ACCIDENT INVESTIGATION - ANALYSIS OF AIRCRAFT MOTIONS FROM ATC RADAR RECORDINGS

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SUMMARY

Ames Research Center, in cooperation with the National Transportation Safety Board, has developed a technique for deriving time histories of an aircraft's motion from Air Traffic Control (ATC) radar records. This technique uses the radar range and azimuth data, along with the downlinked altitude data (from an onboard Mode-C transponder), to derive an expanded set of data which includes airspeed, lift, thrust-drag, attitude angles (pitch, roll, and heading), etc. This technique of analyzing aircraft motions was recently evaluated through flight experiments which used the CV-990 research aircraft and recordings from both the enroute and terminal ATC radar systems. The results indicate that the values derived from the ATC radar records are for the most part in good agreement with the corresponding values obtained from airborne measurements. In an actual accident, this analysis of ATC radar records can provide an important source of data, both to complement the flight-data recorders, now onboard airliners, and to provide a source of recorded information for other types of aircraft that are equipped with Mode-C transponders but not with onboard recorders. The number of aircraft with Mode-C transponders is expected to grow to between 70 and 80 percent of the total United States aircraft fleet (civilian, commercial, and military) in the next few years, implying increased capabilities for the use of this analysis technique.

INTRODUCTION

A valuable source of information for use in analyzing aircraft accidents has been the flight-data recorder, introduced in 1958, onboard United States air carriers. More recently, an additional source of recorded data has become available to the investigator through the introduction of radar recording capabilities at many of the ATC centers (ref. 1). These ATC recordings have proven useful, not only as an additional data source in the investigation of airline accidents (refs. 1 to 3), but also, and possibly of more importance, they can provide information for the analysis of accidents involving aircraft which do not have onboard data recorders (e.g., military, short-haul, and general aviation).

Considering the current and future potential for the use of ATC radar recordings in accident investigation, Ames Research Center (with cooperation from the National Transportation Safety Board Bureau of Aviation Safety, and

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Federal Aviation Agency Field Centers) has initiated a research program to investigate advanced methods for the analysis of this recorded data. The National Transportation Safety Board and the airline industry have previously developed methods to determine some of the basic aircraft quantities, such as position and velocity (ref. 1). The work at Ames Research Center has been aimed primarily at deriving an expanded set of data which includes both the short-period quantities (forces and attitude angles) as well as the long-period quantities (position and velocity).

This paper reviews the analysis techniques which have been developed and illustrates their application to CV-990 experimental flight test data. An example is also included to illustrate their application to actual accident recordings. The current limitations and future potential for the use of ATC recordings in accident investigation are discussed.

ATC RADAR RECORDINGS

ATC radar records can be analyzed in various ways to aid an accident investigation. For example, radar records can be used to derive a time-history reconstruction of the aircraft position with respect to the airways, landing fields, ground obstructions, and other aircraft. In this report, radar position data, along with the altitude data (from an onboard Mode-C transponder), are used to provide a time-history reconstruction of the aircraft dynamic motions. These derived motion data can be used to complement the flight-data recordings onboard airliners and provide a source of recorded information for other aircraft that are equipped with Mode-C transponders[1] (fig. 1) but not with flight recorders.

Current ATC radar systems use transponder beacon replies as a means of determining the position for each target aircraft under surveillance. The transponder replies are resolved into range and azimuth at each radar site. For those aircraft equipped with Mode-C transponders, pressure altitude is also transmitted to the ground. These raw data are transformed into space coordinates (x, y, h) at intervals corresponding to the radar antenna rotational rate, nominally a 5- to 12-sec interval, depending upon the type of radar system.

There are primarily two types of ATC radar systems (fig. 2) that can record these raw data. The Automated Radar Terminal System (ARTS III), located at 61 of the major terminals, provides recorded radar data at intervals of about 5 sec. The National Airspace System (NAS Stage A), located at the 20 enroute centers, provides recorded radar data at intervals of about 12 sec. The following analysis techniques, and later examples, consider data from both these systems.

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[1] For aircraft not equipped with Mode-C, only x, y radar data are available, thus limiting the effectiveness of the three-dimensional motion analysis reported herein.

ANALYSIS METHOD

The technique used to determine the aircraft motions involves smoothing of the raw radar data. These smoothed results, in combination with other available information (wind profiles and aircraft performance data), are used to derive the expanded set of data (fig. 3).

