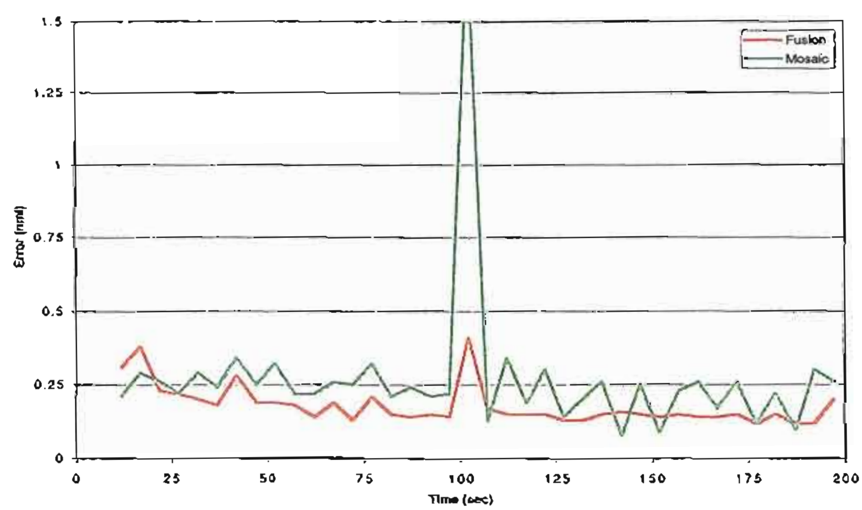


Figure 167. Outlier Test (Outlier at Time 100) - Position Error - CD2 Data - COTS D.

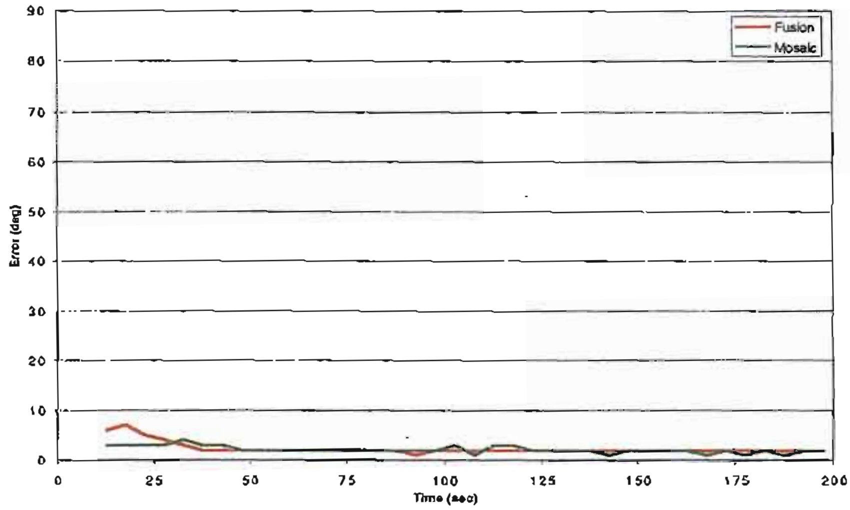


Figure 168. Outlier Test (Outlier at Time 100) - Track Angle Error - Mode S Data - COTS D.

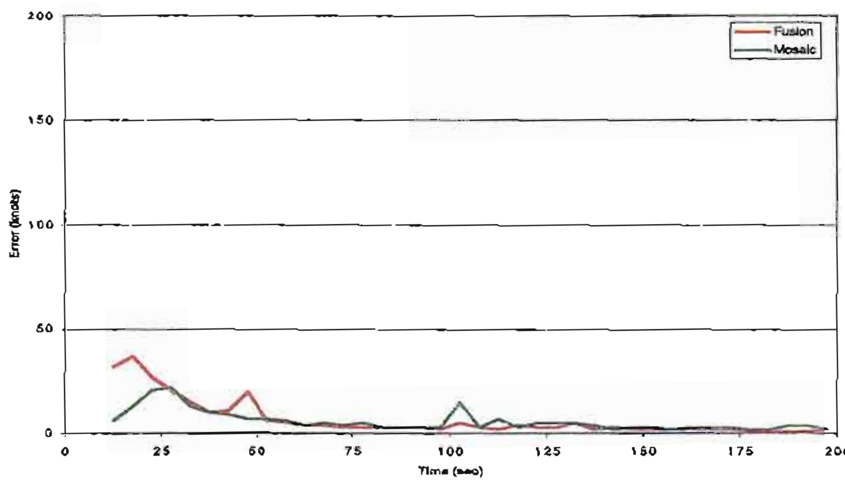


Figure 169. Outlier Test (Outlier at Time 100) - Ground Speed Error - Mode S Data - COTS D.

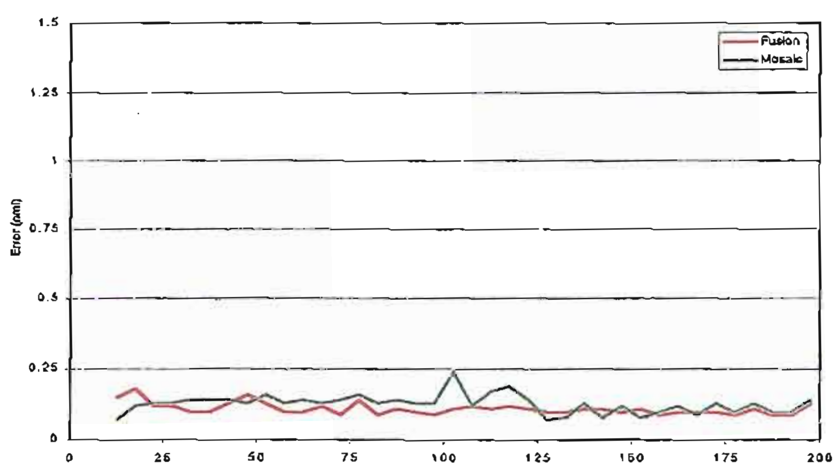


Figure 170. Outlier Test (Outlier at Time 100) - Position Error - Mode S Data - COTS D.

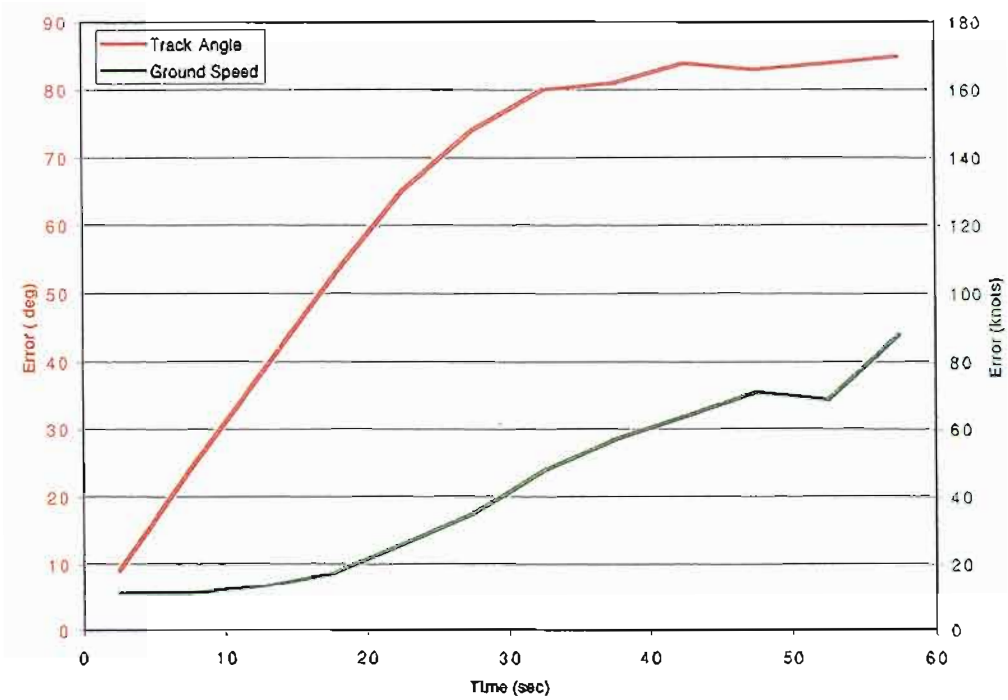


Figure 171. Maneuver Test - Turning (After Straight) - Track Angle & Ground Speed Errors - CD2 Data - COTS A.

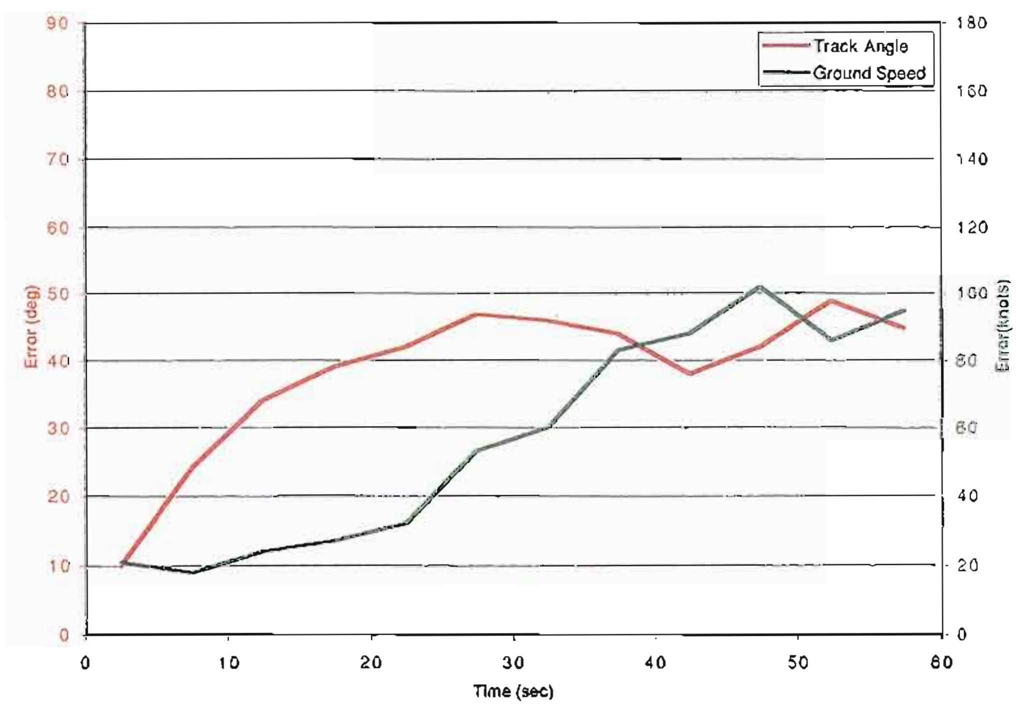


Figure 172. Maneuver Test - Turning (After Straight) - Track Angle & Ground Speed Errors - CD2 Data - COTS B.

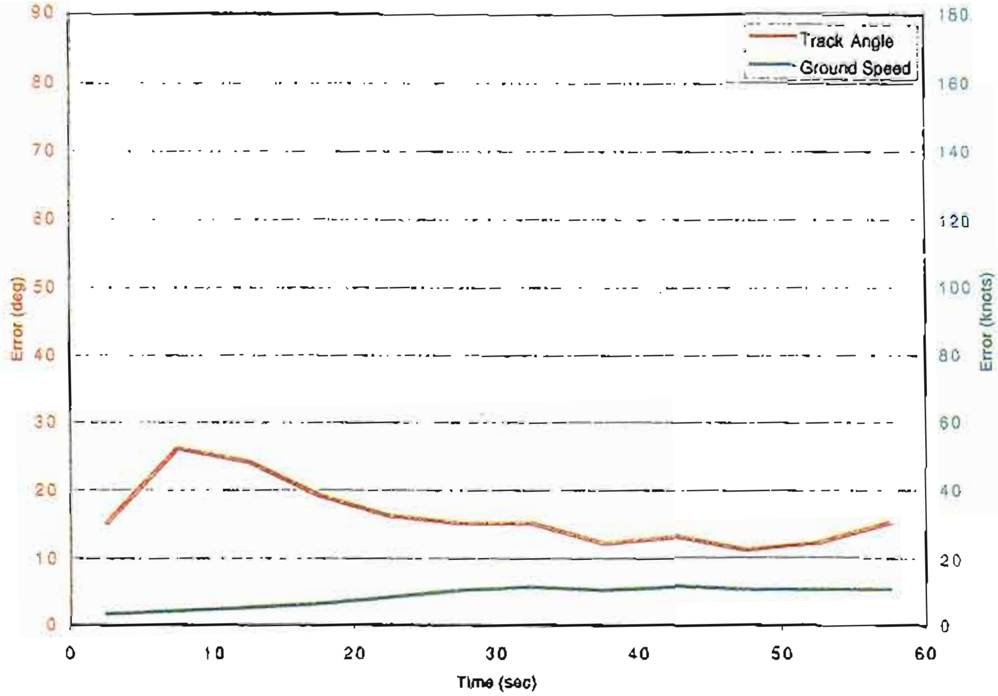


Figure 173. Maneuver Test - Turning (After Straight) - Track Angle & Ground Speed Errors - CD2 Data - COTS C.

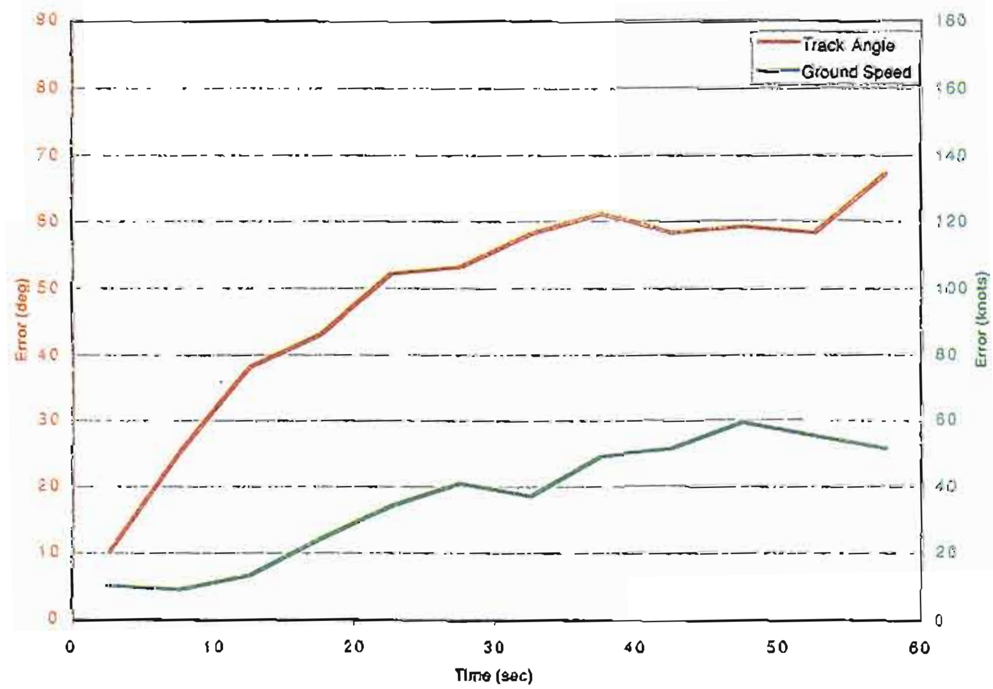


Figure 174. Maneuver Test - Turning (After Straight) - Track Angle & Ground Speed Errors - CD2 Data - COTS D.

