Analysis of General Aviation Accidents Using ATC Radar Records

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General aviation aircraft do not usually carry flight recorders; as a result, the only available data that can be used to reconstruct aircraft motions in an accident may be from air traffic control (ATC) records. Ames Research Center, in conjunction with the National Transportation Safety Board, has been developing methods to utilize the ATC radar position data, along with down-linked altitude data (from an onboard Mode-C transponder), to derive time histories that include airspeed and lift force, and pitch, roll, and heading angles. These analytical methods are illustrated by application in a number of general aviation accident investigations involving different types of aircraft—light planes, commuter airliners, and executive jets—in different types of accident situations, such as takeoff, climb-out, icing, and deep stall. For the future, the trends of increasing ATC radar coverage and accuracy, along with the growing number of general aviation aircraft with transponders, imply increasing capabilities for using ATC records in accident investigations.

Introduction

GENERAL aviation aircraft usually do not carry flight recorders, and in accident investigations the only available data may come from the air traffic control (ATC) records.[1] To provide information about events that occur before and during aircraft accidents, Ames Research Center, along with the National Transportation Safety Board (NTSB), has been developing methods to expand the data from the ATC records.[2-7] These analytical techniques use the ATC radar position records and the down-linked altitude information (from an onboard Mode-C transponder) to derive an expanded set of data which includes the aircraft attitude angles, velocities, and performance. These analytical methods allow investigators to construct a sequence of events before and during an accident that can be used to determine probable cause. Because an increasing number of the general aviation aircraft in the United States are being equipped with Mode-C transponders, there is an increasing number of applications for these analytical techniques.

The purpose of this report is to describe the analytical techniques, illustrate their application in the investigation of general aviation accidents, and discuss how the future trends in the techniques and ATC surveillance will result in continuing improvements in the accuracy of the derived data.

Analytical Method

Current ATC radar systems use transponder beacon replies as a means of determining the position of each target aircraft under surveillance. The transponder replies are resolved into range and azimuth at each radar site. For those aircraft equipped with an altitude encoder, 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 4-12-s interval, depending on the type of radar system.

There are primarily two types of ATC radar systems 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 4-5 s. The National Airspace System (NAS Stage A), located at the 20 en route centers, provides recorded radar data at intervals of about 6-12 s. In the following techniques and examples, data from both terminal and en route surveillance systems are considered.

The technique used to determine the aircraft motions involves smoothing of the raw radar data. These smoothed results, in combinations with other available information (meteorological data and aircraft aerodynamic data), are used to derive the expanded set of motion time histories. The general approach is outlined in Fig. 1; the equations presented in this section are developed in Ref. 4.

A moving-arc least-squares procedure[8] is used to provide smoothed time histories of aircraft position (x,y,h), inertial velocities $(\dot{x}, \dot{y}, \dot{h})$, and accelerations $(\ddot{x},\ddot{y},\ddot{h})$. Using the wind velocities (w_x, w_y, w_h) based on the measurements at local weather stations,† the true airspeed is calculated as

$$V_t = [(\dot{x}-w_x)^2 + (\dot{y}-w_y)^2 + (\dot{h}-w_h)^2]^{1/2} \tag{1}$$

The air velocity vector V_t designates the aircraft wind axis. As formulated in Ref. 4, standard wind-axis equations can be used to provide a set of derived variables.

The specific force along the aircraft wind axis (called excess thrust, a_{ex}) and the specific force normal to the wind axis (called lift, a_L) are determined as

$$a_{ex} = (\ddot{x}\cos\psi_w + \ddot{y}\sin\psi_w)\cos\theta_w + (\ddot{h}+g)\sin\theta_w \tag{2}$$

$$a_L = C_1\sin\phi_w + C_2\cos\phi_w \tag{3}$$

and the wind-axis Euler angles are

$$\psi_w = \tan^{-1}[(\dot{y}-w_y)/(\dot{x}-w_x)] \tag{4}$$

$$\theta_w = \sin^{-1}[(\dot{h}-w_h)/V_t] \tag{5}$$

$$\phi_w = \tan^{-1}(C_1/C_2) \tag{6}$$

where

$$C_1 = \ddot{y}\cos\psi_w - \ddot{x}\sin\psi_w \tag{7}$$

$$C_2 = (\ddot{h}+g-a_{ex}\sin\theta_w)/\cos\theta_w \tag{8}$$

Standard air-data equations, along with V_t, h, and the local air temperature, are used to compute the indicated airspeed V_i, the Mach number M, and the dynamic pressure Q. The

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†Winds and temperatures are measured by weather balloons twice a day.

