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HURRICANE TRACKING USING AN ENVELOPE APPROACH
IMPACTS UPON FORECASTS

Robert C. Sheets
National Hurricane Center
Miami, Florida
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UNITED STATES DEPARTMENT OF COMMERCE / Malcolm Baldrige, Secretary
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National Weather Service / Richard E. Hallgren, Director

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HURRICANE TRACKING USING AN ENVELOPE APPROACH

- IMPACTS UPON FORECASTS

by

Robert C. Sheets
National Hurricane Center

ABSTRACT

A new approach to tropical cyclone tracking utilizing a mass field envelope has been applied to a selected set of hurricanes. The results indicate the technique can provide potential 24 hour forecast error reductions of 10 to 20 percent for slow, erratically moving storms.

1. INTRODUCTION

Tracking of tropical cyclones over the years has primarily focused on the movement of the "eye" and/or the center of the low level circulation and minimum sea level pressure. This center often goes through small scale oscillations (usually less than the diameter of the eye) which are not representative of the more conservative and larger scale motion of the entire storm envelope. This can lead to erroneous interpretations of the hurricane's current movement. Because of the dominance of persistence in short term forecasts, these misleading motions can result in large forecast errors and potentially serious consequences.

Many of these type problems are exemplified by the hurricane Carla case in 1961. The track of hurricane Carla, as derived from hourly (some positions are the same for two hours) land-based radar observations during a period of about 42 hours as Carla approached and moved over the Texas coast, is depicted by the open circles in figure 1. This track exhibits oscillations of the type which cause considerable problems for forecasters and coastal residents. The forecaster tries to "smooth out" these small scale oscillations for use in generating forecasts and associated warnings. However, some of the apparent directional and speed changes can persist for several hours leading the forecaster to believe they represent general motion when after the fact analyses show otherwise. Complicating the matter is that at times, even the smallest of these movements may be the first indications of changes in movement of the hurricane scale system (a hundred to a few hundred kilometers). In those cases, "smoothing" can result in critical delays of recognizing general course changes.

The small scale oscillations shown in figure 1 also likely occurred during more than just the hours shown. Figure 2 shows the advisory positions along with the after-the-fact "smoothed" ("best track") track. The advisory positions themselves show attempts to smooth the track (compare radar positions with advisory positions) and even more smoothing is normally done for

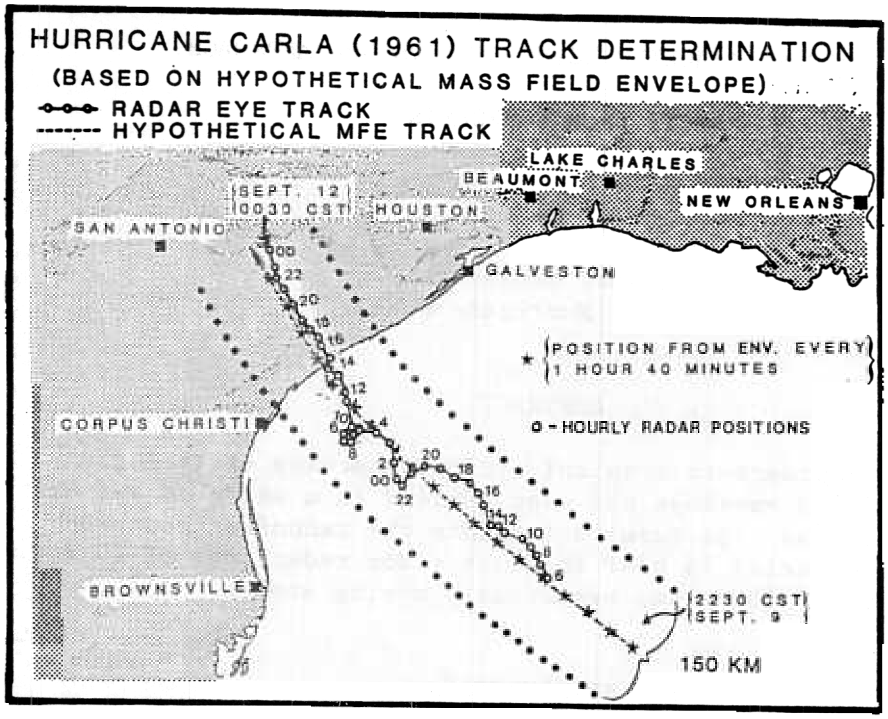

Figure 1. Radar determined track of hurricane Carla (1961) (CST hourly positions shown) with hypothetical mass field envelope track

input to forecasts. However, even with this smoothing, considerable problems resulted based upon poor resolution of the general track in real time. Decisions concerning these forecast tracks become especially critical when a storm is nearing a coast where a slight change in forecasts can alter the actions of several million people.

An examination of the advisories issued for Carla will amply illustrate the problems these type oscillations cause forecasters. At 4 p.m. (all times in the Carla discussion are central standard times) on September 7, a hurricane watch was advised from Morgan City, Louisiana eastward to Apalachicola, Florida. In addition, the advisory stated that "...hurricane warnings UNDOUBTEDLY will be hoisted for a portion of that area on Friday" (next day). That statement was repeated in the 7 p.m. advisory. At 10 p.m. the advisory stated that "...hurricane warnings WILL be hoisted for a portion of that area by noon Friday..." That statement was repeated at 1 a.m. Friday (September 8), but by 4 a.m. the tone of the forecasts and potential warnings started to become a little less certain. The same forecaster who had used the term "UNDOUBTEDLY" 12 hours earlier now extended the hurricane watch to the west to include all of Louisiana and stated that "..hurricane warnings will PROBABLY be issued later today..." The 7 a.m. advisory stated that the hurricane watch may need to be extended farther westward to include the Texas coast. At 10 a.m. the watch was issued and now included the entire Texas coast eastward to Apalachicola, Florida. It was also stated that "...hurricane warnings WILL be issued for a portion of that area tonight or Saturday..." This was only the beginning of the forecast and warning problems for this major hurricane.

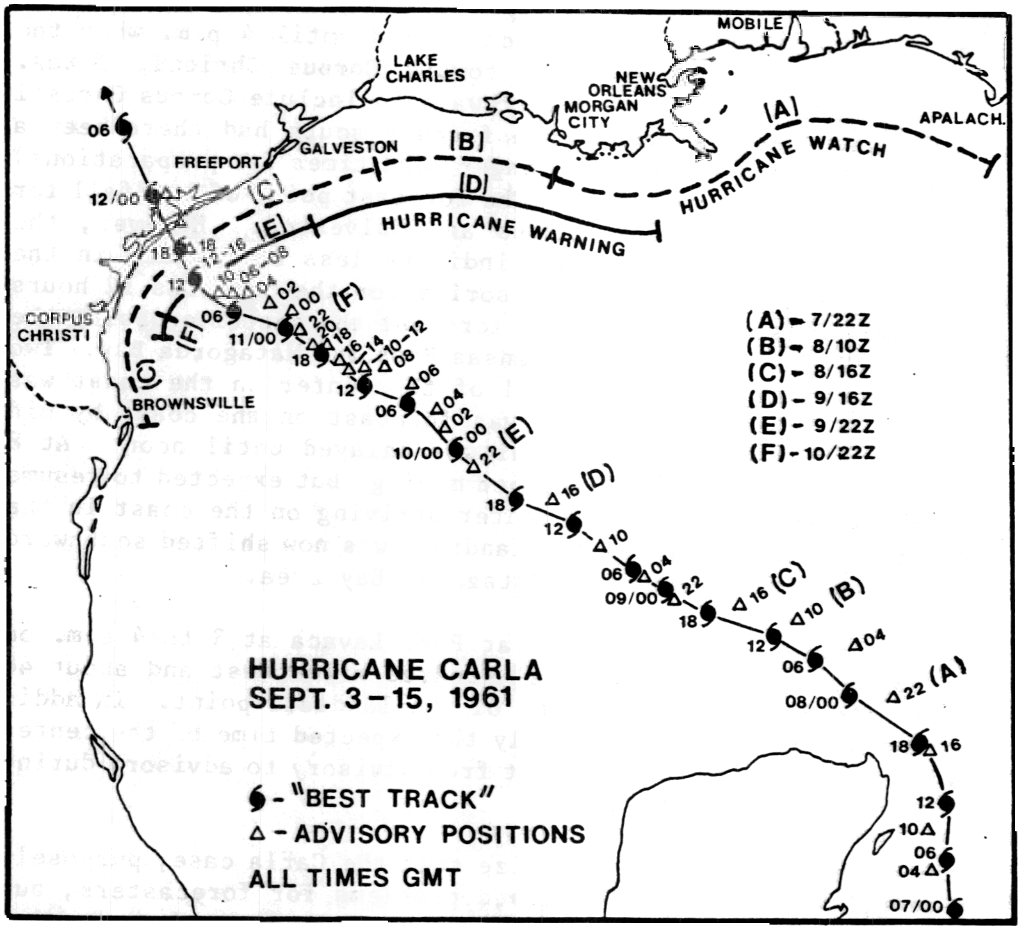

Figure 2. Advisory time initial positions and after the fact "Best Track" 6 hourly positions for hurricane Carla (1961). Also shown are hurricane watch and warning zones along the coast with the letter indicating the zone and corresponding advisory positions of the center of the hurricane at the time of the issuance of the watch or warning.

Hurricane warnings were finally issued at 10 a.m. on September 9. These warnings were for the coast from Freeport, Texas to Grand Isle, Louisiana (well west and one day later than indicated 42 hours earlier). The advisory also stated that the center would move over the upper Texas or western Louisiana coast on September 10. At 4 p.m. September 9, hurricane warnings were extended southwestward to Aransas Pass. The center was now forecast to move inland over the upper Texas coast September 10. At 2 a.m. September 10, the center was forecast to move inland between Aransas Pass and Galveston late that day. At 6 a.m., the advisory stated that the hurricane had moved little during the past few hours, but should resume a northwest movement, crossing the coast "tonight" (Sunday). The 8 a.m. advisory was essentially the same as the 6 a.m. advisory (hurricane remained nearly stationary).

The 10 a.m. advisory indicated the hurricane had resumed its northwest course near 10 mph and the center would move inland between Aransas Pass and Galveston late "tonight". That forecast held until 4 p.m. when the "eye" of Carla began to move directly toward Corpus Christi, Texas. Hurricane warnings were then extended southward to include Corpus Christi and likely would have been extended even farther south had there been a more densely populated area (requiring longer lead times for preparations) between Corpus Christi and Brownsville. The forecast point of landfall for the center remained between Aransas Pass and Galveston. However, the extension of the warnings southward may indicate less confidence in the forecast track than indicated in the advisories for the previous 12 hours or so. The 10 p.m. advisory continued to forecast the center crossing the coast "late tonight", but now between Aransas Pass and Matagorda Bay. Two hours later, the forecast time of arrival of the center on the coast was near "daybreak". At 2 a.m. the center was forecast on the coast by mid morning. At 4 a.m., the time of arrival was delayed until noon. At 8 a.m., the hurricane was said to have stopped moving, but expected to resume a northwest movement shortly with the center arriving on the coast in the afternoon. The possible point of center landfall was now shifted southward to include Corpus Christi through the Matagorda Bay area.

The center finally moved over the coast at Port Lavaca at 3 to 4 p.m. on September 11 (Monday). This was several hundred miles west and about 48 hours later than the initial indications of the landfall point. In addition, the projected point and particularly the expected time of the center of Carla crossing the coast shifted almost from advisory to advisory during the last 24 hours before landfall.

It doesn't take much imagination to realize that the Carla case, purposely described at length above, not only caused problems for forecasters, but also for local officials. Carla occurred in 1961. The tremendous population increases and industrial developments that have taken place in that area since then would compound those problems many times over if a similar incident were to occur today. The problems associated with these uncertainties in the "actual" track are even further compounded today because of the availability of "dial up" radars and satellite imagery which means that many people attempt to do their own "nowcasting". If they are unfamiliar with the Carla type motion they will likely be misled by these short term oscillations and perhaps mislead thousands of others, causing them to delay preparation actions. These delays could greatly increase the danger to their lives and property. The discussion above has been focused on a coastal situation. However, the same principles apply to open water marine and offshore operations and risks.

2. REAL-TIME TRACK DETERMINATION

The primary problem cited above is one of determining the motion of the system with a scale consistent with that for which a forecast is being attempted. In the case of the tropical cyclone, this may be an attempt to predict a swath of about 150 to 200 km in width over which the core of the cyclone will pass. The smoothed track of a system of this scale might be represented by the stars and dashed line in figure 1. The impact upon forecasts and associated warnings can be quite large if such a past and current track can reliably be determined in real time.

The determination of a track representative of the general motion of the tropical cyclone scale system in real time is also complicated by the various observing techniques and systems and their associated strengths and weaknesses. Differences in center positions determined by use of these systems primarily result from the use of different elements or features to define the center position. The satellite-determined positions are based upon cloud features. If no well-formed "eye" is present, considerable subjectivity is introduced resulting in differences from analyst to analyst. A study by Sheets and Greiman (1975) showed that internal consistency errors alone from satellite position determinations were of the order of 30 km or more when no well-formed, visible "eye" was present. Similar results have been obtained at numerous workshops conducted by the National Hurricane Center. When the deviation from the "actual" center is considered, an additional error of another 30 km occurs. These findings from the Sheets and Greiman study are routinely confirmed when positions obtained by the Miami Satellite Analysis unit are compared to those supplied from the U.S. Air Force Global Weather Center. Some of these positions are shown on figures for hurricane Alicia presented later. Unfortunately, many of the accuracy statistics in the literature do not reflect these values because they were derived from deviations from "best tracks" where, because of the lack of ground truth, the "best tracks" themselves are essentially a best "fit" to the satellite-derived positions. That is, those statistics basically represent a measure of the internal consistency rather than absolute errors.

The aircraft determined positions are not without their problems. They are primarily based on wind circulation centers and minimum pressures. The center position of these features may vary with height. Low level cloud features as well as airborne radar displays can also play a role in the reconnaissance aircraft determined positions. Again, a degree of subjectivity is introduced which can result in differences of positions from analyst to analyst. Center positions determined from radar rely on locating the center of the "radar eye" when it is well defined. If no well formed "radar eye" is present, spiral band overlays are used. However, even the radar determined positions using essentially the same techniques differ from those obtained at other sites.

Figure 3 illustrates a number of the problems discussed above. Here, there is an abundance of center "fixes" for hurricane Frederic (1979) as it approached the north coast of the Gulf of Mexico. The sources of these "fixes" are reconnaissance aircraft, satellite and land based radar systems. A close examination of these observations shows large discrepancies (as much as 30 km or more) of positions from the various sources for essentially the same times. These differences are not only present for the various types of systems, i.e. aircraft versus satellite, satellite versus radar and radar versus aircraft, but are also present for radar versus radar, satellite versus satellite and to some degree, aircraft versus aircraft.

Hurricane Frederic was a strong, well defined, hurricane at this stage. Yet, even here, large differences exist. Even larger differences are experienced, as discussed earlier, especially for weaker and less well defined systems. Satellite determined positions for hurricane Harvey

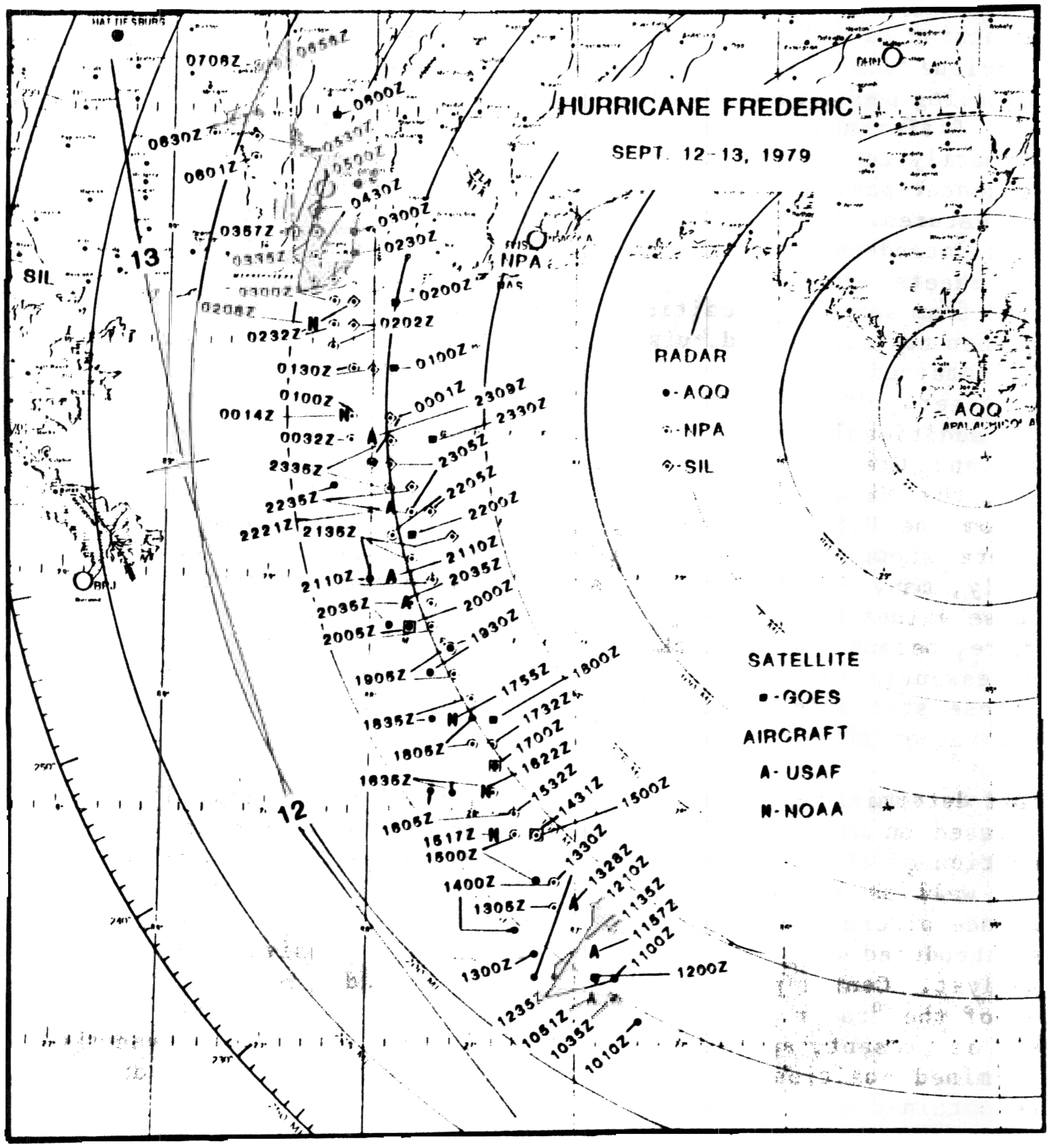

Figure 3. Operationally determined "center" positions for hurricane Frederic (1979) as determined from satellite, aircraft and land based radar.