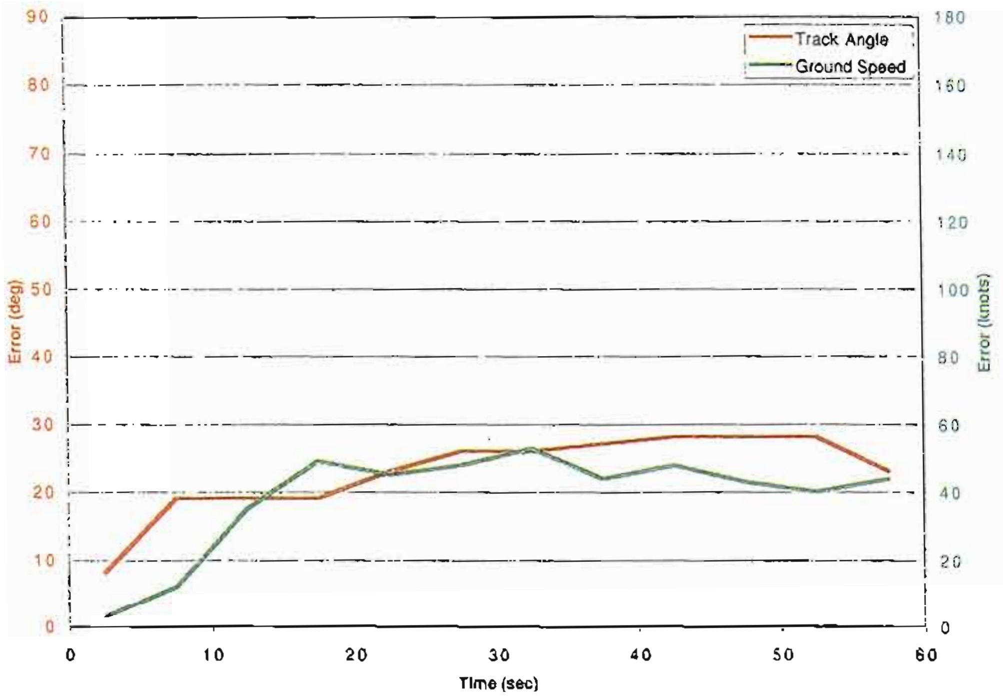


Figure 175. Maneuver Test - Turning (After Straight) - Track Angle & Ground Speed Errors - Mode S Data - COTS A.

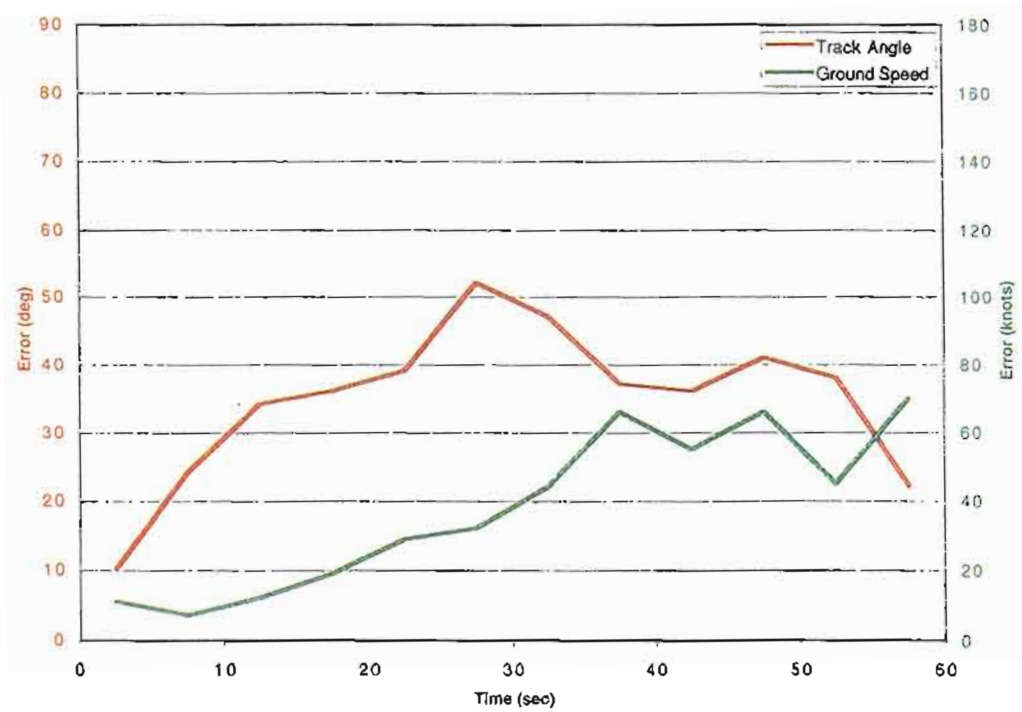


Figure 176. Maneuver Test - Turning (After Straight) - Track Angle & Ground Speed Errors - Mode S Data - COTS B.

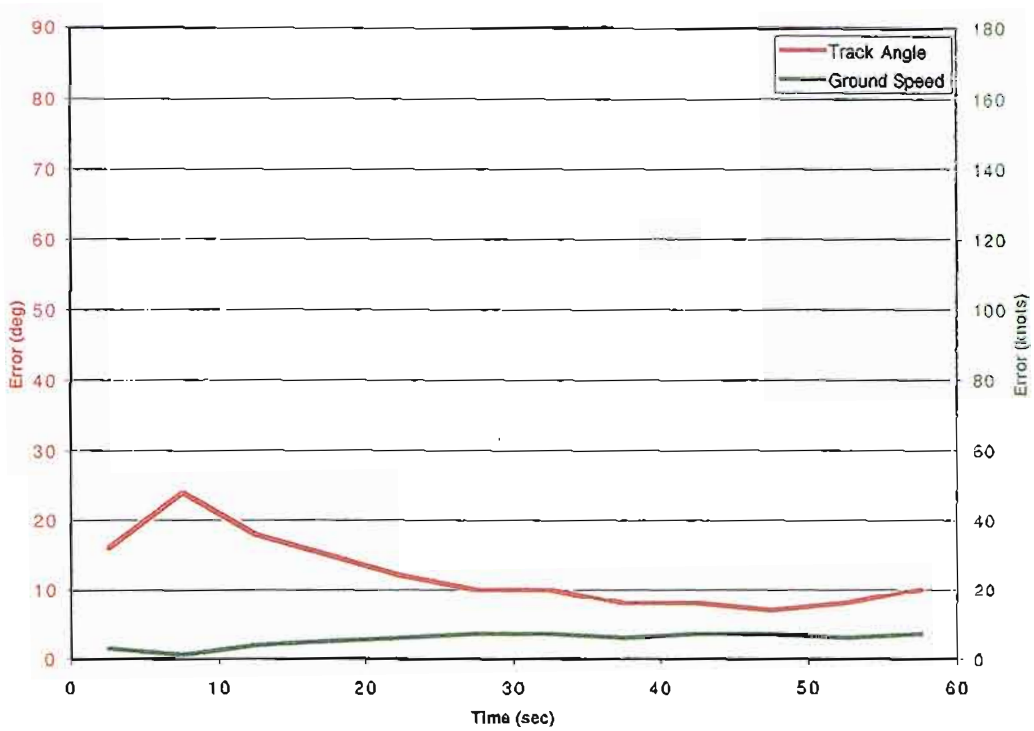


Figure 177. Maneuver Test - Turning (After Straight) - Track Angle & Ground Speed Errors - Mode S Data - COTS C.

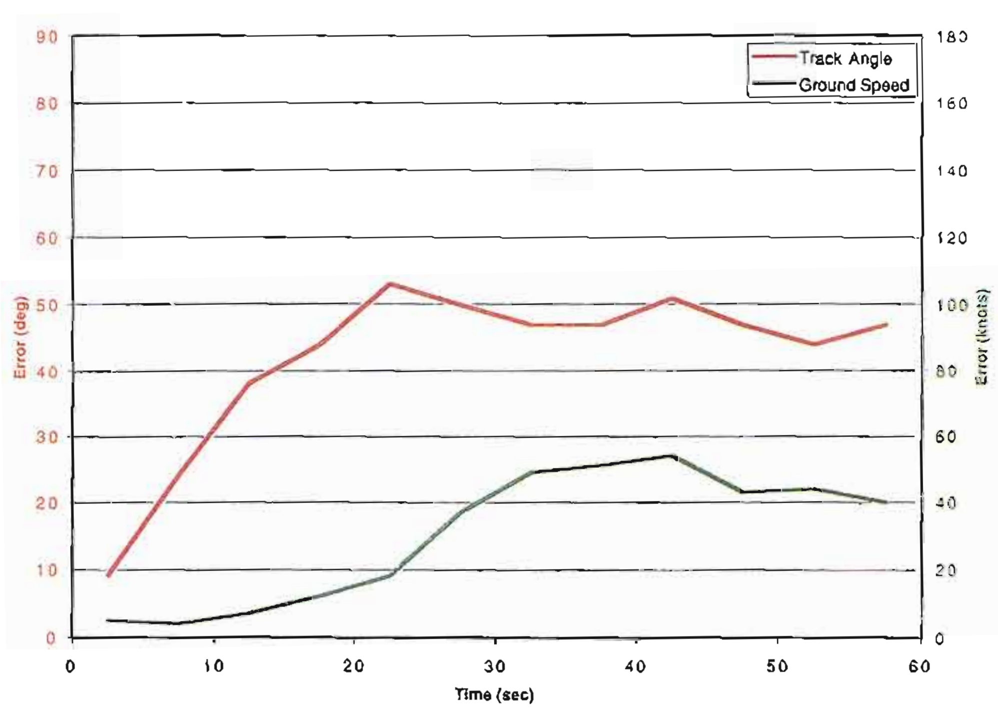


Figure 178. Maneuver Test - Turning (After Straight) - Track Angle & Ground Speed Errors - Mode S Data - COTS D.

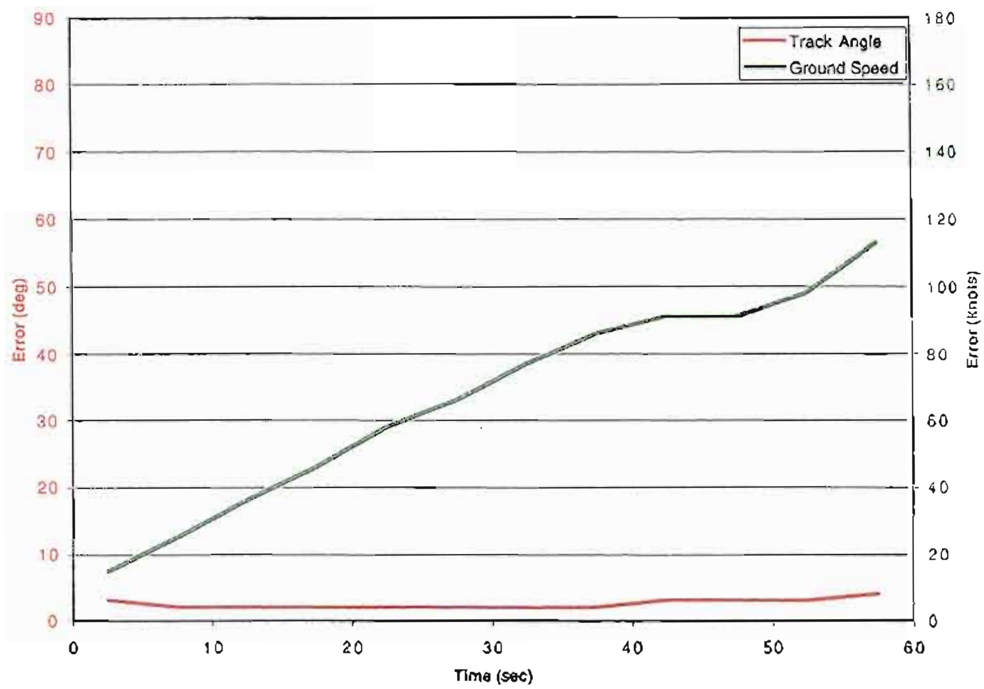


Figure 179. Maneuver Test - Accelerating (After Straight) - Track Angle & Ground Speed Errors - CD2 Data - COTS A.

