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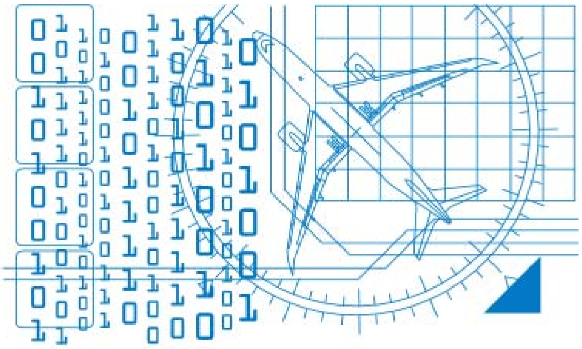

RAP (Radar Analysis Program)
An Interactive Computer Program for Radar Based Flight Path Reconstruction and Analysis

(Presented at the 25th International Seminar of the International Society of Air Safety Investigators, Tuesday October 4th, 1994)

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(* See details re the Authors and the RAP and ADAAPS© Programs at end of this Paper *)

INTRODUCTION

Air Traffic Control Radar Data has been recognized, for many years, as an important tool in aircraft accident investigation. Whereas Flight Data Recorder data requires specialized skills in data transcription and conversion on the part of the investigator/analyst, by comparison radar data is generally available in readily digestible formats, typically either in Range/Azimuth, X/Y or Latitude/Longitude coordinates along with the Altitude and appropriate time base. Seemingly simple coordinate conversion and direct plotting will therefore yield a series of data points which, when connected together, produce a "flight track and profile" of the aircraft's flight. By adding the time base, the "location" of the aircraft as a function of time is the end result, and "ground speeds" are apparently relatively easily calculated.

It is the seeming ease in which radar data can be acquired, plotted and referenced which is in many ways its greatest strength, but unfortunately in some instances is also its greatest shortcoming.

The most important step in a scientific or engineering analysis is that of data interpretation and understanding. Once an investigator is familiar with the measurement and computational processes that the original radar returns have been subjected to on their way to becoming the radar data listings made available by the Air Traffic Control (ATC) authorities, the investigator is better prepared to draw knowledgeable and well-founded conclusions as to what the aircraft probably experienced. It is therefore the purpose of this paper to address issues related to the acquisition, interpretation, analysis and formulation of conclusions, based on ATC Surveillance Radar Data.

PRINCIPLES OF THE ANALYSIS

The sense of human eyesight was not originally intended to view the microscopic world. However the application of science through engineering has given mankind this enhanced ability. Similarly, radar itself was designed to provide an enhancement of the limited visual range and acuity of human eyesight. Radar data is largely generated for Air Traffic Control purposes, to enable the controller to maintain safe separation and guidance of aircraft while they are flying in controlled airspace. The ATC radar system in service today has far greater inherent accuracy than the aircraft separation requirements of ATC controllers. Any valid radar data analysis procedure must serve in a manner similar to a focusing lens, allowing the investigator to resolve the true structure which is inherent (albeit somewhat masked by varying degrees of "noise") within the radar data set. The final accuracy of the resolved result is related to the amount of "noise" that is present in the original radar data recording and processing procedures. Further, for detailed flight simulation purposes the radar data analysis procedure must be able to expand upon the original data set, generating a continuum of results.

The objective of this paper is to outline the development by Accident Investigation and Research Inc. (AIR) of the referenced Radar Analysis Program (RAP), which is an interactive computer program designed to run on a Silicon Graphics computer workstation. This paper will address issues dealt with by AIR in developing this program so as to allow interactive analysis of radar data provided by the ATC Radar System from both an engineering and mathematical analysis approach. This paper will also address the matter of comparing the RAP results against actual flight test data for the purpose of validation and testing of the programming methodology.

TECHNICAL REQUIREMENTS

i) Overview

It is well established that the positional accuracy of a surveillance radar return is in general proportional to the range of observation from the sensor. Further, the degree to which the true target position is offset by an amount from the reported target position mathematically obeys a Gaussian or Normal distribution. Other aberrations also occur, such as "binning", which obey uniform distribution laws. It has been found that in most types of ATC radar performance tests the overall dominant error in the reported radar location as compared to the true aircraft location, can be ascribed to the Gaussian laws of error in measurement, although this is not always the case. This means that the range-azimuth location of a radar return contains measurements which are each corrupted by independent additive measurement noises. Subsequent mathematical coordinate conversion and transformation operations have the potential to add, subtract or have no effect on the absolute value of the original error in measurement. The absolute magnitude and effect of these operations, relative to the original error in measurement, is proportional to the magnitude of the target offset related to the variables used within the ATC conversion process.

Questions arise such as do these operations perturbate or completely alter the original distribution; should they be considered at all and if so are they numerically small or computationally minimized at the processing level compared to the original error of the target measurement; and can the end result still be Normally distributed. Since, from an investigation standpoint, it is impossible to predict the effects of processing of the data in a singular point-wise sense, the above must be tested and proven true and the Gaussian nature of the data must be tested in order to provide assurance of the validity of any mathematical smoothing model which is applied to the original as-received radar data set in order to establish the aircraft's actual flight path, flight profile and ground speeds versus time.

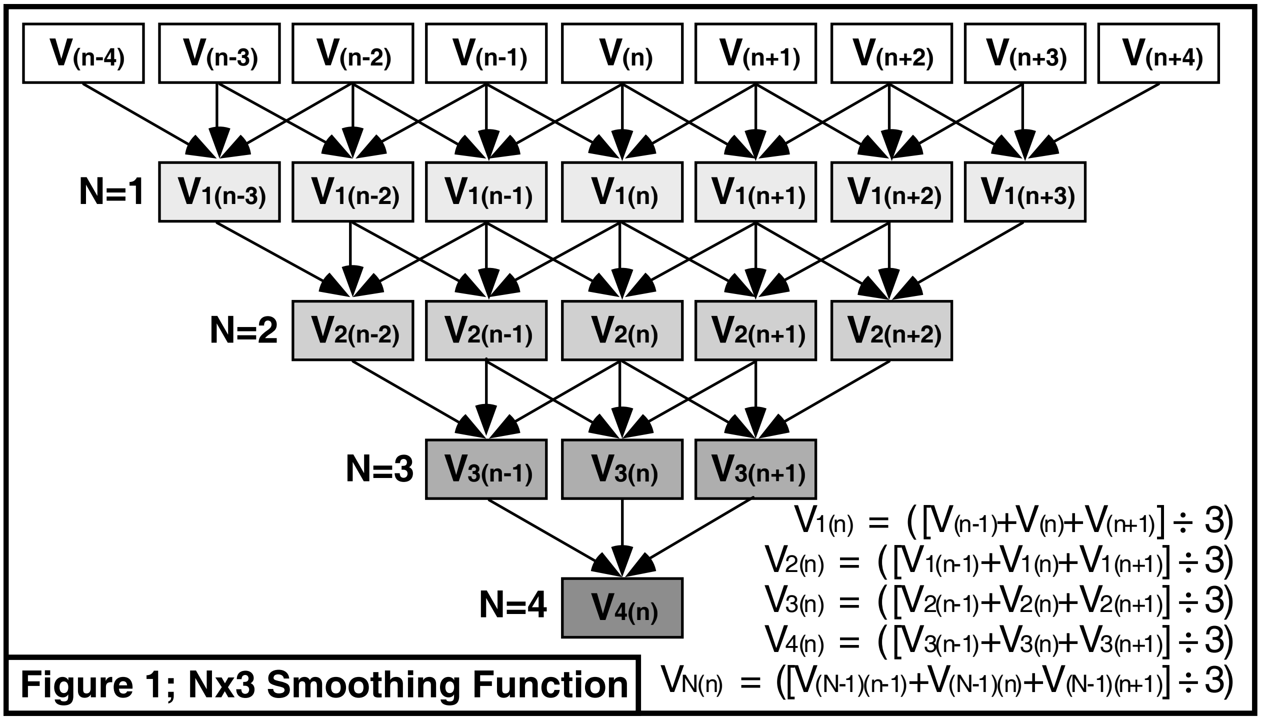
ii) Smoothing

The process AIR employs in the Radar Analysis Program is to time-differentiate the original radar returns such that:

$$dr/dt = v$$

where r can equal the x,y or x,y,z point-pair path distance, t = radar scan time, and v = velocity

thus creating a listing of data that contains one dependent and one independent random variable, velocity and time respectively. It is these unsmoothed velocities (or ground speeds) that are eventually smoothed in the radar analysis program. The smoothing method chosen by AIR is to employ an Nx3 smoothing technique (see Figure 1).



$$V_{1(n)} = ([V_{(n-1)}+V_{(n)}+V_{(n+1)}] \div 3)$$
$$V_{2(n)} = ([V_{1(n-1)}+V_{1(n)}+V_{1(n+1)}] \div 3)$$
$$V_{3(n)} = ([V_{2(n-1)}+V_{2(n)}+V_{2(n+1)}] \div 3)$$
$$V_{4(n)} = ([V_{3(n-1)}+V_{3(n)}+V_{3(n+1)}] \div 3)$$
$$V_{N(n)} = ([V_{(N-1)(n-1)}+V_{(N-1)(n)}+V_{(N-1)(n+1)}] \div 3)$$

Figure 1; Nx3 Smoothing Function

This smoothing process has the advantage that as N goes to 3 and beyond, the Nx3 summation will approximate a near-Gaussian weight function (see Figure 2), so it is in turn appropriate for the Normally distributed errors found within the radar data set itself.

The Nx3 function gives the investigator/analyst a direct measure of the time period with which he is sampling the data, with the value "N" determining the number of adjacent radar returns which are being incorporated into the smoothed value returned, and their respective velocity weighting.

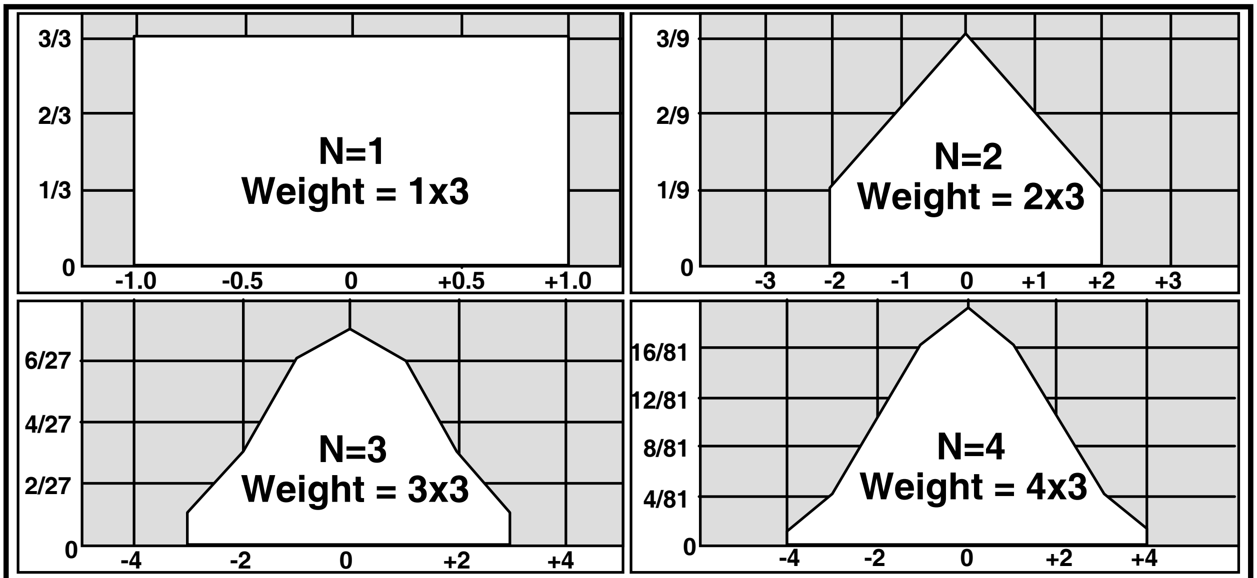


Figure 2; Note that as N 3, Weight Function approaches Gaussian

It is relevant to note that any process designed to smooth "noisy" radar data is in some ways a "double-edged sword", since in all smoothing processes the objective is to, (as far as is practical), remove the unwanted, anomalous data noise yet retain real events. In effect, we require the smoothing process to only smooth the data set just enough so as to remove this undesirable "noise" but at the same time retain real, transient events. The Nx3 is an effective compromise for the aforementioned, since it is locally sensitive yet can remove considerable noise as required.

Any anomalous variability in the time parameter will create a dependency error within the velocity, but analysis by AIR has shown that the time base is recorded such that <u>if properly calculated</u> for real target to target time intervals it contains very little error, and therefore this dependency is minimized. However, large variations are still found within the unsmoothed velocities, thus it is predominantly the spatial error dependency that causes the large velocity fluctuations observed within the data.

<u>iii) Timing Errors</u>

For the purposes of evaluating possible timing errors, it is appropriate to consider the time base associated with various available radar data types. For example during the en-route phase of a flight in the United States, the radar data type that is most commonly available to the investigator after a mishap is the NTAP (National Track Analysis Program) listing. This data type has been discussed in previous ISASI papers, for example the AIR 1989 Paper in the ISASI Annual Proceedings, S. Corrie in the ISASI Journal & M. McMullen's 1992 Paper in the ISASI Annual Proceedings.

