A Digital System for Position Determination

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ONE of the most important functions in the air traffic control (ATC) system is that of aircraft position reporting. A large fraction of the equipment and effort required in CAA operations is involved in the initiation and handling of position reports. A pilot must divert attention from the actual control of the aircraft to talk with ground controllers for the purpose of reporting position, or for the purpose of procedural communications associated with position reports. Many of the adjustments and readings of navigation instruments are performed not because the pilot wishes such frequent information for his own uses but because of the necessity of reporting position. A large amount of electromagnetic spectrum is consumed at present in the position reporting function, and the need for spectrum will increase still further as air traffic control is expanded, unless some new reporting technique is developed.

Future systems of air traffic control will utilize automatic data processing machinery to handle many of the routine functions and will permit the human controller to handle with safety more traffic than he can today. The effectiveness of the combination of human controllers and automatic computers will be greatly improved with the advent of an automatic means of providing frequent and accurate position reports on all aircraft in the system. Unfortunately, there is no existing system of position reporting which meets the requirements of air traffic control.

A great deal of effort has gone into the development of several methods of providing aircraft position information to the traffic control system. The three techniques which have received the most attention are radar, beacon transponder, and data link. The principal advantages of radar is that no equipment is required in the aircraft, but this advantage is offset by the lack of identification, the lack of correlated altitude data, and excessive noise and interference of various sorts. The conversion of the raw signal from the radar into a form suitable for air traffic control requires the continuous solution of a difficult correlation problem involving either a great deal of computing capacity or the full attention of many human operators. Both the beacon and the data link overcome the fundamental problems of radar at the expense of adding equipment to the aircraft and of introducing a number of difficult technical problems which are yet to be solved. At least in the case of the data link, it appears that the various technical difficulties will eventually be surmounted, but the expense in terms of airborne equipment costs and total usage of the electromagnetic spectrum may be quite high.

The purpose of this paper is to present the basic principles of operation of a position reporting technique which satisfies the present and future requirements of air traffic control and overcomes the known technical difficulties in the radar, beacon, and data link systems, and yet promises to accomplish these goals with a minimum of expense. The technique to be discussed is known as Automatic Position Telemetering (APT). The APT system has progressed to date through preliminary design and testing phases which have concentrated on the radio communication portions of the system. The results of this work indicate the feasibility of the proposed system and point the direction for the design of a complete prototype.

The basic requirements for an automatic position reporting system are obtained from a consideration of the present manual techniques, the characteristics of semiautomatic data processing systems, and the operational and technical shortcomings of radar, beacon, and data link. First, the position reporting system must be capable of integration with automatic data processing machines and must eliminate or minimize the manual operations required of pilots and controllers. Second, the total electromagnetic spectrum assigned to the system must be held to a minimum; system planners ought to regard bandwith as one of our most precious national assets. Third, the airborne element of the system must be kept as small and inexpensive as possible because of compounding effects on the weight, reliability, maintainability, and cost of the total airframe system. Fourth, the system design must be based on fundamental logical and physical principles selected to minimize the technical difficulties which have been experienced in recent beacon and data link development programs.

A major design objective is the provision of service to all aircraft in the system on a single radio channel. Accomplishment of this objective completely eliminates tuning operations as far as either the controller or pilot is concerned. The complexity of both the airborne and ground-based portions of the system is greatly reduced if single-channel operation can be realized. A related secondary objective is the minimization of the bandwidth required for the single channel.

If a single channel is to suffice, it is mandatory that some sort of time-division technique be utilized. This leads naturally to completely synchronous operation for allocating use of the channel and to discrete time-slot addresses uniquely assigned to each aircraft. Use of the time-division addressing principle eliminates the need for narrow-beam antennas and complex antenna-guidance equipment.