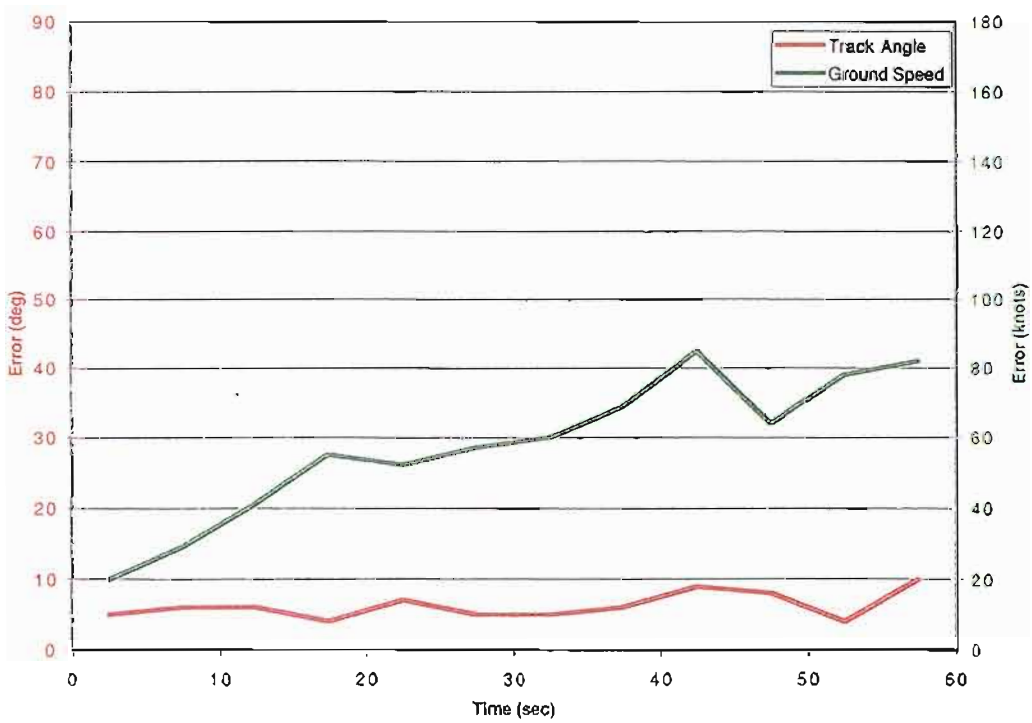


Figure 180. Maneuver Test - Accelerating (After Straight) - Track Angle & Ground Speed Errors - CD2 Data - COTS B.

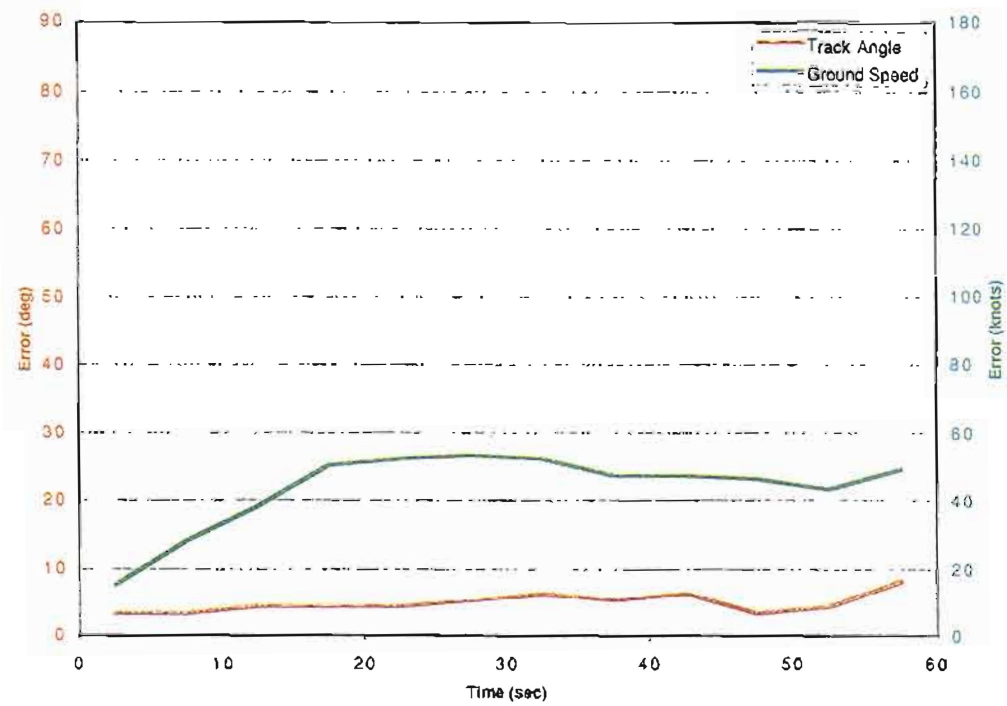


Figure 181. Maneuver Test - Accelerating (After Straight) - Track Angle & Ground Speed Errors - CD2 Data - COTS C.

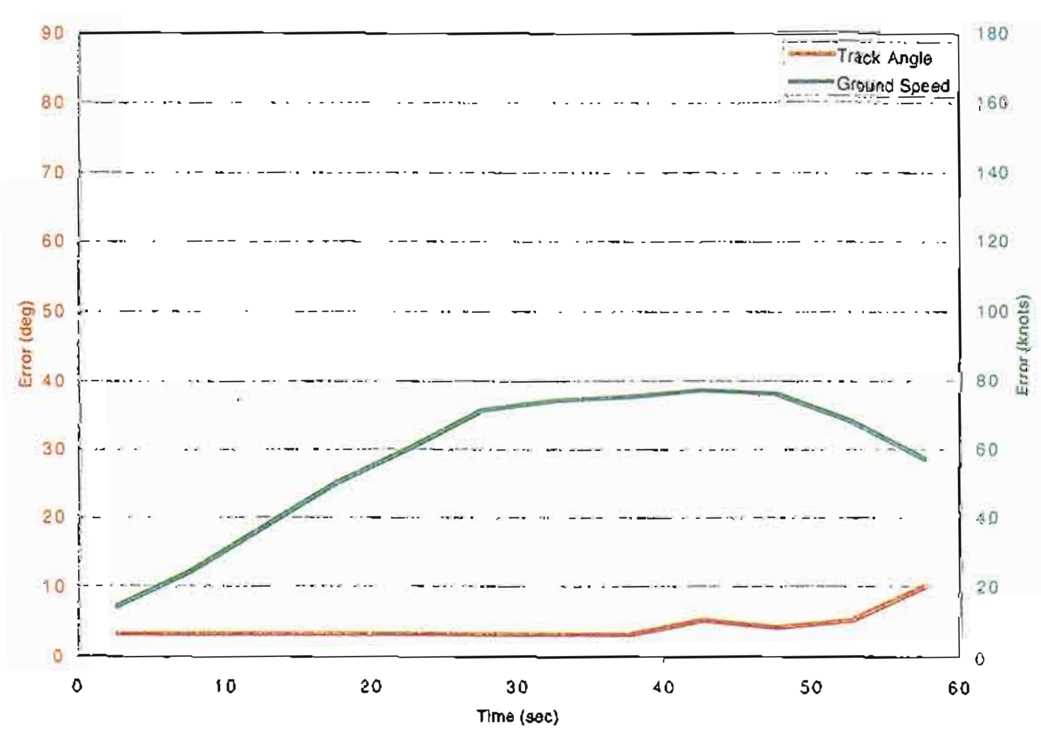


Figure 182. Maneuver Test - Accelerating (After Straight) - Track Angle & Ground Speed Errors - CD2 Data - COTS D.

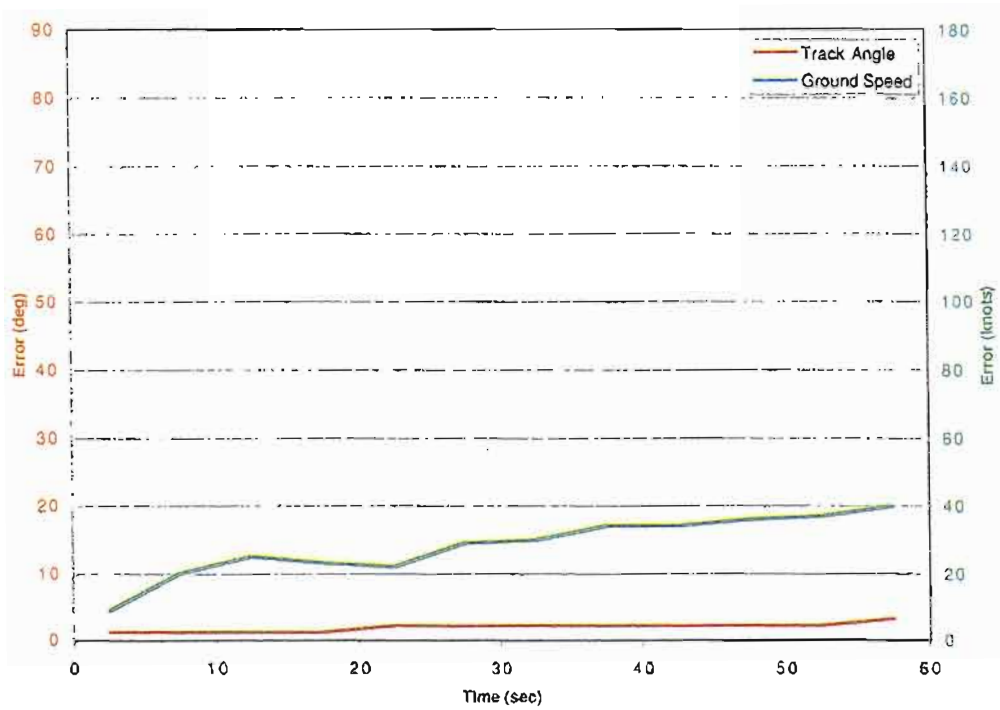


Figure 183. Maneuver Test - Accelerating (After Straight) - Track Angle & Ground Speed Errors - Mode S Data - COTS A.

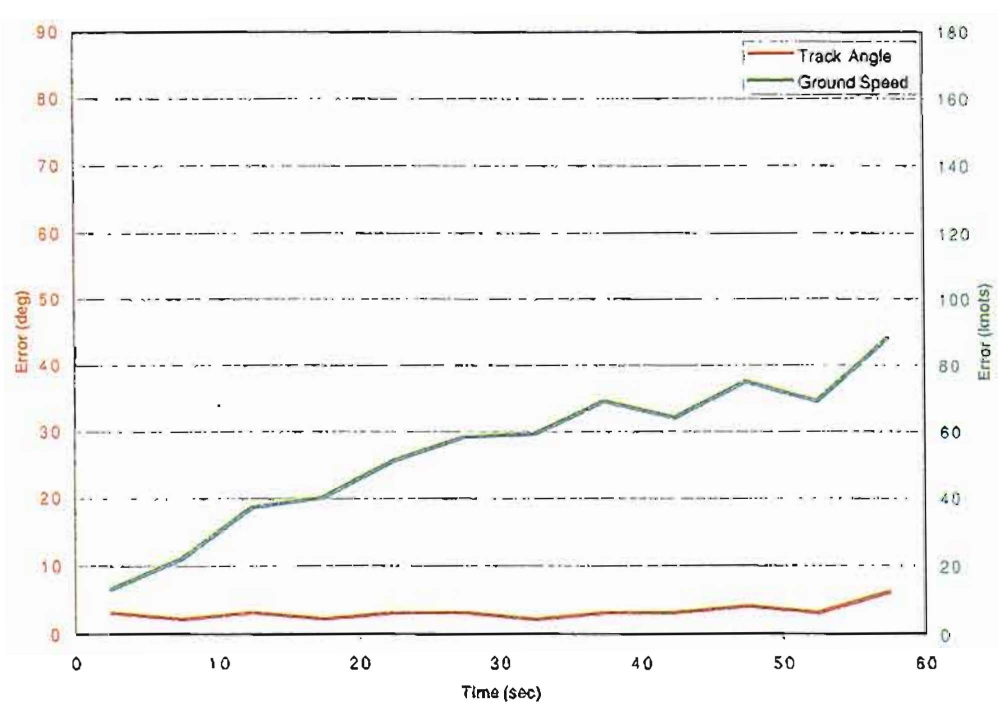


Figure 184. Maneuver Test - Accelerating (After Straight) - Track Angle & Ground Speed Errors - Mode S Data - COTS B.

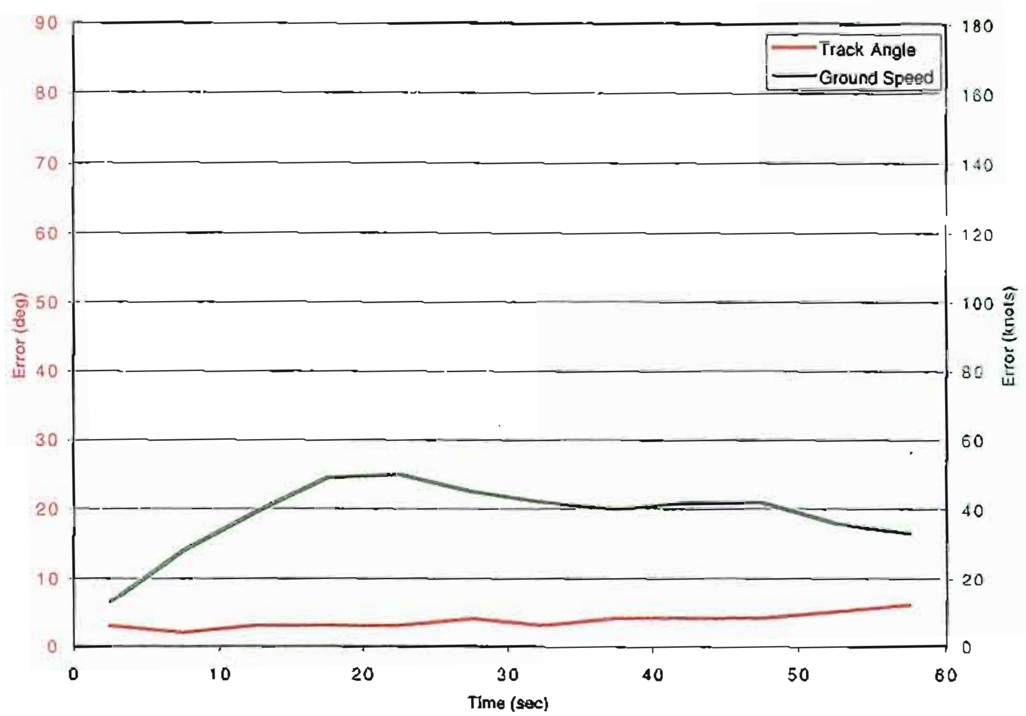


Figure 185. Maneuver Test - Accelerating (After Straight) - Track Angle & Ground Speed Errors - Mode S Data - COTS C.