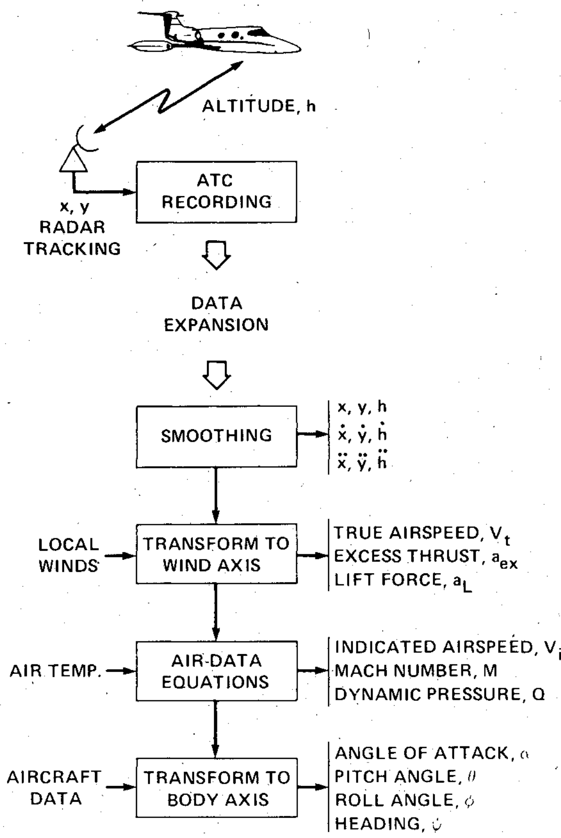

Fig. 1 Data expansion from ATC radar records.

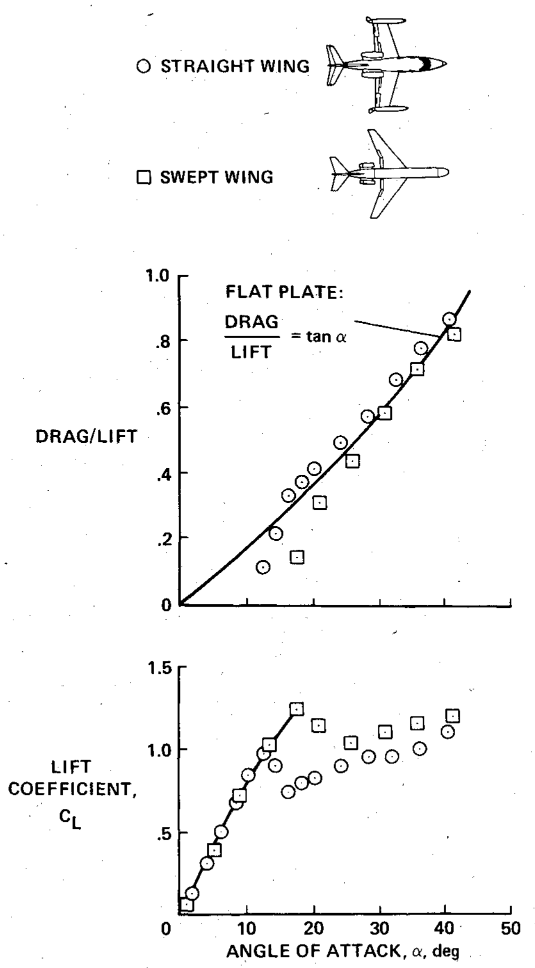

Fig. 2 Example aerodynamic data used to determine angle of attack.