In general, truncation and rounding of the NTAP data time listings was noted by AIR, and accordingly a retiming algorithm was designed to apply to NTAP data to recalculate the time listings to give a more accurate interval time base. In some instances another type of "less" processed data in the USA and Canada may be available to the investigator, this data type is termed ComDig or Common Digitized data. Unlike NTAP, the ComDig data is available in Range-Azimuth-Altitude listings, and represents the first level of the Air Route Traffic Control Center's (ARTCC's) digitized radar processing function. Acquisition of the ComDig data in parallel with NTAP data has enabled AIR to confirm the timing corrections applied to the NTAP data by the RAP program. Figure 3 shows, as an example, original NTAP times as rounded/truncated by the NTAP program to 12 and 11 second integer values versus the AIR-RAP calculated target-to-target times. Comparison of the upper RAP smoothed time interval curve in Figure 3a to the actual ComDig time interval curve Figure 3b, given in decimal seconds, indicates that the time correction is both necessary and accurate.

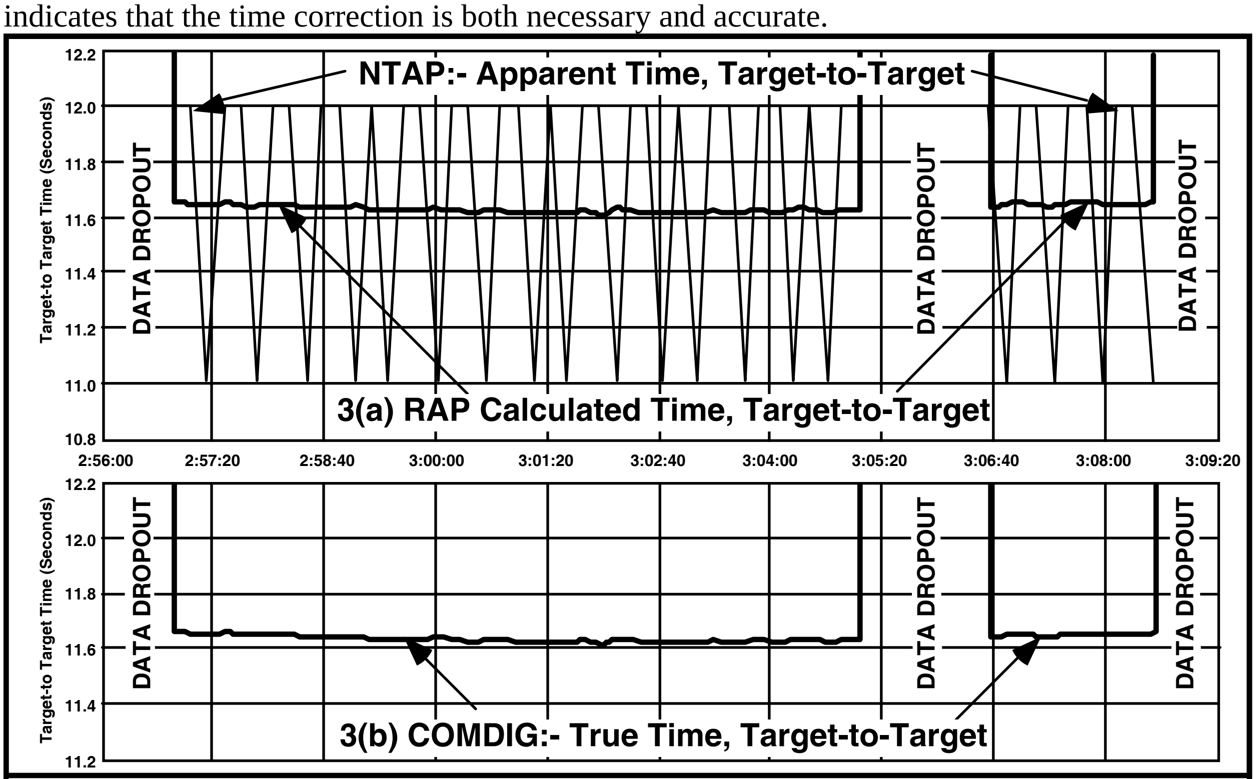
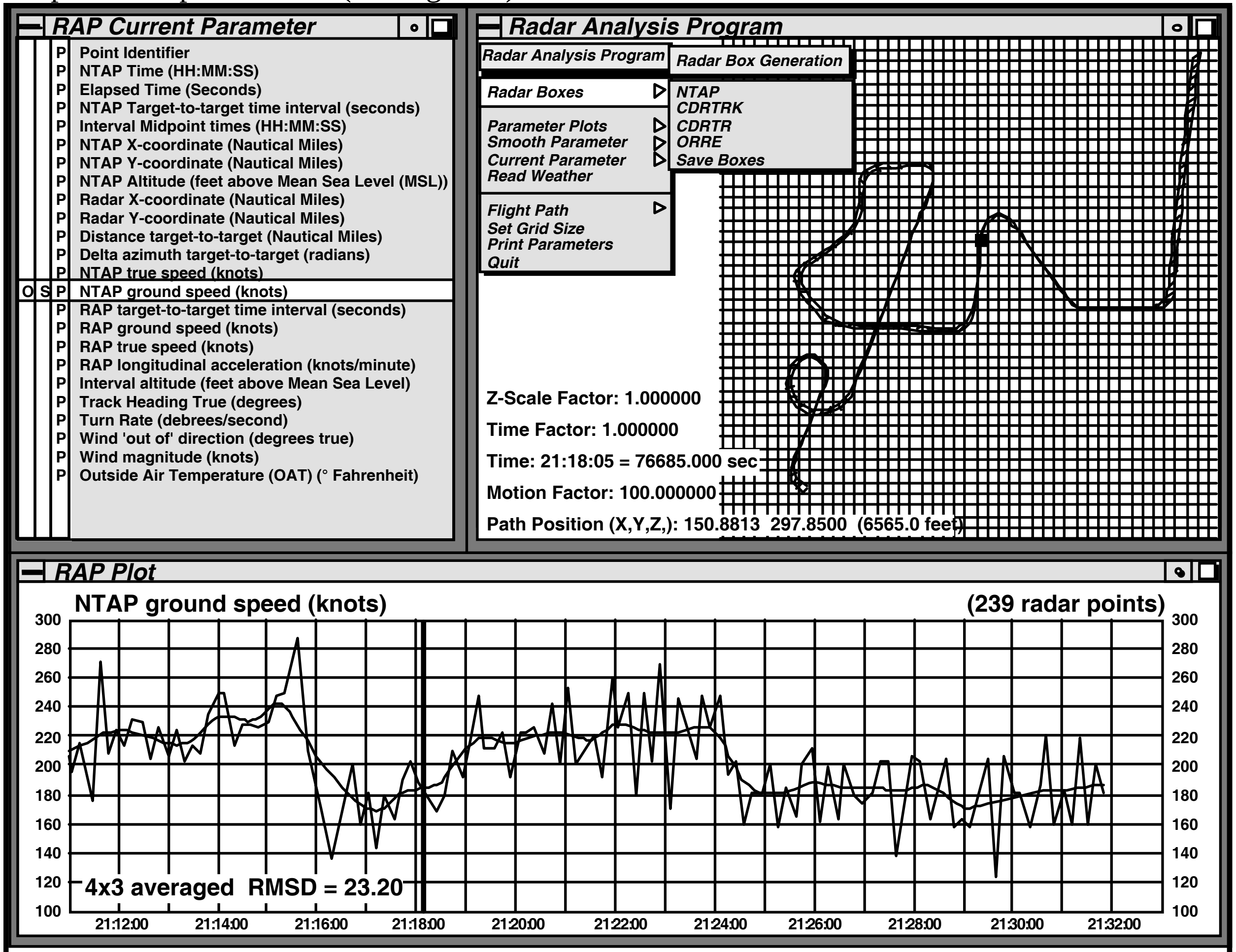


Figure 3; RAP Calculated v. COMDIG True Time Target-to-Target

Since the ComDig time listings are digitized to the nearest millisecond, the integer second values found within the NTAP data listings can be corrected to similar precision by calculating the target positions in azimuth and applying the appropriate radar rotation period. The timing data extracted from the two types of F.A.A. approach control radar data listings ("Target Reports" and "Tracking Data") both have digitized time in milliseconds, so no correction is required, however the data is checked by RAP for general accuracy. It is interesting to note that the times affixed to the Tracking Data listings have been identified as occurring later than the original associated range-azimuth Target Report listings. This is an effect of the delay in data conversion, processing and subsequent display for air traffic control purposes. However, the actual interval times of both listings have been found to corroborate one another, but the one is somewhat retarded from the other.

vi) Normal Scores Plot and Probability Distribution

In typical RAP analyses, after the initial data smoothing, the unsmoothed and smoothed data are plotted and displayed for the investigator's review in the analysis window on the Silicon Graphics computer screen (see Figure 4).



Z-Scale Factor: 1.000000
Time Factor: 1.000000
Time: 21:18:05 = 76685.000 sec
Motion Factor: 100.000000
Path Position (X,Y,Z,): 150.8813 297.8500 (6565.0 feet)

4x3 averaged RMSD = 23.20

Figure 4; RAP Screen Display showing Menus, Track & NTAP Ground Speeds

Additionally the velocity distribution is plotted and displayed in a Normal Scores Plot and a Probability Distribution Histogram in adjacent windows (see Figure 5). The Normal Scores Plot and the Probability Distribution Histogram are used as a test in determining the general symmetry and behavior of the applied smoothing function, and in identifying which interval velocities (the interval velocity being the calculated velocity between two consecutive radar "hits") cannot be explained by the typically expected normally distributed error processes. In a real-world radar analysis, a relatively small number of radar returns within an overall radar data set cannot be explained by Gaussian theory, and may accordingly be tagged as spurious or rogue values. Figure 5 shows an example of a radar data set with "rogue" data points (see Figure 5a) and the same data set with the rogue values removed (see Figure 5b.) Figure 5 therefore shows the statistical probabilities for a large data set in the form of a comparison of the effects of the data removal displayed in the Normal Scores Plots and the Probability Histograms.

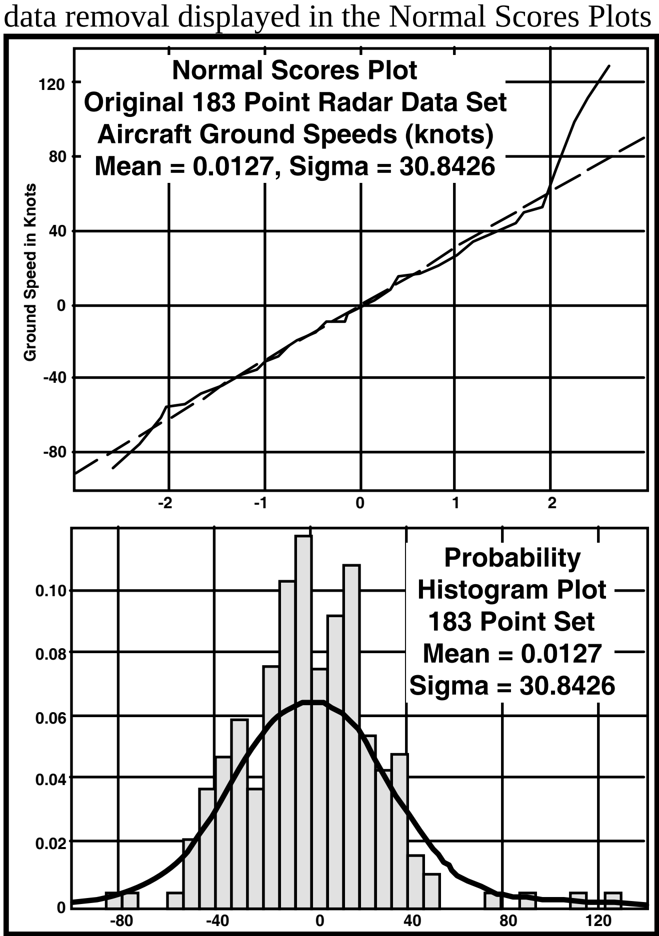


Figure 5a; Radar Data Set with Evident "Rogue" Data Points

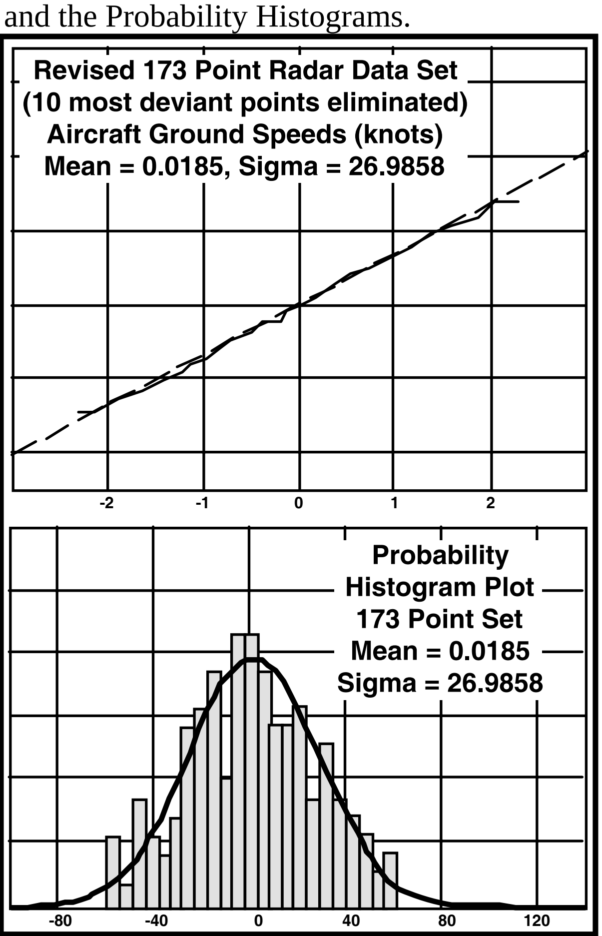


Figure 5b; Effects of Deleting Identified "Rogue" Data Points

The predicted theoretical ideal Gaussian curve with the same mean and standard deviation values is overlaid over each histogram for comparison. It is important to note that in a Normal Scores Plot, a Normal distribution curve is a straight line with slope equal to the distribution's standard deviation.