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Another design objective of major importance is that the amount of information transmitted from the aircraft to the ground environment must be minimized. If possible, the transmission ought to be limited to a single impulse for the sake of simplicity. Any information which could just as well be determined at the receiver, even if this amounts to a redetermination of data previously known at the transmitter, ought to be so determined rather than wasting channel capacity in its transmission. If the ideal of position reporting by means of a single impulse can be realized, then many of the technical problems involved in pulse transmission systems are greatly simplified, in particular, the problem of interference from multipath echo phenomena.

Noise phenomena such as atmospherics, receiver noise, and ignition noise will plague any sort of radio communication system. In order to minimize noise effects, the transmitter must produce high pulse power and the receiver must be designed for low-noise performance and located in a relatively quiet environment. The carrier frequency ought to be selected in the 1000-mc region to obtain an optimum balance between atmospheric noise at lower frequencies and receiver noise at higher frequencies. For the position reporting application, the line-of-sight limitation of UHF communication is actually an advantage because several aircraft can be given the same address provided only that the aircraft are separated by several hundred miles.

All of the requirements and design objectives introduced in the foregoing discussion can be realized in the proposed APT system. In addition, the system is capable of handling traffic densities considerably greater than the densities predicted for 1975. There would be no difficulty in providing APT service to several thousand aircraft simultaneously within the area covered by an air route traffic control center.

The principle of operation of the APT system along with the interrelationship between the major equipments involved is shown in Fig. 1. In each major terminal area, four ground-based receiving equipments are arbitrarily located, provided only that the area of maximum traffic density is central with respect to the four receiver sites. Maximum separation of any two receivers in the group would be about 20 miles. Each aircraft is provided with a transmitter which emits an intense pulse of UHF energy every few seconds. Interference between aircraft in the system is prevented by means of time-division multiplexing techniques.

As shown in the plan view of Fig. 1, the pulse of UHF energy leaves the airborne transmitter at instant t_P and travels outward at the speed of light. At some later instant of time t_A the wave front reaches receiver A. The detected pulse at A is used to sample the contents of a free-running clock, recording t_A in digital form. Immediately thereafter, the binary representation of t_A is serially transmitted on a digital data line to a centrally located Coordinate Conversion Computer (CCC). In similar fashion, the times of arrival of the signal at receivers B, C, and D are obtained and transmitted to the CCC. The equipment at each of the four receiving sites will be referred to as Time of Arrival (TOA) equipments.

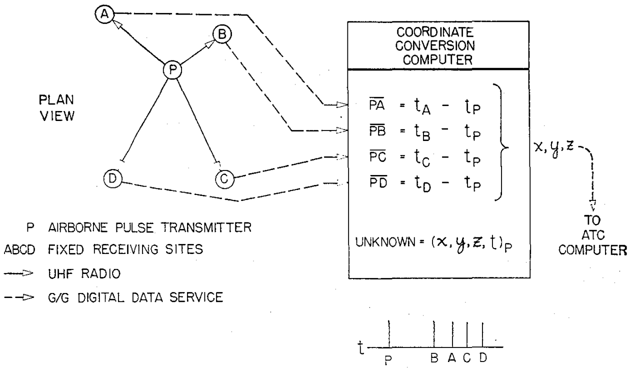

Fig. 1—System diagram.

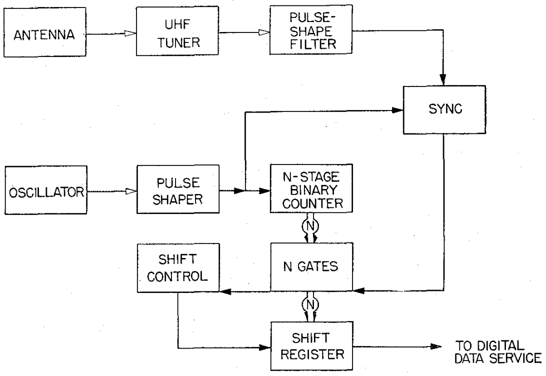

Fig. 2—TOA equipment.