Several types of smoothing techniques (e.g., least squares, Kalman filter/smoothers, etc.) are currently under evaluation at Ames. The smoothing technique used for the results in this report is based on a cubic least-square fit to the recorded raw data (ref. 4). This moving-arc procedure provides a smoothed time history of the aircraft position (x, y, h), the inertial velocities ($\dot{x}$, $\dot{y}$, $\dot{h}$) and accelerations ($\ddot{x}$, $\ddot{y}$, $\ddot{h}$). A transformation of the inertial velocities provides a direct calculation of the ground speed, the track angle, and the flight-path angle. Using the known winds (usually recorded twice a day at local weather stations), these inertial data are transformed to the aircraft stability axes to provide true airspeed, the component of force along the airspeed vector (thrust-drag), the component of force normal to the airspeed vector (lift), and the orientation of the total force vector (roll angle). The derived quantities which have been discussed so far are aircraft independent. Further derivations, based on aircraft dependent performance data, can determine the aircraft angle of attack, which is used in a transformation from the stability axes to derive the pitch and heading angles.

Thus, time histories can be derived of altitude, airspeed, attitude angles (pitch, roll, and heading), and acceleration forces (lift, thrust-drag). The accuracy of the derived information, however, will depend on several factors, such as the aircraft speed, the type of maneuvers being performed, the distance from the radar site, wind uncertainties, aircraft performance uncertainties, etc. The following examples illustrate the accuracy of the technique.

CV-990 FLIGHT-TEST EXPERIMENTS

In these experiments (fig. 4), the quantities derived from ATC radar records are compared with the actual values measured by the instrumentation system onboard the CV-990 aircraft. Figures 5 and 6 show representative comparisons of the radar-derived data (dotted lines) with the corresponding onboard measurements (solid lines). Measurements included air data (altitude and airspeed), accelerometer (lift and thrust-drag) and inertial platform (pitch, roll, and heading angles) time histories.

The experimental results presented in figure 5 were derived from ARTS III radar records obtained during CV-990 flight operations at the Los Angeles terminal. These records include a landing approach to about 60 m above the runway, followed by a go-around and a 180° turn. These radar data were recorded once each 4.7 sec.

The experimental results in figure 6 were derived from NAS Stage A (Oakland Center) radar records of the CV-990 descending into the Stockton, California airport. These records, obtained during normal flight operations, begin from a cruise condition at an altitude of about 10 km, followed by routine trim changes and descending turns down to an altitude of about 3 km. These radar data were recorded once each 12 sec.

The accuracy of the quantities derived from both radar systems have the same general trends. There is poor accuracy in some of the quantities derived during rapid orientation changes of the aircraft; however, there is relatively good accuracy in most of the quantities derived during the steadier portions of flight.

The errors that occur during rapid orientation change are found primarily in the values of lift, pitch, and roll angle. Rapid changes in these variables can go undetected because of the large time span (4.7 to 12 sec) between the radar records.

During the steadier portion of the flight (e.g., steady turns, ascent, descent, etc.), most of the derived data are obtained with remarkably good accuracy. These radar-derived data are generally of sufficient accuracy to provide important information in the analysis of aircraft accidents. One representative application in an accident analysis is illustrated next.

APPLICATION WITH ACTUAL ACCIDENT RECORDS

This example is based on ATC radar data available from an airliner accident near Thiells, New York, on December 1, 1974. This aircraft, on a climbout from JFK, stalled at an altitude of about 8 km and entered an uncontrolled, spiralling descent into the ground. The stall was precipitated by an erroneous airspeed indication which had resulted from blockage of the pitot heads by atmospheric icing (ref. 5).

Radar data were available during the climbout, stall, and the initial portion of the uncontrolled, spiralling descent. Only limited radar data were available during the later stages of descent, below about 6 km, because of intermittent transponder returns. A derived time history of the aircraft motions is presented in figure 7 (dotted lines). Also shown for comparison are the four quantities (altitude, airspeed, normal force, and heading) available from the onboard foil-type flight recorder.