angle of attack α is determined in the low-angle (linear) range as

$$\alpha = \alpha_0 + a_L W/QSC_{L_\alpha} g \tag{9}$$

where the values α_0 and (W/SC_{L_α}) depend on the particular aircraft. In the high-angle (stall or poststall) range, the angle of attack is determined through the flat-plate relationship

$$\alpha = \tan^{-1}(a_D/a_L) \tag{10}$$

where a_D/a_L is the drag/lift ratio ($a_D \approx gT/W - a_{ex}$). These low- and high-angle relationships are illustrated in Fig. 2 using representative wind tunnel data.[9,10]

Using α, and assuming no sideslip, the body-axis Euler angles are determined as

$$\theta = \sin^{-1}(\sin\alpha\cos\theta_w\cos\phi_w + \cos\alpha\sin\theta_w) \tag{11}$$

$$\phi = \tan^{-1}\left(\frac{\cos\theta_w\sin\phi_w}{\cos\alpha\cos\theta_w\cos\phi_w - \sin\alpha\sin\theta_w}\right) \tag{12}$$

$$\psi = \psi_w + \tan^{-1}\left(\frac{\sin\alpha\sin\phi_w}{\cos\alpha\cos\theta_w - \sin\alpha\cos\phi_w\sin\theta_w}\right) \tag{13}$$

Thus time histories can be derived of airspeed, specific forces (lift and excess thrust), and attitude angles (pitch, roll, and heading). The accuracy of this derived information was evaluated in the flight-test experiments reported in Ref. 3. Some applications of this analytical method in the investigation of general aviation accidents will be described next.

Application Examples

These analytical methods have been applied with the available ATC radar records in a number of general aviation accident investigations. To illustrate the nature of the results obtained using these techniques, four representative examples are considered here. In these examples, no flight-recorder data were available to aid in reconstructing the aircraft motions. Consequently, the derived data from the ATC records are the only sources of information regarding the aircraft motions that were available to the NTSB in conducting the accident investigation. The first three examples are chosen to illustrate the differences in the ATC data that are available for analysis and to illustrate how the results from the analysis are used to determine the sequence of events before and during the accidents. The fourth example is used to examine, in more detail, the consistency of the derived data.

Example 1

This example is based on the ATC radar from a light-twin accident in Illinois, in April 1979. This aircraft was in a climb from an altitude of 13,700 ft in an attempt to go above icing conditions. During the climb, at about 15,000 ft, the aircraft entered an uncontrolled spiraling descent. En route radar data were available (at 6-s intervals) during the original cruise, the attempted climb, and the initial portion of the uncontrolled spiraling descent. Only limited data were available during the later stages of the descent, below 13,000 ft, because of intermittent transponder returns.

Figure 3 presents the derived airspeed, pitch angle, and roll angle, along with the altitude down-linked from the aircraft. The derived time histories in Fig. 3 indicate that during the attempted climb, the aircraft experienced a progressive series of stalls. In each of the stall regions, noted in Fig. 3, there is a decrease in airspeed followed by a decrease in pitch angle. These regions of stall are also associated with changes in roll angle, leading to large roll angles and the subsequent entry into an uncontrolled spiral descent. As shown, the analysis of the radar data provides a consistent set of time histories describing the probable aircraft motions.

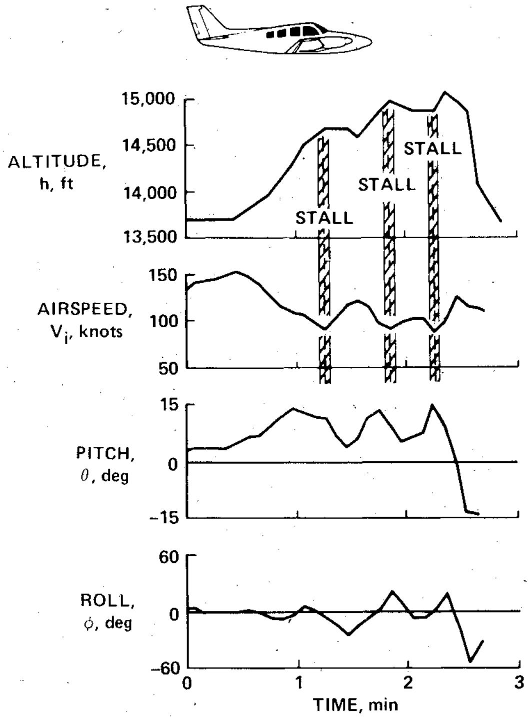

Fig. 3 Derived data from ATC radar records: light-twin icing accident over Illinois, April 1979.