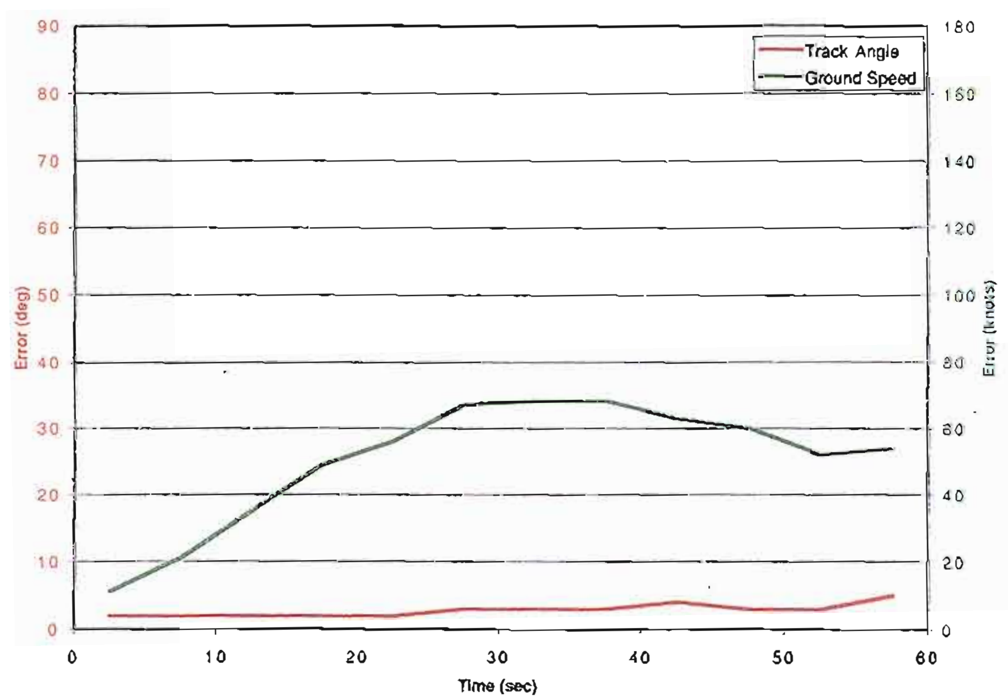


Figure 186. Maneuver Test - Accelerating (After Straight) - Track Angle & Ground Speed Errors - Mode S2 Data - COTS D.

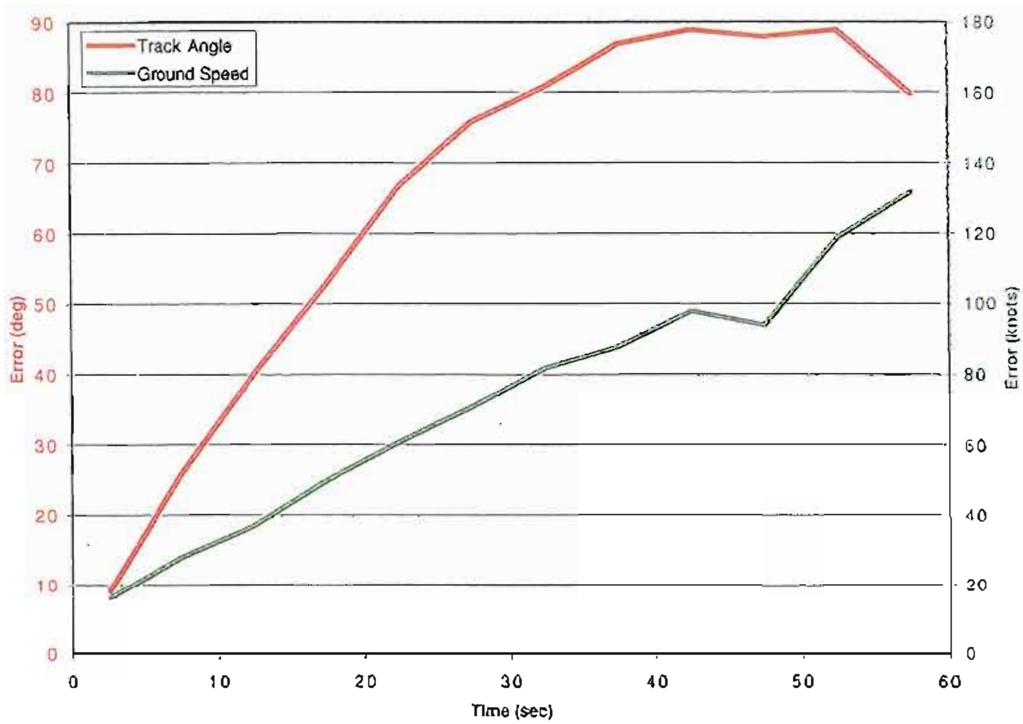


Figure 187. Maneuver Test - Turning & Accelerating (After Straight) - Track Angle & Ground Speed Errors - CD2 Data - COTS A.

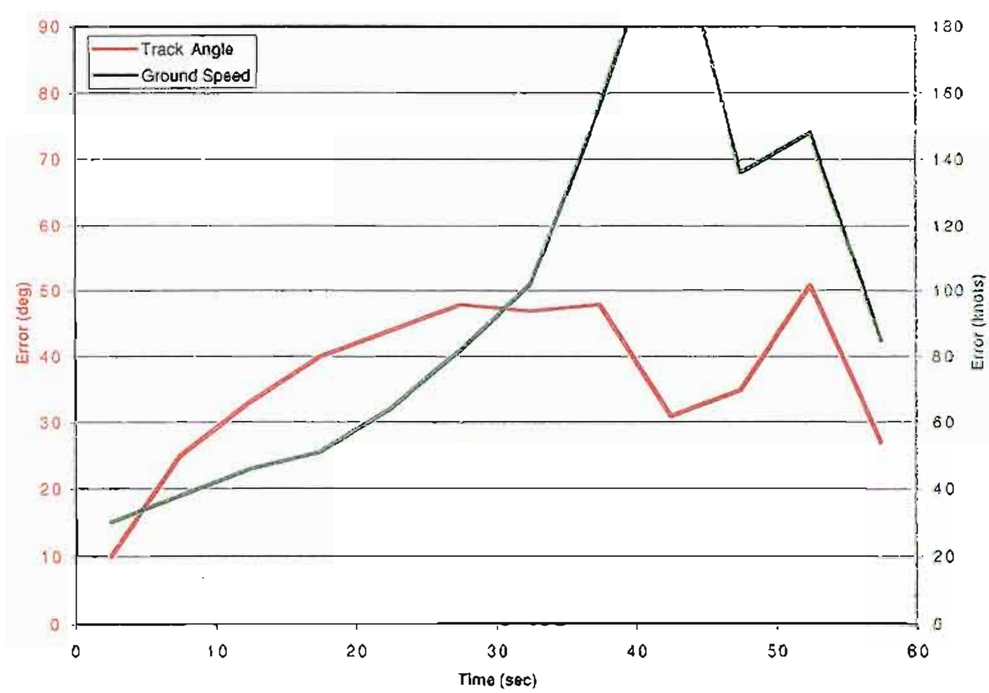


Figure 188. Maneuver Test - Turning & Accelerating (After Straight) - Track Angle & Ground Speed Errors - CD2 Data - COTS B.

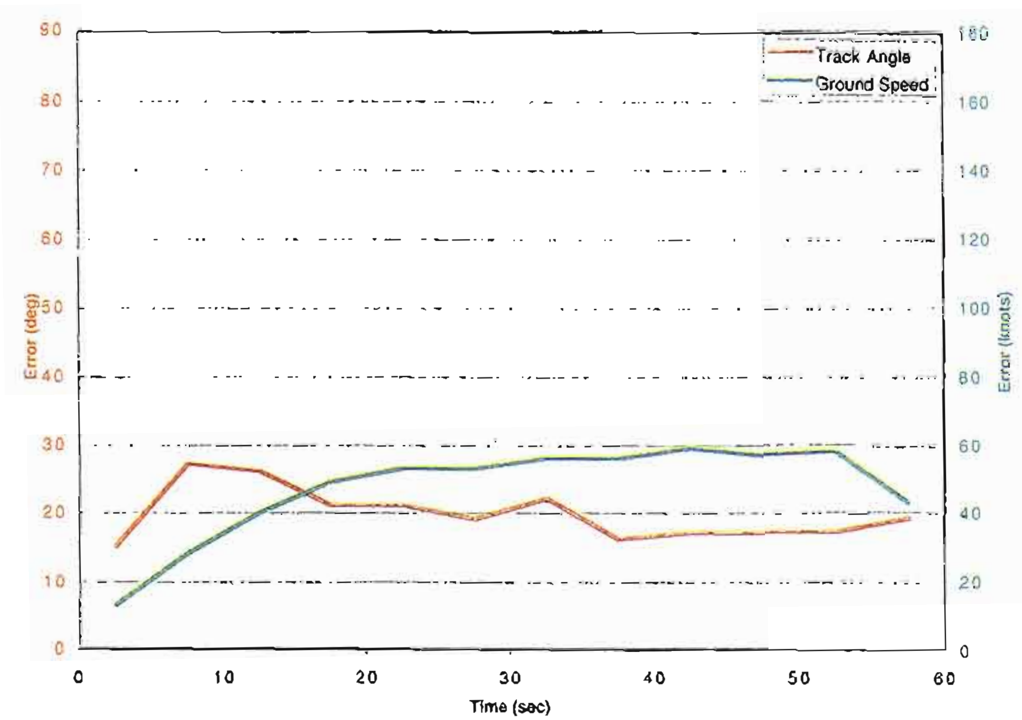


Figure 189. Maneuver Test - Turning & Accelerating (After Straight) - Track Angle & Ground Speed Errors - CD2 Data - COTS C.

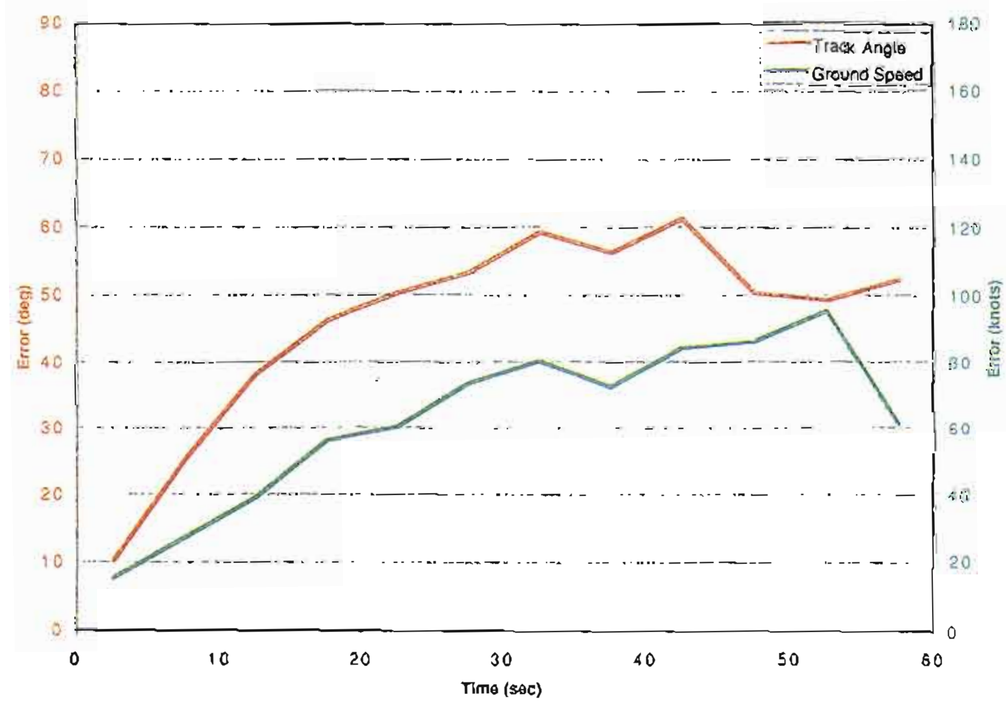


Figure 190. Maneuver Test - Turning & Accelerating (After Straight) - Track Angle & Ground Speed Errors - CD2 Data - COTS D.

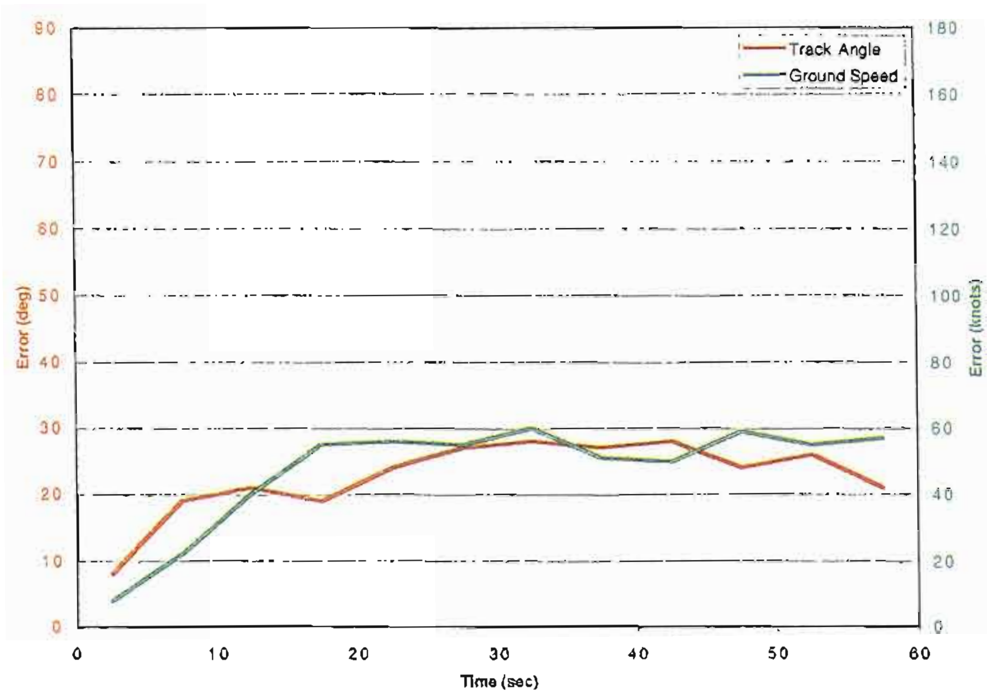


Figure 191. Maneuver Test - Turning & Accelerating (After Straight) - Track Angle & Ground Speed Errors - Mode S Data - COTS A.