The comparison of the radar-derived airspeed with the onboard airspeed measurement clearly shows the time at which the pitot head became blocked with ice. Beyond that time, the radar-derived data indicate a decreasing airspeed that reached a minimum near the stall and then increased during the descent. The values of normal force derived from the radar data generally agree with the onboard measurement, except that the radar data cannot reproduce the short-term peak excursions which are actually experienced by the aircraft. The values of pitch angle derived from the radar data indicate a maximum angle of about 27° during stall, followed by values as steep as -25° during the initial portion of descent. The values of roll and heading angles derived from the radar data indicate the point at which wing drop occurred and the aircraft started into the spiralling descent.

CURRENT LIMITATIONS AND FUTURE TRENDS

The preceding examples (figs. 5 to 7) have illustrated the capability of deriving time histories of the aircraft motions from ATC radar recordings. However, the experience gained through analyzing the CV-990 data and through applications to accident investigations indicates certain limitations in the use of ATC radar recordings for the analysis of aircraft dynamics. As noted earlier, the slow data rate from radar recordings precludes the determination of rapid orientation changes of the aircraft. Radar data also may have voids (no transponder returns) during some extreme, uncontrolled maneuvers, such as spiralling descents. Also, current ATC radar recordings do not provide coverage of all aircraft operations. For instance, radar coverage generally does not extend to the ground level (for ground roll, liftoff, touchdown, etc.) and may not be available in remote areas.

In spite of these limitations, ATC radar records can provide an important source of data, both to complement the flight-data recorders onboard airliners and to provide a source of recorded information for other types of aircraft not equipped with onboard recorders. At the present time, only about 1.5 percent of the total aircraft in the United States have onboard flight-data recorders; whereas, about 30 percent have Mode-C transponders. The number of aircraft with Mode-C transponders is expected to grow to between 70 and 80 percent of the total aircraft fleet in the next few years (ref. 6). Because of this rapidly increasing number of aircraft with Mode-C transponders (fig. 1), the number of flight operations which can be analyzed by ATC recordings is steadily growing.

A look into the future also indicates that several features of the Upgraded Third Generation ATC System (refs. 6 to 8), which is now undergoing evaluation by the Federal Aviation Agency, may ease some of the limitations noted above and could provide additional sources of data for use in accident investigations (fig. 8). For instance, the advanced transponders could provide increased accuracy and increase the number of downlinked quantities. The proposed terminal surveillance systems could extend coverage to the ground and provide increased accuracy and higher data rates. The proposed space satellite ATC systems could provide coverage over the ocean and eventually provide worldwide coverage. These future trends of increased coverage, better accuracy, higher data rates, and an increased number of downlinked quantities, along with the growing number of aircraft with transponders, imply increasing capabilities for the use of ATC records in accident investigation.

CONCLUDING REMARKS

This paper has presented some results based on a technique for deriving time histories of additional aircraft states from ATC radar records of x and y position and altitude. This technique smooths the raw radar data and, using other available information (wind profiles and aircraft performance), derives an expanded set of data which includes airspeed, lift, thrust-drag, pitch, roll, and heading angles, etc.

Applications in this paper illustrate that the largest errors in the derived data occur during rapid orientation changes of the aircraft. For the steadier portions of flight (ascent, descent, turns, etc.) the derived quantities are generally of sufficient accuracy to provide important information in the analysis of aircraft accidents.

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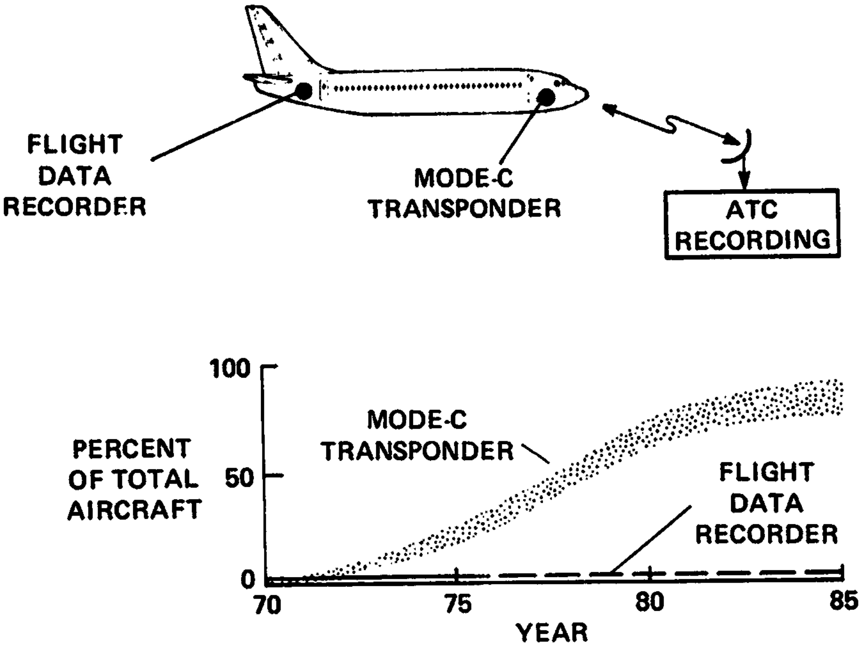