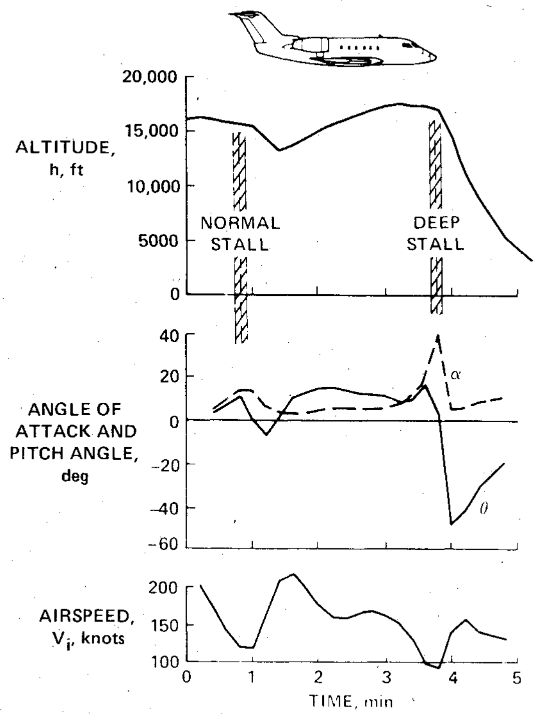

Fig. 4 Derived data from ATC radar records: executive-jet deep-stall accident near Mojave, Calif., October 1980.

Example 2

This example is based on the ATC radar records available from an executive-jet deep-stall accident near Mojave, Calif., in October 1980. During engineering flight tests the aircraft encountered deep stall, and a drag chute was used to permit a stall recovery. However, after stall recovery, the drag chute failed to release and the aircraft descended to the ground. En route radar data were available at 12-s intervals during the stall tests, the recovery, and the subsequent descent to the ground.

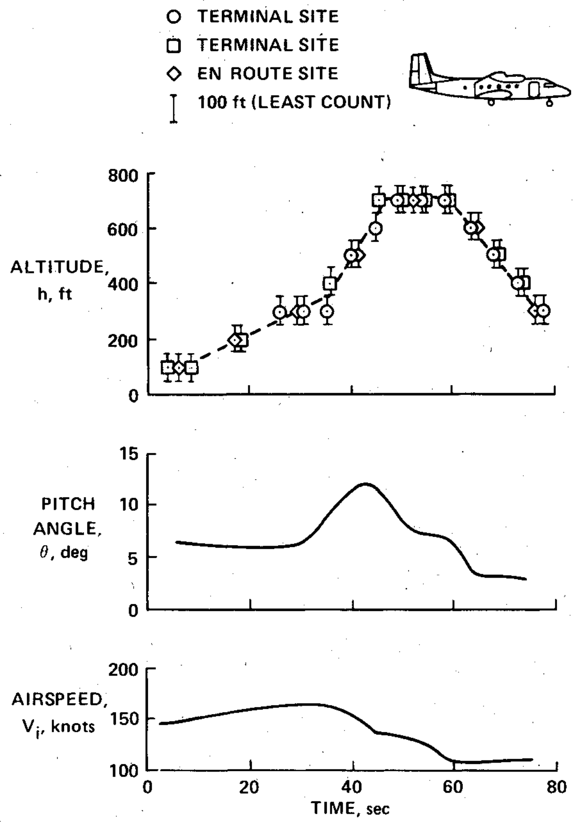

Fig. 5 Derived data from ATC radar records: commuter airliner takeoff accident at Los Angeles Airport, March 1978.