(1981) were in error by more than 100 km (one day more than 200 km) on two consecutive days. About one week later, similar errors were observed for hurricane Irene.

As noted earlier, figure 3 depicts radar determined positions which differ from site to site even though they used essentially the same techniques. Some of the reasons for these differences are illustrated in figure 4. This figure is a schematic illustration in vertical cross section form of a sloping "radar eyewall" situation for a tropical cyclone. The case illustrated is for two different radar sites located at near equal

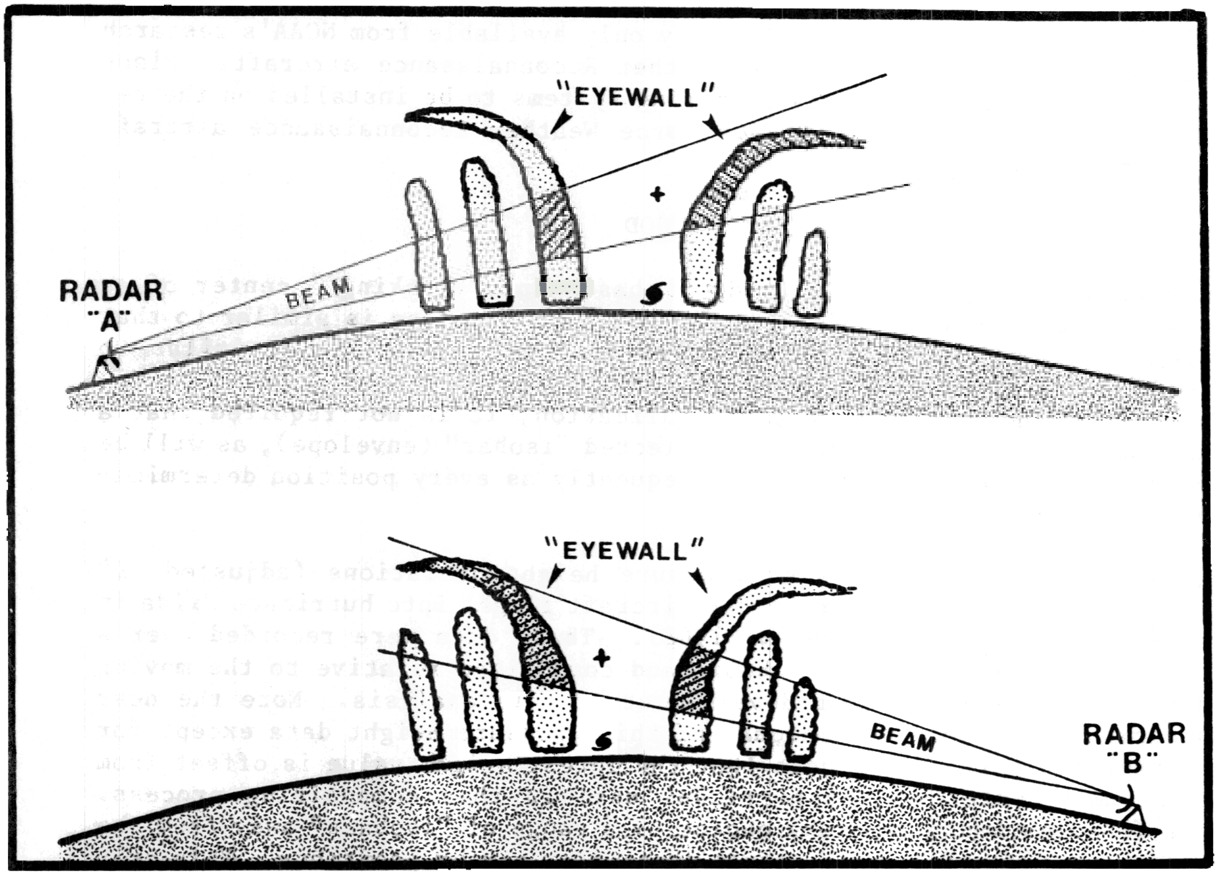

Figure 4. Schematic drawing of a vertical cross section through a tropical cyclone as observed from two different radar sites. Resultant center position is shown by the tropical cyclone symbol.

distance, but on opposite sides from the center of the tropical cyclone. However, due to the sloping eyewall, the center positions determined from the "radar eye" displayed at each site (tropical cyclone symbol) are considerably different. If the radar sites were also located at different distances from the "eye", even larger differences would be expected because of different elevation viewing angles and beam filling characteristics. This characteristic would occur even with a circular "eyewall". If the more typical case of asymmetries in the radar "eyewall" structure, both vertically and horizontally occurred, there would be even larger differences.

One way to arrive at a "smooth" track would be to simply apply some "best fit" filter routine to all available center positions. Perhaps some sources of observation could be given more influence in this routine than other types of information. However, because of the differences cited above and other factors discussed later concerning filtering, an erroneous real time track would likely result.

This paper describes a technique for the operational determination of past and current motion of the tropical cyclone scale system based on the use of Improved Weather Reconnaissance System (IWRS) type data. Preliminary results utilizing this technique and their impacts on associated forecasts and warnings are also discussed. The data required for operational application of this technique are presently only available from NOAA's research aircraft and one U.S. Air Force Weather Reconnaissance aircraft. Plans presently call for these data gathering systems to be installed on the remainder of the standard U.S. Air Force Weather Reconnaissance aircraft during the next few years.

3. METHOD

The method utilized in this study is based upon tracking a center of an envelope determined from the mass field. This envelope is similar to that depicted by the shaded ring in figure 5. This process is similar to tracking the center of a closed isobar on a surface analysis. However, in the case of the tropical cyclone application, it is not required that a fixed value "isobar" be used. The selected "isobar" (envelope), as will be demonstrated later, can change as frequently as every position determination.

Figure 5 shows an analysis of pressure height deviations (adjusted "D" values) recorded onboard a research aircraft flight into hurricane Hilda in 1964 (after Hawkins and Rubsam, 1968). These data were recorded over a period of a little over three hours and composited relative to the moving center of the hurricane for development of this analysis. Note the near concentric nature of the contours of this pressure height data except for the inner contours. Also note that the lowest height value is offset from the assumed center of the hurricane used in this compositing process. These features imply that any choice of a range of "isobars" away from the vortex central region would result in similar center positions. This critical assumption will be discussed in greater detail later.

The primary goals of development of this tracking technique are that it: 1. Be uniquely measurable and tractable in real time with easy operational application; 2. Provide a stable track (minimizes scatter of points) for a range of tropical cyclone strengths and sizes with near equal reliability; 3. Remove small scale oscillations that <u>are not</u> <u>representative</u> of the movement of the tropical cyclone scale system; and 4. Depict changes in direction and speed such as recurvature, small scale loops, etc., that <u>are representative</u> of the tropical cyclone scale system movement.

These later two factors generally preclude the use of simple mathematical filters in time and space since tropical cyclone scale systems can make loops etc., similar in deminsions to those represented by the small scale oscillations. To meet these criteria, we must define an envelope which will only minimally be affected by small-scale oscillations such as trochoidal motions and then determine if that envelope remains sensitive to changes in the motion of the tropical cyclone scale system.

In order to properly define an appropriate conservative feature for a given stituation, we need to have some understanding of possible sources of "error". Neuman and Boyd (1962) studied the track of hurricane Carla (figure 1) and its relationship to the radar depiction of the hurricane. They indicated that the center of the hurricane seemed to migrate toward "a high intensity spot in the wall cloud radar echo". Figure 6 illustrates a hypothetical situation with an "eyewall" (light shaded area) with an

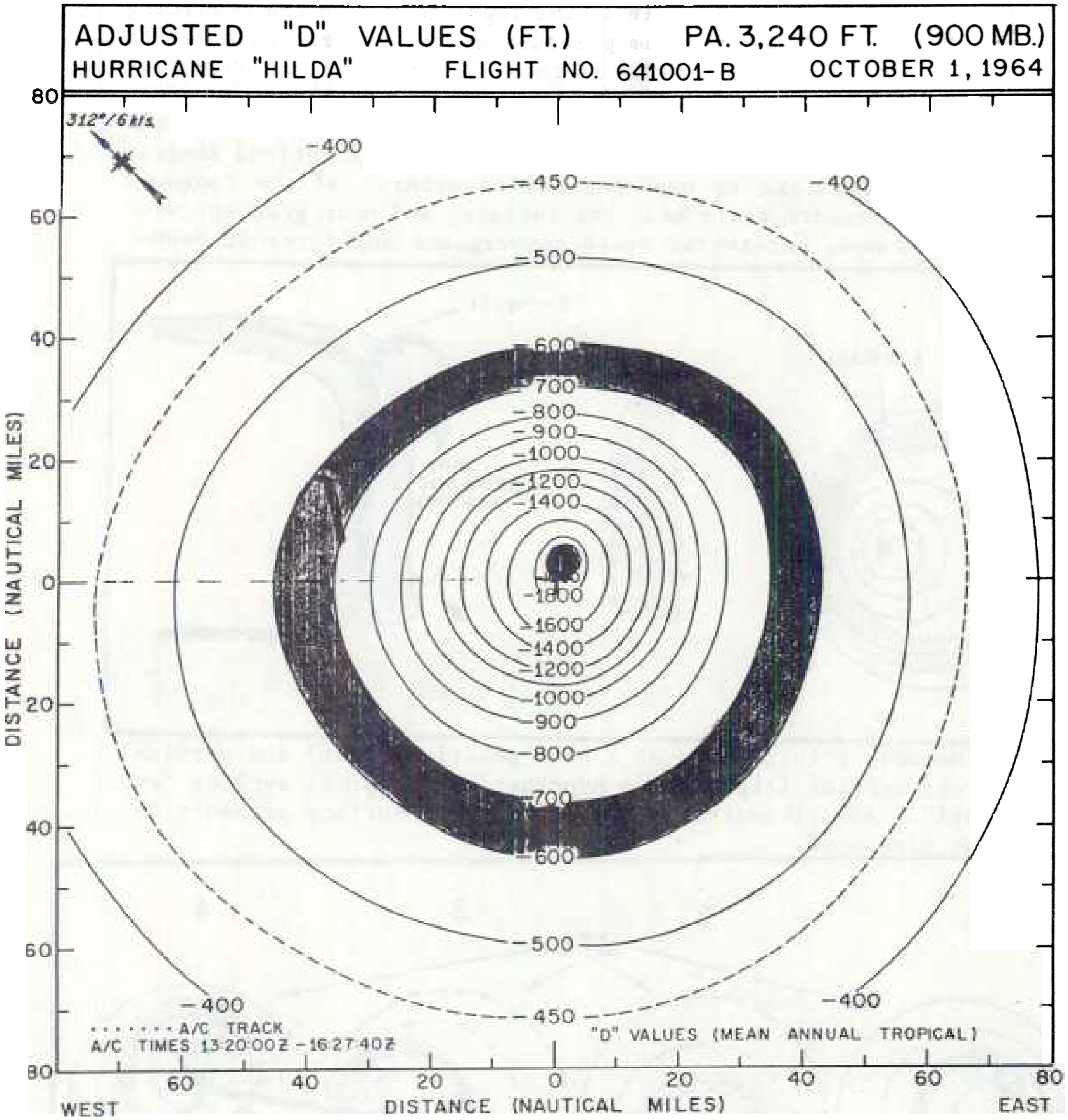

Figure 5. Analysis of adjusted "D" values for hurricane Hilda (1964) (after Hawkins and Rubsam, 1968).

imbedded "high intensity spot" in a plan view (left) and a vertical cross section (right). Also depicted in this hypothetical illustration are contours (isobars) of the surface pressure field which show the minimum pressure displaced from the center of the "eyewall" toward the convectively active region of the "eyewall". In this illustration, the "high intensity spot" generates or is the result of a strong vertical circulation that results in extreme warming on the inner edge of the eyewall adjacent to the "high intensity spot".

Figure 7 illustrates this situation in a time lapse form with the resulting motion of the "radar eye" and minimum pressure center as well as a yet to be defined pressure field "envelope". In this illustration, if only surface friction and near gradient winds are considered (actually, some cross isobaric flow must be occurring, but for purposes of this simple illustration, we assume near gradient wind conditions), small scale motions similar to trochoidal motions might be hypothesized to occur. If the contours shown represent a pressure field near the surface, and near gradient wind conditions are assumed, horizontal speed convergence would result down-

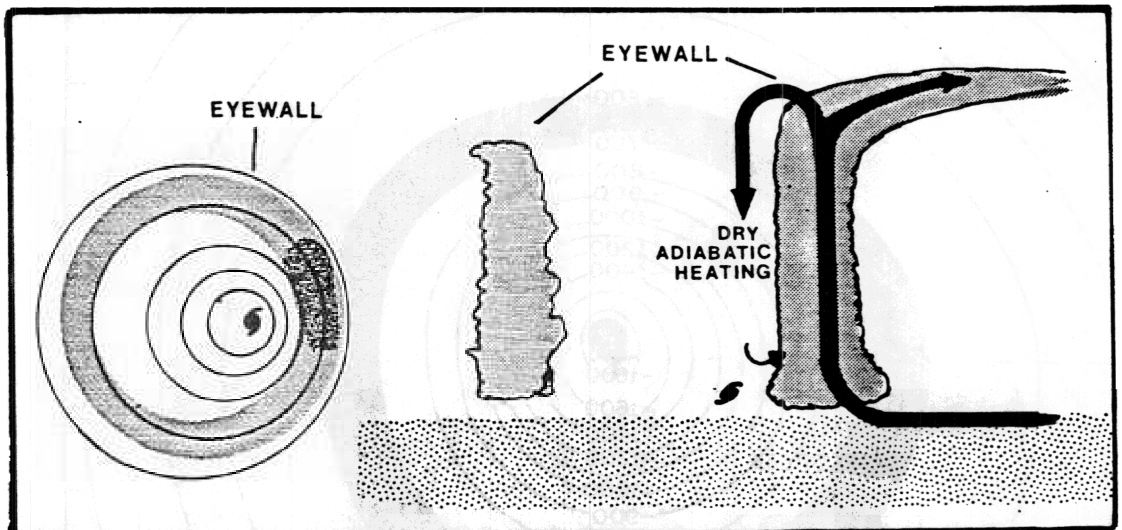

Figure 6. Schematic illustration of a plan position (left) and vertical cross section (right) of a hypothetical tropical cyclone "eye wall". Also illustrated are contours of surface pressure in the plan view.

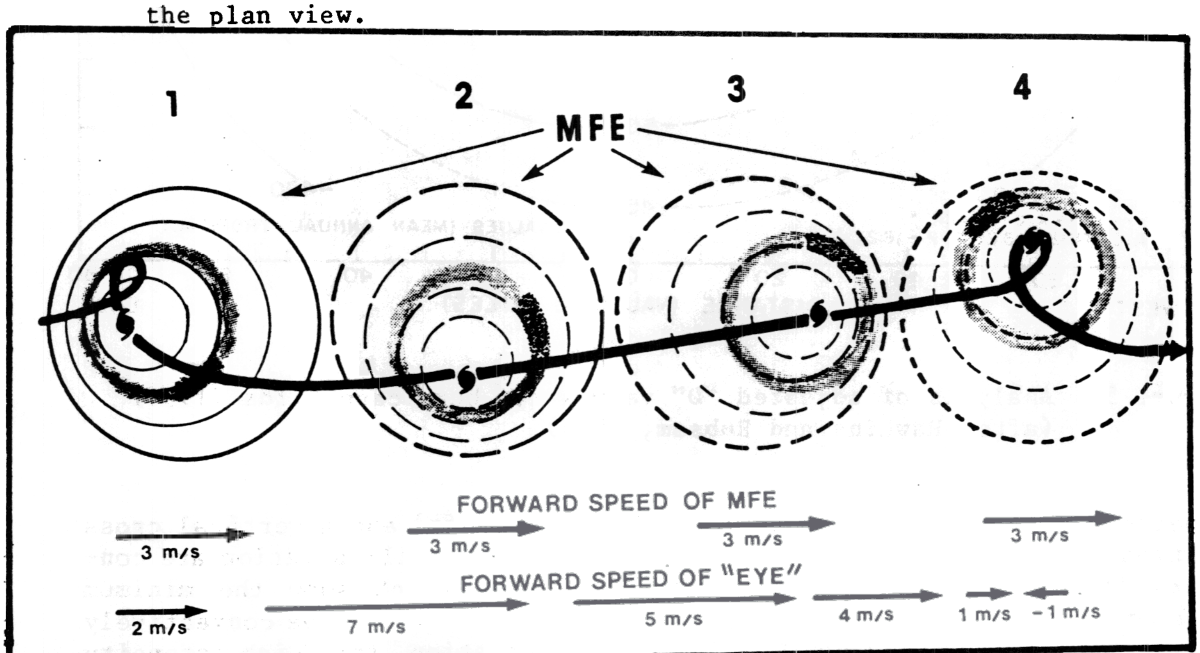

Figure 7. A hypothetical time lapse sequence of the plan position shematic of figure 6 along with a minimum pressure center track (bold solid line) and a hypothesized mass field envelope (MFE) track.

stream from the largest pressure gradients. Due to surface friction effects, this could support the maintenance of a strong vertical circulation resulting in the the "high intensity spot" and associated pressure field illustrated in figure 7 (no attempt is made here to speculate which initiates which, i.e., "high intensity spot" first or asymmetric pressure field first).

Because of the displacement of the "high intensity spot" downstream, the resultant vertical circulation and associated heating would cause the pressure center and radar "eye" center to be displaced toward the "high intensity spot". The resultant motion of the radar "eye" and pressure centers could then be as depicted in figure 6 and similar to that described by Neuman and Boyd (1962) for the Carla case. In this hypothesized situation, the small scale oscillation is restricted to the diameter of the "eye". (This is not intended to be an in depth discussion of trochoidal motion, but as a conceptual illustration of small scale oscillations which can produce erroneous interpretations of the tropical cyclone scale motion. It is these motions that we are attempting to remove through an appropriate definition of an envelope for use in the tracking the tropical cyclone scale system.)

An envelope which will minimally be affected by scales of motion discussed above and yet be easily measured and tracked must be determined. Figure 8 illustrates pressure profiles derived from IWRS type data collected in hurricane Allen (1980) on two consecutive days. The envelope is chosen to be at a radius hopefully far enough from the center to be minimally affected by oscillations of the scale of the "eye" and yet at a location where gradients are sufficient so that there is no ambiguity about the location of the selected pressure value. In this case, a radius of approximately three to four times the radius of maximum winds (see figure 9) was chosen. In practice, the pressure profile is plotted similar to that shown in figure 8 where the abscissa is longitude for an east-west pass and latitude for a north-south pass. An arbitrary pressure value for the envelope for that pass through the vortex is chosen which is located at a radius of roughly (within a few km) of two to three times the radius of maximum winds.