Each of the four unknowns can be determined in theory from the four TOA measurements. One way of stating the functional relationships between these quantities is shown in Fig. 1. However, there is no interest in t_P and precise values of aircraft altitude cannot be obtained from the TOA data. Thus a practical design for the CCC would provide for the calculation of x and y only, and the altitude z must be found by another method. The output data from the CCC is transmitted in serial form over a digital data line to locally or remotely located ATC data processing equipment.

A block diagram of the major sections of each TOA equipment is shown in Fig. 2. The oscillator, shaper, and counter constitute a high-speed digital clock capable of resolving intervals of a fraction of a microsecond. The precision of this counter is directly related to the precision of the final position measurement (1 µsec = 0.186 mile). The received pulse is used to sample the high-speed counter and transfer its contents to a shift register. The received pulse also initiates a series of shift pulses to transmit the

TOA information to the CCC. The number of stages, N, in the high-speed counter must be sufficiently large to insure that no more than one end carry occurs during the passage of a wave front across the net of four TOA stations.

To make the UHF transmission highly reliable in spite of various noise phenomena, it may be necessary to send doublets or triplets rather than single pulses. The purpose of the "pulse-shape filter" shown in Fig. 2 is to produce an output pulse when and only when the input signal is within appropriate tolerance limits of the coded waveform transmitted by the airborne unit.

The airborne pulse transmitter for the APT system is shown in Fig. 3. The transmitter proper consists of a high-power modulator which excites a cavity-tuned power oscillator. The approach which appears most practical employs a hydrogen thratron discharging a delay line to modulate a "lighthouse" triode. Pulse power levels of several kilowatts are desired. Satisfactory results were obtained during the tests with a pulse power of 1.5 kw and there appears to be no difficulty in designing economical modulators and oscillators that will produce up to 10 kw.

Positive identification is provided and intrasystem interference prevented by means of a synchronized time-slot counter in each aircraft. The counter in any given aircraft is set to the aircraft address each time that the "framing pulse" is received from the ground. The framing pulse is sent to all aircraft simultaneously at the rate of about once a minute. The address counter in each aircraft counts down toward zero under the control of a medium-precision oscillator in the airborne equipment. When the address counter reaches zero and produces an end-carry pulse, the modulator is triggered. Since each aircraft would be given a different address, the UHF impulses all occur at different times.

The operation of the proposed address timing technique can be clarified by considering a typical example. In Fig. 3 and Fig. 4, the following numerical parameters are assumed: framing-pulse period = 1 minute, number of addresses = $2^{12} = 4096$. It is further assumed that the aircraft address is established by means of four octal switches. The aircraft chosen for the purposes of this example has address 13 (octal). The framing pulse transfers the number 13 (octal) from the address switches to the counter, and once each 15^{-} msec the counter contents are reduced by one. As the address counter changes from 0000 to 7777, the end-carry pulse is produced and the UHF transmission occurs.

The framing pulse is transmitted from ground to air by multiplexing it on the VHF and UHF voice channels to economize on both equipment and bandwidth. Since the addressing technique proposed does not require precise timing, the framing pulse can be handled on an audio channel. Assuming that the voice signal could be cut off at about 4 kc without serious loss of fidelity, it seems practical to use a subcarrier of about 6 to 8 kc for the framing pulse. In order to reject extraneous noise pulses, it is desirable to employ two or three short bursts of the subcarrier for each framing signal. The purpose of the pulse-shape filter shown in Fig. 3 is to decode the waveform used for the framing signal in order to distinguish it from various interfering signals. The framing-pulse transmitters are synchronized on a national basis via transmissions over lf channels from a central timing standard. Frequency-control servomechanisms are provided to keep the framing pulses together during outages or noisy periods on the LF channel.