Figure 4 presents the derived airspeed, pitch angle, and angle of attack, along with the altitude down-linked to the ground. The derived time histories in Fig. 4 illustrate a normal stall (part of the engineering flight tests) as well as the deep stall. For the deep stall, flat-plate Eq. (10) was used to derive the angle of attack. Even though the radar data were available at only 12-s intervals, the derived results still provide a consistent definition of the aircraft motions before and during the accident.

Example 3

This example is based on the ATC radar records available from a commuter airliner accident at Los Angeles Airport in March 1978. A twin-turboprop aircraft lost power in both engines shortly after takeoff. Terminal radar data, from the two sites at the Los Angeles Airport, were available (intermittently) during ground roll, liftoff, and in flight. Additional en route radar data were also available in flight.

Figure 5 presents the derived pitch angle and airspeed, along with the combined set of intermittent altitude data down-linked from the aircraft. The derived time histories indicate a rapid increase in pitch angle at an altitude of about 300 ft. The aircraft leveled out at about 700 ft, where the airspeed decreased to about 110 knots. The airspeed remained slightly above 100 knots during the subsequent descent. Even though the data from the individual sites were intermittent, the combined data provided a consistent set of records that was used to make a reasonable derivation of the aircraft motions.

Example 4

This last example is based on the radar data from an executive-jet accident during departure from the Washington National Airport (Fig. 6). In this accident, the aircraft position data were recorded at two ATC radar sites: Washington National Airport and Andrews AFB. This specific example was chosen because it allows a comparison of

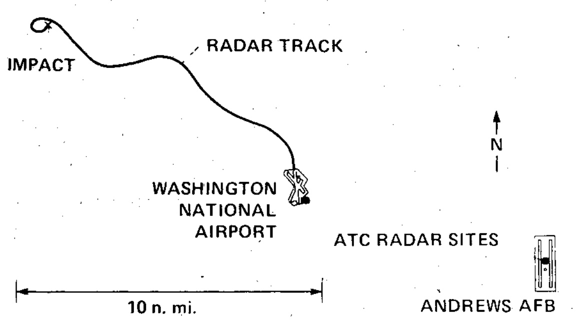

Fig. 6 Executive-jet accident near Washington, D.C., April 1977.

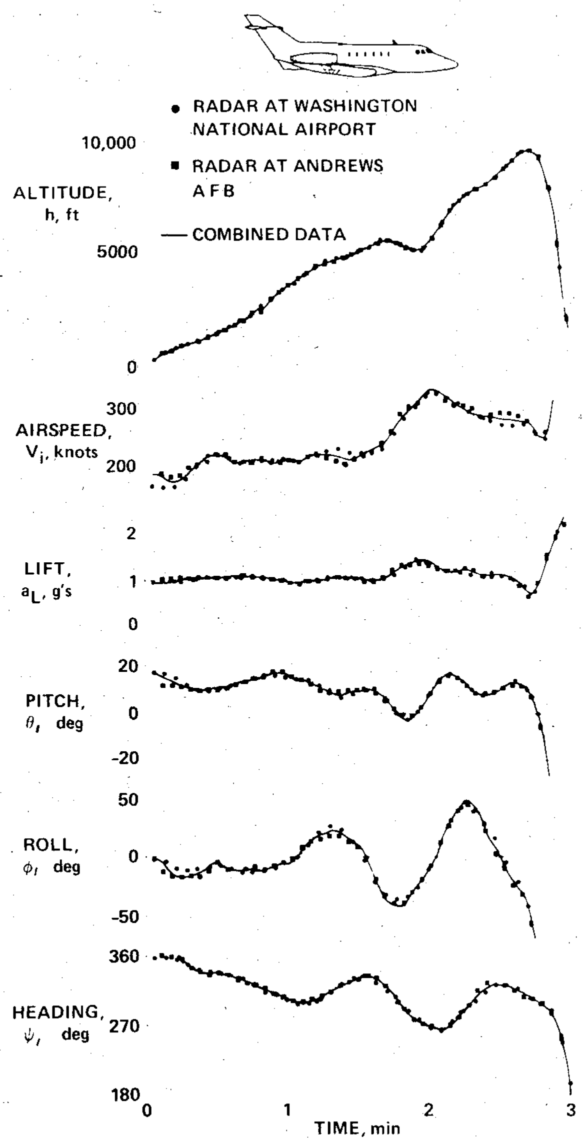

Fig. 7 Derived data from two sources of ATC radar data: executive-jet accident near Washington, D.C., April 1977.

data derived using two different tracking radars at diverse locations. Thus some insight may be gained into the consistency of the data-expansion techniques. The radar data were available shortly after takeoff and during the climb-out to a maximum altitude of about 9000 ft. Because of intermittent transponder returns, only limited data were available during a following rapid descent to the ground.