For an east-west pass, the longitude of the chosen pressure value on one side of the center is determined and then the longitude of the exact same pressure value on the other side of the vortex is determined. The center point for the longitudinal component of the envelope at the time of the east-west pass is then just the mid point between these two longitudinal values. The time of this longitudinal "fix" is the mid time between the time of the two envelope end points. The same process is used to obtain the latitudinal component on a north-south pass (see appendix I). These component positions are then plotted as functions of time. A different pressure value (can be any measure of pressure such as height of standard pressure surface, "D" value, or extrapolated sea level pressure) can be chosen for each pass through the hurricane. This means that a quasi-steady state condition of the mass field on the scale of the envelope is only assumed for the time it takes to fly across the storm from one end point on the envelope to the same pressure value point on the other side of the center (about 30 minutes).

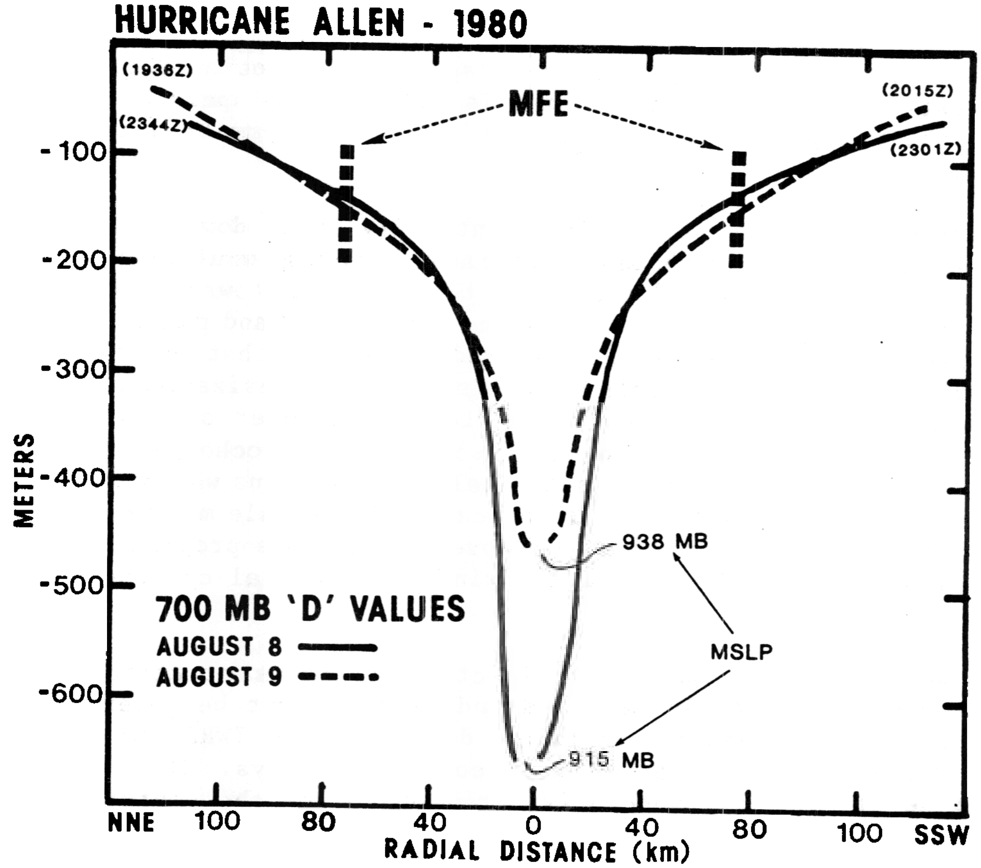

Figure 8. Pressure profiles (adjusted "D" values) for hurricane Allen (1980) and an arbitrary mass field envelope value.

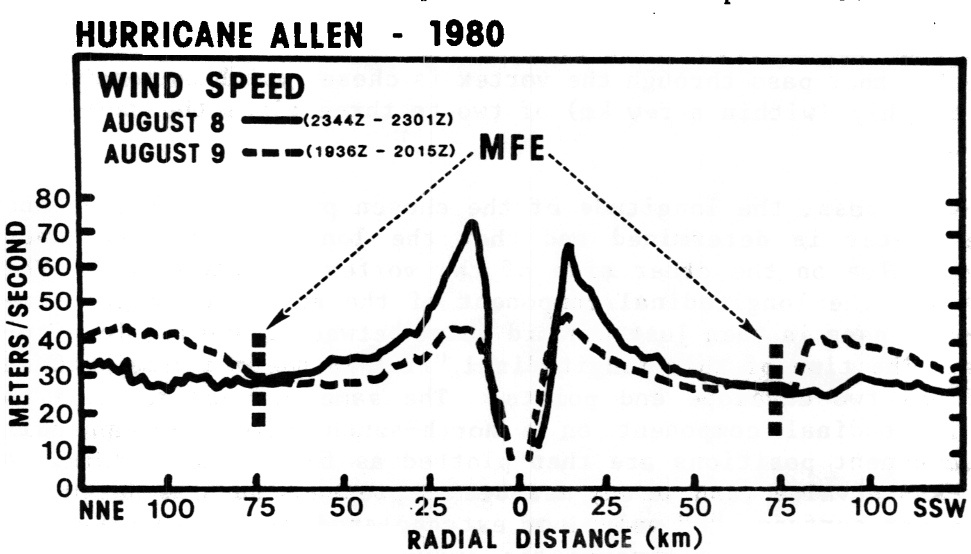

Figure 9. Wind speed profiles corresponding to the pressure profiles depicted in figure 8 along with the relative position of the chosen mass field envelope (MFE) value.

Figure 10 illustrates the standard "ALPHA" pattern used in hurricane reconnaissance missions and how it is utilized to track a northeastward moving storm. The solid stars in figure 10 correspond to the envelope values indicated by the heavy dashed lines in figure 8. The aircraft records the chosen value for the envelope at time T on the west side during its west to east traverse through the tropical cyclone vortex. Thirty-six minutes later (T+0:36) the aircraft records the same pressure height value on the opposite side of the vortex center as was observed at time T. This defines the initial envelope for that pass. (There is nothing magical about this value. It could have been slightly smaller or larger with no impact on the results as will be shown later.) During this 36 minute period, the system has moved toward the northeast at 10 m/sec. Therefore, the envelope has been displaced toward the northeast (second set of dots describing the circle). This introduces a small error along the flight track (about 1 km in this hypothetical illustration) in the longitudinally determined position (open star). (Note that the potential cross track error (latitudinal error for this pass) is quite large.) The longitudinal location of the envelope for this pass is simply the mid-point of longitude and time for the two points on the envelope.

The aircraft then flies toward the northwest and then proceeds southward through the approximate center of the vortex. An arbitrary pressure height value (same or different from that used for the west to east pass, but still at two to three times the radius of maximum winds) is chosen. That value is recorded at latitude 21 degrees and 40 minutes north at time T+1:40. The same value is encountered on the opposite side of the vortex at time T+2:16 near latitude 20 degrees and 20 minutes north. The latitudinal position at T+1:58 is then 21 degrees north.

As noted earlier, a potential cross-track error using an envelope method can be large. These errors can be reduced by filtering or time fitting of the data to circles. However, these approaches will also desensitize the system to recognition of changes in motion. That is the primary reason for the component approach to these position determinations. Another potential source of error is if the envelope used is elliptical with the defining axes oriented differently than along the cardinal points. However, the potential error here would have little impact on forecasts and warnings unless the elliptical envelope rotated rather rapidly (period of hours). That is, a skewed (not oriented along the cardinal points), nonrotating, elliptical envelope would produce a slightly offset, but parallel, track to that produced by a circle. The possible 5 to 10 km offset, would have little impact on the associated forecast and possible warning zone. Figure 11 illustrates a hypothetical sequence of these "ALPHA" patterns and the determined center positions in latitude and longitude components. The insert shows the envelope center positions plotted in component form (latitude and longitude) as functions of time. The components are then used to construct the track. (A simple method for application of this technique is given in Appendix I.) The result would then be similar to the hypothetical illustration in figure 1, where the stars represent the center of the envelope. The stars also represent the frequency of envelope positions possible, using a repetitive "ALPHA" pattern.

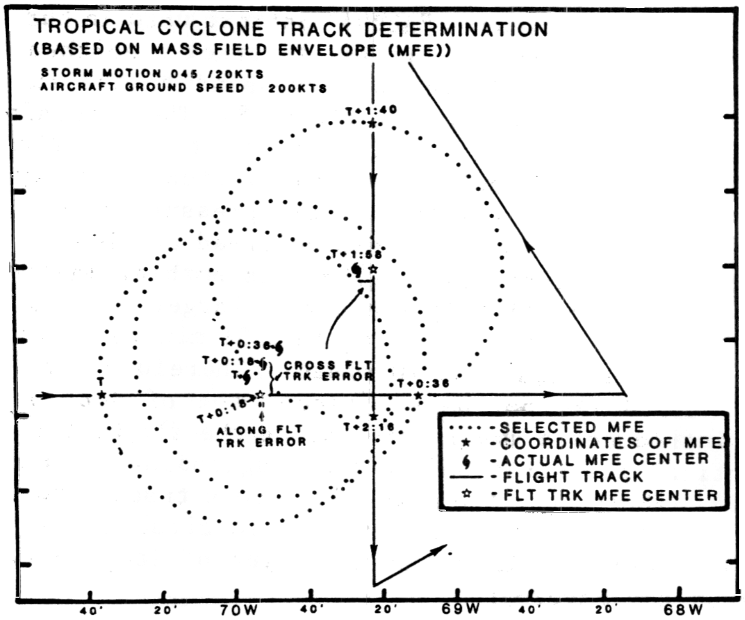

Figure 10. A reconnaissance aircraft "ALPHA" pattern (solid line) for a northeastward moving tropical cyclone as applied in the mass field envelope tracking technique. The dots indicate the chosen envelopes and the tropical cyclone symbol indicates the actual center position of the envelope.

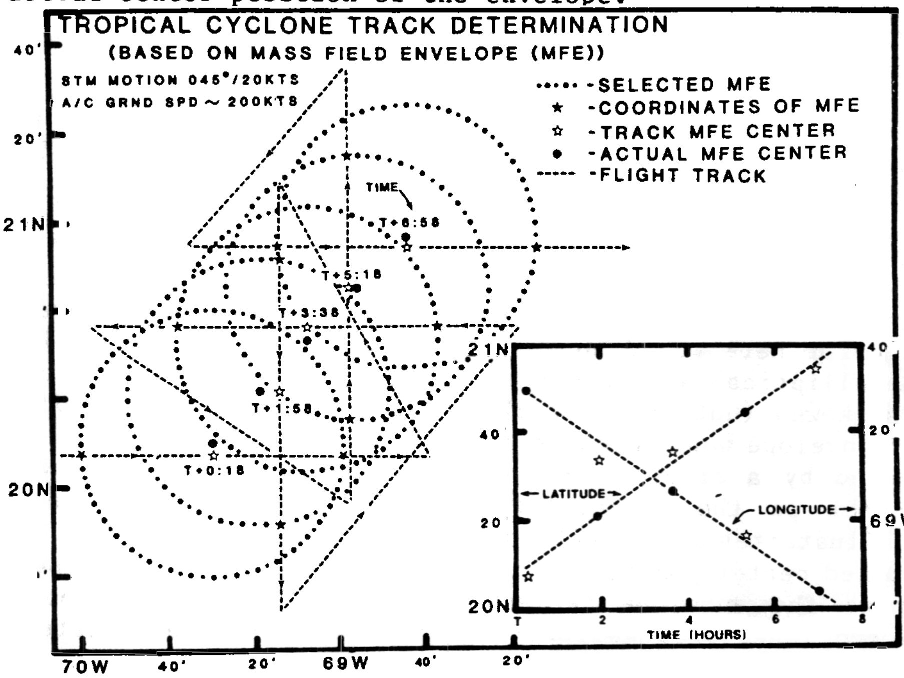

Figure 11. A sequence of "ALPHA" patterns (dashed lines) for a northeastward moving tropical cyclone as applied in the mass field envvelope (MFE) tracking technique for determining the storm track. The inset depicts the envelope (dots) center position determination in latitude and longitude components as functions of time.

4. RESULTS

The technique described above was applied to an extensive set of data collected by NOAA's research aircraft in hurricane Gert (1981). Figure 12 shows the track of hurricane Gert. Figures 13 and 14 show plots of latitudes and longitudes, respectively, versus time for hurricane Gert determined by use of the envelope technique. The standard error of estimates (adjusted for sample size throughout this paper) for a polynomial "fit" to these data were quite small. They were comparable to similar "fits" for positions determined from the excellent research aircraft reports and considerably better than satellite derived center positions shown in figures 15 and 16 (the dashed curves shown are the envelope derived data polynomial fits, but the statistics for the aircraft and satellite positions are based upon the listed polynomial fits to those data points).

These results were quite encouraging for several reasons. Some of these are: 1. The derived positions closely approximate the after-the-fact "best track" with no single major deviations from that track; 2. The system seemed not to be very sensitive to a chosen radius of the envelope as long as it was considerably larger than the radius of maximum winds. That is, the standard error of estimate for a sample using envelope radii of about 75 km were essentially the same as for a sample using radii of about 110 km; and 3. The period covered in the storm's life included portions of the

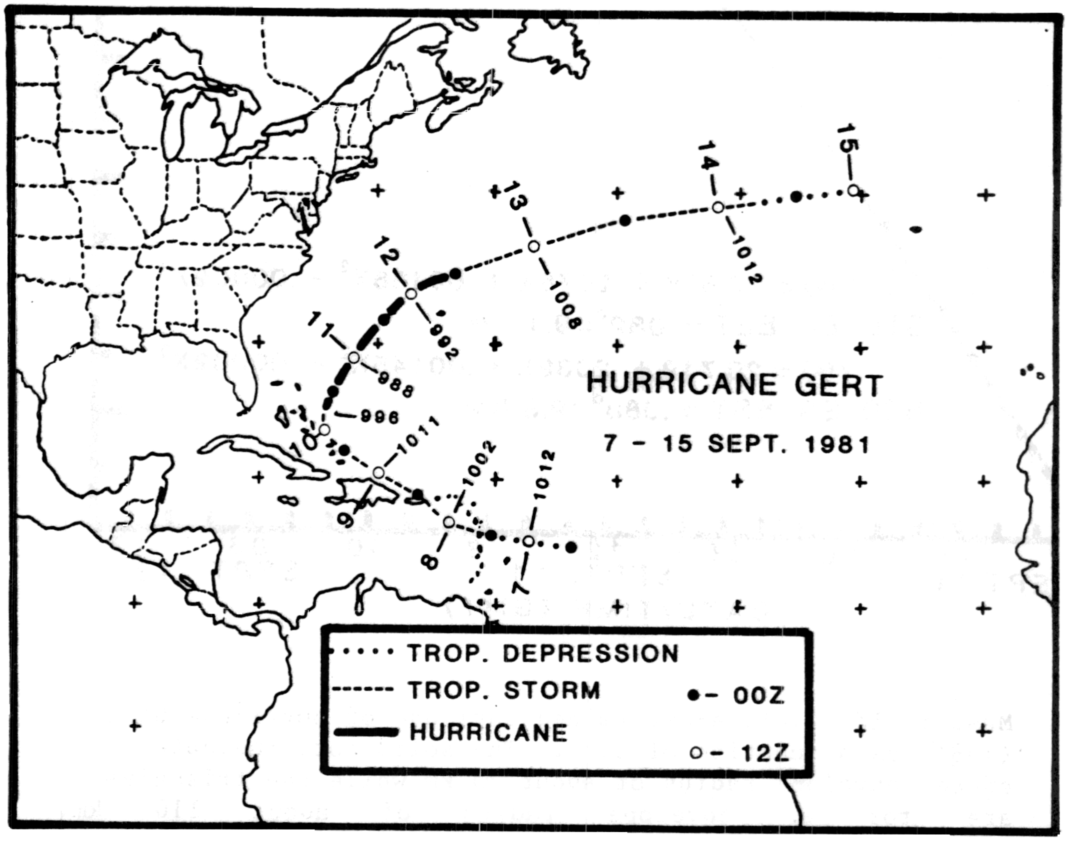

Figure 12. The "Best Track" for hurricane Gert (1981)

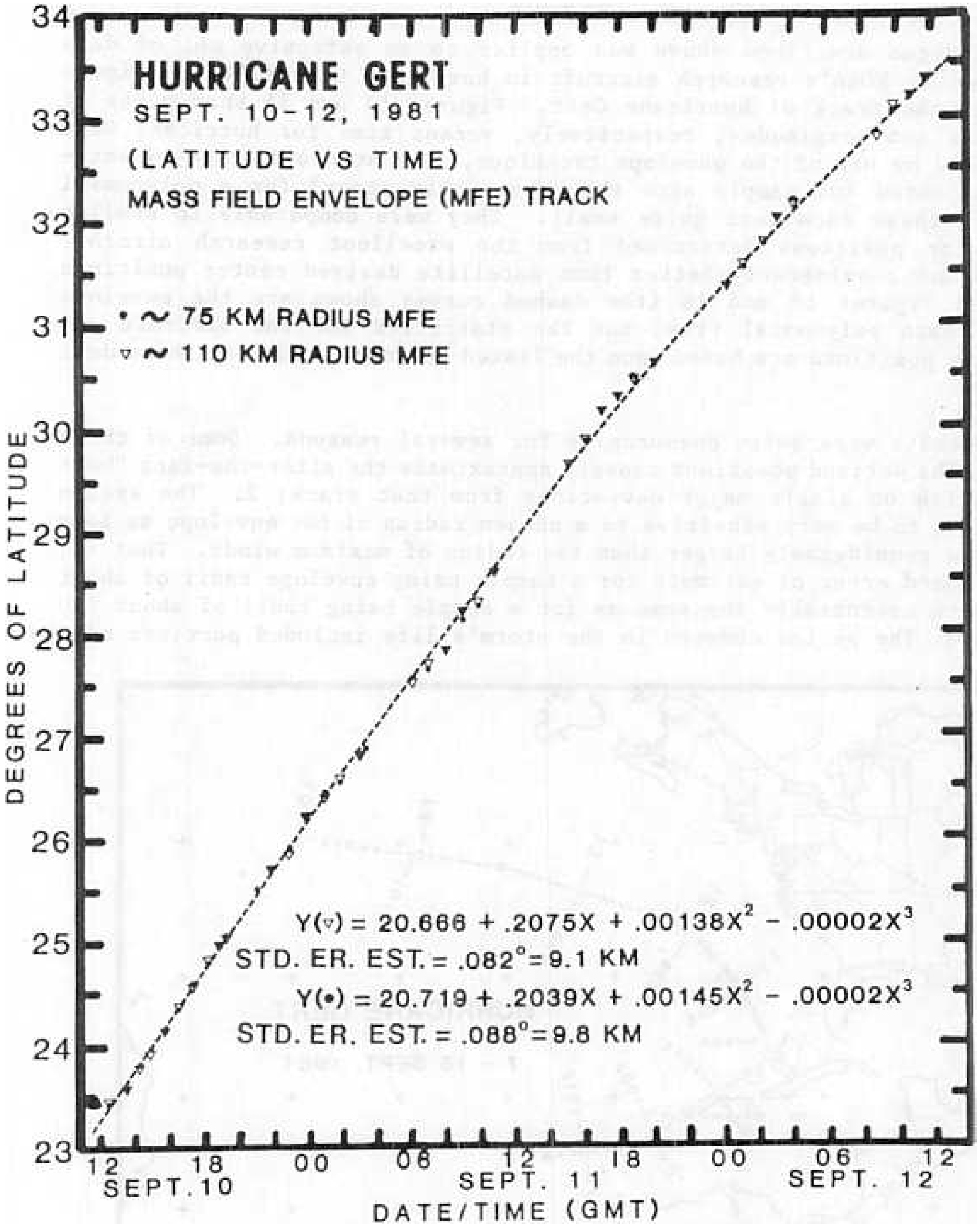

Figure 13. Mass field envelope-determined latitude of hurricane Gert (1981) as a function of time. The solid dots indicate a chosen envelope radius of about 75 km while the triangles are for an envelope radius of about 110 km.