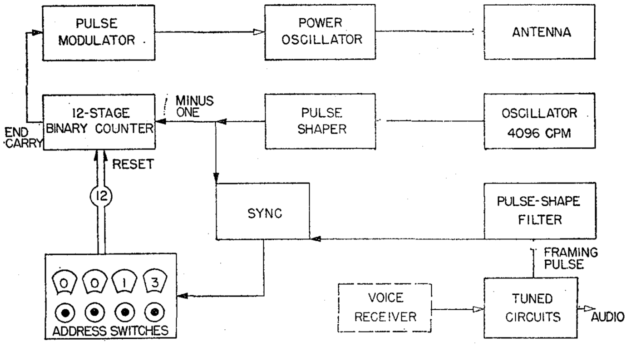

Fig. 3—Airborne equipment.

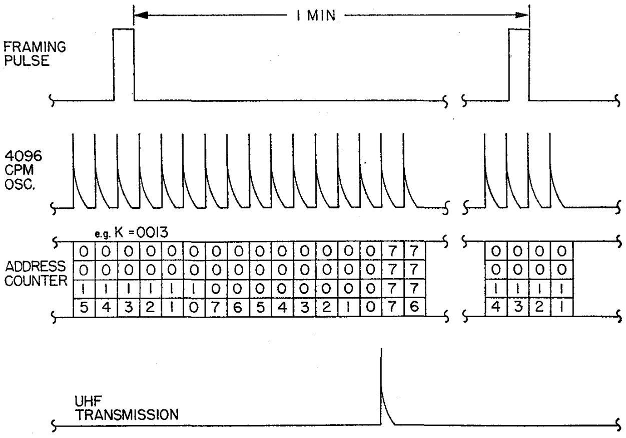

Fig. 4—Timing.

It should be noted that the APT system provides both position and identification data to the ground environment without actually transmitting either one of these quantities. Both the position and the identification are determined at the final receiver on the ground the position by a precision time-difference technique and the identification by medium-precision time division. To add automatic reporting of altitude, the altitude signal is multiplexed on the air-to-ground transmission. Altitude data can be readily included in the APT system by providing a second UHF pulse such that the spacing between the two pulses represents the altitude code. One way to produce the second pulse is to use the end-carry pulse from the address counter

TABLE I

A POSSIBLE SET OF PARAMETERS

	Airborne Pulse Transmitter		
Reporting rate:	Enroute phase	1	msg/min
	Terminal phase	8	msg/min
Number of addresses:	Enroute phase	2048	a/c
	Terminal phase	256	a/c
Number of time slots:	Enroute phase	$1\times2048=2048$	slots
	Terminal phase	$8\times256=2048$	slots
	Total	4096	slots
Time-slot duration		$60/4096=14.65$	msec
Carrier frequency		1400	mc
Pulse power		10	kw
Pulse duration		0.2	μsec
Timing for altitude pulse:	Minimum delay	1000	μsec
	Maximum delay	2600	μsec
	TOA Equipment		
Receiver bandwidth		5	mc
Antenna height		100	feet
Clock-oscillator frequency		5	mc
Number of stages in clock		9	bits
Clock cycle duration		$2^9\times0.2=102.4$	μsec
Maximum span of TOA net		$102.4\times0.186=23.1$	miles
Message content:	Time of arrival	9	bits
	Altitude	6	bits
	Parity check	1	bit
	Spares	3	bits
	Total	19	bits
Message rate		4096	msg/min
Shift rate		$19\times4096/60=1297$	bit/sec
Altitude-oscillator frequency		0.04	mc
Number of altitudes		$1600\times0.04=64$	levels
	APT System		
Minimum altitude coverage:	Terminal phase	0	feet
	Enroute phase	4000	feet
Maximum range		90	miles
Precision:	Inside TOA net	0.05	mile
	At maximum range		
	azimuthal	0.5	mile
	radial	1.5	mile
	At 50-mile range		
	azimuthal	0.3	mile
	radial	0.5	mile

to drive a delay multivibrator which produces two pulses to trigger the modulator. The delay between the two pulses would be controlled by an electromechanical connection from a sealed aneroid altimeter in the aircraft. In the TOA equipment, the first received pulse would be used to start an altitude counter and the second pulse would transfer the contents of this counter to an extension of the shift register shown in Fig. 2. The second pulse would also be used to reset the altitude counter. Thus, the altitude information turns out to be the only data actually transmitted from the aircraft to the ground in the usual sense of the term "transmission," while the position and identification are both ground-derived.