Time histories in Fig. 7 show the derived data using either the records from the radar site at Washington National Airport (dots) or the site at Andrews AFB (squares). Also shown for comparison is a combined derivation (solid line)

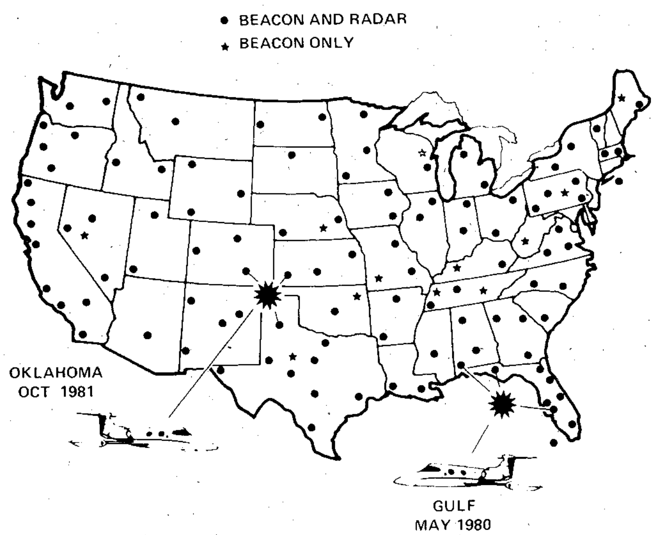

Fig. 8 En route surveillance sites and the locations of two executive-jet accidents.

incorporating both sets of records. The comparisons show that the two independent solutions are generally in agreement. Both solutions show the same variations in airspeed, lift, and attitude angles (pitch, roll, and heading) and both indicate a slowly divergent oscillation in the roll angle, leading to large values of roll angle at peak altitude, followed by a descending spiral. As shown, the point-to-point scatter in the derived data is relatively small compared with the magnitude of the overall variations in the aircraft motion.

Discussion

The preceding examples illustrate the capability of deriving time histories of aircraft motions from ATC recordings. However, as previously mentioned, there are certain limitations in the use of ATC recordings for the analysis of aircraft dynamics. As discussed in these examples, radar data may have voids (no transponder returns) during extreme maneuvers, such as spiraling descents, and also during operations near the ground, such as takeoff and landing. Another problem is that the low data rate from radar recordings precludes the determination of rapid orientation changes of the aircraft.

One way to reduce the problems of data voids and low data rates is to utilize all of the available radar records. In general, multiple ATC records can be used to fill in the gaps that may be present when the records from only one ATC site are considered. Examples 3 and 4 illustrate situations in which multiple radar data were available in the terminal area. Multiple radar records are also sometimes available in the en route situation, as illustrated in Fig. 8. In the accidents in the Gulf of Mexico (May 1980) and in Oklahoma (October 1981), radar data from different en route surveillance sites were available for application with the methods outlined in this report.

Future Trends

To more fully utilize multiple ATC records, new analytical approaches are being evaluated. One promising approach is to apply the state-estimation method outlined in Ref. 6. State estimation involves the use of aircraft equations of motion to determine a set of forcing-function time histories that provide a "best fit" to the available radar data. The aircraft equations of motion in a wind-axis frame[4] are

$$\ddot{x} = a_{ex}\cos\theta_w\cos\psi_w + a_L(\cos\phi_w\sin\theta_w\cos\psi_w + \sin\phi_w\sin\psi_w) \quad (14)$$

$$\ddot{y} = a_{ex}\cos\theta_w\sin\psi_w + a_L(\cos\phi_w\sin\theta_w\sin\psi_w - \sin\phi_w\cos\psi_w) \quad (15)$$

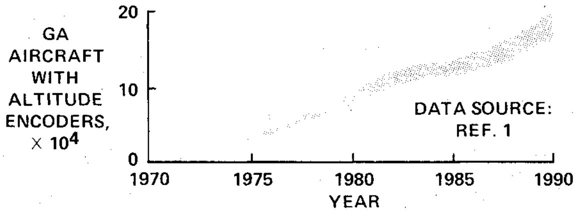

Fig. 9 Increasing number of general aviation aircraft with altitude encoders (from Ref. 1).