Figure 1.- Two sources of accident recordings.

	ENROUTE	TERMINAL
COVERAGE	CONTINENTAL USA	61 MAJOR AIRPORTS
RADAR SYSTEM	NAS STAGE A	ARTS III
TIME BETWEEN DATA POINTS	≈ 12 sec	≈ 5 sec

Figure 2.- ATC radar recording capabilities.

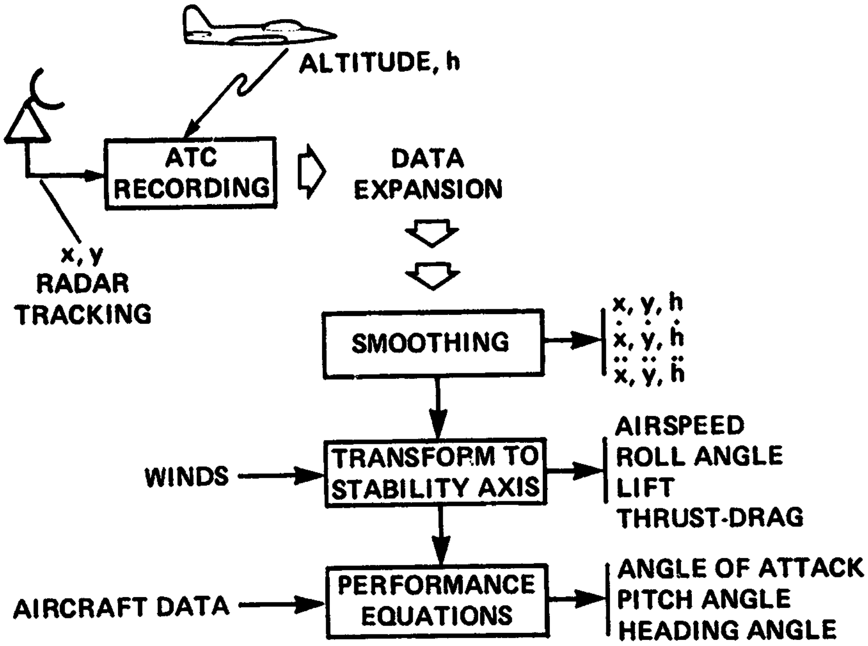

Figure 3.- Data expansion from ATC radar recordings.

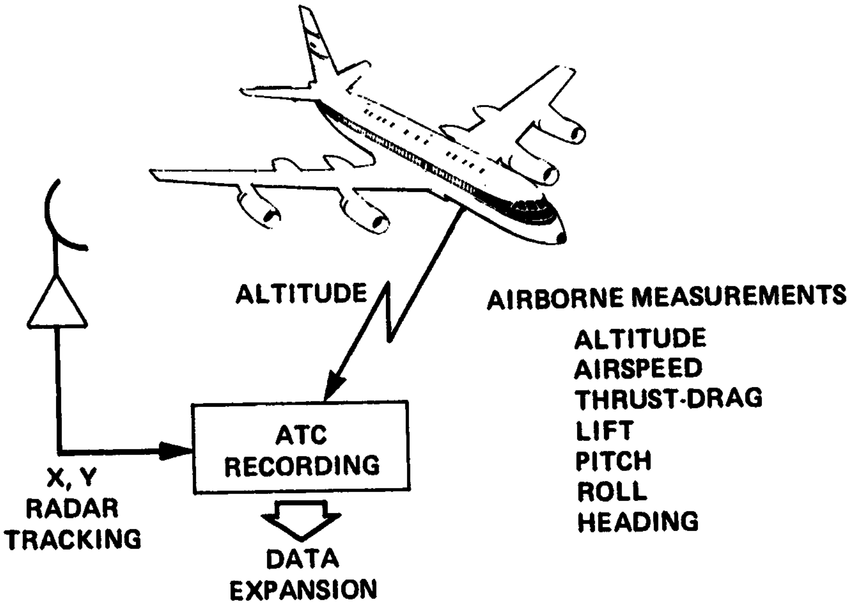

Figure 4.- Evaluation of radar derived data using CV-990 measurements as a standard for comparison.