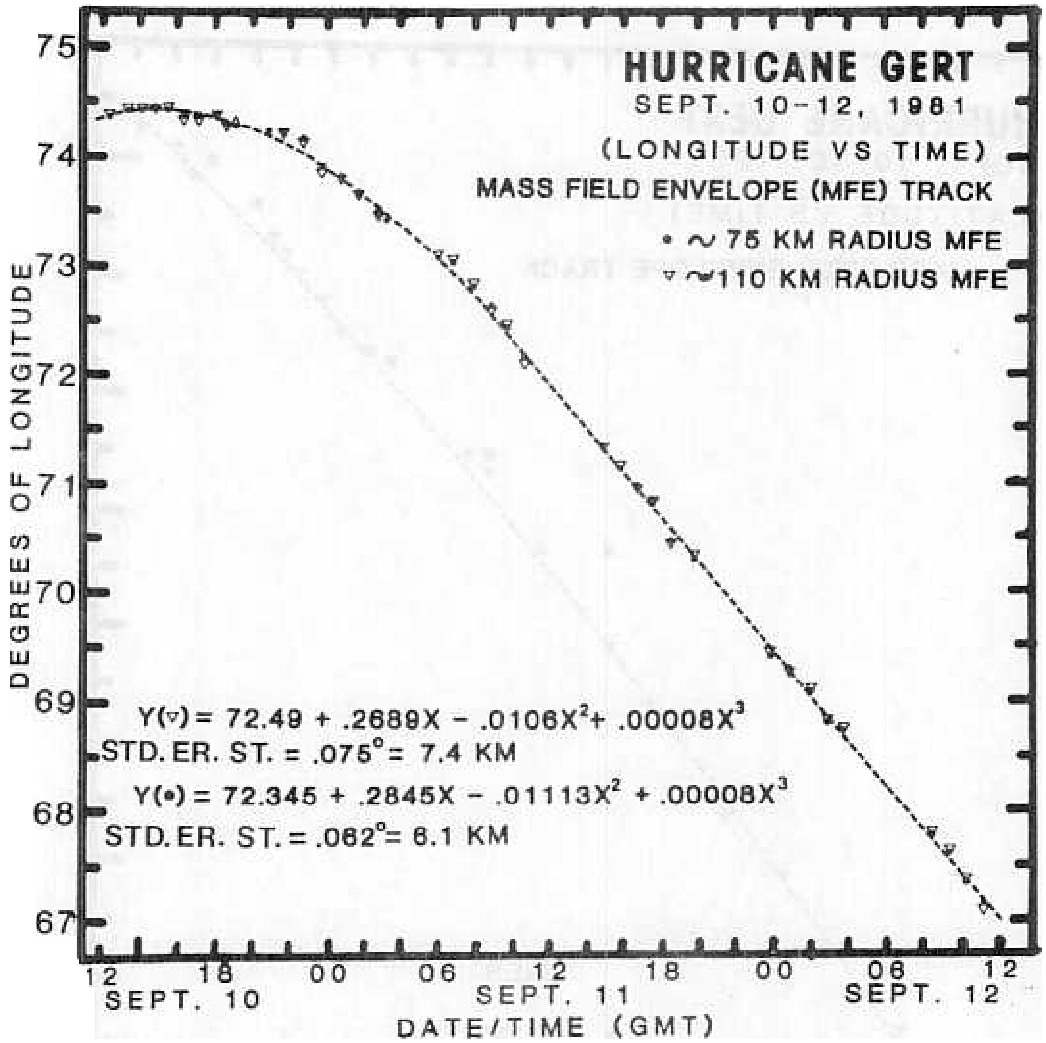

Figure 14. Same as figure 13 except for longitude.

tropical storm and hurricane stages and recurvature. These results seem to satisfy at least three of the goals for an operational system mentioned earlier. That is, the track was easily determined with very small standard deviations from the best track over a period of significant intensity changes and during recurvature. However, Gert did not appear to exhibit the type of small-scale oscillations described in the introduction section of this paper. Therefore, no valid test of the scheme under those conditions was possible. (Some small scale oscillations may have occurred, but were not large enough to be documented by satellite or standard reconnaissance "fixes".)

The first opportunity to test the scheme on a system approaching land where excellent radar coverage was also present occurred during hurricane Alicia (1983). The data sample was much more limited than for Gert and unfortunately, optimum patterns for application of this technique were not flown. In spite of these data limitations, the results were extremely

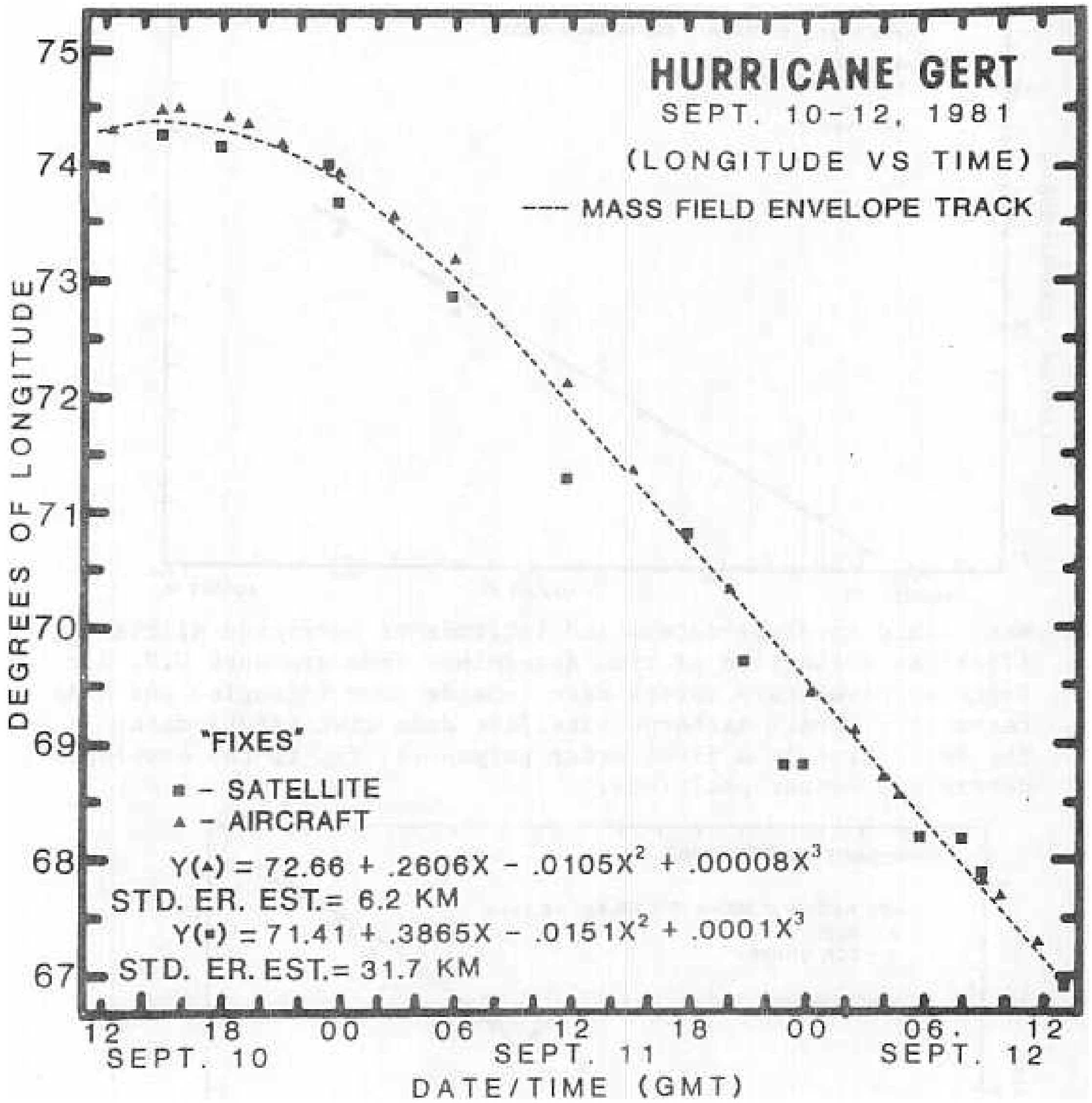

Figure 16. Same as figure 15, except for longitude.

encouraging. Figures 17 and 18 show the envelope-determined latitude and longitude positions, respectively, versus time for hurricane Alicia. Also shown are first (latitude) and second (longitude) order polynomial fits to those data points. Points labeled by the letter R indicate that the pattern flown was not along the cardinal directions. This deficiency required rotation of the flight pattern data which introduces some potential error. In addition, the supplementary vortex data used in the earlier periods is not of the quality desired for the aplication of this technique. However, the standard error of estimates (adjusted for sample size) are still quite small for these data sets for a first and second order polynomial fit. Figures 19 and 20 show the center positions of Alicia determined from the Lake Charles, Louisiana radar along with the envelope data fits. Note the oscillatory nature of the radar "fixes".

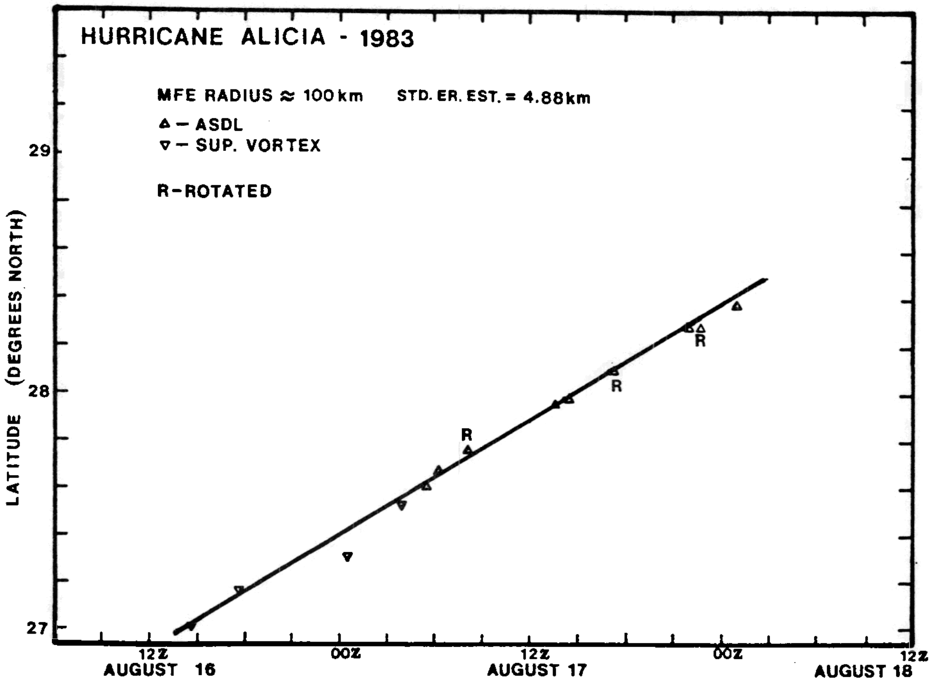

Figure 17. Mass field envelope-determined latitude of hurricane Alicia (1983) as a function of time determined from standard U.S. Air Force supplementary vortex data (upside down triangle) and NOAA research aircraft airborne satellite data link (ASDL) data. The solid line is a first order polynomial fit to the envelope-determined center positions.

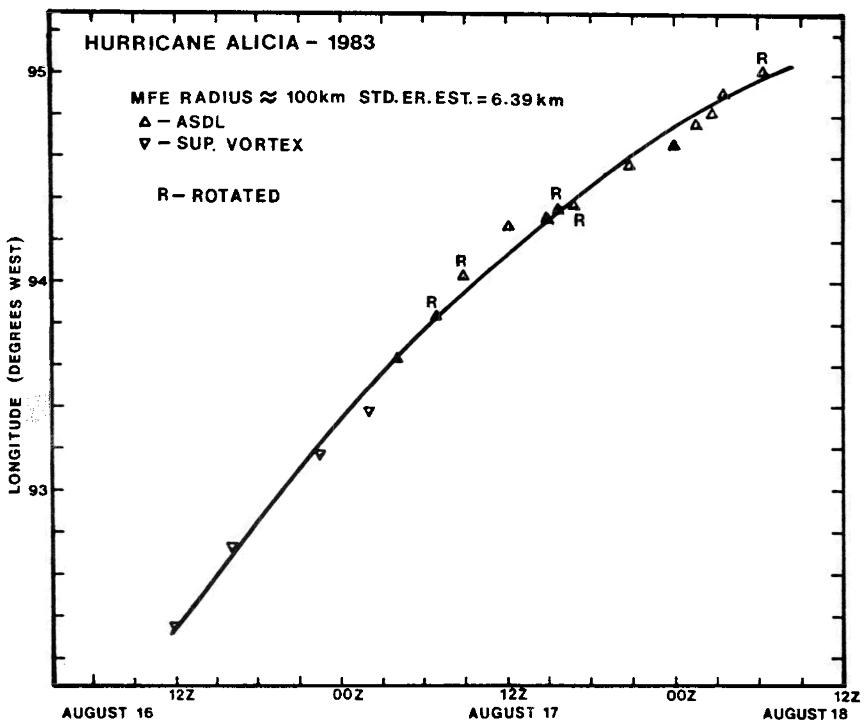

Figure 18. Same as figure 17 except for longitude and a second order polynomial fit to the envelope-determined center postions.

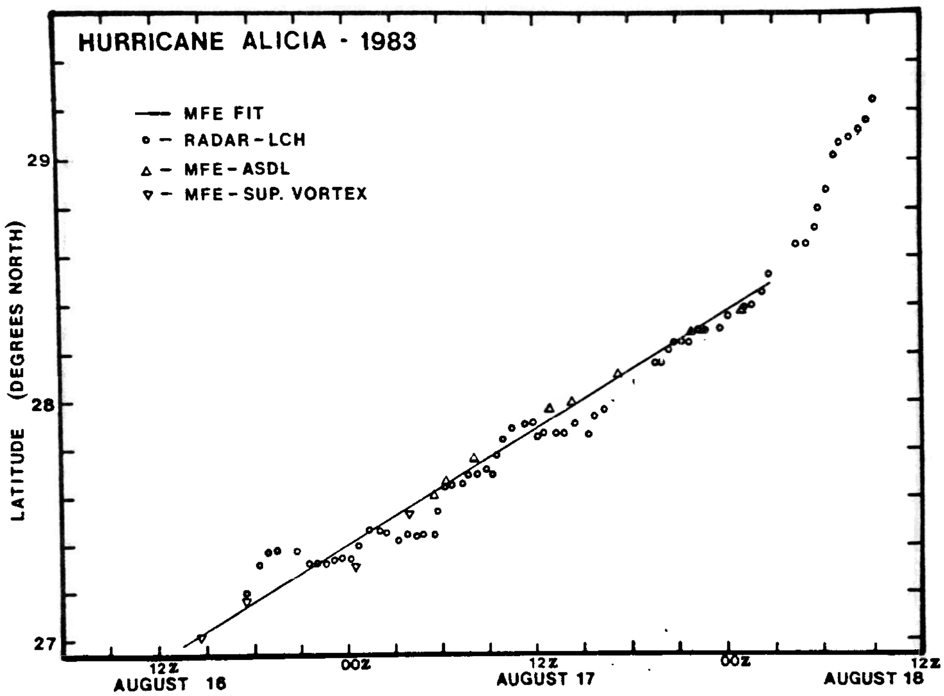

Figure 19. Latitudes of the center of hurricane Alicia (1983) as determined from National Weather Service WSR-57 radar at Lake Charles, Louisiana (circles) and from the mass field envelope data in figure 17. The solid line is the same as for figure 17

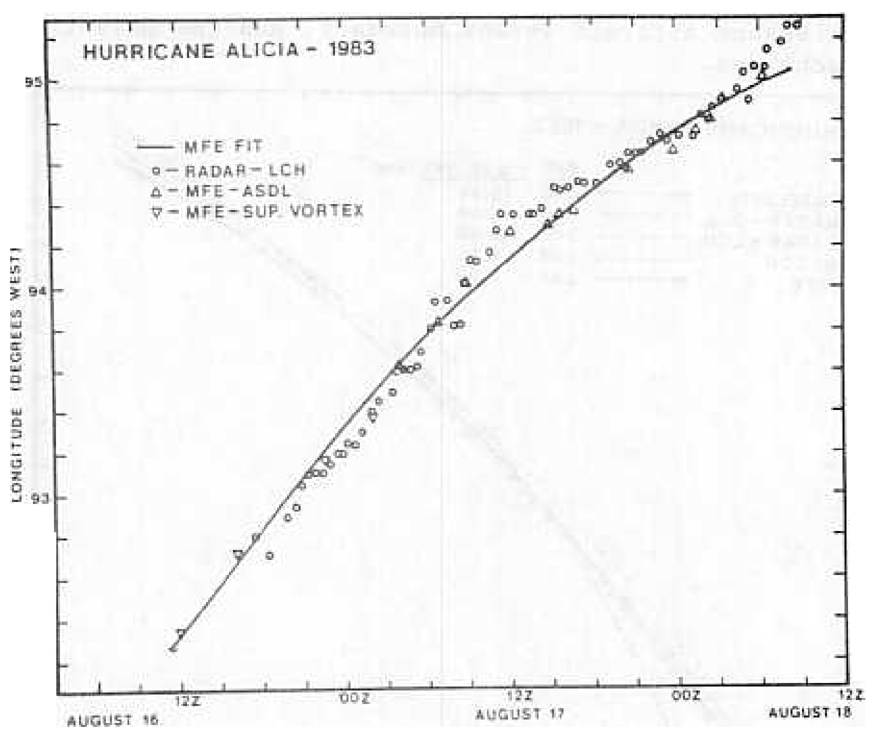

Figure 20. Same as figure 19 except for longitude and a second order polynomial fit to the envelope-determined center postions.