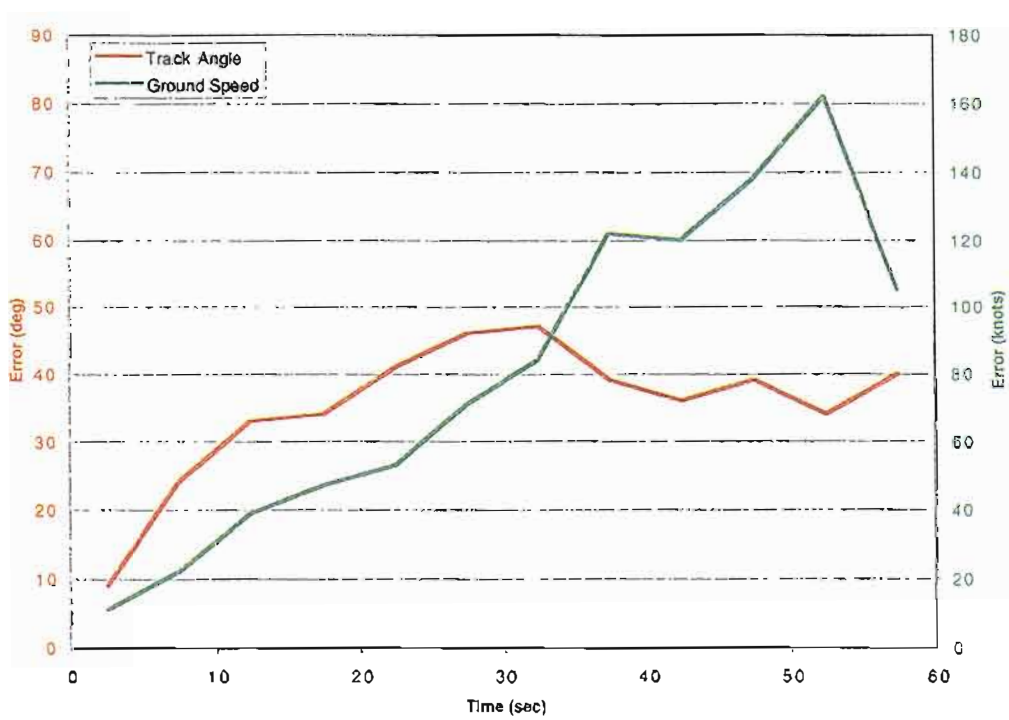


Figure 192. Maneuver Test - Turning & Accelerating (After Straight) - Track Angle & Ground Speed Errors - Mode S Data - COTS B.

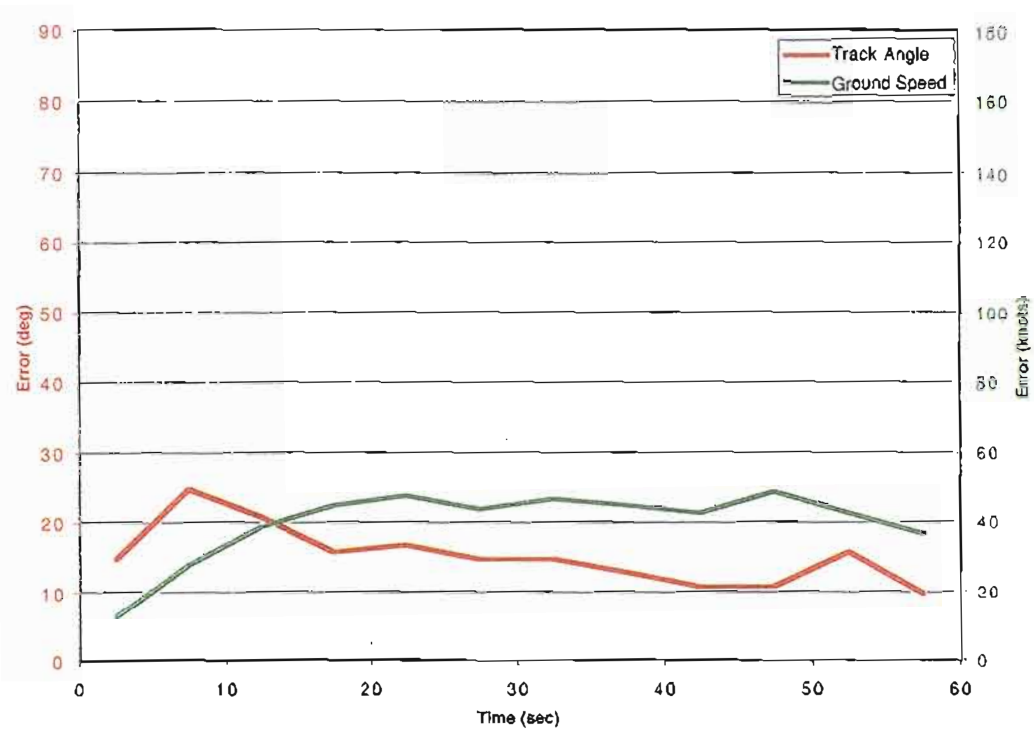


Figure 193. Maneuver Test - Turning & Accelerating (After Straight) - Track Angle & Ground Speed Errors - Mode S Data - COTS C.

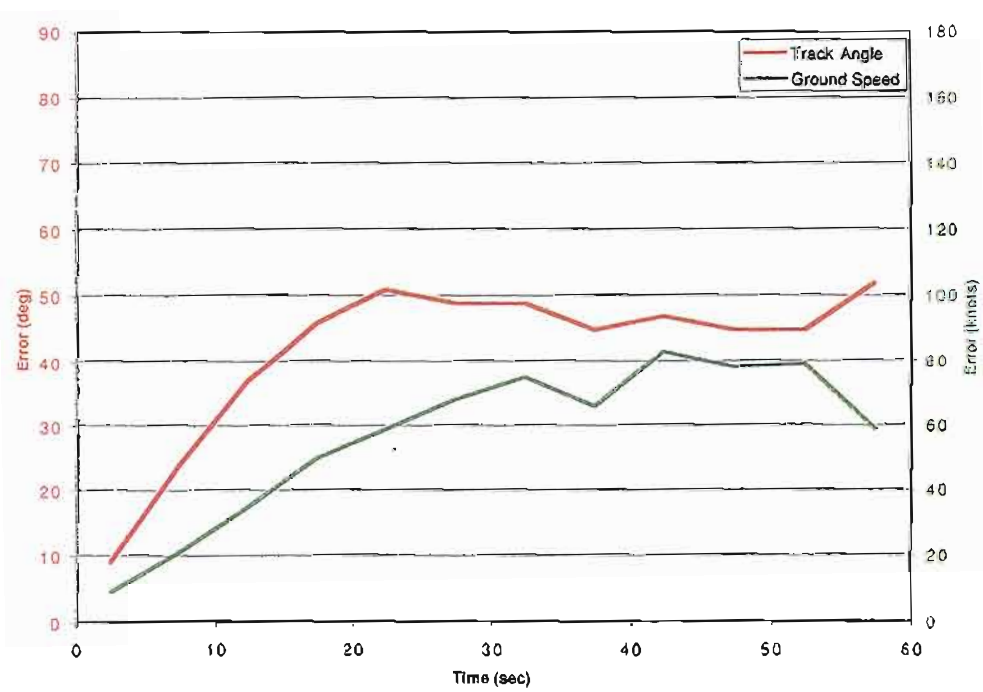


Figure 194. Maneuver Test - Turning & Accelerating (After Straight) - Track Angle & Ground Speed Errors - Mode S Data - COTS D.

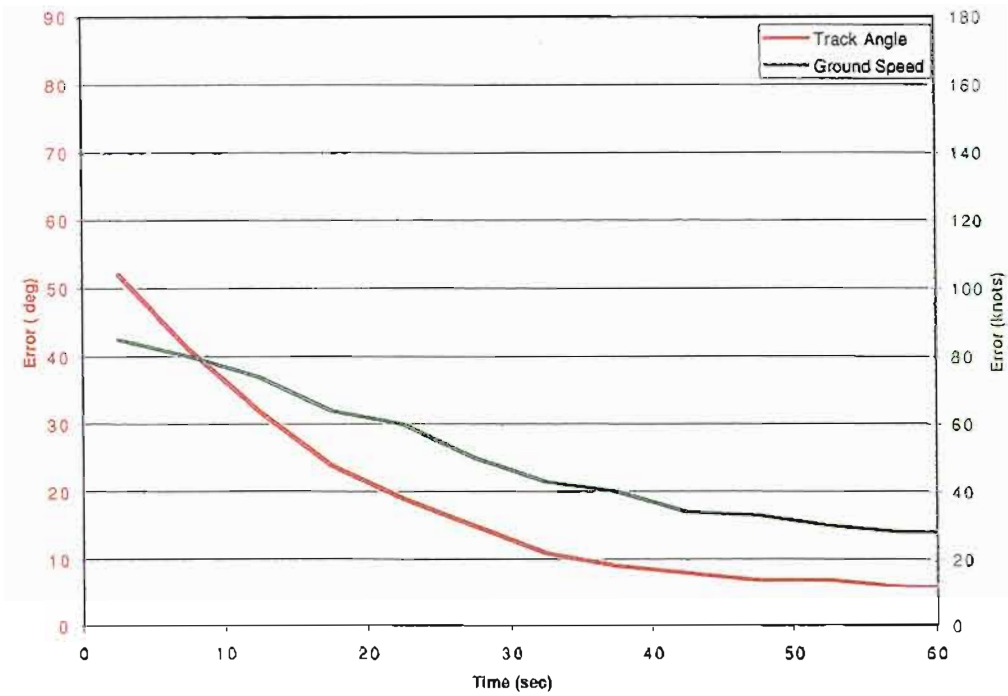


Figure 195. Maneuver Test - Straight (After Maneuver) - Track Angle & Ground Speed Errors - CD2 Data - COTS A.

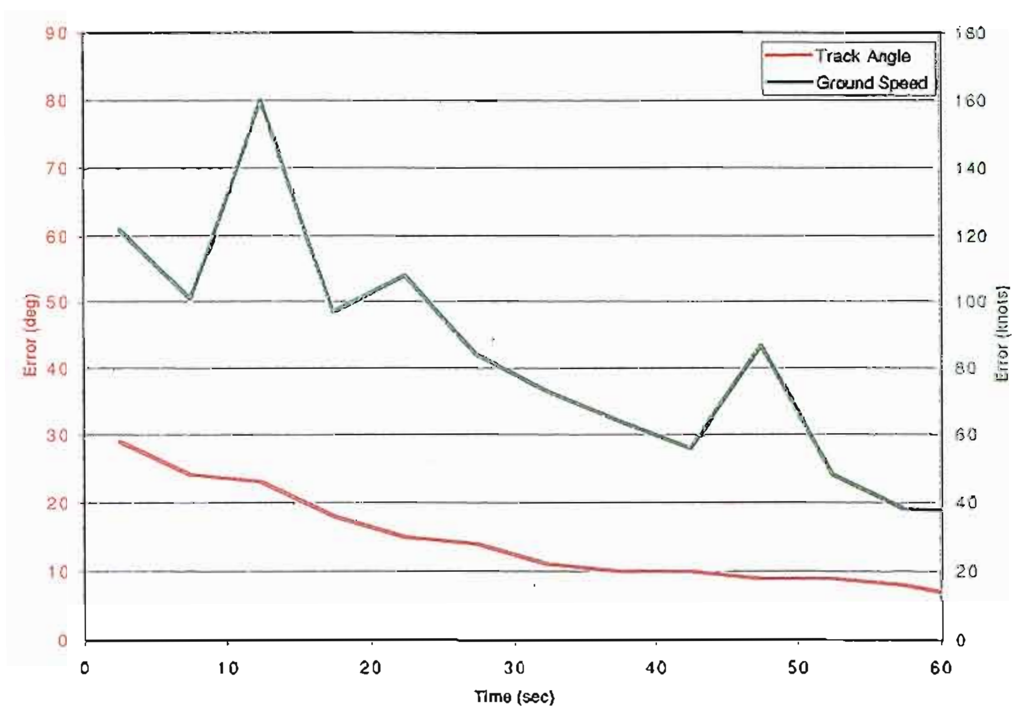


Figure 196. Maneuver Test - Straight (After Maneuver) - Track Angle & Ground Speed Errors - CD2 Data - COTS B.

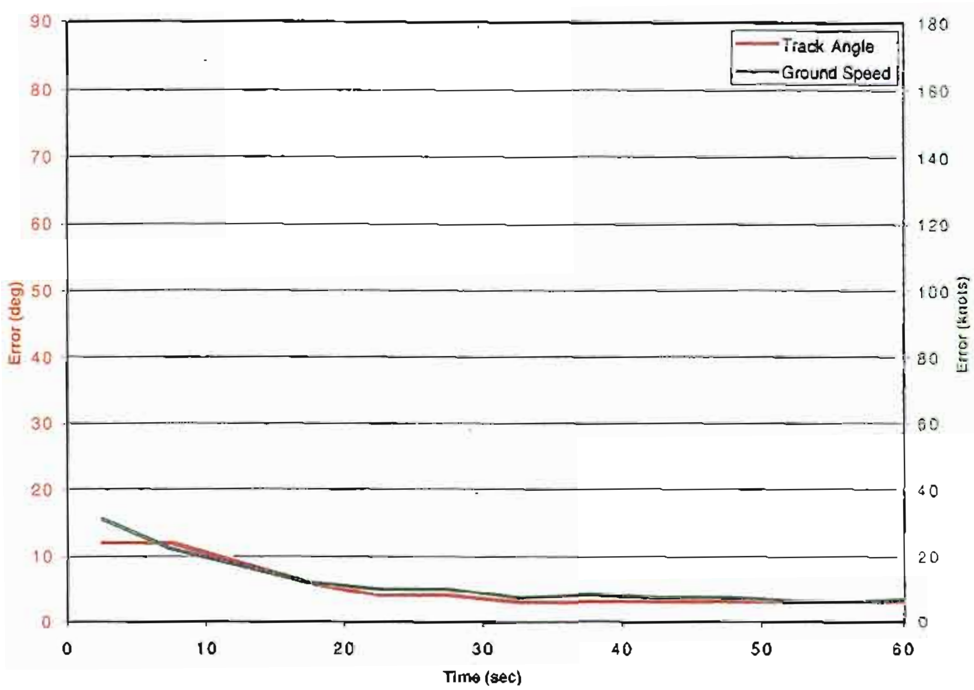


Figure 197. Maneuver Test - Straight (After Maneuver) - Track Angle & Ground Speed Errors - CD2 Data - COTS C.