The Normal Scores Plot plays an important role in the RAP program analysis. Radar systems are complex processing entities and the Normal Scores Plot provides the investigator with an unbiased technique for evaluating if the original unsmoothed velocities are Normal (or Gaussian in distribution), and also for tagging abnormal or suspect radar returns. The necessity for having an unbiased, scientific method for identifying such suspect data points is based on the premise that the incorporation of these erroneous, non-Gaussian data values into the total radar data set biases the analysis. Because of this bias, the typically large errors associated with them will significantly reduce the effectiveness of local data values, which contain the predicted normal error distribution within the mathematical smoothing algorithm. It is interesting to note that common spectral analysis smoothing procedures also accomplish essentially the same effect (amongst others) from the point of view of a frequency analysis. That is to say, if the signal is passed through a filtering process, the higher frequency terms are usually cut off by the filtering algorithm, and it is these high frequency, potentially high amplitude contributors that the Normal Scores Plot identifies as spurious, allowing for direct correction algorithms to be applied.

There are two methodologies available within the RAP program for dealing with these rogue data values. One method is to simply delete out the spurious data from the original data files and run the analysis over without incorporating the adverse effect of these suspect values. Alternatively, the Program can incorporate (where allowable) a forward and backward tracking predictive algorithm, basing the prediction on the past and future history of the radar track and returning a new radar coordinate that more accurately represents the probable target location relative to its nearest neighbors. At this point in the development of the Radar Analysis Program, AIR is exploring the suitability of various potential predictive tracking algorithms, such as the alpha-beta tracker and Kalman Filter tracker methods especially when prediction is required in flight path sections involving maneuvering aircraft. It is also planned that AIR will develop a future module within RAP to simulate the original noisy data based on the smoothed aircraft flight track and speeds.

Before the smoothed velocity values are accepted, the Program utilizes a module that allows for comparative numeric analysis. Presently the RAP program allows comparison with simple averaging techniques, with the least squares moving arc technique and with certain types of spectral analysis techniques. Although AIR has found that the Nx3 smoothing function in general yields the best, most readily discernible results, it should be noted that in some instances spectral analysis outperforms the Nx3 method. This is true particularly if the data is very noisy and provided spectral analysis is not required to estimate beginning or end point speeds, for which certain types of spectral analysis are notably unsuitable due to the uncertainty of the periodicity beyond the termination of data. Additionally, spectral analysis has been found to become relatively insensitive to real transient speed changes by applying a minor change in cut off to the Filtering Factor; and the Nx3 weight function outperforms, for example, Fourier smoothing when the data is essentially well behaved. The Program is also designed to return a measure of the amount of noise within the data to aid in the determination of the application of appropriate smoothing techniques.

END POINT ANALYSIS

One of the most difficult aspects of radar data analysis is end point interpretation, that is, the last few radar returns in a radar data set. Most smoothing processes ideally require data to be available before and after the value to be determined through smoothing in order to return a result with a high degree of confidence. For example, averaging techniques normally require values to exist on both sides of the data value being calculated. Spectral analysis or wave function type smoothing processes assume the data is periodic and, as such, behave poorly at the beginning and end of the data set, and also may be locally insensitive to transient data behaviour due to the cut-off of relevant frequency components. The RAP program employs a comparative type of technique for optimization of end point analyses (see Figure 6). The original weight function is modified when approaching the end of the data set in such a manner as to maintain its original relative weighting. The values available in the leading arm of the weight function will drop point-wise until, in general, N less than the values available when compared to the trailing arm reaches the final smoothed velocity interval value.

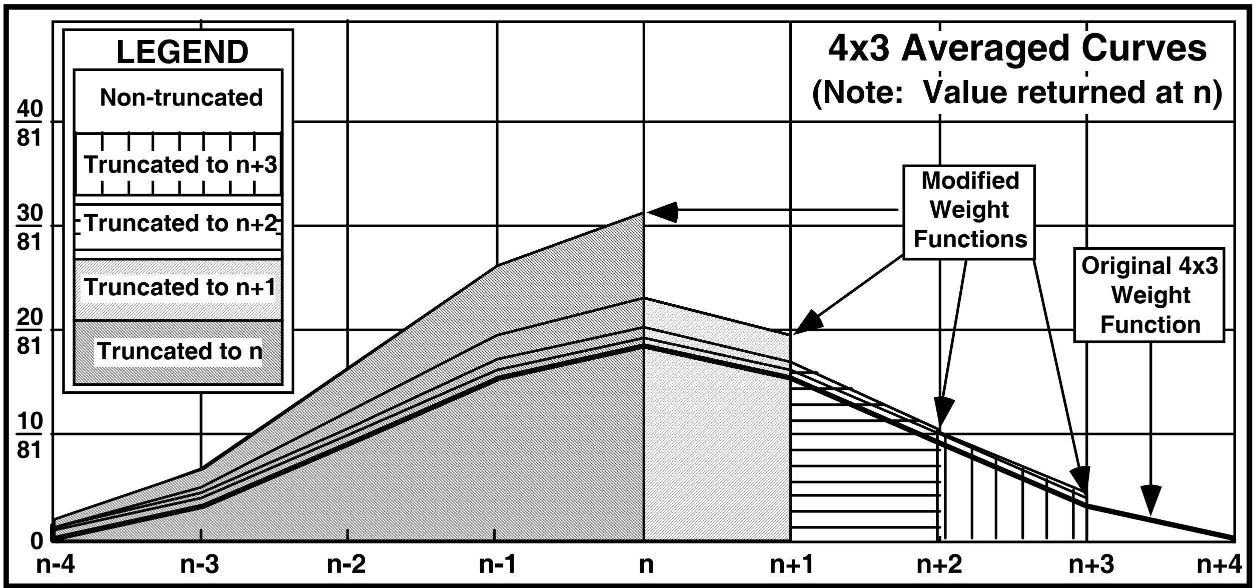


Figure 6; Illustration of Weighting Effects of Truncated End Points

As the end points are approached, the loss of data is accommodated by distributing each data point's smoothing weight contribution amongst the remaining averaging contributors. This is termed a convolution, and subsequently arrives at a speed value corresponding to the final radar data interval velocity. To test the convolution the modified weight functions are treated in such a manner that the entire data set is successively truncated, such that each and every available data series is treated as having a new series end point when moving through all the data, approaching the analysis in a forward and backward direction by appropriate truncation. The behavior of the convolution truncation algorithm is then compared on a point-by-point basis to the original "good" smoothed values, and a statistical output or deviation table is generated which will affix a "certainty value", for the real end points based on the algorithmic behavior of the convolution/truncation algorithm relative to the known entire data set behavior. This certainty value could be the standard deviation of the table, and the mean value is used to show that the result is not biasing the end point speed either up or down. Additional deviations could be referenced yielding additional inference. An example is the standard deviation can be inferenced with a probability of success of 2:1, however the deviation table can be expanded to give greater confidence, i.e. standard deviation plus or minus 3 knots may have a hypothetical probability of success of 5:1. This type of inference is well known to have relevant applications to single sample uncertainty analysis, and a single sample set is exactly the type of data available after an aircraft mishap.

BASIC DATA TYPES

Figure 7 shows the RAP speed analysis and statistical plots for a ComDig data listing. The standard deviation was determined to be 16 knots for this particular data set, which in AIR's experience indicates that the data is fairly well behaved.

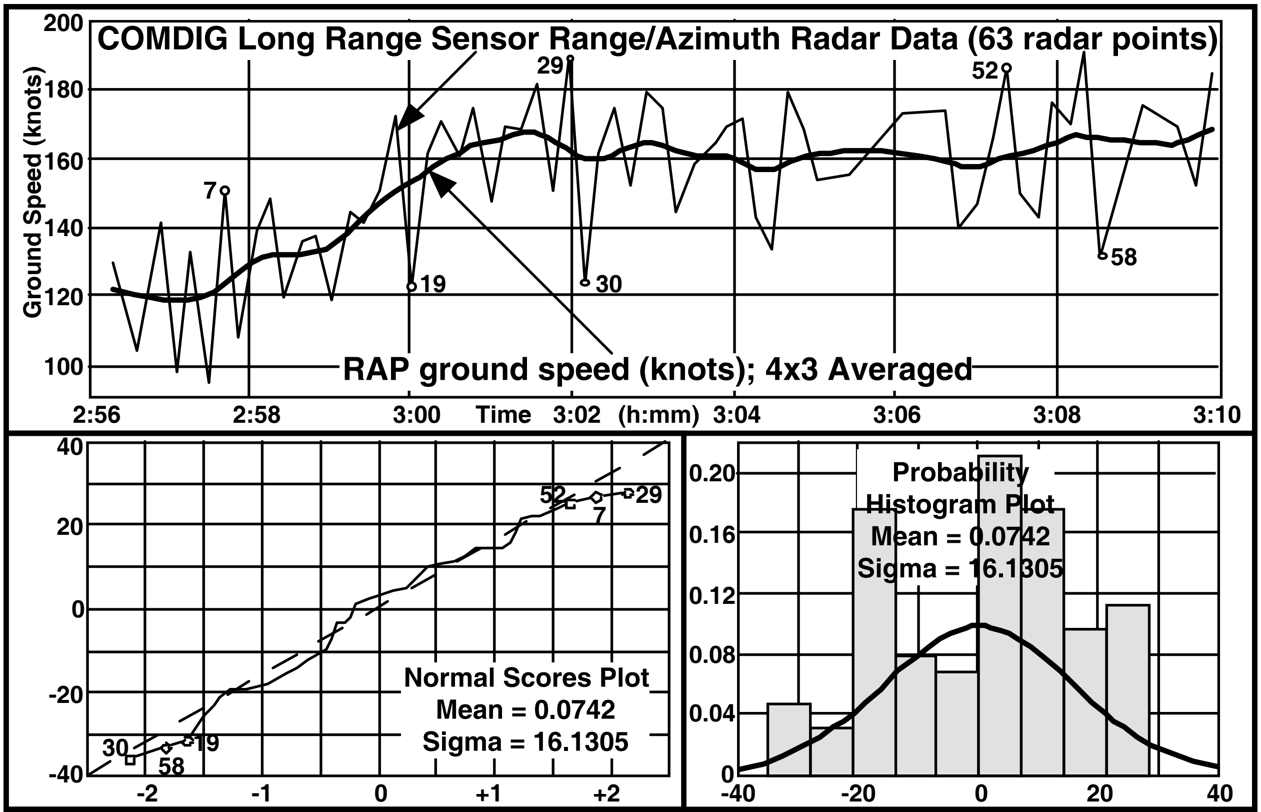


Figure 7; COMDIG Range/Azimuth Radar Data Set

For comparison, Figure 8 displays the same radar data in the standard NTAP format. Although more processed by the radar computer system, the NTAP data's statistical distribution appears more "Normal" in comparison to the total distribution, however the radar processing has increased the standard deviation slightly by approximately 1 knot over the 63 samples.