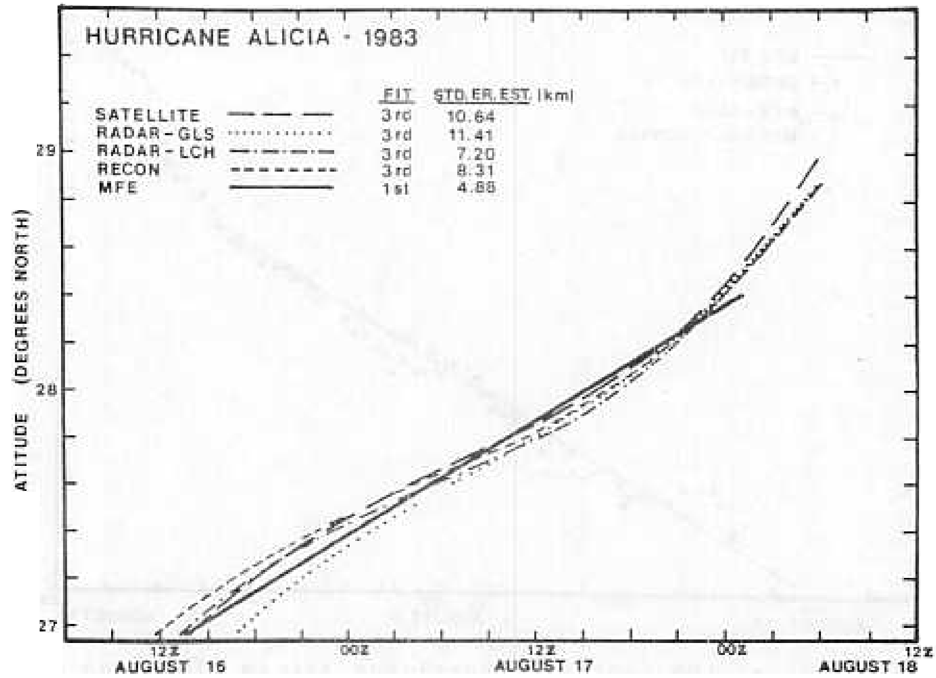

Figure 21. Independent polynomial fits and standard error of estimates (adjusted for sample size) for the latitude of the center of hurricane Alicia as determined from satellite, radar, reconnaissance aircraft vortex messages, and the mass field envelope technique.

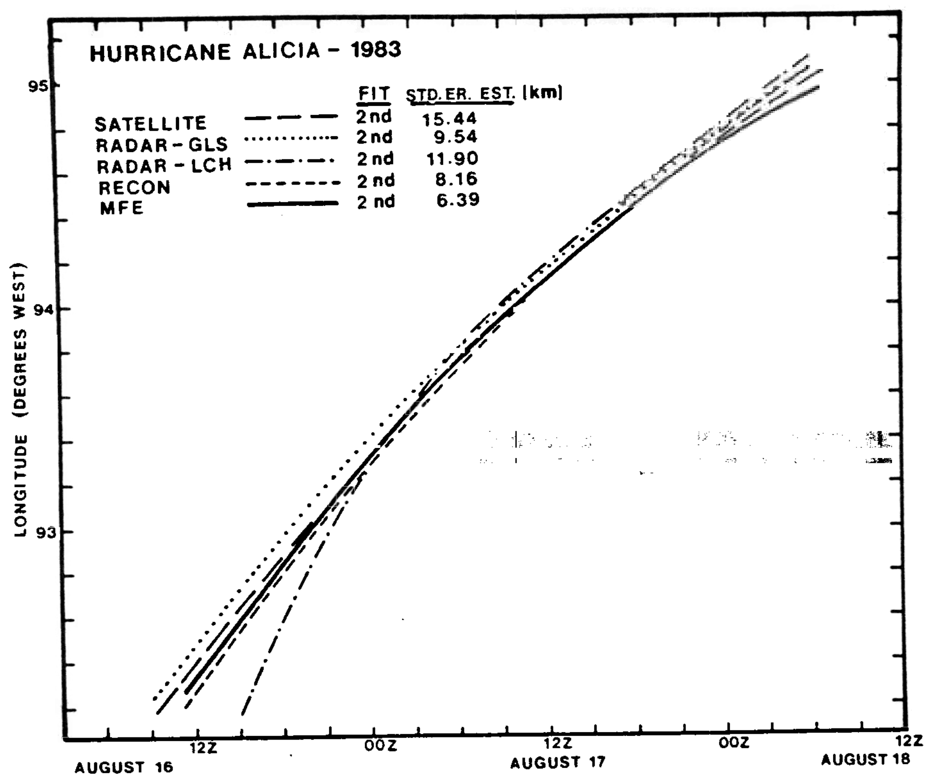

Figure 22. Same as figure 21 except for longitude.

Figures 21 and 22 show polynomial fits to satellite, radar, standard reconnaissance aircraft, and envelope-determined positions for Alicia's latitude and longitude, respectively versus time. Note the comparatively small standard error of estimates for the envelope-determined data fits.

Figures 23 through 25 show the composite Alicia envelope-determined track versus standard aircraft reconnaissance, satellite, and radar "fixes", respectively. Note the nearly stationary situation indicated by standard aircraft reconnaissance, satellite, and particularly radar "fixes" for the period from about 1100 GMT to 1800 GMT on 17 August. Although envelope position data are limited during this period, there is no indication of the "looping" or stalling during this period. That is, this technique seems to have correctly removed this apparent small-scale oscillation from the derived track.

To remove these small-scale oscillations is highly desirable for warning purposes since they can affect the location as well as the timing of warnings. Two simple tests are possible with this set of data to determine

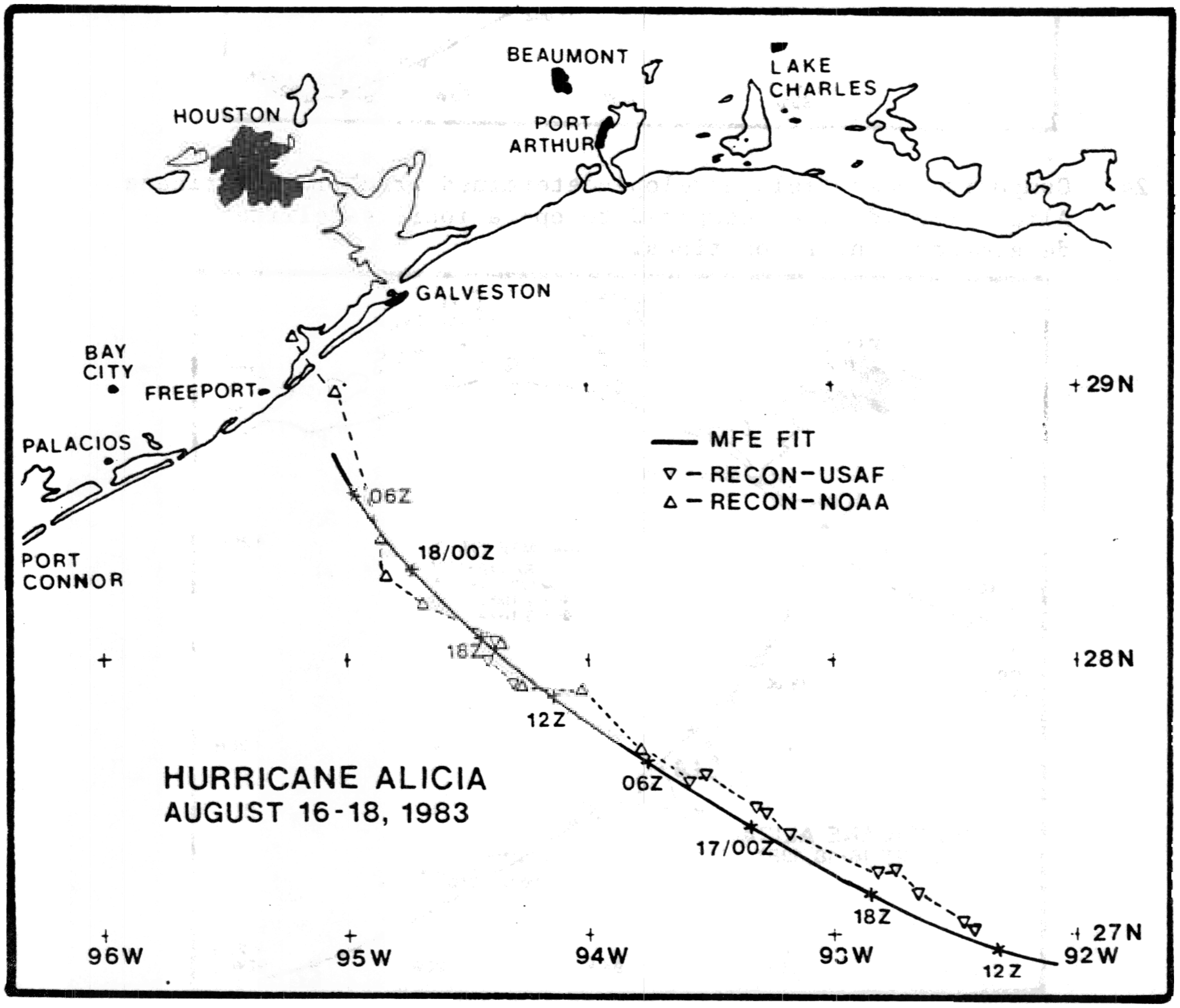

Figure 23. Composite mass field envelope-determined track for hurricane Alicia (solid line) compared to operational reconnaissance aircraft-determined center positions.

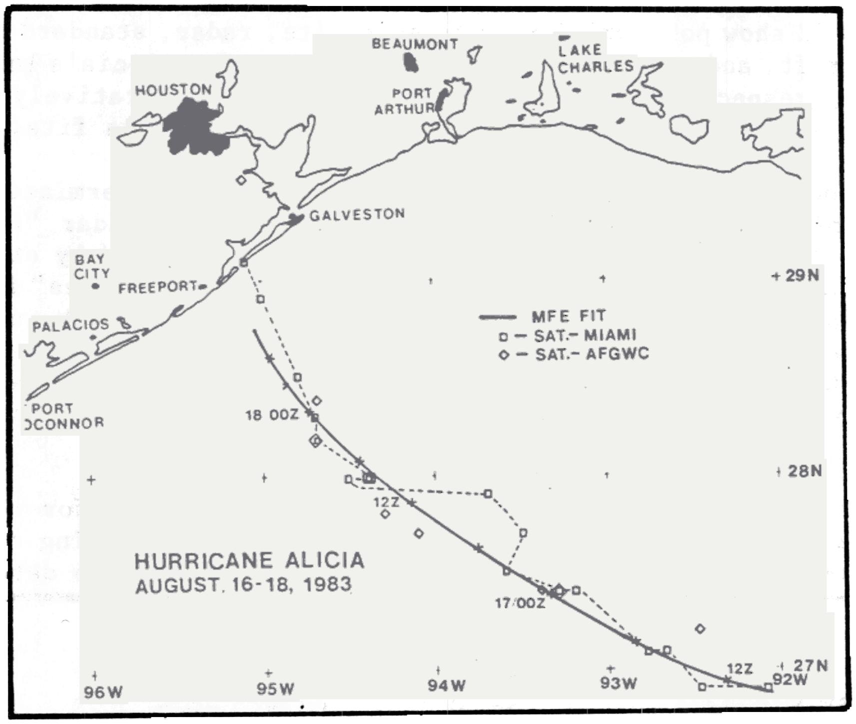

Figure 24. Composite mass field envelope-determined track for hurricane Alicia (solid line) compared to operational satellite-determined center positions.

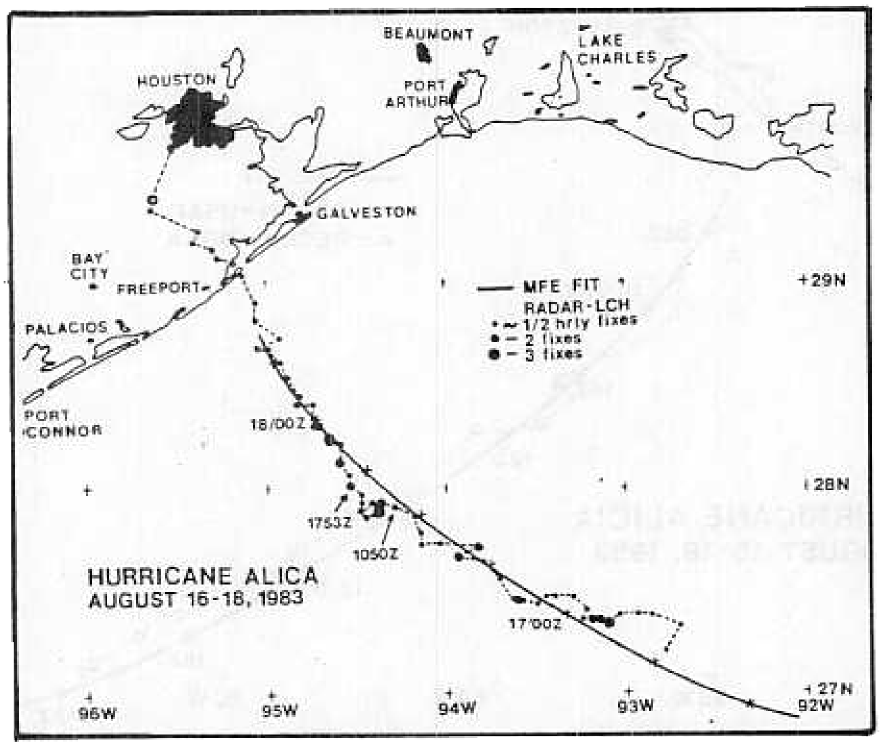

Figure 25. Composite mass field envelope-determined track for hurricane Alicia (solid line) compared to operational Lake Charles, Louisiana based radar-determined center positions.

if the hurricane-scale system stalled during this period as indicated by the standard observing techniques, or did the system continue to move on the rather steady course as indicated by the envelope derived track. One check is to simply look at the change of pressure with time at a location toward where the hurricane is moving. If no synoptic-scale change in pressure is taking place over the area, the pressure should remain steady if the hurricane is "stalled", i.e., not approaching the station of interest. If the hurricane is continuing to move, i.e., continues to approach the station of interest, the pressure should continue to fall. The rate of fall should also increase as the hurricane gets closer and the pressure gradient increases. These conditions will exist if no major changes in the pressure gradients of the hurricane at these larger radii occur at the same time.

Figure 26 shows a pressure trace (diurnal variation removed) for stations located at Galveston and Alvin, Texas. The periods of "apparent stalling" are shown by the shaded areas superimposed in the figure above the pressure curve (also see inset for storm track). There are some fluctuations in pressure versus time (particularly for the Alvin trace on the 17th from 0600 to 1200 GMT), but the pressure in general continues to show a rather steady decrease during the periods of apparent stalling, indicating the continued approach of the hurricane.

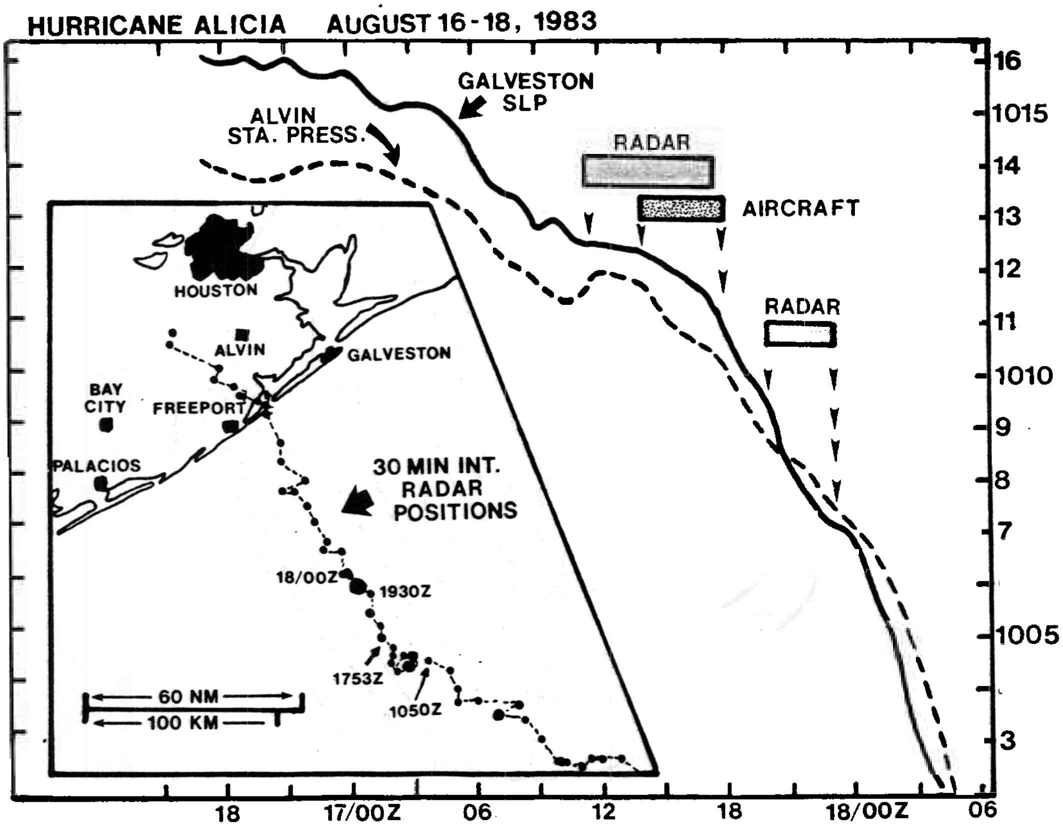

Figure 26. Profile of sea level pressure changes (diurnal variation removed) at Galveston and Alvin, Texas during the approach of hurricane Alicia. Inset shows 30 minute interval radar-determined positions.

A more rigorous test of whether the hurricane did or did not stall can be obtained by compositing the research aircraft pressure data collected during this period. Figure 27 illustrates an analysis of the pressure data collected during the period from 1225 GMT to 1800 GMT on 17 August. The compositing for this illustration was done relative to the hurricane center, assuming the center had stalled. Note the distortion of the pressure contours (case studies by Hawkins, Sheets, Colon, etc., all indicate that pressure contours on the scale represented by the larger radii here are usually circular or elliptical).

Figure 28 shows an analysis of the same data as for figure 27, but now composited relative to a center assumed to be moving as indicated by the envelope-determined track shown in figures 17 and 18. Note the lack of distortion of the pattern at larger radii, but the presence of distortion at the smaller radii. These analyses indicate that the hurricane represented by the scale of the larger radii was moving as indicated by the envelope determined track (did not stall) and that the central core was oscillating about the track and/or rather rapidly changing in central pressure!