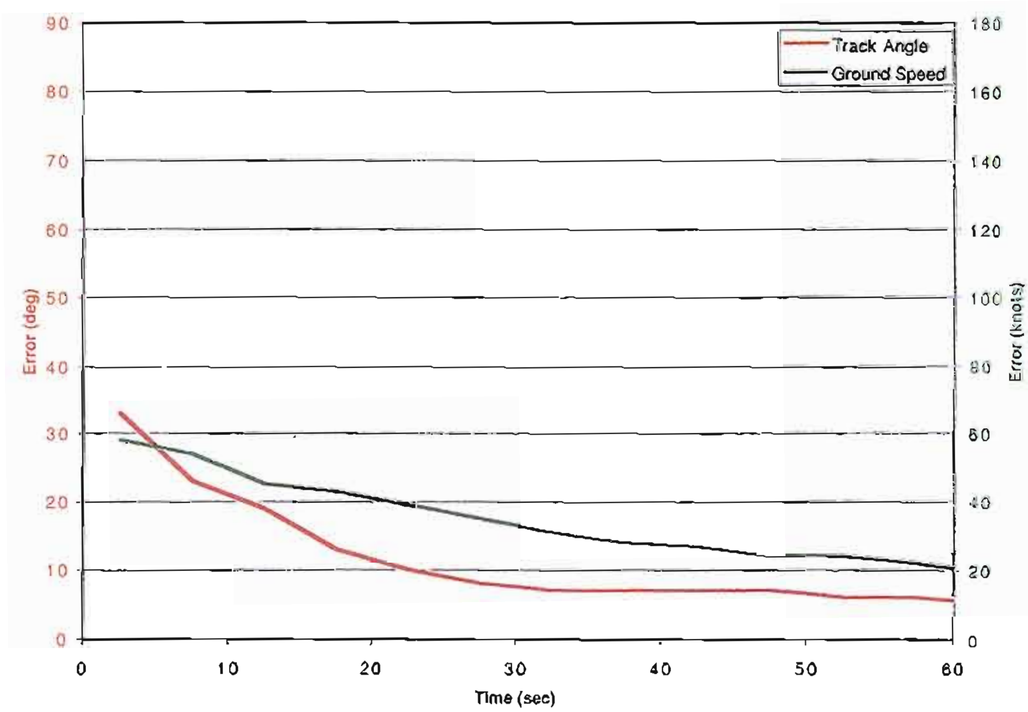


Figure 198. Maneuver Test - Straight (After Maneuver) - Track Angle & Ground Speed Errors - CD2 Data - COTS D.

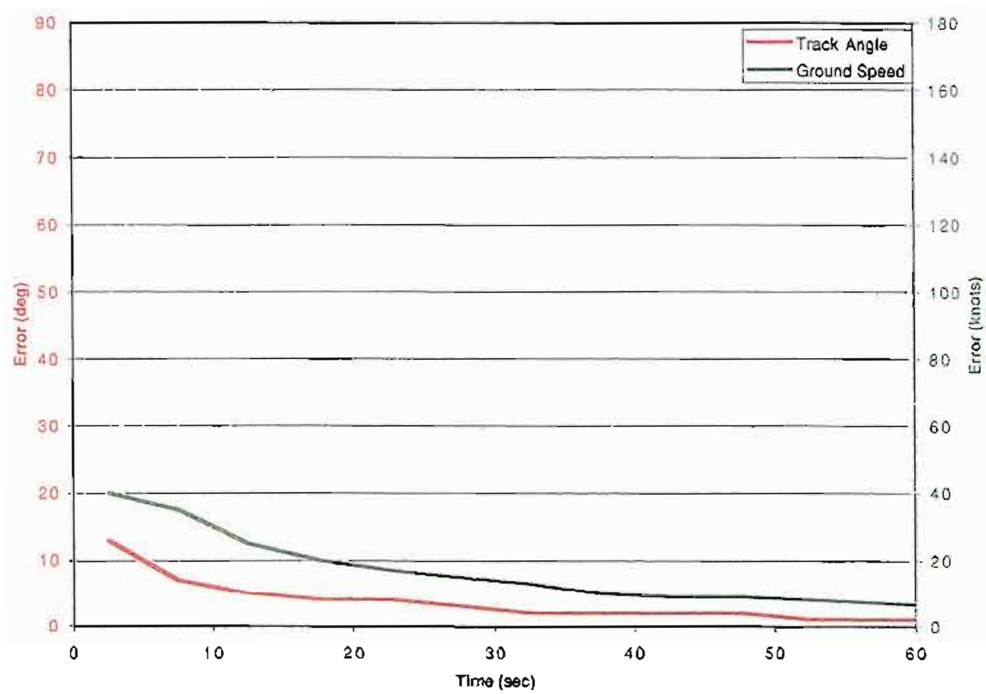


Figure 199. Maneuver Test - Straight (After Maneuver) - Track Angle & Ground Speed Errors - Mode S Data - COTS A.

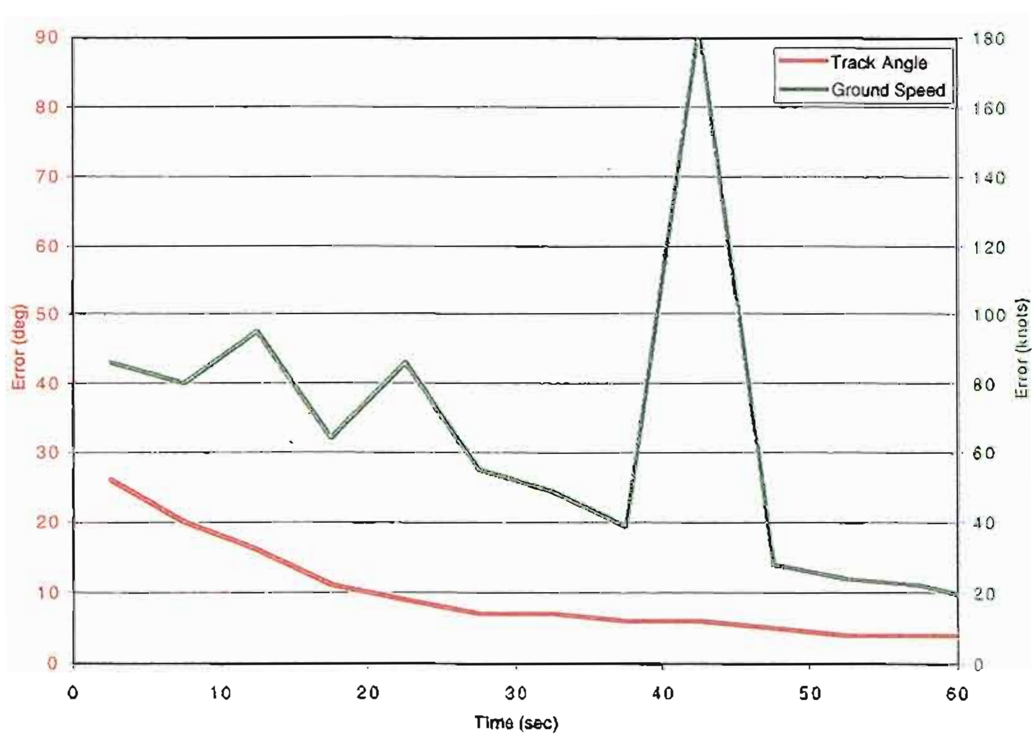


Figure 200. Maneuver Test - Straight (After Maneuver) - Track Angle & Ground Speed Errors - Mode S Data - COTS B.

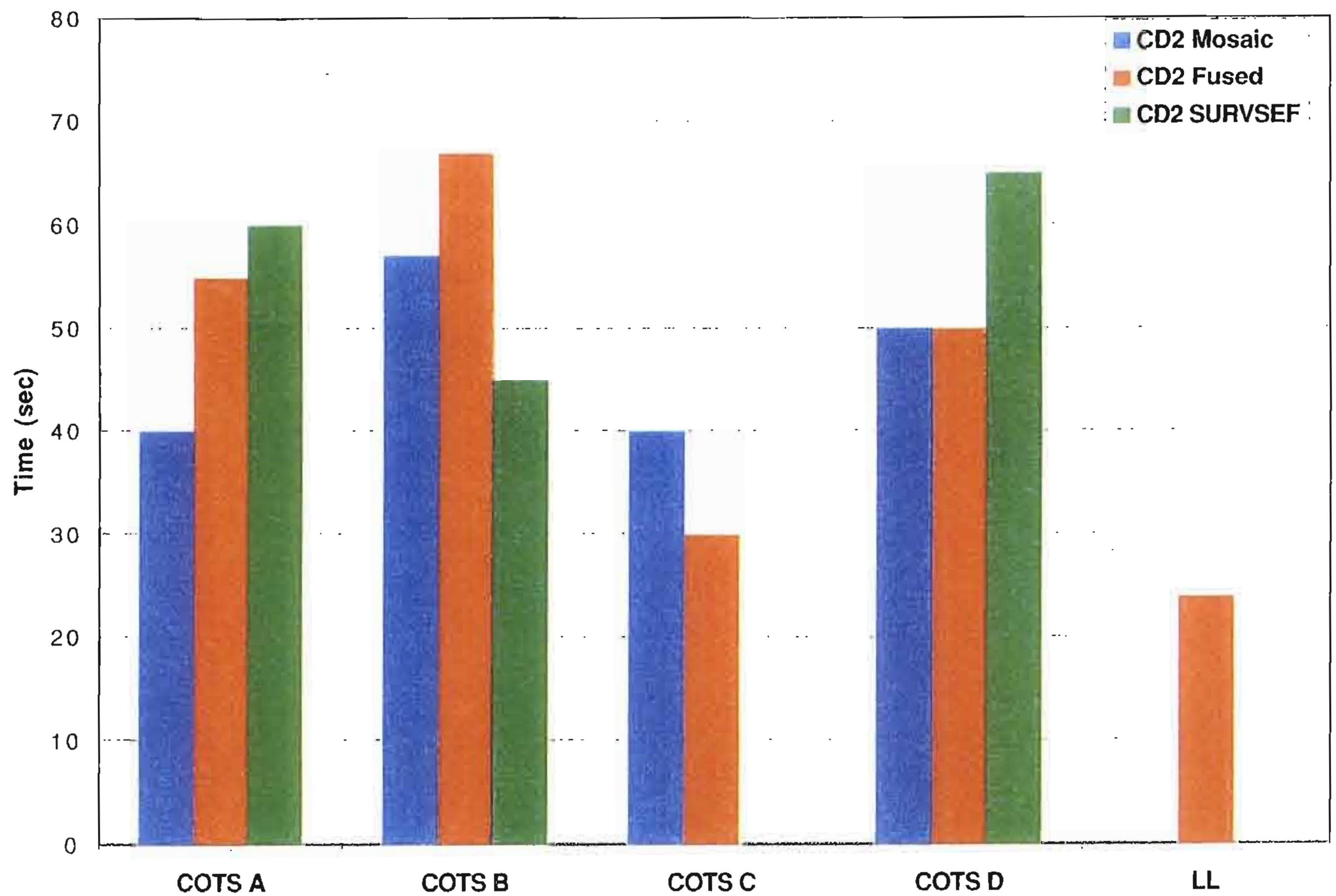


Figure 204. Time for Track Angle to Reach Accuracy of 10 Degrees - CD2 Data.A

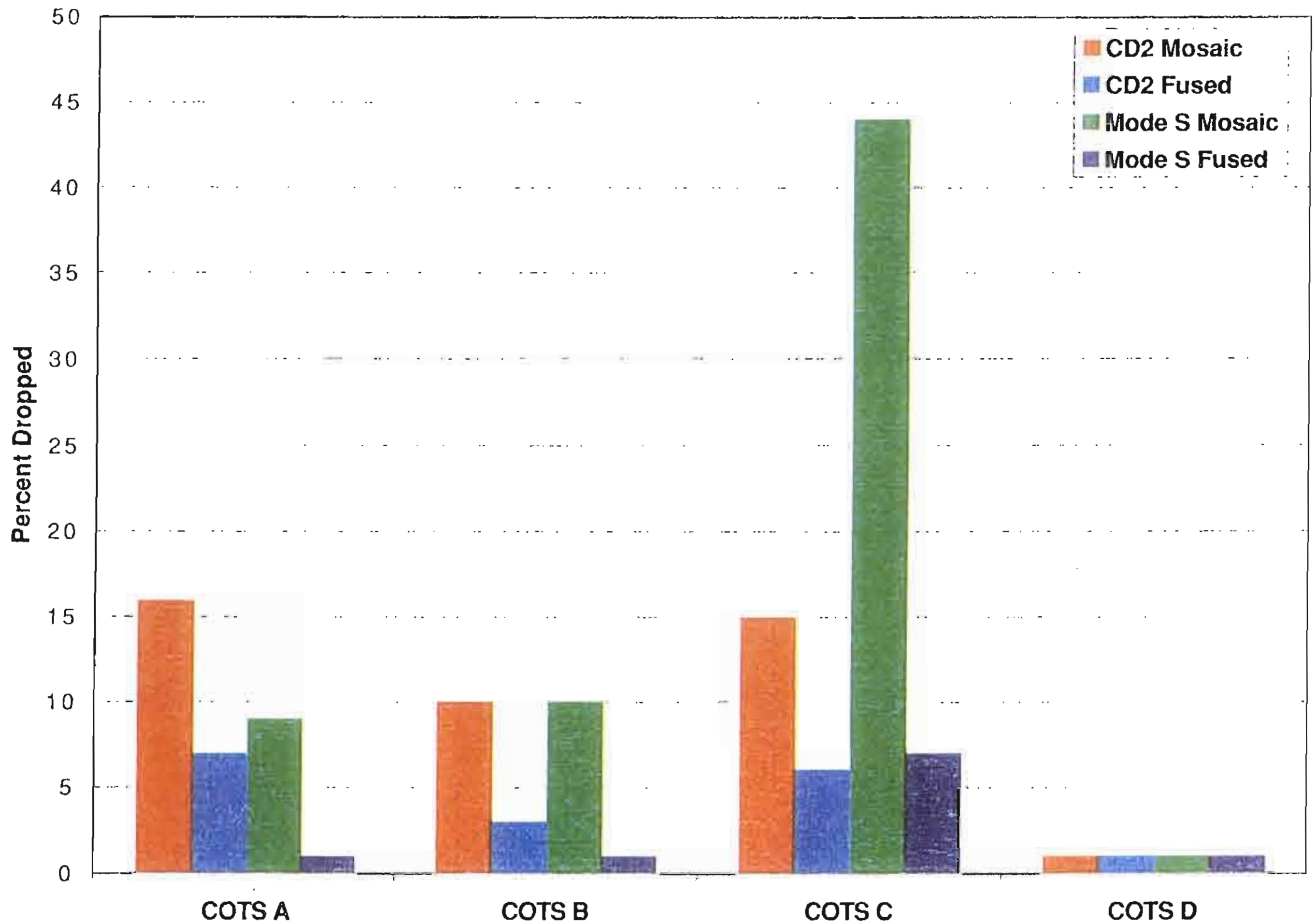


Figure 205. Percent of Tracks Dropped During Test Scenario.