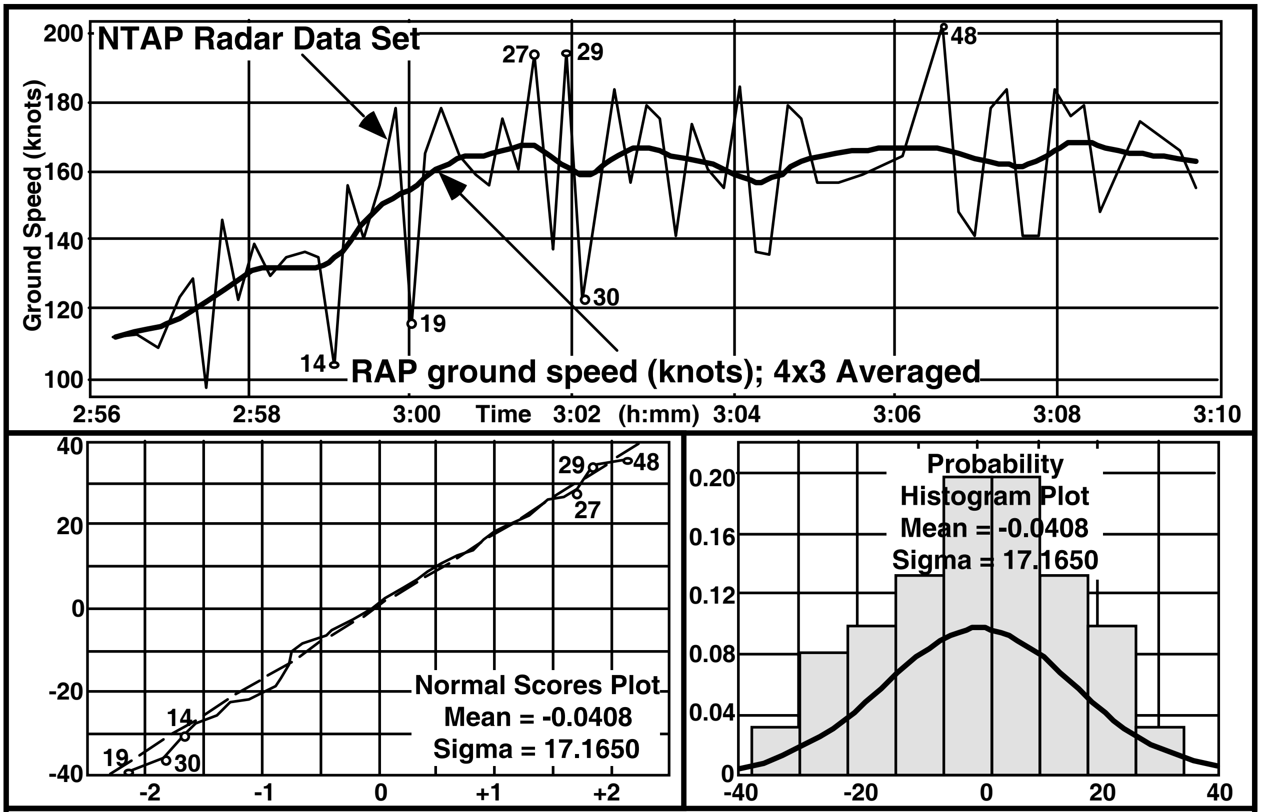


Figure 8; Comparable NTAP Radar Data Set

The possibility exists that the radar system computer processing variables have been calculated in such a manner as to minimize the addition of "noise" to the original range-azimuth data. Further, the additional symmetry above and beyond the original ComDig statistical distribution is indicative of certain smoothing algorithms being invoked in the Multiple Radar Data Processing (MRDP) function of the F.A.A. computer system that are responsible for the processing and display of en-route radar data. The variables used in the filtering and conversion algorithms utilized by the F.A.A. in the conversion from range-azimuth to X-Y coordinates are designed to minimize the rejection of valid target displays and to minimize the addition of projection error induced spatial noise to the original target measurements within the confines of the computer system architecture. The latter arises from the necessity of "mosaicing" the data from multiple radar sites, within a large geographic area, onto the Airspace Cartesian System Plane through a stereographic projection technique, which has been found to minimize projection error in going from the generalized oblate spheroidal earth's surface to the system's flat plane and vice versa.

Since it is difficult to give examples of when the radar data processing functions convert normally distributed radar spatial measurement errors to non-normally distributed data sets, an extreme example has been chosen to illustrate this point. Figure 9 shows the calculated original unsmoothed and smoothed radar based speeds for an aircraft on a stabilized final approach into a major international airport.

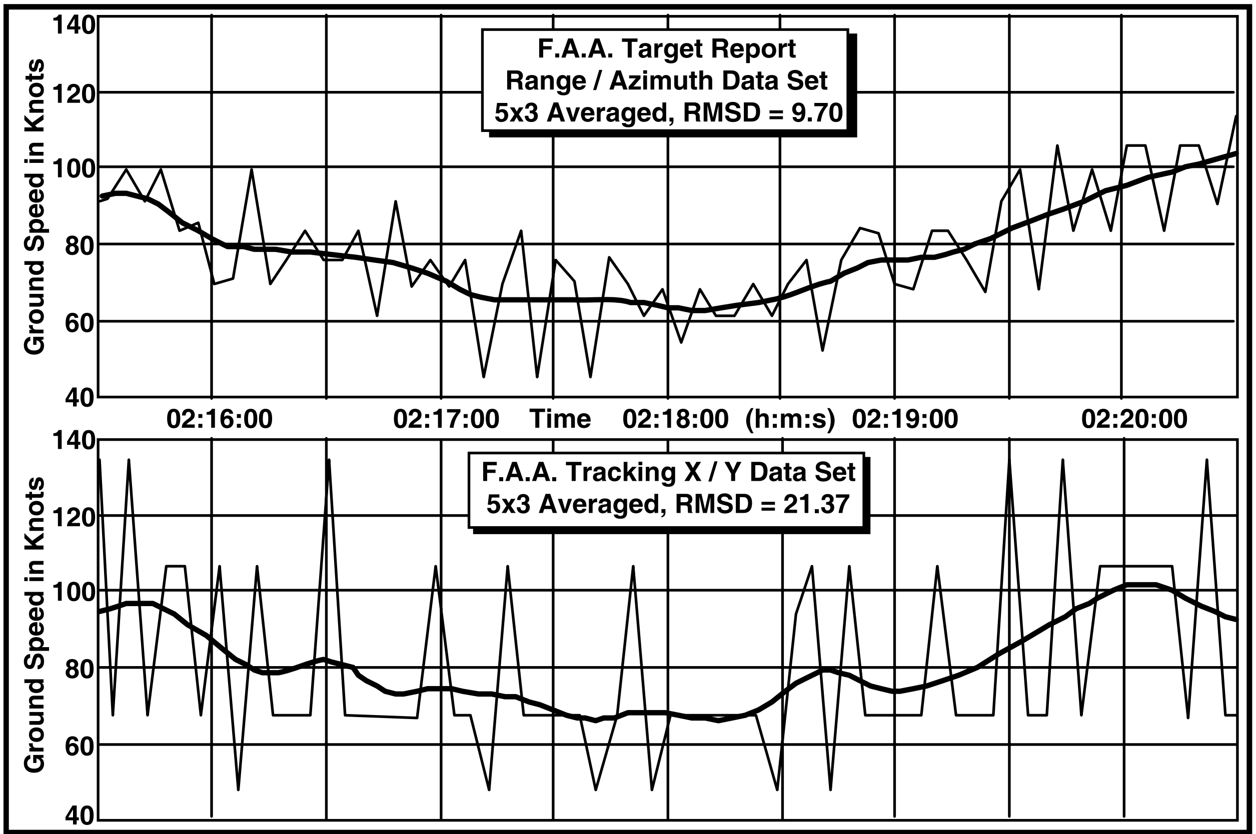


Figure 9; Comparison - Range/Azimuth v. Processed TRACON Data

The upper graphic shows unsmoothed and RAP smoothed curves which represent the aircraft's ground speed based upon the original range-azimuth data produced by an airport surveillance radar, located close to the landing runway and utilizing a higher frequency sampling rate of 4.7 seconds (compared to the typical 10 to 12 second NTAP sampling rate). The lower unsmoothed and RAP smoothed curves show the same source base range-azimuth data after it has been processed and converted to X/Y coordinates within the TRACON (Terminal Radar Control) ATC system. This data shows evidence of the phenomenon termed "binning", whereby the X/Y coordinates are converted into a Cartesian grid system by the data processing; which exhibits itself in the velocity curve being constrained to only certain discrete values, rather than the more continuous values exhibited in the original range-azimuth data set.

Figures 10 and Figure 11 also indicate that the "binning" is dominating the statistical distribution in the X/Y data set as compared to the range-azimuth data set. Figure 10 compares the statistical probability histogram for the "binned" X/Y data set against the range/azimuth data set, and it is apparent that the "binned" histogram is skewed negatively, and its standard deviation has increased to more than 21 knots. The range-azimuth data set histogram, by comparison, is much more symmetric and narrow, with a standard deviation value of less than 10 knots.

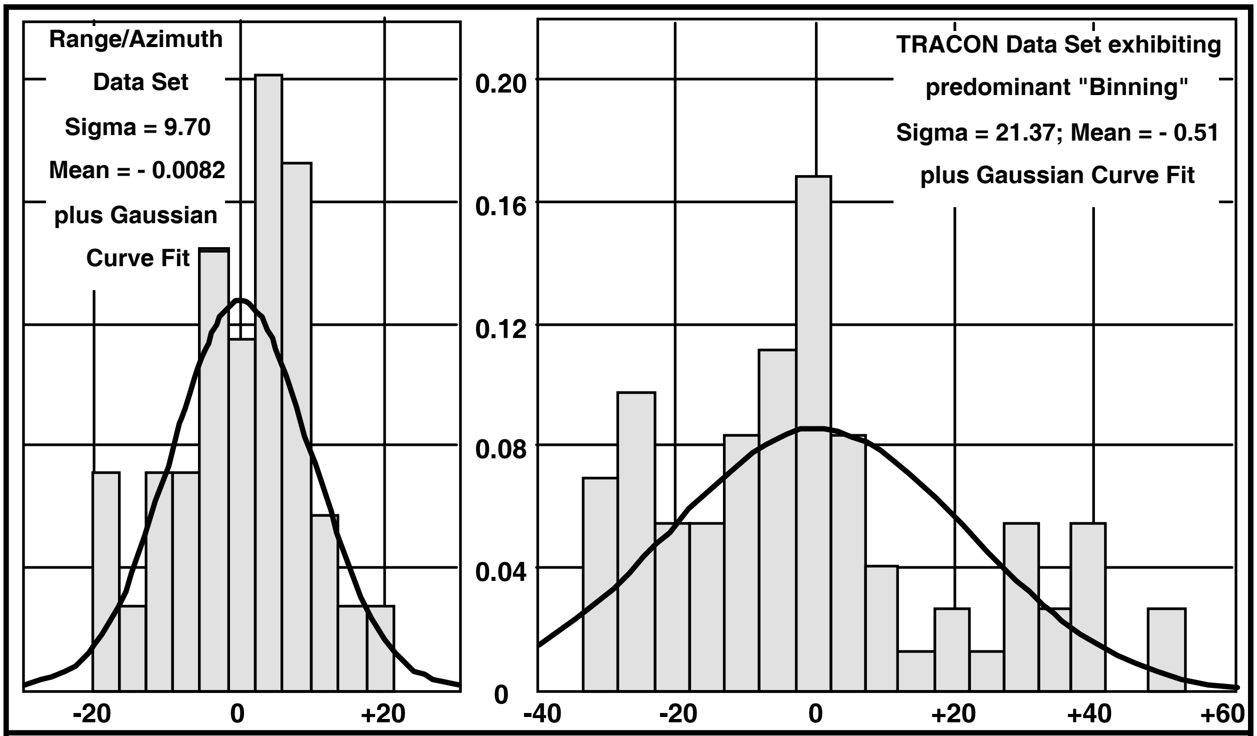


Figure 10; Data Set Quality Compared to Gaussian Distributions

Additionally, Figure 11 shows that the Normal Scores Plot for the original range-azimuth data set is closely comparable to the Gaussian theoretical ideal model. By comparison the strongly "binned" X/Y data set no longer approximates a straight line but is parabolic in shape, indicating that the "noise" in the radar data is not Gaussian (or Normal) in nature. It should be noted that this example is extreme insofar as the ground speed of an aircraft on approach is relatively slow and, with the high sampling frequency typical of approach radar, the "binning" phenomenon will quantitize the apparent aircraft speed as the "noise" due to "binning" approaches a significant value when compared to the smoothed aircraft ground speed. The level of quantitization is related to the geometric relationship of how the aircraft crosses the coordinate system grid, and the number of discrete "binning" cells that are traversed in each radar sweep period.