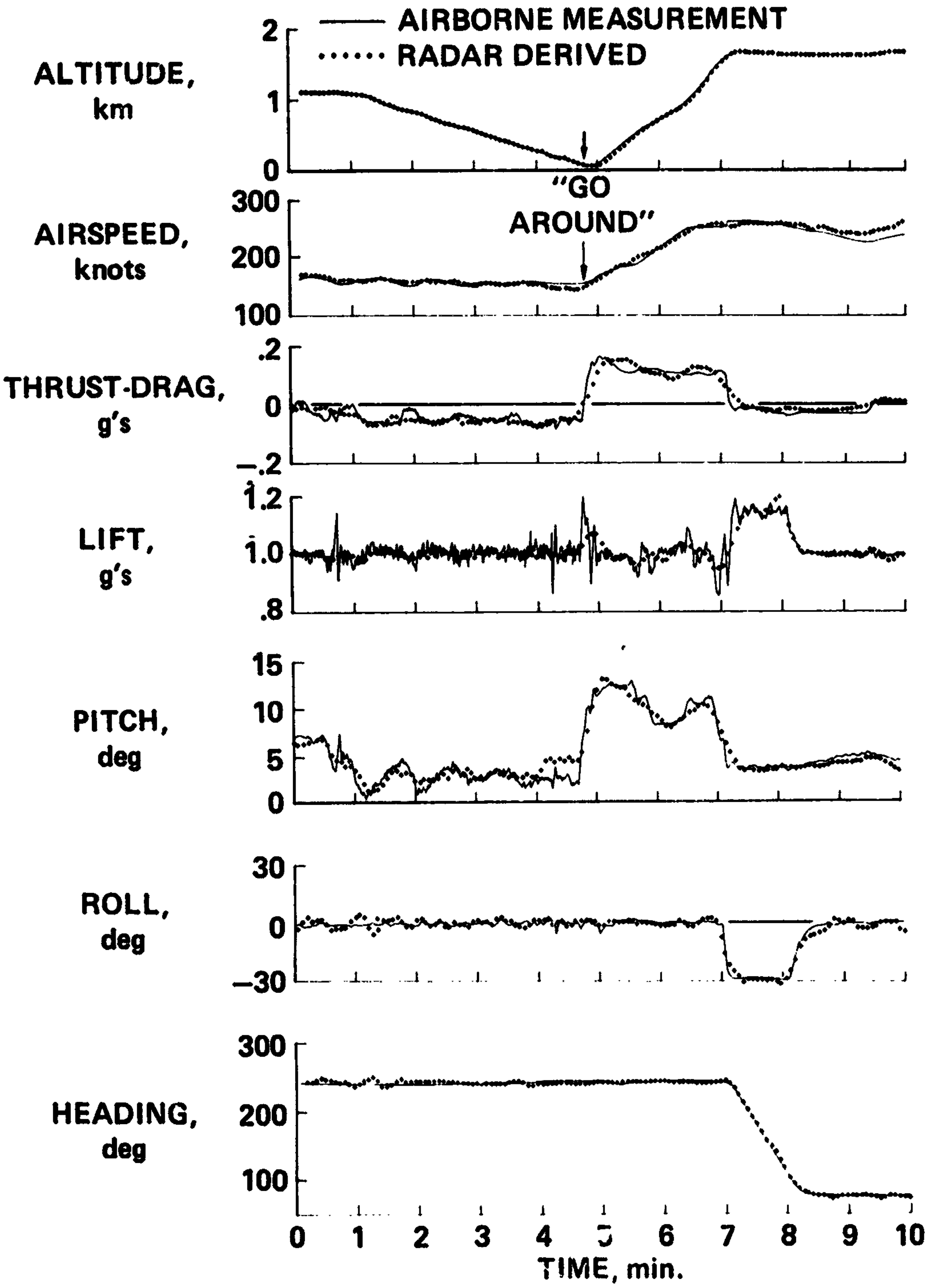

Figure 5.- ARTS III radar derived data compared with CV-990 measurements.