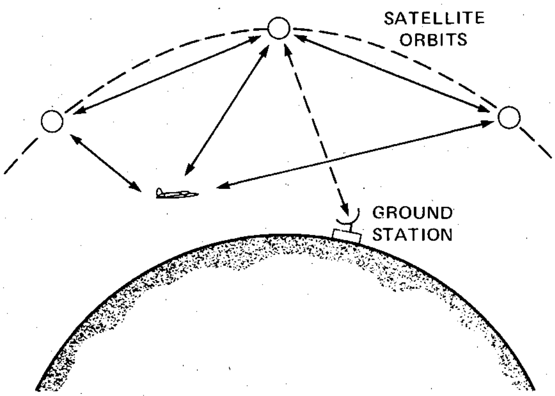

Fig. 10 Future satellite-based air traffic control.

$$\ddot{h} = a_{ex}\sin\theta_w + a_L\cos\phi_w\cos\theta_w - g \tag{16}$$

where a_{ex}, a_L, and ϕ_w are the derived forcing functions (the other variables θ_w, ψ_w, etc., are computed as discussed previously). The time histories of the forcing functions (a_{ex}, a_L, ϕ_w) are estimated[6] such that they provide a best fit to the available radar data (x,y,h). This state-estimation technique provides a continuous time history of the aircraft motions, utilizing each of the multiple radar points that are available at different times along the trajectory.

Together with the increasing availability of multiple ATC records and the continuing development of new analytical methods, there are also continuing and important changes in the ATC systems. As illustrated in Fig. 9, there is an increasing number of general aviation aircraft equipped with altitude encoders (Mode-C transponders). By 1990 it is expected that about 200,000 general aviation aircraft will have Mode-C transponders.[1] After 1990, current plans[11] are to introduce the advanced Mode-S transponder, which will provide enhanced capabilities for accident investigation. The Mode-S transponder has the capability for additional downlink quantities and provides for increased accuracy in radar position data. By the year 2000, it is planned that every aircraft flying above 6000 ft will be equipped with Mode-S transponders.

Looking beyond the ground-based radar systems, we may eventually have a satellite-based ATC surveillance system, as illustrated in Fig. 10. Such a future system uses a triad of range links to provide accurate position measurements of aircraft over most of the Earth.[12] This worldwide network would provide records of x, y, and h in the same form as those used with the analytical methods discussed in this report. As a result, it appears that the experience and methods considered here may have application well into the future.

Concluding Remarks

A technique for deriving time histories of aircraft motions from ATC radar records has been described. This technique smooths the raw radar data and, using other available information (meteorological records and aircraft aerodynamics), derives an expanded set of data which includes, for example, airspeed and lift, and pitch, roll, and heading angles.

These analytical methods have been successfully applied, in conjunction with the National Transportation Safety Board, in a number of general aviation accident investigations. Because general aviation aircraft are not typically equipped with flight recorders, these methods provide the only quantitative information on the aircraft motions available during the investigation. The applications have included different types of aircraft, such as light piston-props, executive jets, and commuter turboprops, as well as different accident situations, such as takeoff, climb-out, icing, and deep stall.

The future trends in analytical techniques and ATC surveillance will further improve the ability to derive aircraft motions from ATC records. The use of a new state-estimation approach appears promising as a means of utilizing multiple ATC records in order to reduce the problems owing to data voids and low data rates. Increased ATC radar coverage, increased position accuracy, and an increased number of down-linked quantities, along with the growing number of general aviation aircraft with transponders, imply increasing capabilities for the use of ATC records in accident investigations.

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