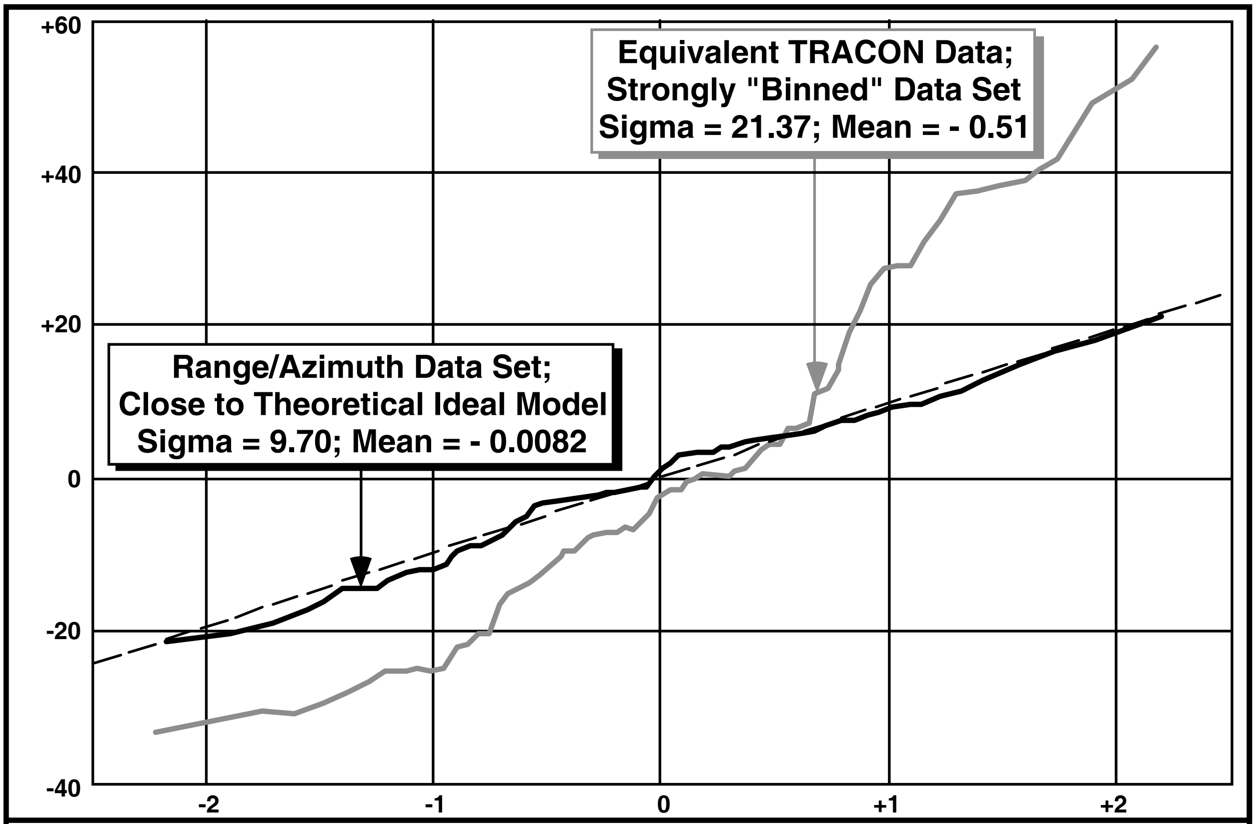
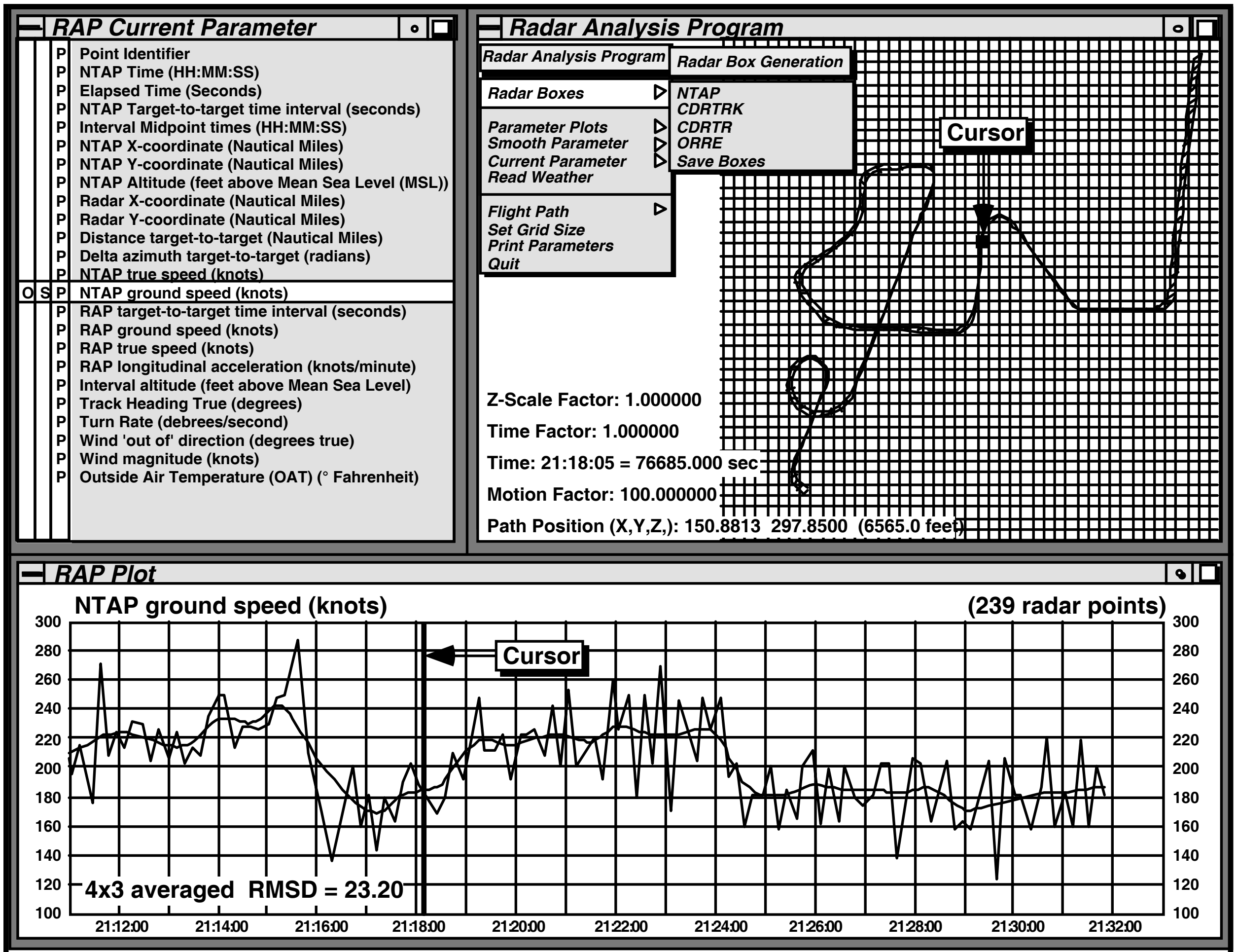


Figure 11; Normal Scores Plots - Normal and Strongly "Binned" Data

A TYPICAL RAP SESSION

i) Start-up

A typical RAP computer session begins with the radar data listings being read into the computer program. After successful read-in and validation of the data, a screen such as shown in Figure 12 typically appears, and is generally present throughout the radar analysis session.



P Point Identifier
P NTAP Time (HH:MM:SS)
P Elapsed Time (Seconds)
P NTAP Target-to-target time interval (seconds)
P Interval Midpoint times (HH:MM:SS)
P NTAP X-coordinate (Nautical Miles)
P NTAP Y-coordinate (Nautical Miles)
P NTAP Altitude (feet above Mean Sea Level (MSL))
P Radar X-coordinate (Nautical Miles)
P Radar Y-coordinate (Nautical Miles)
P Distance target-to-target (Nautical Miles)
P Delta azimuth target-to-target (radians)
P NTAP true speed (knots)
O S P NTAP ground speed (knots)
P RAP target-to-target time interval (seconds)
P RAP ground speed (knots)
P RAP true speed (knots)
P RAP longitudinal acceleration (knots/minute)
P Interval altitude (feet above Mean Sea Level)
P Track Heading True (degrees)
P Turn Rate (debrees/second)
P Wind 'out of' direction (degrees true)
P Wind magnitude (knots)
P Outside Air Temperature (OAT) (° Fahrenheit)

Z-Scale Factor: 1.000000
Time Factor: 1.000000
Time: 21:18:05 = 76685.000 sec
Motion Factor: 100.000000
Path Position (X,Y,Z,): 150.8813 297.8500 (6565.0 feet)

4x3 averaged RMSD = 23.20

Figure 12; RAP Screen Display showing Menus, Track & NTAP Ground Speeds

The screen consists of a parameter listing window that allows for the display of selected parameters (such as ground speed, true air speed, calibrated air speed, meteorological data, acceleration, altitude and heading amongst others). Figure 12 also shows typical "pop-up" menus allowing selection of the features necessary for graphical display of data, statistics and numeric analyses and various Input/Output features amongst others.

Figure 12 also shows the dynamic moving cursor that is available on both the 3-D Flight Path and the mathematical graphic displays. The vertical cursor bar seen on the ground speed display is linked to the cursor traveling along the displayed flight path such that the mathematical parameters relating to any location along this path can be determined readily and directly.

ii) Analysis

Figure 13 shows the same data set as illustrated in Figure 12, with the Normal Scores Plot and the Probability Histogram and associated theoretical Gaussian curve displayed.

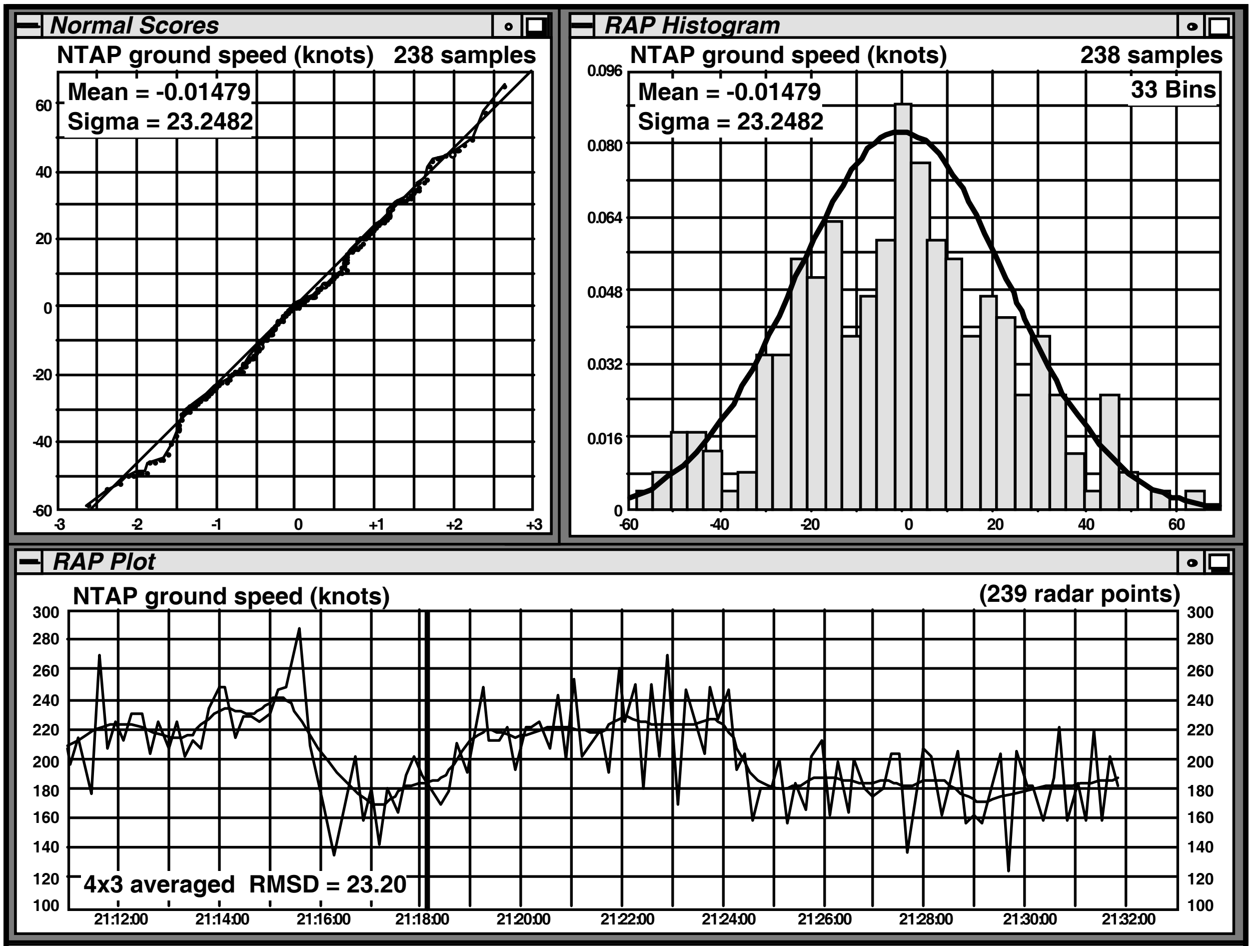


Figure 13; RAP Screen Display; Normal Scores Plot, Speeds & Histogram

A further refinement to the 3-D Flight Path display available to the investigator is to display the three-dimensional "Tolerance - Probability Boxes" around each of the radar data point locations which reflect the known/expected spatial error distribution implicit in the radar system. These boxes represent the calculated volume of space within which the aircraft most probably will be located upon application of the flight path reconstruction algorithm at the time at which the associated radar "hit" was recorded (see Figure 14)

The size, shape and orientation of the radar boxes is dependent on the range-distance and azimuth angle of the aircraft with respect to the radar sensor, and on the type of radar data to be analyzed.

As mentioned previously, after preliminary analysis of the RAP output the investigator may attempt to recompute the path by amending the data points which failed the test for normality. As noted earlier, the program is specifically designed to identify, in an unbiased manner, those data values that do not meet this test.