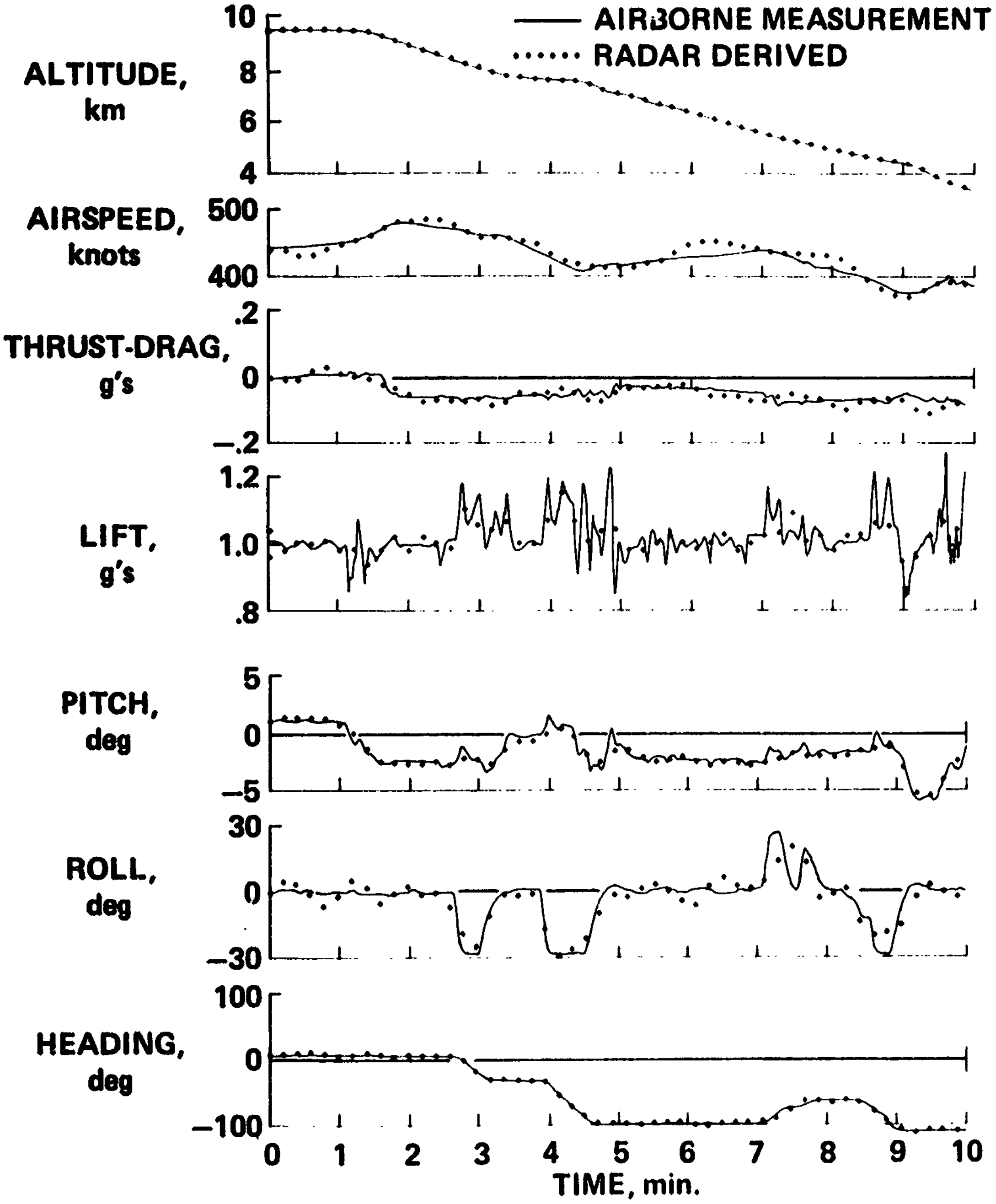

Figure 6.- NAS Stage A radar derived data compared with CV-990 measurements.