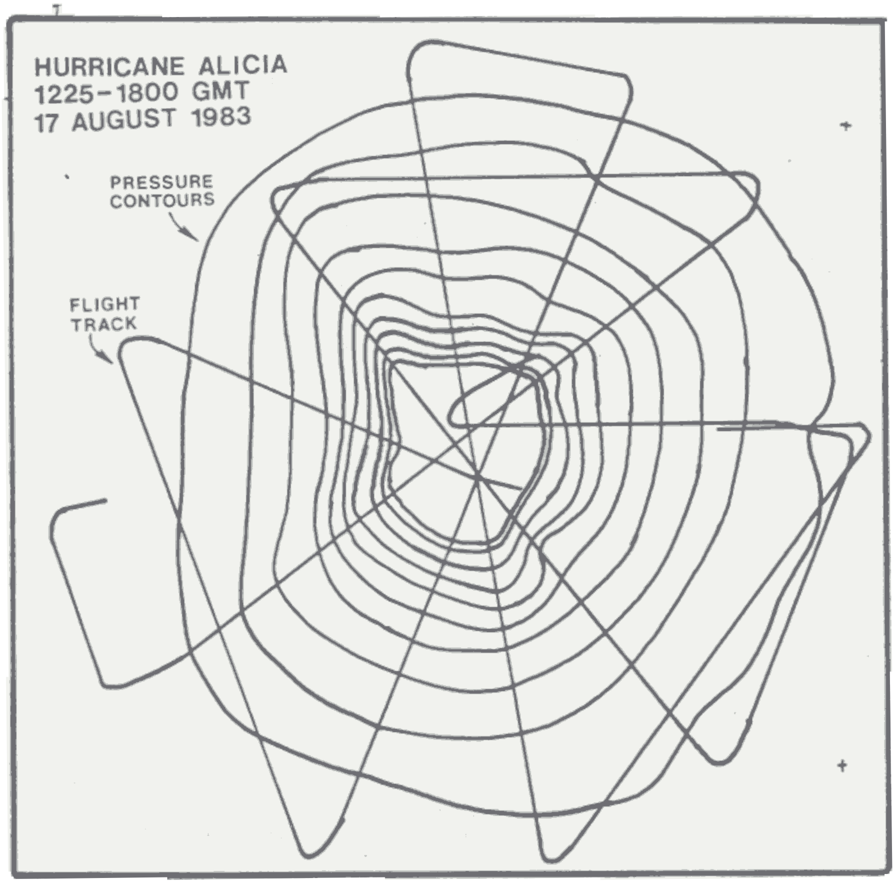

Figure 27. Pressure field analysis for hurricane Alicia composited from research aircraft data collected over the period of 1225 GMT to 1800 GMT on August 17, 1983. The data are composited relative to an assumed stationary (storm stalled) center.

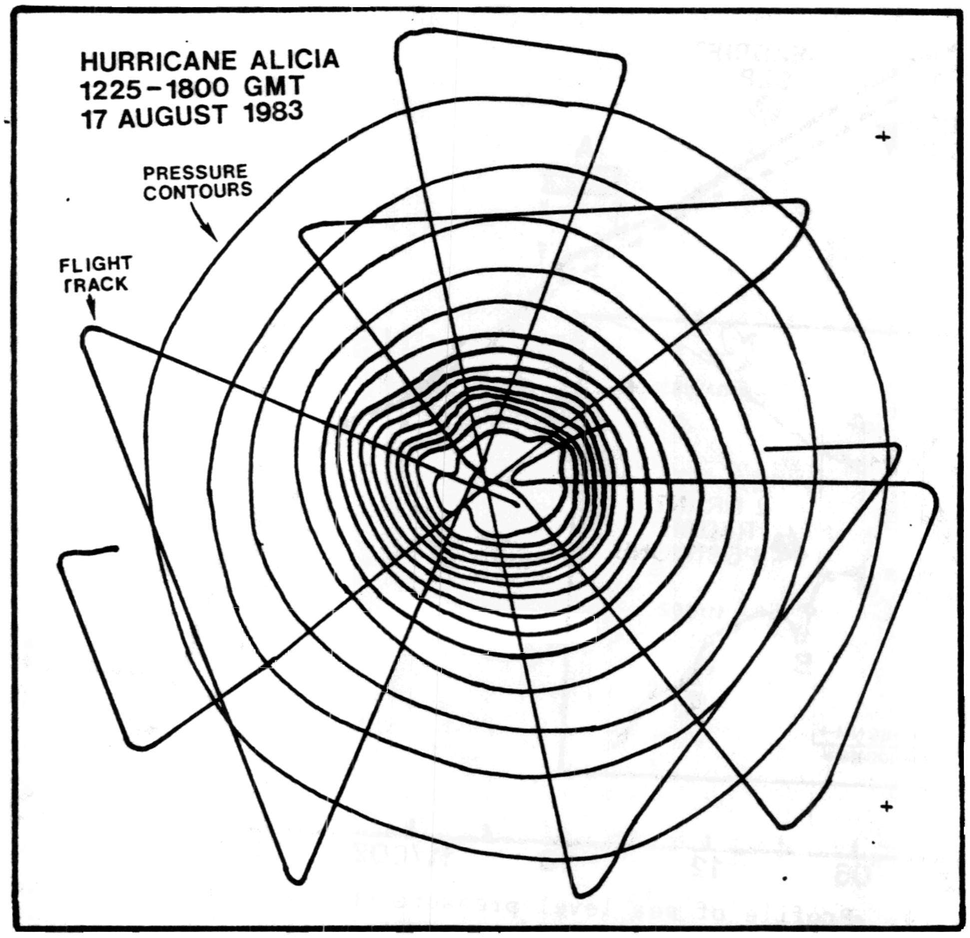

Figure 28. Pressure field analysis for hurricane Alicia composited for the same period and data as in figure 27. For this analysis, the compositing was done relative to a center assumed to be moving as indicated by the mass field envelope-determined track for this time period.

The Alicia case supports the hypothesis that this tracking technique correctly removes the small-scale oscillations that are not representative of the tropical cyclone scale motion for which a forecast is being attempted (swath of 150 km to 200 km in width). The fact that such small-scale oscillations are not representative of the tropical cyclone scale motion is also supported by the results shown in figure 29. This figure is similar to that of figure 26 except that it is for the hurricane Carla case illustrated in figure 1. Pressures recorded at two coastal locations during the period Carla approached were plotted. Except for some unexplained near fluctuation for the Seadrift sea-level pressure profile near 0600 GMT on September 11, a general fall of pressure took place at these land stations throughout the period plotted. This included the periods when the "radar eye" of Carla either stalled or moved away from those stations (see shaded zones and inserts).

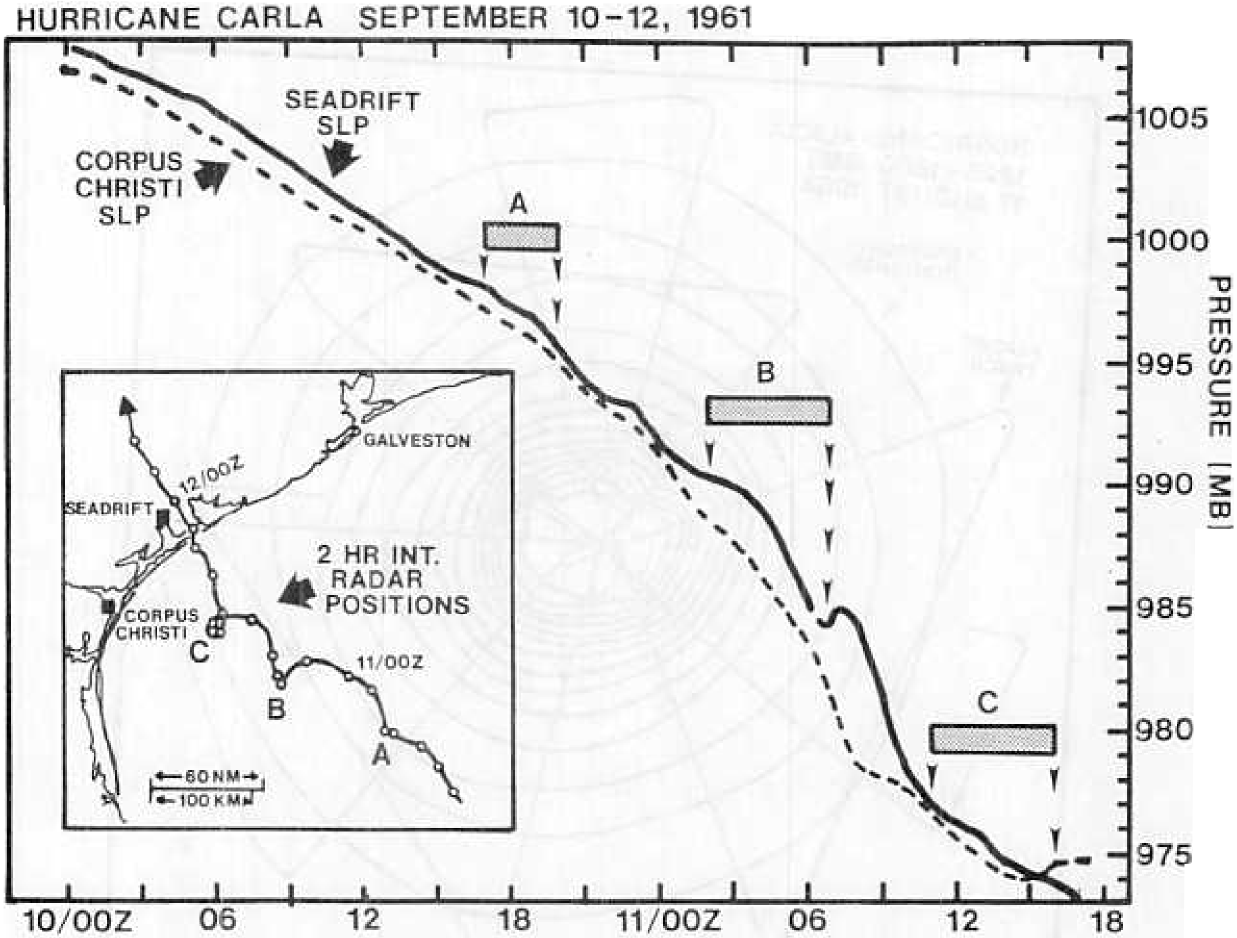

Figure 29. Profile of sea level pressure changes (diurnal variation removed) at Corpus Christi and Sea Drift, Texas during the approach of hurricane Carla. The inset shows two hour interval radar-determined center positions.

The Alicia case supports the hypothesis that this tracking technique satisfies the goals of providing a track which removes the small-scale oscillations and represents the hurricane-scale system movement for a range of storm strengths. However, the final criteria listed earlier remained in question since the track of Alicia remained relatively smooth with no small scale changes in direction and speed that were representative of the hurricane-scale system movement. It remained to be determined if the technique would resolve these scales of motion which are also quite important for the forecast and warning process. Hurricane Elena (1985) offered the opportunity to make this determination.

Figure 30 shows the track of hurricane Elena. For the first time, a nearly continuous sequence of "ALPHA" patterns (figure 11) providing IWRS type data were flown. These NOAA aircraft flights covered the period of near 1800 GMT on 31 August through 0600 GMT on 2 September. These times cover the period Elena made a loop in the northeast Gulf of Mexico. The envelope tracking technique described earlier was applied in a partial operational mode during this period.

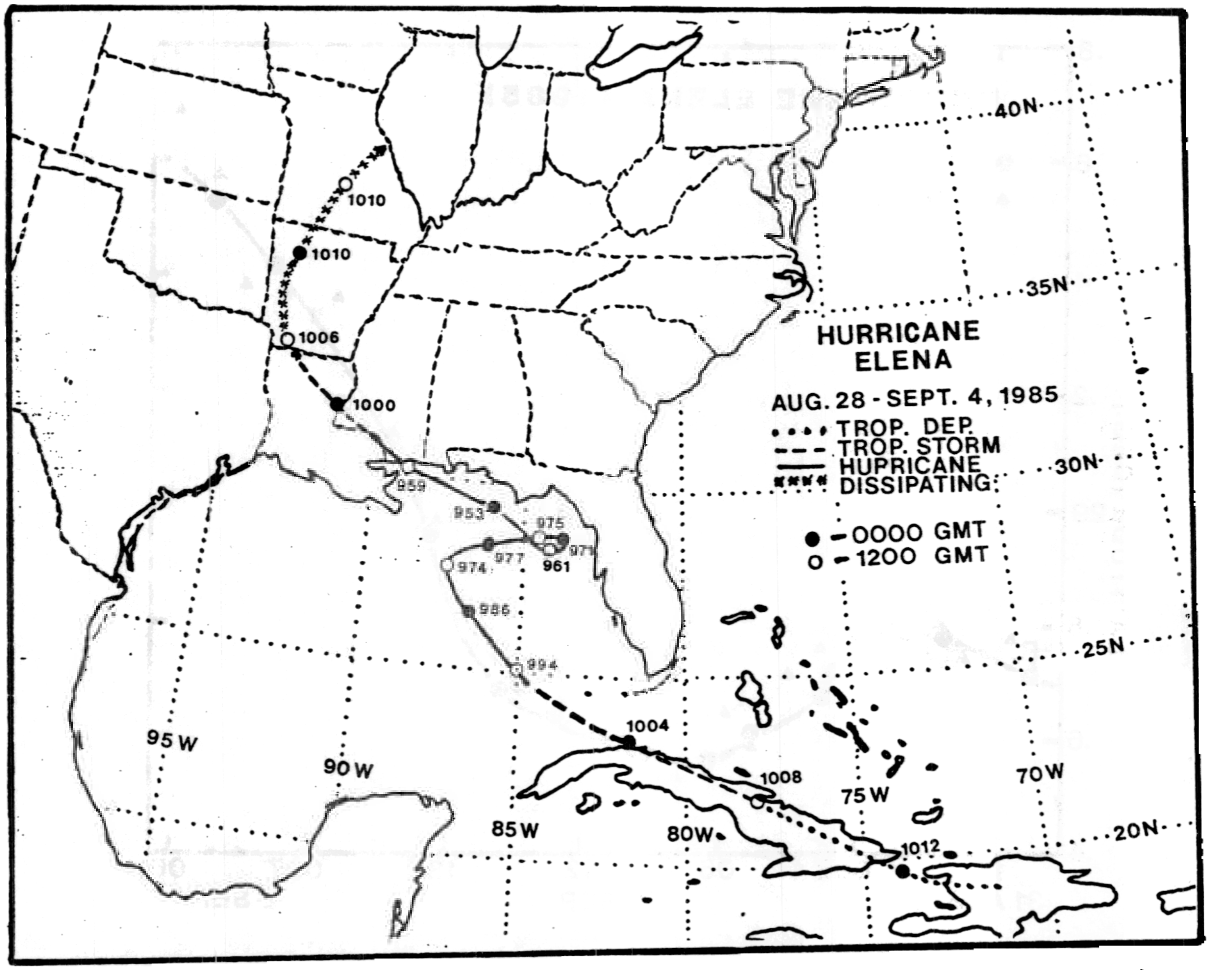

Figure 30. The after the fact "Best Track" for hurricane Elena (1985)

Figures 31 and 32 show the results of application of this technique for the latitudinal and longitudinal components, respectively. The large dots represent the envelope-determined latitudes and longitudes and the triangles are the positions provided by the operational "Vortex" messages. Note that relatively smooth curves can be fit to the envelope-generated data points with almost no deviations from those curves. Any deviations that do exist are generally less than 2 to 4 km (this includes two longitude positions near 0600 GMT on September 1 which probably have some error introduced due to inertial navigation system problems experienced on this flight) during this period of slow and erratic motion! By contrast, the "Vortex fixes" show considerably more scatter about these curves during this period.

Figures 33 and 34 show the composite "vortex" and envelope-determined tracks, respectively. Note the apparent erratic movement for the "Vortex" track during this period as compared to a rather smooth envelope-determined track. The "tick" marks along the envelope-determined track depict hourly positions. Note the rather steady deceleration in forward speed as the hurricane enters the loop (through 01/0000 GMT) and the acceleration as the hurricane exits the loop. If point-to-point motions were determined from

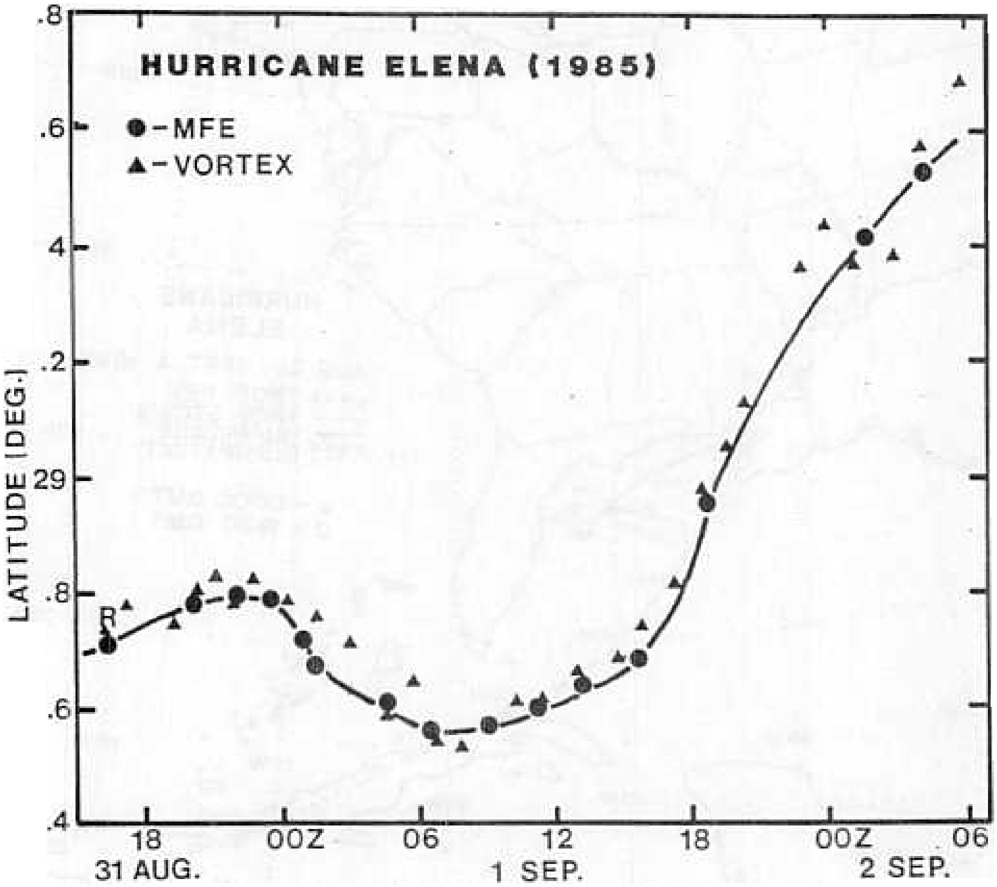

Figure 31. Mass field envelope-determined latitude (large dots) as a function of time with superimposed "vortex" center positions (triangles) from reconnaissance aircraft for hurricane Elena.

the "vortex" positions, very erratic directional and speed motions would be depicted. This Elena case then illustrates that the technique does indeed resolve the motion of the hurricane on this scale, depicting the rather dramatic changes in direction and speed.