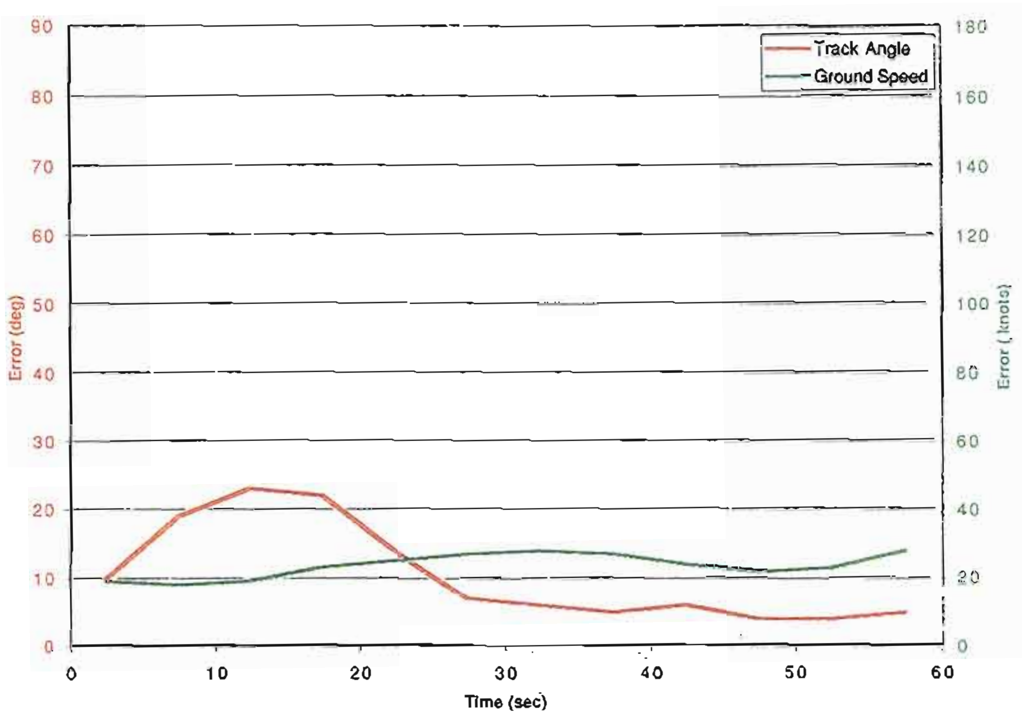


Figure 206. Maneuver Test - Turning (After Straight) - Track Angle & Ground Speed Errors - CD2 Data - Lincoln.

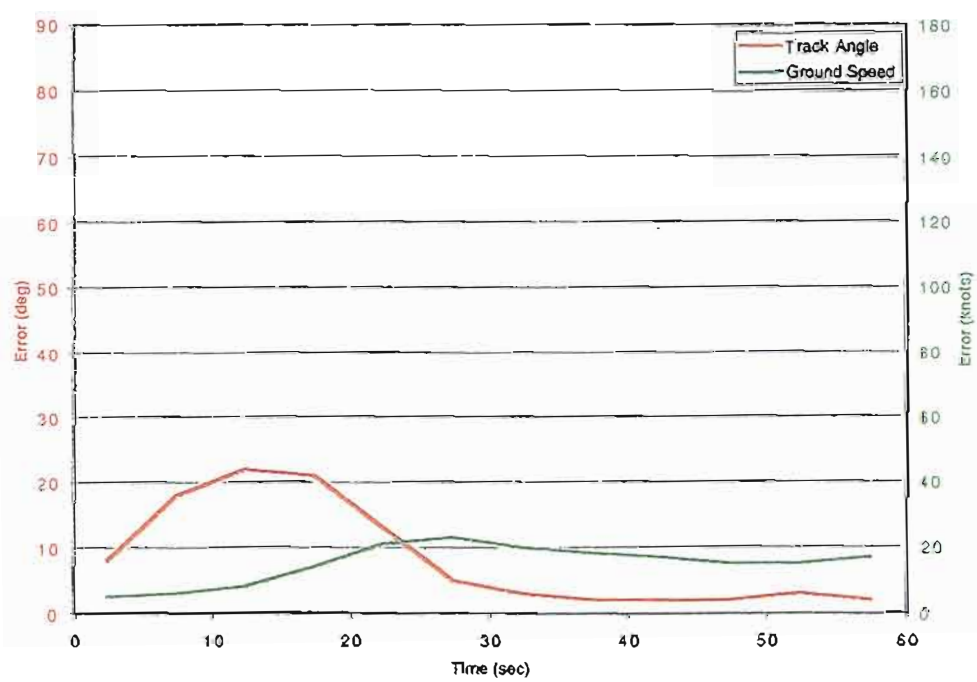


Figure 207. Maneuver Test - Turning (After Straight) - Track Angle & Ground Speed Errors - Mode S Data - Lincoln.

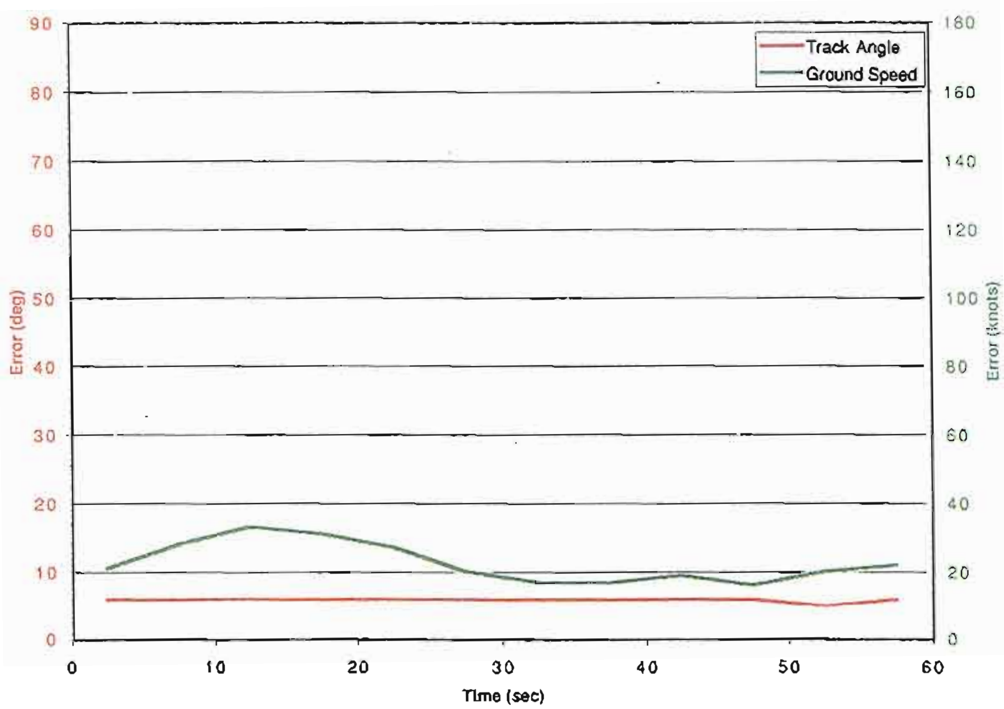


Figure 208. Maneuver Test - Accelerating (After Straight) - Track Angle & Ground Speed Errors - CD2 Data - Lincoln.

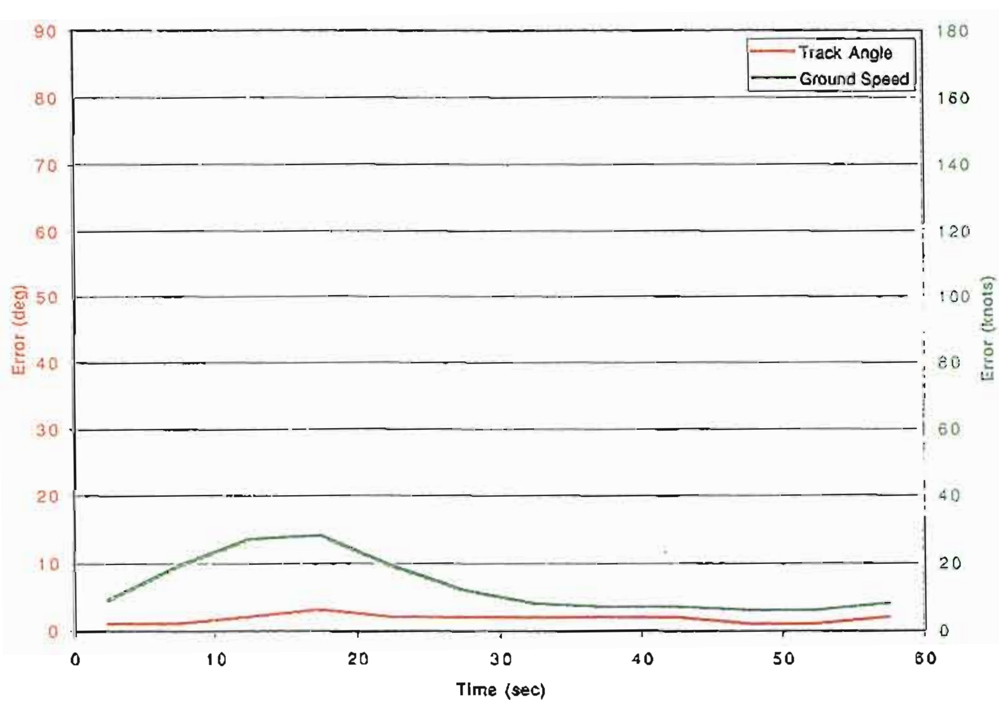


Figure 209. Maneuver Test - Accelerating (After Straight) - Track Angle & Ground Speed Errors - Mode S Data - Lincoln.

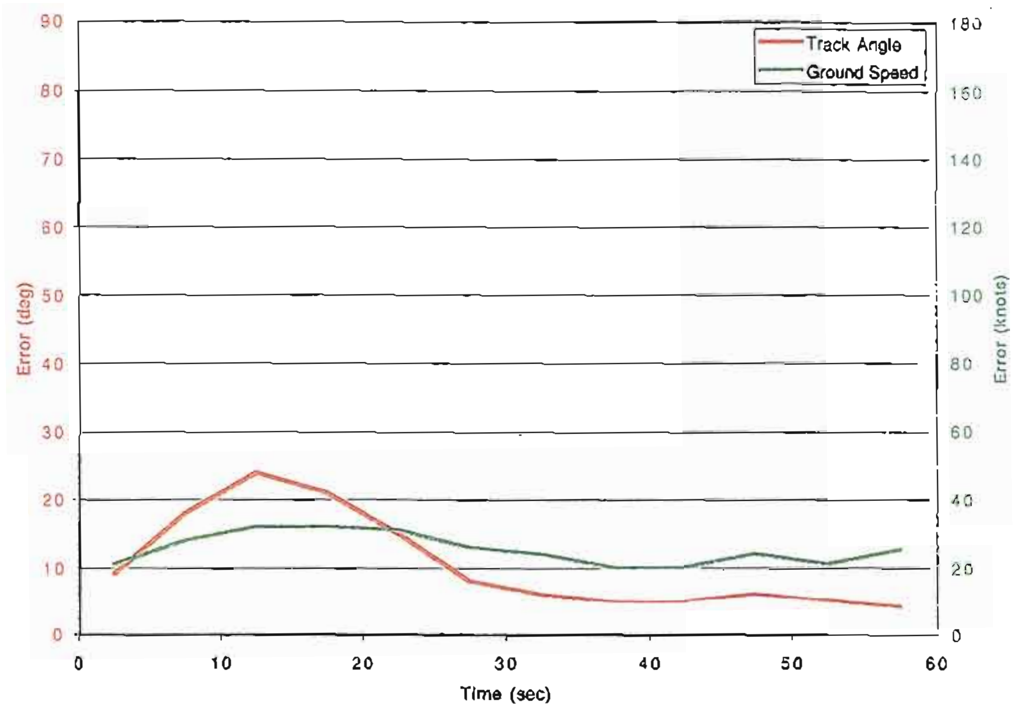


Figure 210. Maneuver Test - Turning & Accelerating (After Straight) - Track Angle & Ground Speed Errors - CD2 Data - Lincoln.

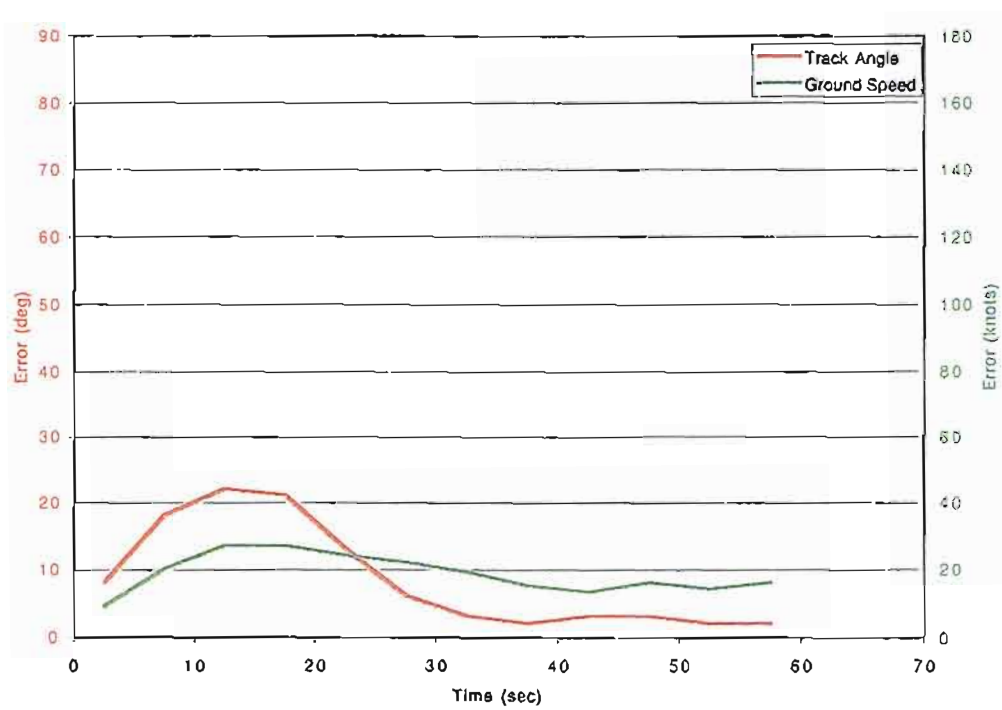


Figure 211. Maneuver Test - Turning & Accelerating (After Straight) - Track Angle & Ground Speed Errors - Mode S Data - Lincoln.