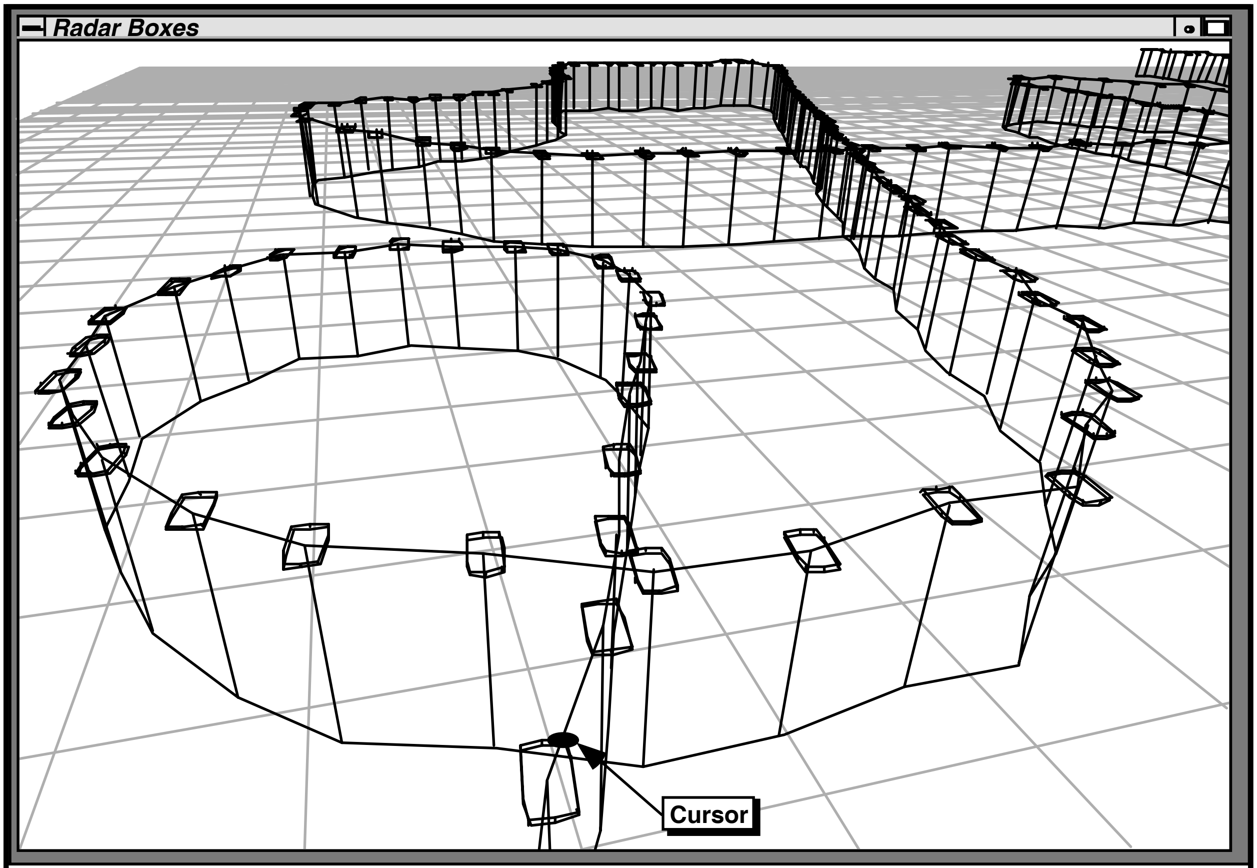


Figure 14; RAP Screen Display showing Track and Radar Tolerance Boxes

Since the mathematical procedures require the random variable within the radar data set to be Normally or near-Normally distributed, the Normal Scores Plot is an effective tool for detecting obvious departures from Normality. As stated previously, the options are two fold:-

- Editing out of the non-normal data and regenerating the analysis (see Figure 15); or
- Regenerate these target locations by invoking the previously mentioned extrapolation/ interpolation predictive algorithm.

Previous work in the field of radar data analysis has found that the computational accuracy of the analysis, particularly the generation of a smoothed ground track from the smoothed flight parameters, will usually encounter difficulty when the aircraft experiences a change in heading. Extensive analysis of radar data has shown that when comparing flight data recorder heading data with that calculated by smoothing radar data, radar tends to predict the aircraft track commences the turn sooner than the FDR indicated, and similarly continued the turn for some time after the FDR reported cessation of the heading change. In general, it is found that the absolute value of the change in heading is accurate, however there is an apparent spreading in time of this change in heading due to the lower sampling period of the radar data.

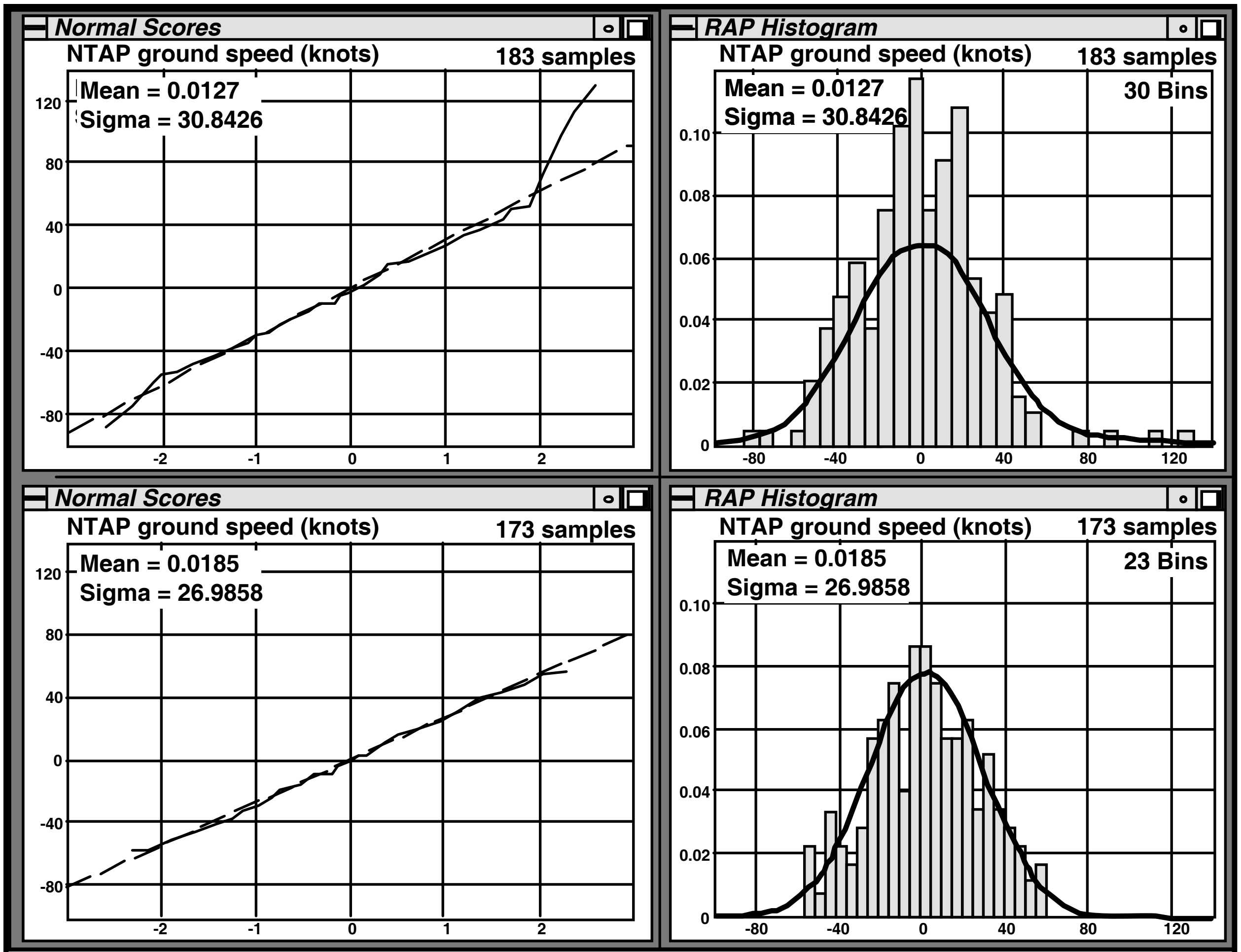


Figure 15; Display showing Effects of Deletion of Identified "Rogue" Data Points

With the invocation of the radar tolerances box into the 3-D flight path window, RAP allows the investigator to see an immediate graphical depiction of the previously described radar spatial error tolerances. The program has a module for "windowing" the turn rate and, in effect, modeling the location of the aircraft approaching a turn in x-y space relative to the radar tolerance boxes, and then (through an interactive graphical interface) altering the wave-form shape in the turn rate window and dynamically seeing the effect as the flight coordinates are recalculated throughout the turn. This interactive process allows an optimal track to be determined by the further invocation of a dynamic sensitivity analysis, which recomputes the coordinate locations by minimizing the Root Mean Square (RMS) deviation in x-y space. When performed correctly, the results are visually obvious as the aircraft tracks smoothly through the turn and onto the new track with an excellent fit to the original data and error tolerances. This technique provides an analytical and interactive approach that addresses the "noise" inherent in the radar data, and relates the same to the engineering tolerances that can be used to correlate the mathematics with the expected spatial variation predicted by the radar performance model. It should be emphasized that this turn modeling in no way affects the original ground speed results returned by the program, but is merely used so that the aircraft's speed, heading and altitude will fit the best realistic path through the original radar data points, and in turn provide the most probable positions of the aircraft as a function of time. It is still the investigator who will have control of the handling of the data, the level of smoothing and the generation of the flight track and profile. The RAP program is merely a scientific environment for analyzing and reconstructing the aircraft flight path based on ATC radar data.

iii) Summary

In summary a typical RAP Session consists of:-

1) Entry of the original radar data.
2) First-pass smoothing of the radar ground speeds.
3) Identification of any radar data points that do not appear Normally Distributed.
4) Correction (by editing or algorithmic procedure) of the Non-Normally Distributed data.
5) Final-pass smoothing of the radar ground speeds, and comparison to alternative numeric smoothing or filtering procedures methods and techniques.
6) Application of statistical tests to derive a scientifically quantified measurement of data behavior and to define confidence for endpoint speed analysis
7) Curve fitting in x-y-z of the aircraft speeds, headings and altitude to the engineering defined radar tolerances. Best fit and minimization of Root Mean Squared (RMS) deviation over the entire data set which passes the test for Normality
8) Outputting of engineering data parameters, ground speeds, headings, turn rates, true airspeeds, calibrated airspeeds, altitudes, accelerations, meteorological inputs, et al; and statistical and aerodynamic analyses.
9) Optional, generation of a real-time, animated flight track from the ground-based radar data, and linkage of same to Air Traffic Control communications. (Note:- The Aircraft Data Acquisition Analysis and Presentation System (ADAAPS) or some similar sophisticated computer graphics simulation program is required to exercise this option, RAP does not include this capability but supports the necessary File Formats.)

iv) Functionality and Expandability

A functional block diagram illustrating the general flow of the Radar Analysis Program can be seen in Figure 16.

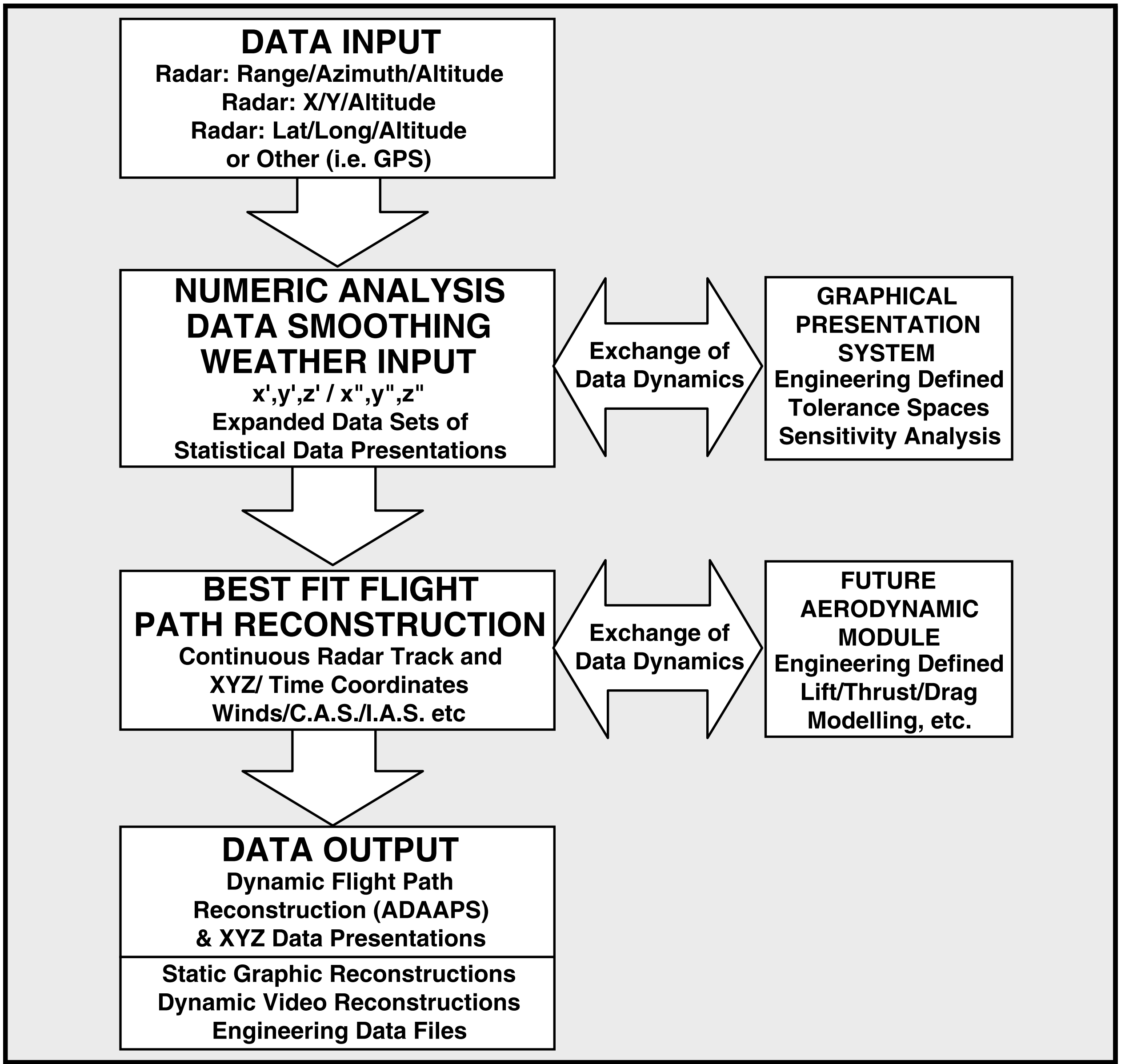


Figure 16; Radar Analysis Program (RAP) Functional Block Diagram

Currently RAP supports four different types of radar data input, and has been designed in such a manner that any future new data formats can be converted and displayed with a minimum of module reprogramming. RAP provides output that makes it compatible with the sophisticated Aircraft Data Acquisition Analysis and Presentation System software. This enables output to ADAAPS for data presentation purposes, and although RAP presently supports its own plotting tools, ADAAPS offers a more flexible plotting environment. Animation of the RAP radar analysis is also supported as the program outputs the file formats necessary for the dynamic real-time flight reconstruction playback capabilities supported by ADAAPS.