5. IMPACTS ON FORECASTS AND WARNINGS

Apparent stalling or looping can cause considerable consternation for forecasters and hurricane decision makers alike. The timing and location of warnings and associated actions can critically be affected by such apparent movements. The situation is much more compounded today as compared to a few years ago because of the tremendous increases in coastal populations and the availability of "dial up" radar displays and satellite imagery which are constantly being displayed to the general public. They and other decision makers may see these small-scale motions and by extrapolation of these false indicators of general storm motion, take inappropriate actions. These actions could include costly evacuation of areas which might not need to be evacuated, or worse yet, the dangerous delaying of evacuations for a looping or apparent stalling case. Often, as the "center" of these storms comes out of one of the small-scale loops, they accelerate forward. The

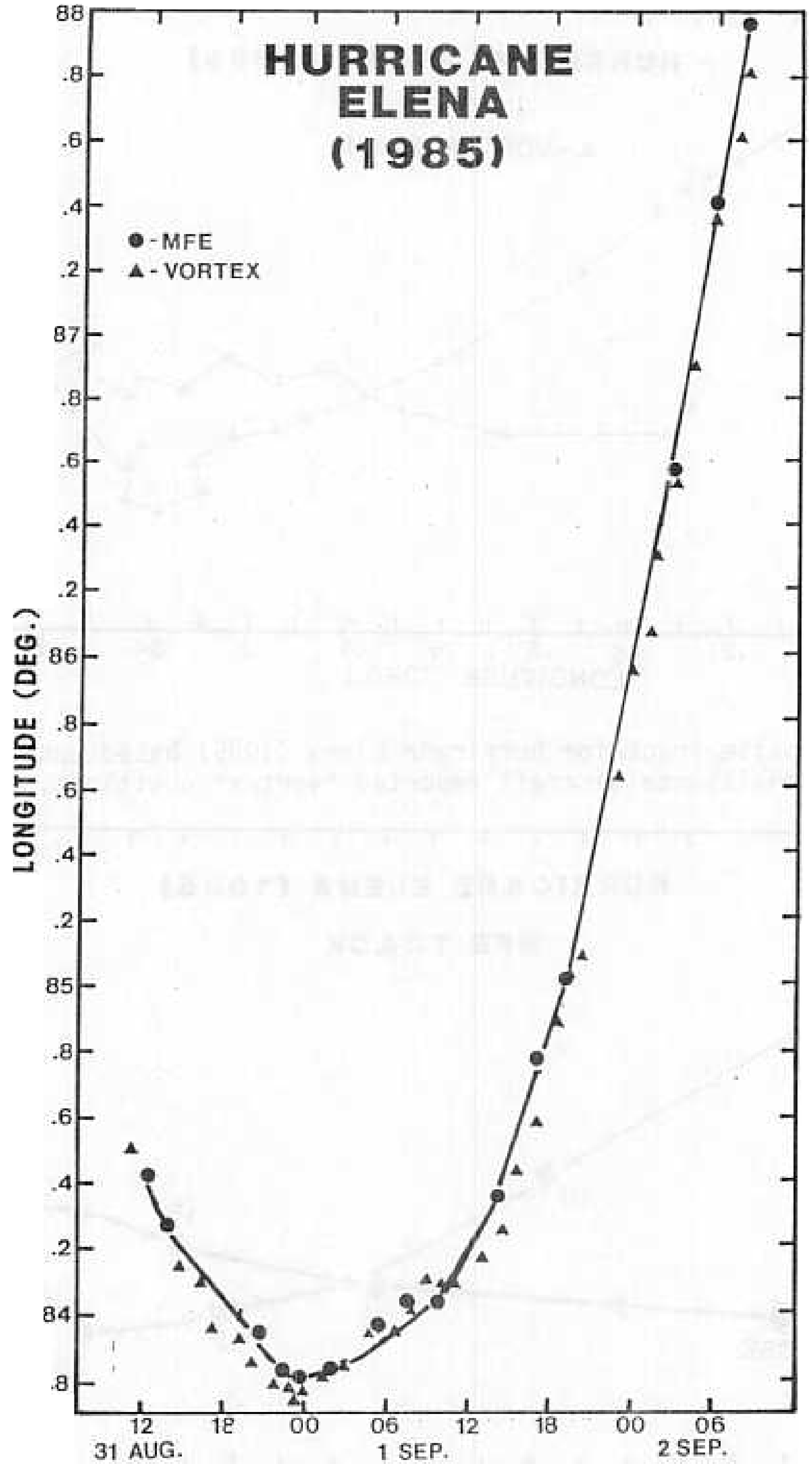

Figure 32. Mass field envelope-determined longitude (large dots) as a function of time with superimposed "vortex" center positions (triangles) from reconnaissance aircraft for hurricane Elena.

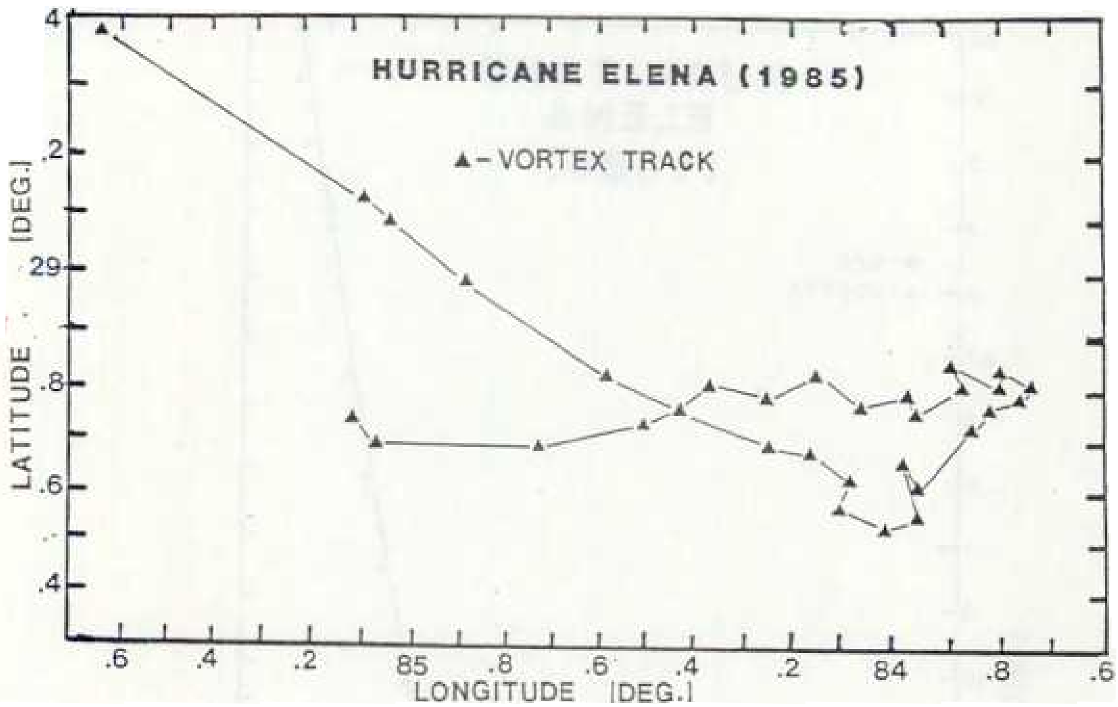

Figure 33.

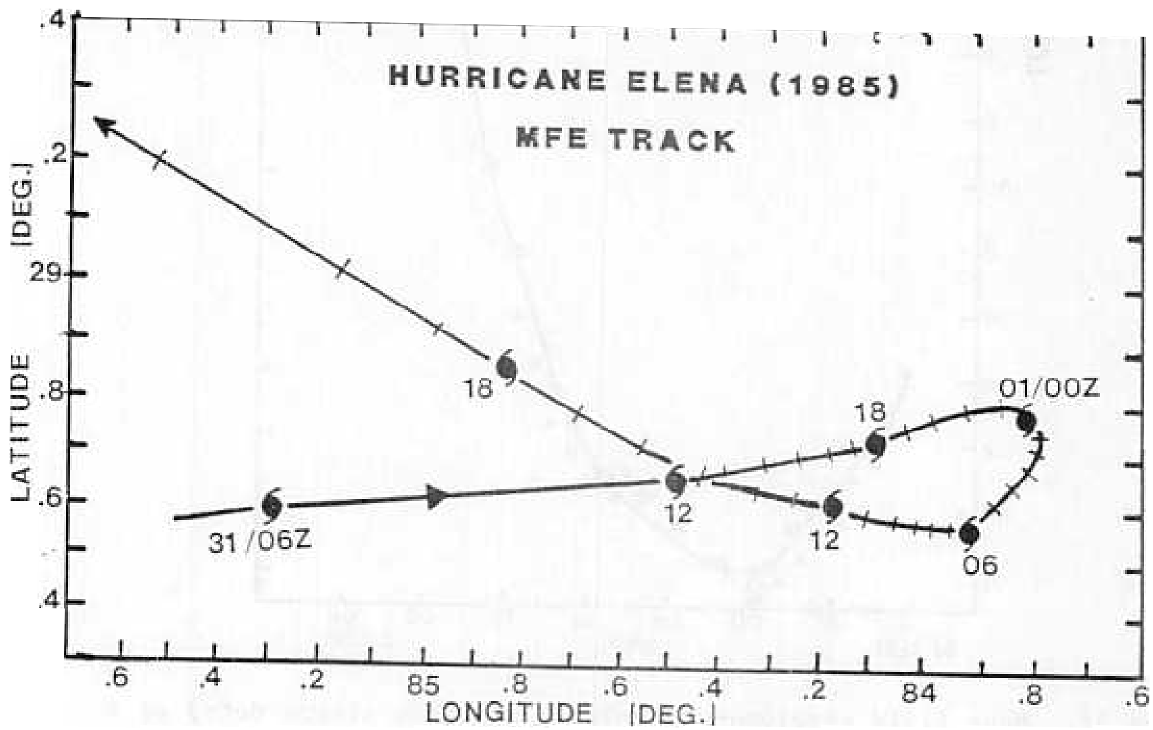

Figure 34. Composite track for hurricane Elena (1985) based on mass field envelope-determined positions (figures 31 and 32). The "tick" marks along the track are at hourly intervals.

results could be catastrophic if preparation actions had been delayed because of the apparent "stalling" of the storm. By contrast, if the hurricane is actually making a major change in direction and the tracking technique used "filtered out" or delayed the detection of that change in motion, that could also be disastrous.

The Alicia case would seem to support the hypothesis that the envelope technique is only minimally affected by misleading small-scale motions while the Elena case indicates that the technique is capable of resolving important changes in motion of the hurricane-scale system. The impact of such information can be quite large in terms of warnings and associated actions. The CLIPER (Neumann and Pelissier, 1981) model was used to quantify the possible impacts of envelope-determined tracks upon forecasts, as compared to operational CLIPER forecasts without the envelope technique input.

Initial and past motions of a hurricane have considerable impact upon hurricane forecast guidance products as demonstrated by a study by Neumann. In that study Neumann used the CLIPER model to examine effects of intitial and past motion on CLIPER generated forecast tracks for the period of 1972 to 1984 (table 1). In this unpublished study, Neumann compared forecast results using operational past and present motion inputs to the model versus those produced by using after the fact smoothed "best track" inputs. As indicated earlier, the operational forecaster attempts to provide a smooth track for input to the models. However, even with this smoothing, considerable improvements result from after the fact "best track" inputs. The improvements are 55, 32, 19, 11, and 4 percent, respectively, for 12-, 24-, 36-, 48-, and 72- hour forecasts! Of course, comparable improvements cannot be expected in real time solely from better inputs since the "best track" data contains post initial time information. However, this study shows the potential for quantitative improvements from initial data inputs that might be provided by a real-time application of the envelope technique generated track data.

The track information generated by use of the envelope technique for hurricane Gert and hurricane Alicia presented earlier was used in an operational simulation to try to quantify potential forecast track improvements from these data sets. In the case of hurricane Gert, an operational hurricane forecaster was given envelope-determined positions in component form (latitude and longitude) available prior to an initial forecast period. The forecaster then constructed a past and initial track, solely from these data, for use as inputs for the CLIPER model. After that input was generated, additional envelope-generated position data available up to the time of the next initial forecast period was given to the forecaster. That data was used along with the past data to generate past and present tracks for inputs for the next forecast period. Eight such forecast periods were available for this case. The results from these inputs were then compared to those generated operationally (table 2).

The errors resulting from operational inputs to the CLIPER model are already less than average "official" forecast errors (Neumann and Pelissier, 1981) for the Atlantic basin for the 12 through 48-hour forecast periods (94, 202, 452, and 699 km for 12-, 24-, 48-, and 72-hour forecasts, respectively). However, the operational simulated envelope inputs provided substantial improvements over these forecast tracks during the shorter forecast periods (31, 19, and 11 percent at 12-, 24-, and 36 hours, respectively), fading to little difference for the 48- and 72 hour forecast periods (6 and 4 percent, respectively).

A similar test was made using data obtained for hurricane Alicia. In this case, there were 5 forecast periods where MFE input data were available. To further test the sensitivity of the system, three different individuals were chosen to provide the operational simulation envelope data inputs for the CLIPER model. One was a hurricane forecaster (different than the one for the Gert case), one was a foreign meteorologist (not a hurricane forecaster) visiting the National Hurricane Center (NHC) and one was a computer programmer at NHC. The results are shown in table 3. Note that the operational inputs again provided forecasts substantially better than the "official" averages cited earlier. However, the envelope data inputs produced substantial improvements over these already good values for the shorter forecast periods for the hurricane forecaster and the visiting meteorologist. Improvements were comparable to those obtained by the hurricane forecaster for the Gert case. The computer programmer, however, rigidly drew for each data point and obtained only a small improvement.

The hurricane Elena case was conducted in a semi-operational mode. This means no comparable test could be made of operational inputs versus envelope approach inputs since the envelope-generated information was partially being used operationally. A check was made in any case, and the inputs were very similar. In this case the improvement ranged from 8.8 percent at 12 hours to 8 percent at 24 hours and lesser amounts for longer forecast periods for a sample of 8 forecast periods covering the period of the loop shown in figure 34.

Figure 35 graphically illustrates the impact of these forecast improvements. The locations of the hurricane at the initial forecast times are depicted by the numbers 1 through 5 along the actual hurricane Alicia track. The points of forecast landfall for CLIPER forecasts generated for these intial periods are illustrated by dashed lines (operational inputs) and solid lines (hurricane forecaster envelope generated input (MFE-OP-GBC)) with the associated numbers corresponding to the initial forecast periods. Again, considerably less scatter for the point of landfall forecasts is shown for the envelope generated inputs as compared to the operational inputs. Table 4 quantifies these forecast landfall tracks in terms of time and displacement along the coast. The time of actual landfall of the center of the hurricane was near 0800 GMT on 18 August. Displacements in time were linearly interpolated along the forecast tracks. One effect of this type of interpolation was the 6 hour slow forecast for the envelope input for a base time of 18/0000 GMT. This resulted because the storm accelerated rapidly after the center of the hurricane made landfall. The interpolated forecast position for this time was only 35 km from the actual landfall point and the displacement along the coast of the forecast track from the actual track was only 10 km for this forecast. Also,

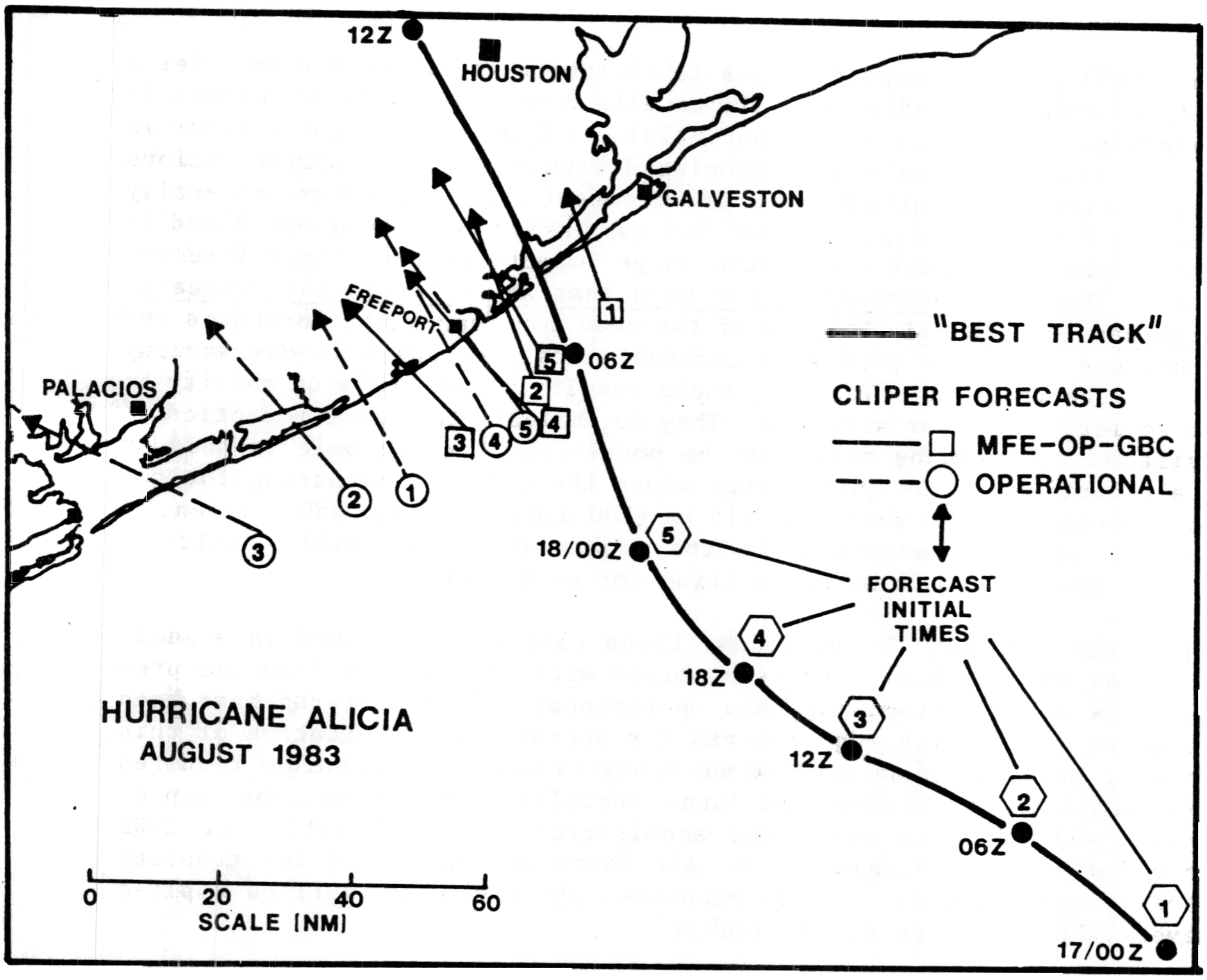

Figure 35. Hurricane Alicia actual track (bold solid line) and CLIPER forecast landfall points for operational input (dashed line and circled numbers) and hurricane forecaster operationally simulated mass field envelope (MFE) track input (thin solid line and numbers enclosed by squares). The numbers along the track correspond to the indicated initial forecast time and the same numbers for the operational and mass field envelope based forecasts.

note that the envelope associated forecast track displacements along the coast from the actual landfall point only ranged from 11 to 46 km for all forecasts for the 32 hour period before landfall. The operational input forecast track displacements were also very good, but were substantially higher, ranging from 45 to 193 km.