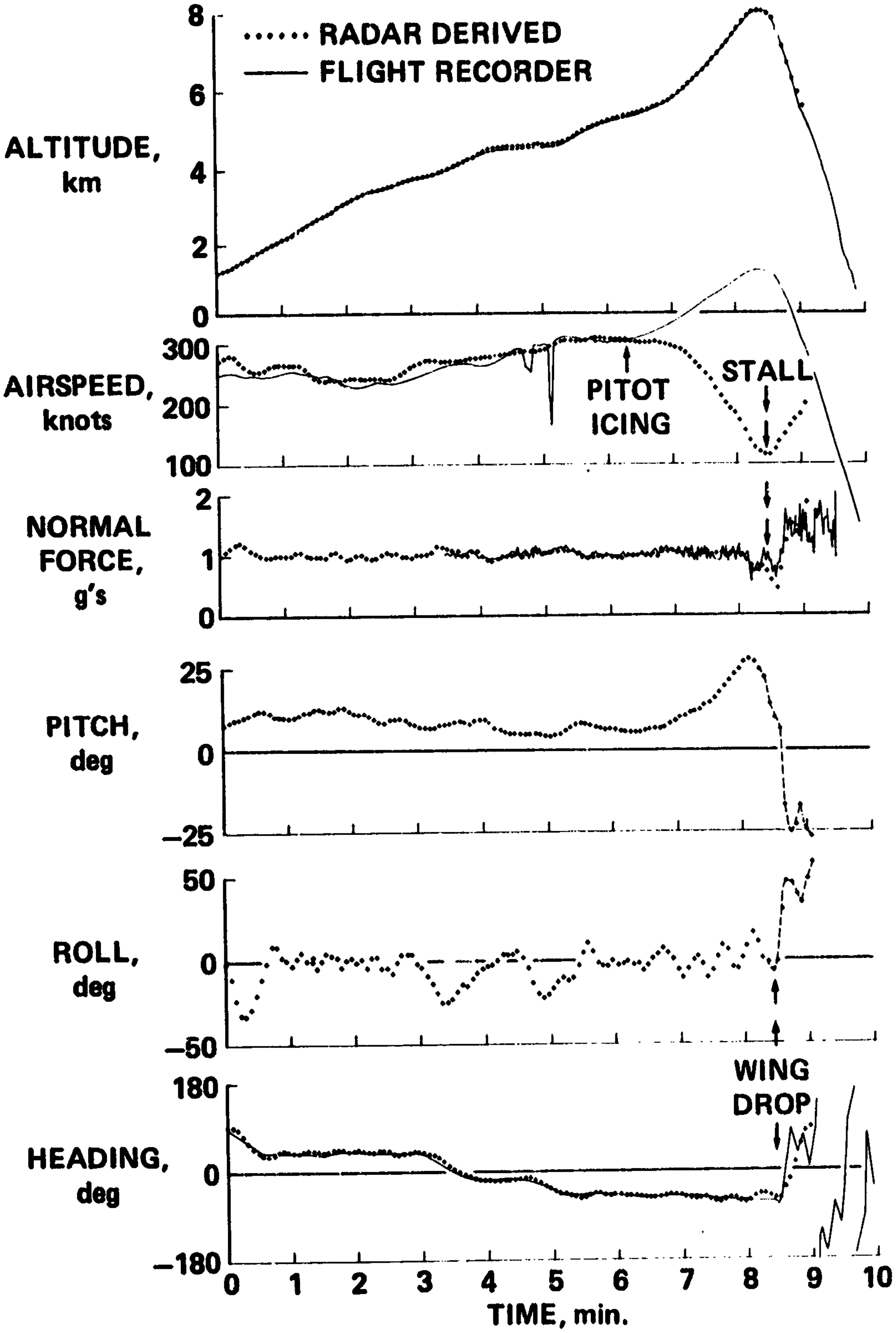

Figure 7.- Data from actual accident.

UPGRADED 3RD GENERATION ATC SYSTEM ELEMENTS	INCREASED CAPABILITIES FOR ACCIDENT INVESTIGATION			
	COVERAGE	ACCURACY	DATA RATE	DOWN LINKS
DISCRETE ADDRESS BEACON SYSTEM		X		X
UPGRADED ATC AUTOMATION	X			
AIRPORT SURFACE TRAFFIC CONTROL	X	X	X	
AERONAUTICAL SATELLITES	X			X

Figure 8.- Future trend in ATC systems.