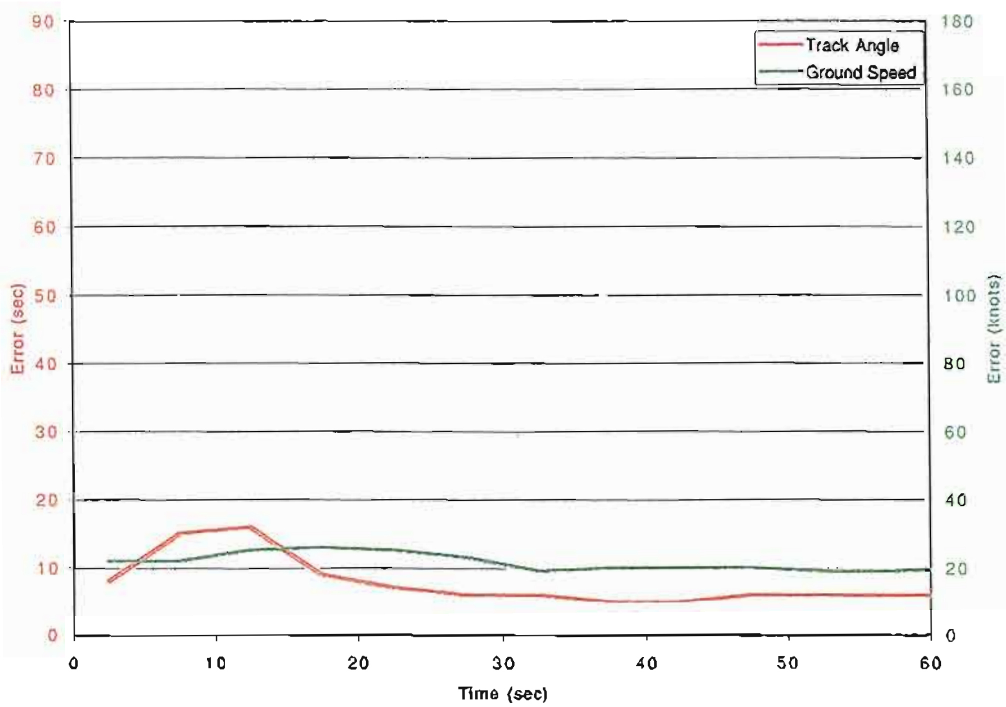


Figure 212. Maneuver Test - Straight (After Maneuver) - Track Angle & Ground Speed Errors - CD2 Data - Lincoln.

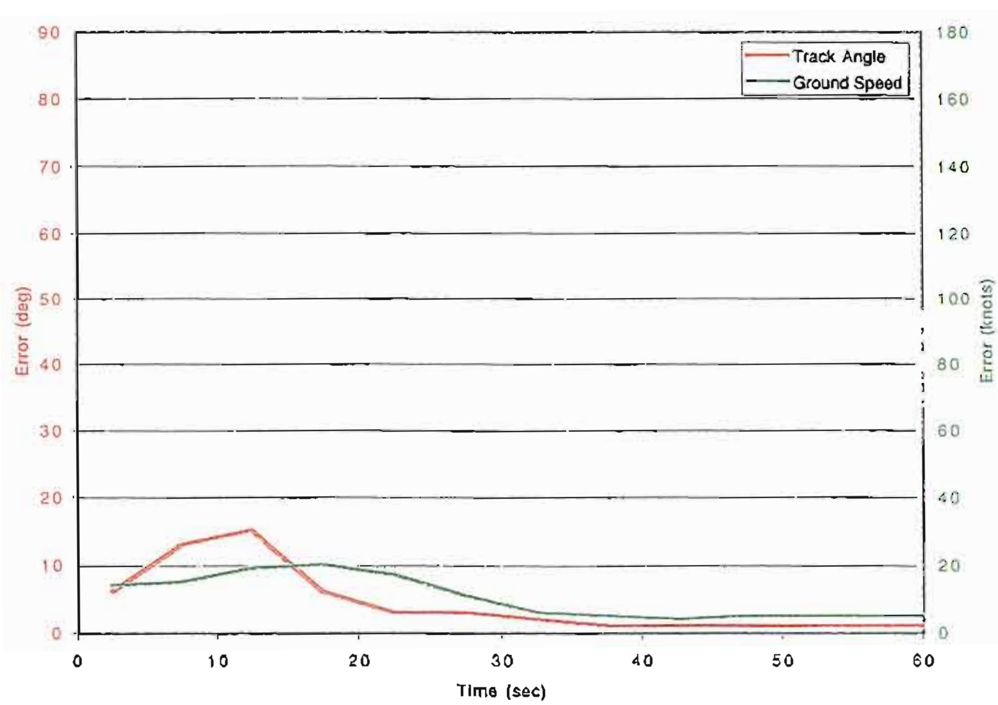


Figure 213. Maneuver Test - Straight (After Maneuver) - Track Angle & Ground Speed Errors - Mode S Data - Lincoln.

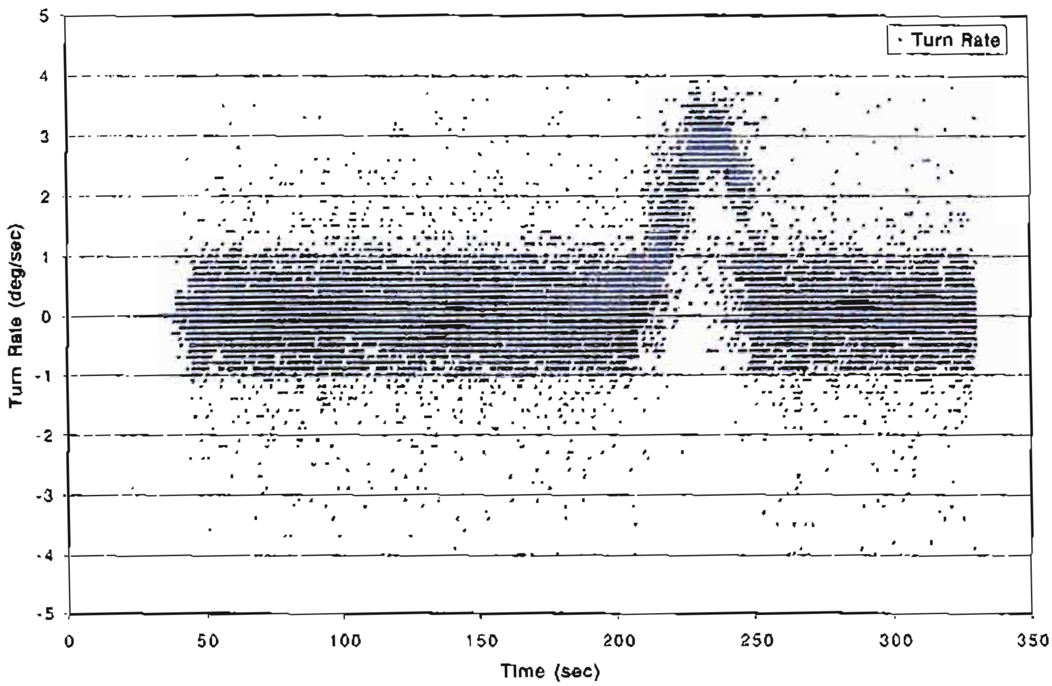


Figure 214. Computed Turn Rate Values - Turn 200-230 Seconds @ 3 Deg/Sec - CD2 Data - Lincoln Filter.

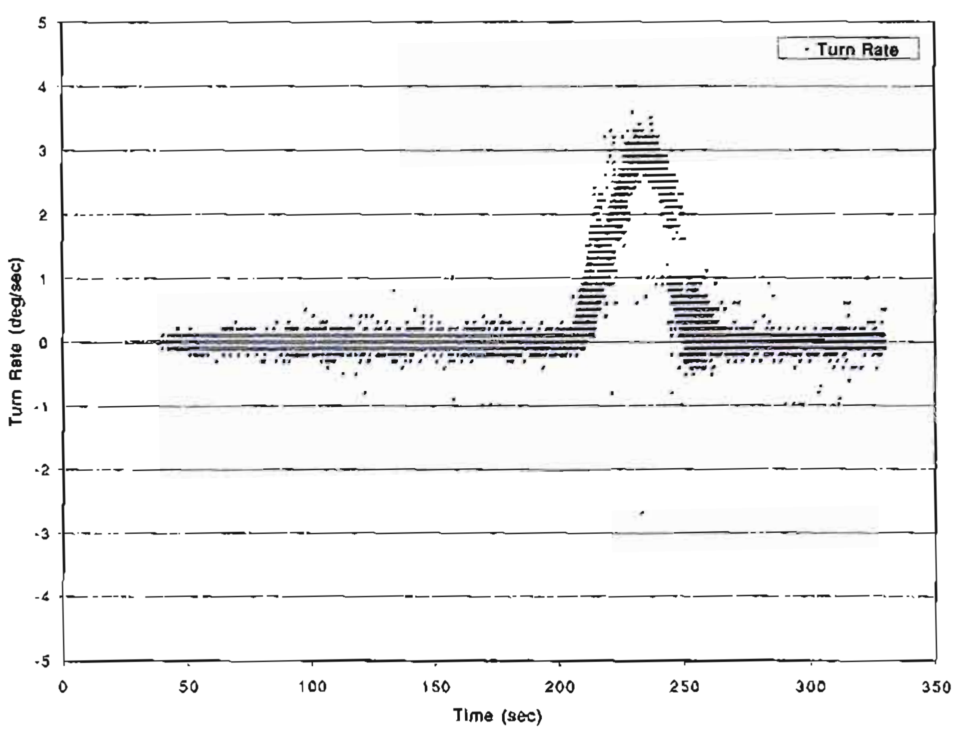


Figure 215. Computed Turn Rate Values - Turn 200-230 Seconds @ 3 Deg/Sec - Mode S Data – Lincoln Filter.

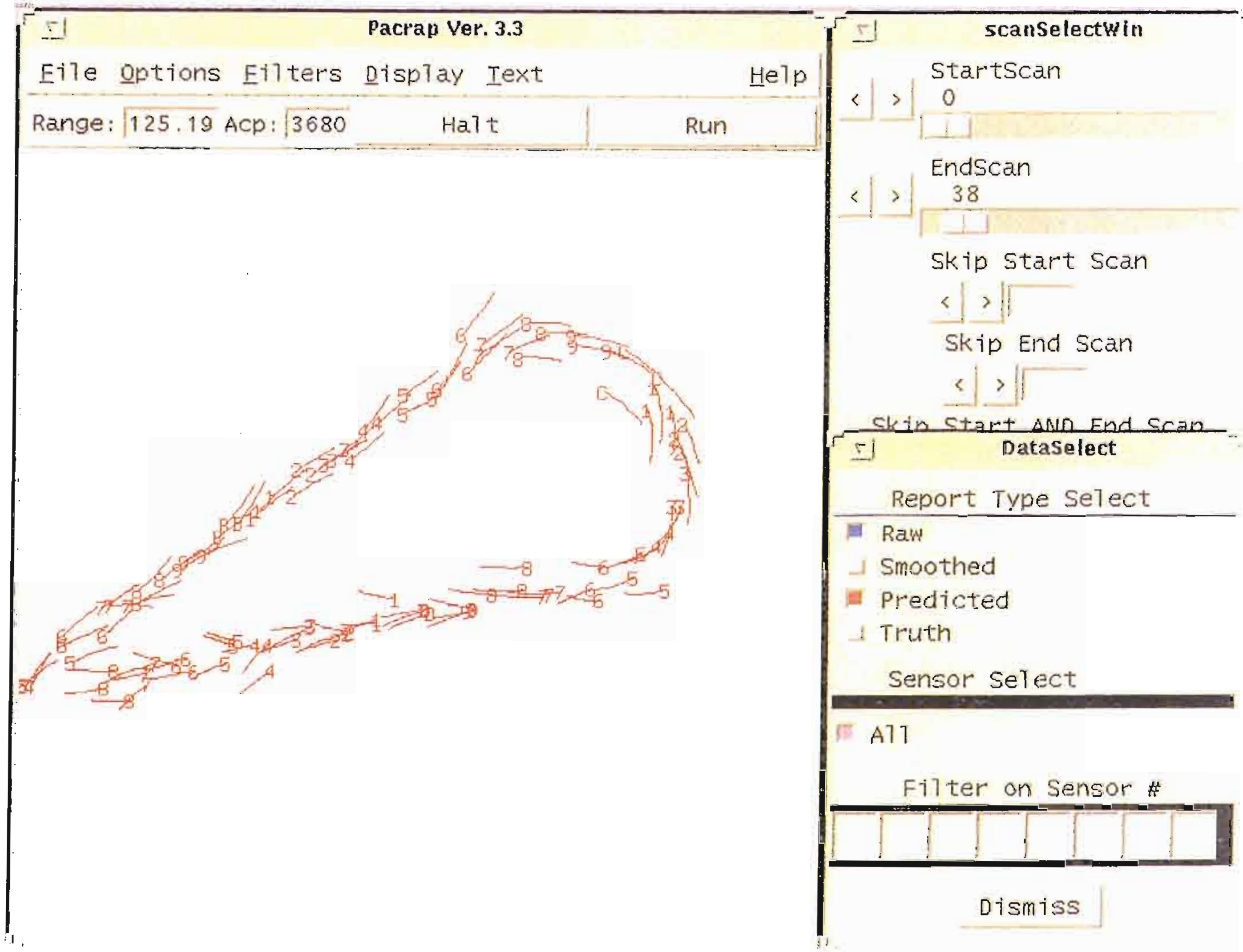


Figure 216. Sample Tracking Performance on Recorded Data During a Turning Segment - Lincoln Tracker.

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[1] Registration Errors in a Netted Air Surveillance System, MIT-LIN-TN-1980-40, W. L. Fischer et al., 2 September 1980.

[2] ASR-9 Processor Augmentation Card (9PAC) Data Extraction and Analysis Capability, 92PM-ASR/9-26, G.R.Elkin, 6 July 2000.