An example of a typical dynamic flight path screen display is shown in Figure 17. In this display, a dozen aircraft tracks, all based on RAP analysis of their individual radar records, are shown as they approach Kennedy International Airport on Long Island, New York. The identifier at the head of each track is the aircraft ID plus its current altitude in hundreds of feet.

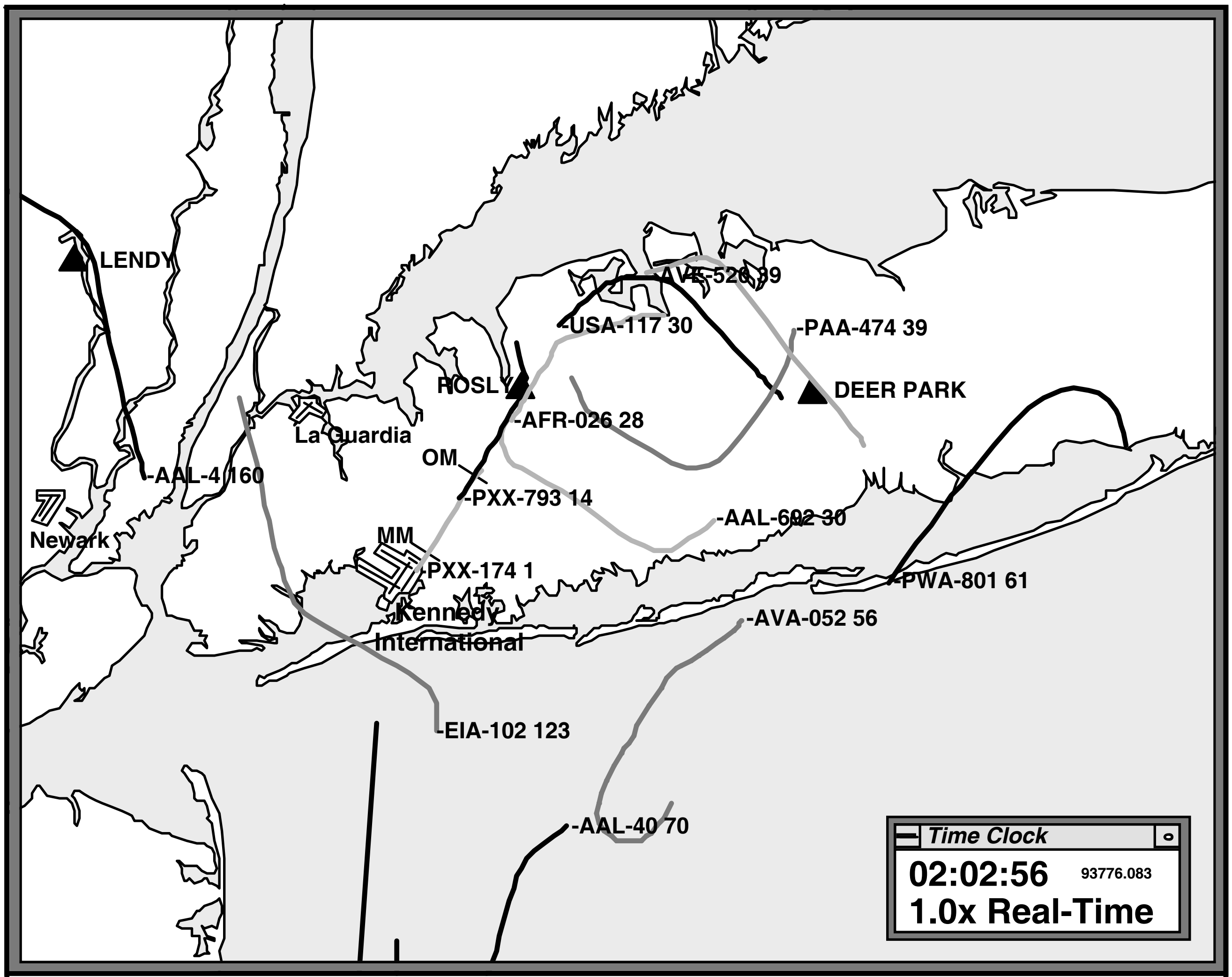


Figure 17; RAP Analysis/ADAAPS Dynamic Flight Path Screen Display

The length of the past track trailing behind the current location can be varied by the investigator to whatever time period deemed suitable (in this case it has been set to 5 minutes). The time clock window in the lower right-hand corner indicates the current clock time (in this case 02:02:56 UTC) and the rate of reconstruction playback (in this case 1.0x Real-Time, adjustable upwards any amount times real-time or downwards to a fraction of real-time). It should be readily apparent that the availability of such a dynamic flight reconstruction playback capability represents a powerful investigative tool for the accident investigator.

USE OF RADAR AND FDR DATA TO DETERMINE WINDS ALOFT

Occasions may arise when radar data can be combined with flight data recorder data to determine the actual wind directions and magnitudes so as to assist in an investigation. This could be of particular value, for example, in cases where wind shear or microburst encounter are suspected; since the most serious encounters tend to occur close to airfields, which are in turn usually in close proximity to high sample rate Approach Control Radar systems which would provide optimum data for such purposes.

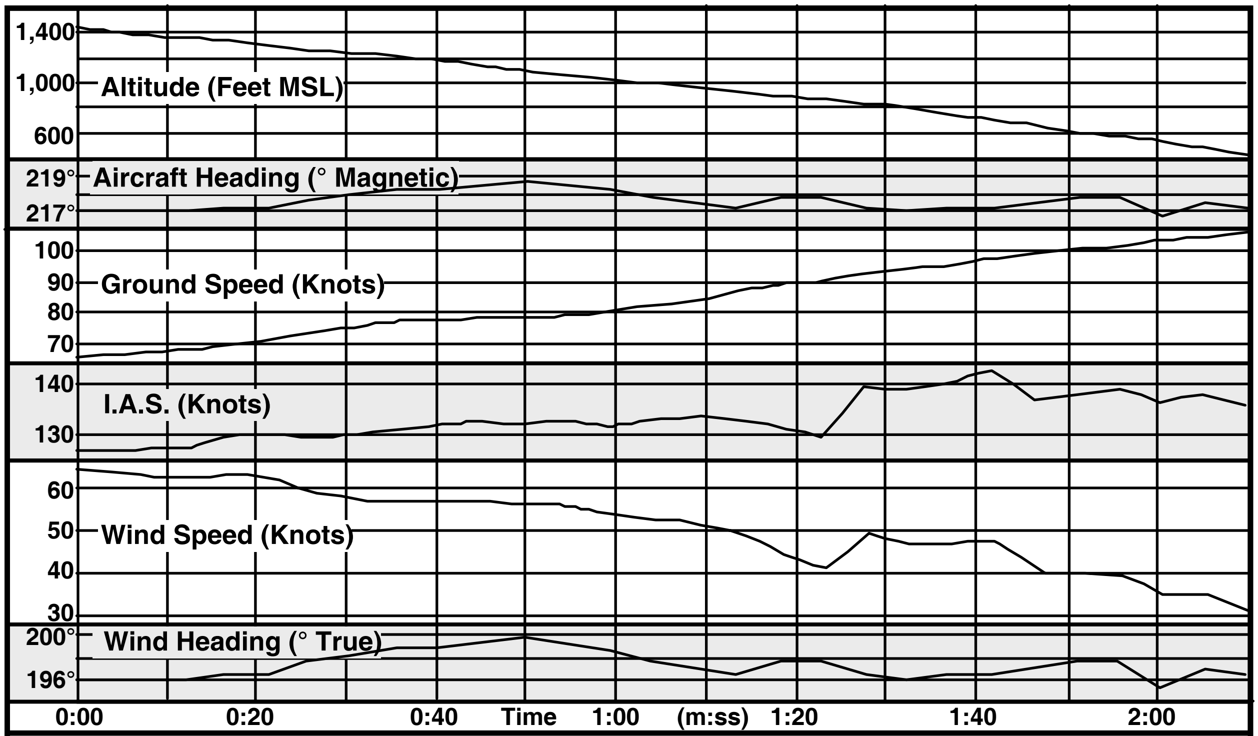


Figure 18; Wind Data Calculation from Radar and FDR Information

Figure 18 shows the result of using ATC radar data in conjunction with DFDR data to determine sudden wind shifts encountered by an aircraft on final approach. The DFDR parameters of Indicated Airspeed, Altitude and Compass Heading were combined with temperature aloft, radar based aircraft ground track heading, and RAP ground speed. Since the IAS curve indicated sudden speed excursions on approach, and the aircraft was on an essentially constant track and heading, the ground speeds resolved an increase in headwind component of approximately 8 knots followed by a similar decrease. This was consistent with the experience of previous aircraft, which had reported ±10 knots variations in headwind component from 800 feet to the ground. The aircraft immediately following the subject aircraft, however, experienced an extreme glide-slope deviation and resultant ground proximity warning, and was forced to execute a missed approach as it attempted to land at the airport. It was also known that the winds were of nearly constant heading, and that the turbulence/shear was a result of a decrease/increase in the headwind component.

FLIGHT TEST VALIDATION OF RAP ANALYSES VERSUS IN-FLIGHT RECORDED PERFORMANCE

A series of flight tests were performed in the latter part of 1992 and the early part of 1993. A twin-engined turboprop aircraft was suitably equipped with a video camera such that the parameters of airspeed, altitude and heading were recorded against a time base from the flight instruments. The F.A.A. were requested to provide radar data, which covered several of these flights, so that correlations could be obtained between the recorded flight instrument based flight parameters and the corresponding radar program based performance results.

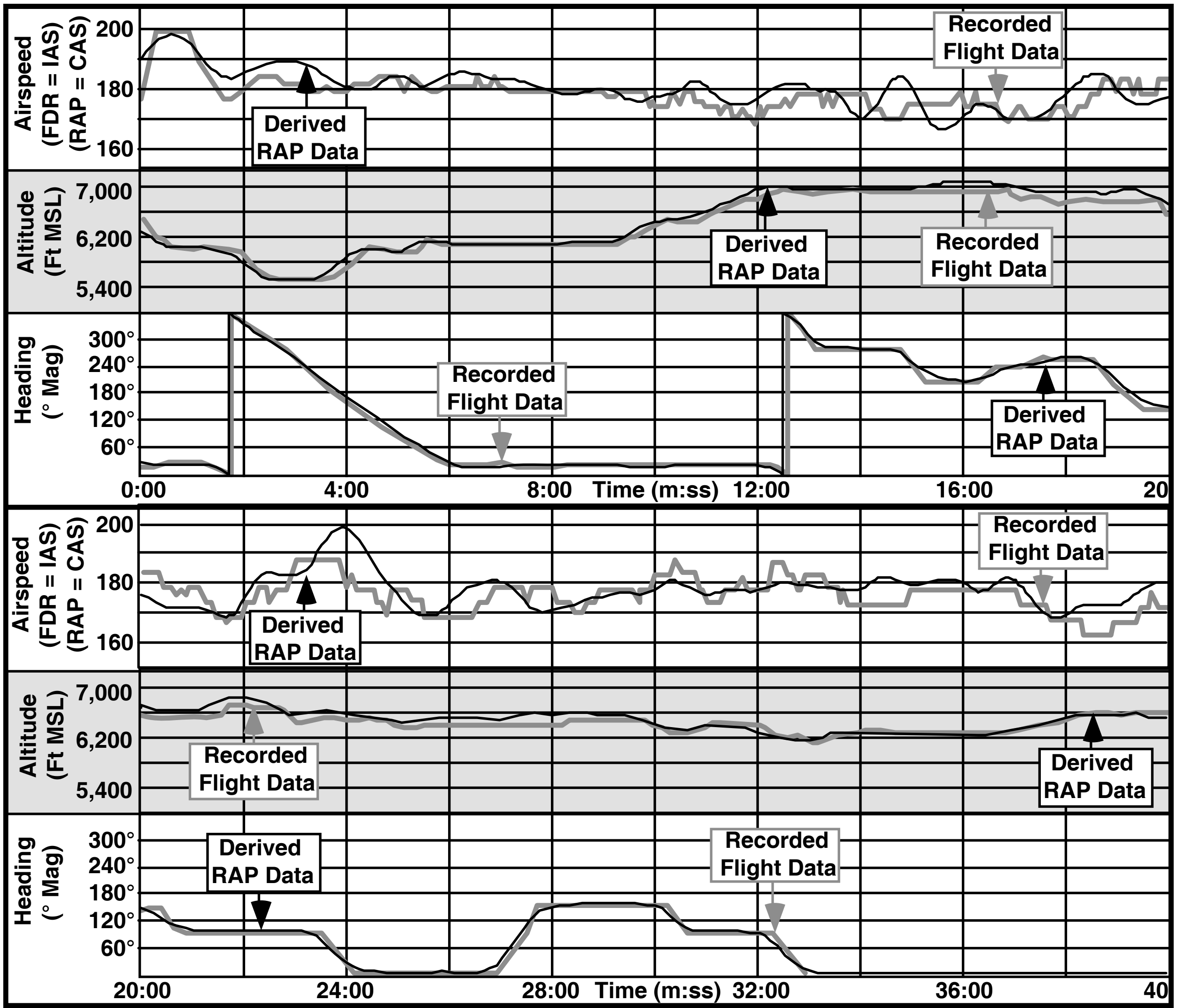


Figure 19; Flight Test - Comparison of FDR to RAP NTAP Data

In Figure 19, the flight test data is compared to the Radar Analysis Program output for calibrated airspeed, heading and altitude. The altitude values are in excellent agreement with those measured onboard the aircraft. In general, this is to be expected as it is the aircraft's transponder that is returning the encoded altitude readings to the radar antenna. The heading data follows the general aircraft measured heading quite well, with the absolute values showing reasonable correlation. The expected (uncorrected) spreading of the heading response during turns as discussed earlier is evident in all of the flight tests results. Further, the radar based airspeed data shows the program was able to track the airspeed usually within seven knots, which is considered a good correlation when one considers that the original raw radar data speeds show ground speed fluctuations of up to ±60 knots. The locations that diverged from the ±7 knot spread were in general short-term transients, and were associated with the extreme speed fluctuations within the data that were accepted as Gaussian. These values are understood if considered to contain observations drawn from the tails of the Normal Distribution and may require retesting/resampling using the predictive algorithm for comparison purposes. These values were also associated with heading changes and periodic loss of data. It is relevant to point out that the program also depends on meteorological input such as winds, temperatures and pressures aloft to convert from ground speed to airspeed. Although usually acceptable, the determination of wind speed and direction by the meteorologist is sometimes a difficult task, and large fluctuations in wind speed and direction during the flight can and do occur.