6. SUMMARY

The mass field envelope approach to hurricane tracking was first proposed by the author several years ago with preliminary testing and results accomplished during hurricane Gert (1981). These results were presented at an American Meteorological Society meeting in San Diego, California in 1982. Testing has been slow since then because of the lack of appropriate IWRS type data. However, data collected in hurricanes Alicia (1983) and

Elena (1985) provided opportunities to thoroughly test the system under a variety of critical conditions. The results from those tests are extremely encouraging. They indicate the potential for substantial improvements in hurricane track forecasts and associated warnings and resultant actions during critical storm situations. The greatest improvements are generally within the 24-hour forecast period, but such major changes as exhibited in the hurricane Elena case could have large impacts at the longer forecast periods. These improvements do not mean that an answer to the forecast problem has been found! Because of the need for long-range forecasts and warnings due to highly populated coastal areas, considerable overwarning will still be required. That is, these results do not imply an ability to increase lead times for warnings! They do indicate that some reduction of the size of the warning areas may be possible. The economic impacts of such a reduction can be quite large since the cost for preparing for the average warned coastal sector of 715 km (300 n.m.) is about $50 million. A 10 to 20 percent reduction in these warned areas would result in potential savings of $5 to $10 million for each event.

As indicated earlier, the hurricane Elena case was conducted in a semi-operational mode. These results combined with the results from the previous cases were so promising that operational flight patterns have been adjusted to comply with requirements for operational application of this technique. However, to obtain maximum benefits from this technique requires routine availability of IWRS type data. Therefore, full operational implementation will need to await the acquisition and installation of IWRS systems for all the standard U.S. Air Force aircraft used for tropical cyclone reconnaissance. In the meantime, the technique will be applied whenever IWRS type data are available.

7. REFERENCES

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Table 1. Comparison of CLIPER forecast mean vector errors (km) on operational and "Best Track" modes for Atlantic basin tropical storms and hurricanes from 1972 through 1984 (after Neuman).

Forecast Period	12 hr	24 hr	36 hr	48 hr	72 hr
Operational Mode	122	246	372	500	723
Best Track Mode	56	167	300	442	694
Percent Improvement	55	32	19	11	4
Sample Size	1606	1449	1274	1110	820

Table 2. Comparison of CLIPER forecast mean vector errors (km) on operational and mass field envelope modes for hurricane Gert (1981)

Forecast Period	12 hr	24 hr	36 hr	48 hr	72 hr
Operational Mode	83	187	352	703	1203
MFE-OP-Simulation	57	152	313	564	1153
Percent Improvement #	31	19	11	6	4
Sample Size	8	8	8	8	8

- MFE input versus Operational input to CLIPER model.

Table 3. Comparison of CLIPER forecast mean vector errors (km) on operational and mass field envelope modes for hurricane Alicia (1983). Mass field envelope inputs were provided by a hurricane forecaster (GBC), a computer programmer (BD), and a visiting meteorologist (MET) in an operational simulation mode.

Forecast Period	12 hr	24 hr	36 hr	48 hr	72 hr
Operational Mode	59	143	245	365	671
MFE-OP-GBC	41 (31%)	102 (28%)	200 (18%)	335 (8%)	611 (9%)
MFE-OP-BD	57 (3%)	133 (6%)	228 (7%)	358 (2%)	623 (7%)
MFE-OP-MET	46 (22%)	119 (17%)	213 (13%)	350 (4%)	623 (7%)
Percent Improvement#	19	17	13	5	8
Sample Size	5	5	5	5	5

- Average improvement for MFE input versus Oper. input to CLIPER model

Table 4. Comparison of CLIPER hurricane Alicia landfall forecasts on Operational and MFE hurricane forecaster generated track modes.

	OPERATIONAL MODE DISPLACEMENTS			MFE-OP-GBC MODE DISPLACEMENTS		
INITIAL DATE/TIME	TIME # (HRS)	COASTAL @ (KM)	18/08Z * (KM)	TIME (HRS)	COASTAL (KM)	18/08Z (KM)
17/00 GMT	+5:30	61	78	+5:30	17	59
17/06 GMT	0	80	80	-1:30	15	19
17/12 GMT	+4:00	120	146	+3:30	46	59
17/18 GMT	-12:00	33	78	-2:00	28	30
18/00 GMT	-2:30	28	31	-6:00	11	41

- Forecast landfall time before (+) or after (-) actual landfall time.
@ - Displacement along coast of forecast from acutal landfall point.
* - Displacement of interpolated forecast position at 18/08Z (time of acutal landfall) from actual landfall point.

APPENDIX I: METHODS OF APPLICATION OF THE MASS FIELD ENVELOPE TECHNIQUE

Simple methods for determination of the mass field envelope are illustrated in figures I-1 through I-4. Figure I-1 shows a plot of "D" values versus longitude for an east-west pass through the center of the hurricane. A scale along the top of the figure indicates the time of the observations. This graph could be any measure of pressure such as height of standard pressure surfaces, extrapolated sea level pressures, etc., as well as the "D" values illustrated.

Figure I-2 shows a smooth curve drawn through the plotted "D" values. Figure I-3 shows a selection of a point on the smooth curve (heavy cross). The selection of this point on one side of the center then requires the selection of the same "D" value on the opposite side of the center of the storm. The selection of this point is somewhat arbitrary and could be a few km to the left or the right of the selected value with equal results. i.e., approximately two to three times the radius of maximum winds. The dashed lines in the vertical show the longitude for each of these two points, (scale on bottom of graph). The values determined are 74.10 W on the east side which results in 76.25 W on the west side. The mid-point is then 75.08 W. The time of the "fix" is the mid-time between the two points or 0702 GMT. The determination of the center point using this approach takes one to two minutes if a plotting routine has been implemented to plot the profiles.

Figure I-4 illustrates a simple technique for the envelope center determination when computer generated plots illustrated in figures I-1 through I-3 are not available. This technique requires a sheet of graph paper and a listing of the data (perhaps teletype listing). Table I-1 shows a sample listing from an east-west pass through hurricane Elena (1985). Three or four data points are chosen located roughly at twice the radius of eyewall or maximum winds. The lightest wind reported on this pass was near 0222 GMT. Also, wind speeds change rapidly between 0219 GMT and 0220 GMT and then change little between 0219 GMT and 0209 GMT. Therefore, the eyewall is assumed to be near the time 0220 GMT. Four data points between 0210 GMT and 0213 GMT are chosen as a range which will contain the designated MFE value. Four additional data points are chosen from the opposite side of the storm from these data points which contain the same general range of "D" values. Figure I-4 is then plotted using these values and their associated longitudes. The top of the figure contains the range of longitudes for the east side of the storm for this pass (0210 GMT to 0213 GMT). The plotted values are indicated by the solid squares. The bottom of the figure contains the range of longitudes for the west side of the storm for this same pass (0232 GMT to 0235 GMT). These values are plotted on the same graph using triangles. A curve is then fit to each of these two data sets. Where these lines cross indicates the exact pressure or pressure height or deviation value defining the envelope (of no significance except that it is located about twice the radius of the eyewall or maximum winds). The location of the envelope center is then the mid-point between the two longitudes where these lines cross, i.e., 83.0 and 84.6 which gives a center position of 83.80 degrees west. The time of the "fix" is the mid-time between these two points or about 0223 GMT. This is the acutal technique that was used operationally during hurricane Elena for most of the points contained in figures 31 and 32 of the main text. The values can be selected, plotted and center positions determined in two to three minutes time.

The techniques illustrated in figures I-1 through I-4 are applied to north-south passes through the hurricane to obtain latitude positions. These sets of positions are then plotted independently for latitude versus time and longitude versus time. Values are then interpreted from the graph of these functions for the composited track or position at any time.

TABLE I-1. Sample of ASDL data (IWRS type data) transmitted by NOAA reasearch aircraft in hurricane Elena (1985) and received at the National Hurricane Center.

ASDL SEP 01, 1985
NOAA3 1405 ELENA
OBSERVATION PERIOD: 0209Z - 0238Z

TIME	LAT	LON	PRESS ALT(FT)	D-VALUE (FT)	HT STD PRESS SFC (M) OR SLP (MB)	WIND(KTS)	TEMP (C)	DEWPT (C)
0209	28.73	82.83	5110	-202	1390	177/062	+17	+15
0210	28.72	82.90	5100	-202	1390	180/063	+17	+16
0211	28.72	82.97	5197	-237	1378	181/067	+17	+15
0212	28.72	83.03	5207	-275	1366	174/075	+17	+15
0213	28.72	83.12	5212	-334	1348	178/076	+17	+16
0214	28.72	83.18	5331	-390	1329	172/073	+17	+17
0215	28.70	83.25	5341	-470	1304	180/076	+17	+17
0216	28.70	83.32	5459	-547	1277	175/069	+19	+18
0217	28.70	83.40	5560	-636	1248	177/069	+19	+18
0218	28.70	83.47	5607	-707	1225	176/062	+20	+19
0219	28.70	83.53	5723	-816	1190	175/068	+19	+19
0220	28.68	83.62	5877	-909	1155	167/028	+21	+19
0221	28.68	83.68	5914	-891	1158	097/008	+23	+17
0222	28.67	83.77	5862	-880	1164	060/007	+22	+16
0223	28.67	83.83	5871	-871	1167	005/018	+21	+18
0224	28.67	83.92	5866	-836	1179	355/036	+20	+18
0225	28.67	83.98	5788	-778	1198	004/049	+21	+17
0226	28.68	84.05	5790	-708	1220	010/052	+20	+17
0227	28.68	84.13	5635	-641	1244	010/059	+20	+18
0228	28.70	84.20	5552	-570	1269	010/070	+19	+18
0229	28.70	84.27	5534	-491	1293	011/069	+18	+18
0230	28.70	84.35	5512	-421	1314	004/064	+20	+16
0231	28.72	84.42	5375	-365	1335	013/064	+19	+16
0232	28.72	84.50	5304	-311	1353	017/061	+18	+16
0233	28.73	84.57	5306	-262	1368	016/064	+17	+16
0234	28.73	84.65	5271	-236	1377	008/065	+17	+16
0235	28.75	84.72	5170	-207	1388	007/064	+17	+16
0236	28.75	84.80	5156	-178	1397	007/065	+17	+16
0237	28.77	84.85	5204	-174	1397	006/063	+16	+16
0238	28.77	84.78	5198	-186	1394	010/060	+17	+16

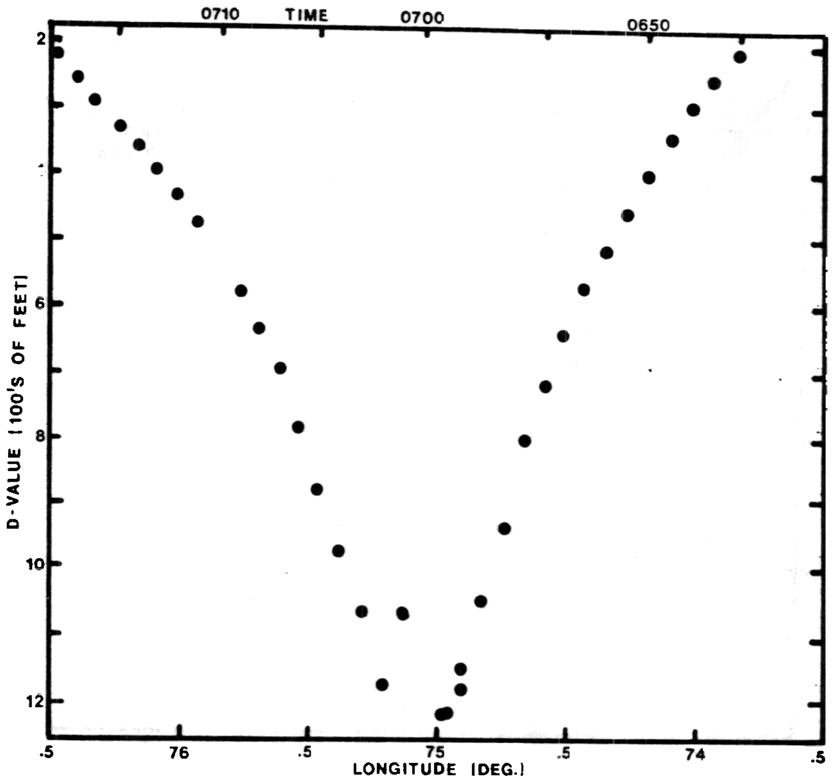

Figure I-1. Plot of "D" values versus longitude for east to west pass through a hurricane.

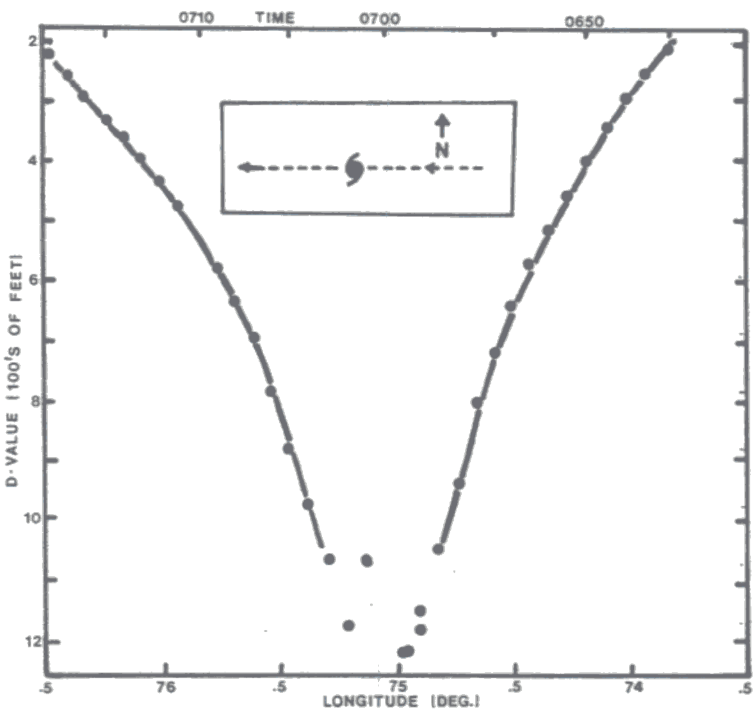

Figure I-2. Same as figure I-1 with smooth curve drawn through the data points and an insert showing the orientation of the flight path associated with this figure.

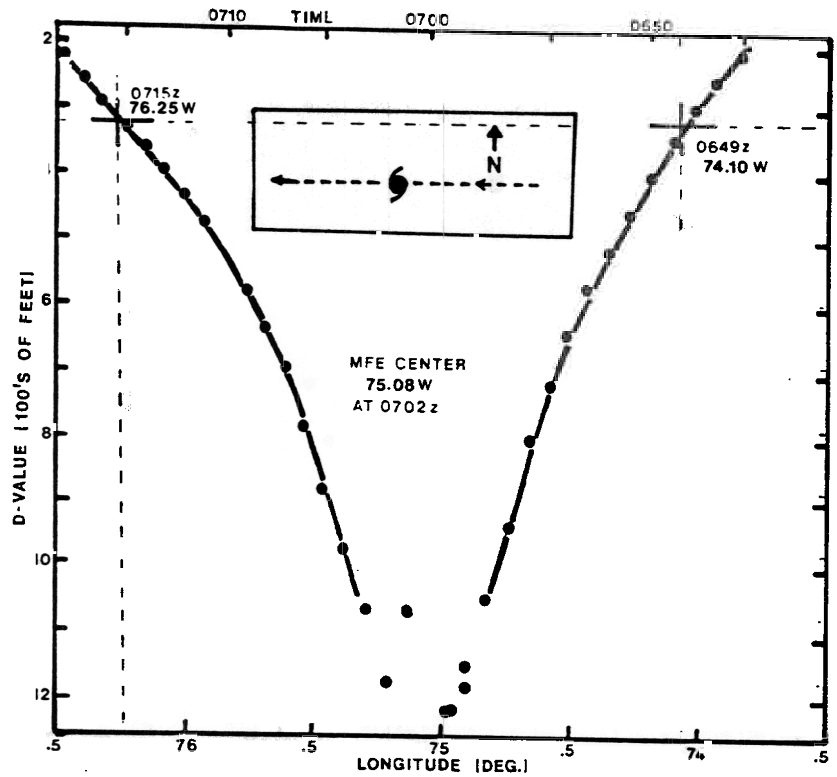

Figure I-3. Same as figure I-2 with mass field envelope selected points (heavy crosses) on the smoothed curve and the calcualted envelope center.

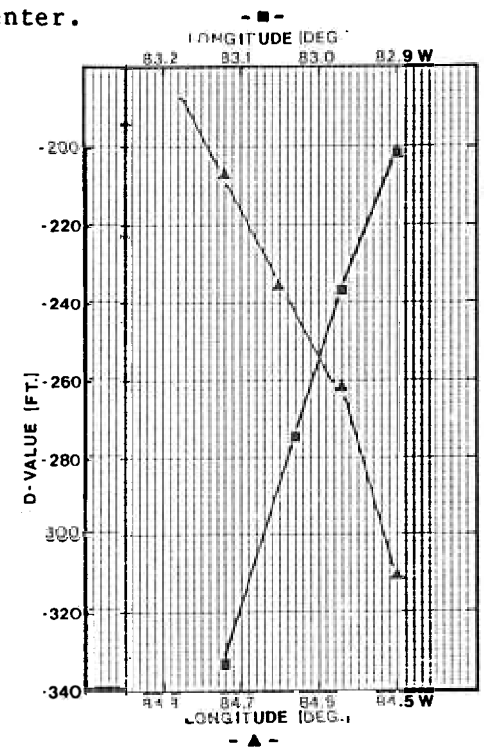

Figure I-4. Illustration of determination of a mass field evnvelope center using three to four one minute data points on each side of the center from table I-1. The center point is 83.80 W.