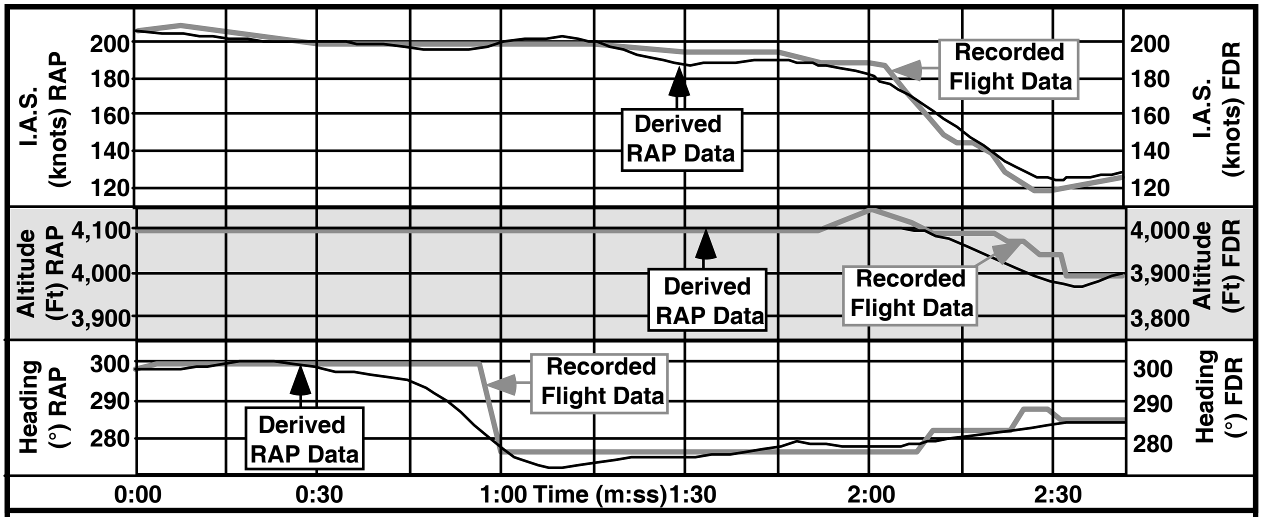


Figure 20; Approach to Stall Flight Test - Comparison of FDR to RAP NTAP Data

Figure 20 represents a test flight whose purpose was an attempt to model the speeds encountered by an aircraft experiencing significant deceleration in flight. The aircraft experienced an ongoing recorded deceleration in the order of 1.25 knots per second until stall buffeting made the reading of the videotaped instruments impossible. Figure 20 shows that the Radar Analysis Program was able to resolve the deceleration profile with good accuracy, and also illustrates the slow response time of the radar derived aircraft headings.

As noted above, in general altitude values are typically in close agreement with those measured onboard the aircraft. However, it is interesting to note that there is not necessarily such close correlation over all time (see Figure 20). In some instances the radar processing may apply a different pressure correction than the altimeter setting set by the pilot. Divergence's of up to 200 feet have been observed, however since the transponders are commonly reporting altitude based on a 29.92 standard MSL pressure, all aircraft within the same airspace will have the same correction applied, and so this is not an Air Traffic Control safety concern. This test flight's altitude data (see Figure 20) from the radar indicated 4,100 feet MSL whereas the altitude onboard the aircraft indicated 4,000 feet. This type of discrepancy may be relevant in runway approach type accidents where the reported radar altitude may be slightly offset and the actual relationship of the aircraft's true height above ground level is important.

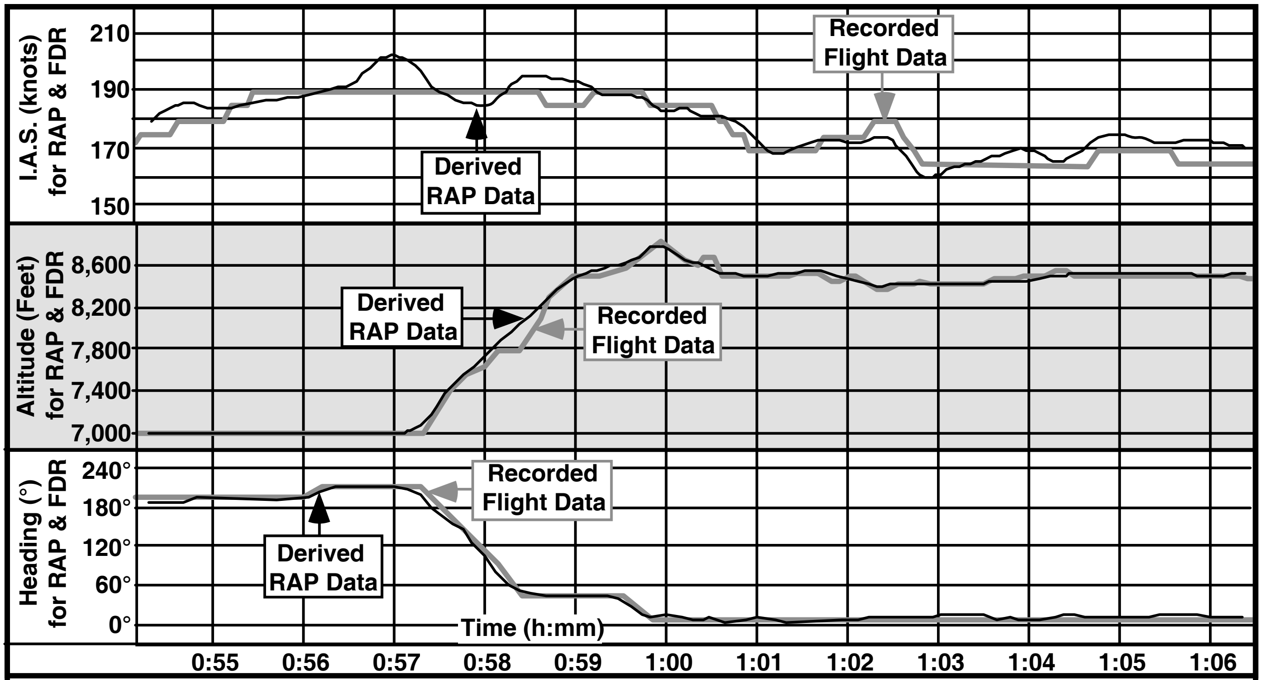


Figure 21; Flight Test - Comparison of FDR to RAP Range/Azimuth Data

Figure 21 represents a further test flight comparison of RAP derived performance data versus in-flight documented performance data. In this case, the radar data available was range/azimuth data as opposed to the more commonly available NTAP data used in the two earlier reported test flights.

CONCLUSIONS

Actual flight test analysis has confirmed that the Radar Analysis Program is able to model the airspeeds, headings and altitude experienced by the aircraft in flight quite accurately provided the noise in the original radar data remains at an acceptable level. Usually any data exhibiting a RMS (Sigma) deviation of around 25 knots or less provides good results. As the

RMS deviation increases, the smoothing necessary also increases, and as such the absolute accuracy of the result is decreased accordingly. In order to effectively use ATC radar data for accident investigation, the aircraft should remain within generally acceptable flight regimes such as those found during most general aviation and commercial flights; otherwise more sophisticated adaptive filtering techniques are required to smooth the "white noise" that extreme aircraft maneuvers inject into the system. The spreading in time of the rate of turn based on radar data has been confirmed, and the turn sharpening algorithm within RAP addresses this issue. The altitude based on the radar data may diverge somewhat, for periods of time, when compared to the aircraft's actual altitude. Radar data when combined with flight data recorder data can be used to determine the wind direction and magnitude in certain instances and enhance investigative results. The Radar Analysis Program is designed to establish the most probable aircraft flight track, flight profile, enroute speeds and end point speeds, based upon the available ATC radar data.

SUMMARY

Into the future, hopefully before the turn of the century, the aviation world will have more accurate and advanced radar computer systems in place. It is expected that the airways facilities will leave behind the technology of the 60's and 70's, and make a technological leap forward to the 64 bit and beyond RISC based architecture. This will increase computational and storage power far beyond that prevalent today. Monopulse and Phased Array radar systems will supersede the Pulse Repetition type Surveillance Radar's of today, and the inherent accuracy of the radar data will improve accordingly. Global Positioning Systems (GPS) combined with Mode-S aircraft transponders downloading telemetry data amongst other parameters will be another wave of the future.

Accordingly this Radar Analysis Program (RAP) has been designed in such a manner as to be able to make use of this additional data when it becomes available, and to represent it on a high end scientific and graphics workstation. It should be emphasized that RAP is designed and expected to be a dynamic entity, and is not in any way to be considered, in its current stage of evolution, as being complete and absolute and "carved in stone" as the only and definitive method of analyzing available radar data. On the other hand, it is logically based on a deep understanding of the processes implicit in the production of radar data, and has been tested against actual flight test data as documented in test aircraft. In many regards the program represents a leap forward in expectation of the future proliferation of available flight data within the international airspace environment. When RAP is combined with other sophisticated workstation based, graphics oriented analytical programs such as ADAAPS, it represents what is becoming a powerful and necessary investigative tool.

* About the Authors *

Steve Roberts holds degrees in physics and geophysics, and is currently an associate partner of Accident Investigation & Research Inc. (AIR) as a physical scientist and research analyst. Steve has undertaken extensive research into the analysis of air traffic control radar, and the computerized integration of radar and flight data recorder information, cockpit voice recorder and ATC communications, and witness, weather and terrain information; and is the chief technical designer of, and supervised the computerized implementation of AIR's Radar Analysis Program. Steve was also prominent in the development of AIR's virtual reality modeling computer capabilities, working in association with the National Research Council of Canada in the creation of ADAAPS.©

Robin McLeod holds a degree in mechanical engineering. He spent 9 years with Rolls Royce, the last 5 as an advanced gas turbine failure analyst. Robin then worked for 8 years with the Canadian Department of Defense Materiel Laboratories as Head of the Materials department, followed by a further 13 years with the Canadian Aviation Safety Board, including 8 years as Chief of Engineering Analysis and then Acting Director of Engineering; and has been V.P. Engineering at AIR since 1985. He has written several papers and lectured extensively on accident investigation, materials failure analysis, radar data analysis and flight track reconstruction, and the use of computers in accident investigation.

Max Vermij holds a degree in mechanical engineering and a masters degree in materials engineering. He has spent over 30 years in the aviation and instrumentation industries, of which the last 18 were as an Aviation Accident Investigator. Max was head of the electrical/mechanical engineering analysis laboratories of the Canadian Aviation Safety Board for eight years and has been V.P. Research at AIR. He has written several papers and lectured extensively on the analysis of instruments, light bulbs, electrical system failures, flight data/cockpit voice recorder analysis, radar data analysis and flight track reconstruction.

Terry Heaslip holds a diploma in aeronautical engineering, a degree in metallurgical engineering and a masters degree in materials engineering. He worked as an accident investigator with the RCAF and subsequently with the Canadian Aviation Safety Bureau, now the Canadian Aviation Safety Board, including 11 years as head of Aviation Safety Engineering Branch; and is currently President of AIR since 1983. He has written many papers and lectures extensively on many aspects of accident investigation, and is a Fellow of ISASI.

* About the Program *

Graeme MacWilliam holds a degree in Mathematics, and is presently employed by Software Kinetics Limited (SKL) as a computer software analyst. He previously worked for 5 years at the Canadian Defence Research Establishment Ottawa (DREO) in the electronic warfare simulation section. For the last 5 years Graeme has worked at the National Research Council of Canada's (NRC) Institute for Aerospace Research (IAR) developing the ADAAPS © software. Graeme has been the lead programmer for the Radar Analysis Program (RAP) since October 1993, and was responsible for the RAP computer code design and implementation for Version 1.0 of RAP. RAP is written in the C Language.