The high-speed counter used in the TOA equipment is not synchronized with any of the other counters in the TOA net. The effect of synchronization is accomplished much less expensively by the provision of a set of equipment identical to that used in the aircraft but located on the ground near the center of the net. TOA signals arriving at the CCC during the time slot assigned to the ground-based pulse transmitter are then compared with the values which would have been obtained if the four counters had actually been synchronized. The differences so obtained are then held in temporary storage in the CCC and are used to correct the TOA values received during each of the other time slots in the frame. The additional calculations required in the CCC amount to a few subtractions and represent no important increase in the amount of electronic equipment required.

The principal computing problem which the CCC must solve is the conversion of the hyperbolic coordinates represented by the TOA values to a more convenient set of coordinates for use by the controllers and data processing machines involved in ATC operations. The output coordinates from the CCC may be chosen to be rectangular or geodetic with very little difference as far as the cost of the CCC is concerned. Several possible designs of the CCC have been considered; one based on table look up and interpolation, a second method based on an iterative technique, and a third and most promising method based on direct calculation. The time provided for each computation cycle is sufficiently long that the CCC requirement can be met with a simple design based on a serial arithmetic unit controlled by a fixed program. The special geometry associated with each TOA net can be accommodated by well-known storage techniques. Since no human intervention is required in the normal operation of the CCC, the input-output requirements are easily satisfied.

The numerical values of the APT parameters may be chosen from a fairly wide range of values; in many cases the range of practical choice extends over several orders of magnitude. The numerical values of the parameters used in Table I are presented in the interest of clarity and do not necessarily represent recommended values. Some of the more flexible parameters are: the number of time slots, the time-slot duration, and the reporting rate. These parameters are limited only by the requirement that the interval between reports from the same aircraft must equal the product of the number and duration of the time slots. This requirement is modified if a higher reporting rate is desired in the terminal phase of aircraft flight than in the enroute phase. For example, the 4096 time slots discussed earlier could be divided into two groups of 2048 slots each. One of these groups could be used to handle 2048 aircraft in the enroute phase of flight, and the remainder could be divided into 256 groups of 8 slots each to accommodate an additional 256 aircraft in the terminal phase with a reporting rate 8 times that used in the enroute phase. By properly choosing the numerical values involved, the pilot's attention required in the setting of the APT address can be limited to a single setting of the address switches just before take-off, plus the operation of a two-position switch at the beginning of the enroute phase of flight and once again at the beginning of the terminal phase.

The precision of the APT system in the near zone depends only on the TOA clock resolution. At maximum range, the precision depends on the ratio of the TOA station spacing to the clock resolution. For a value of clock resolution of 0.2 μsec and a TOA station spacing of 20 miles, the precision will vary from about 0.05 mile inside the net to about 1.5 miles at a range of 90 miles. At long range, the azimuthal precision is considerably better than the radial precision.

The automation of the position reporting function will eliminate a large fraction of the present communications load. Greater precision of position data will reduce the frequency of conflicts with a corresponding reduction in the number of transmissions required to each aircraft. A standard clearance signal requiring no human intervention can be employed except in the small number of cases requiring special transmissions. It therefore appears doubtful that an automatic ground-to-air data service can be justified for more than a small fraction of the aircraft in the future ATC system. These reasons explain the emphasis of this paper on the air-to-ground reporting service and the neglect of the reverse direction of transmission.

The proposed APT system meets the basic requirements of position reporting for air traffic control. In the interest of economy, the special needs of the more advanced aircraft ought to be met by providing additional equipment to supplement that used for the basic functions. All aircraft in the system need not carry high-precision navigation equipment plus automatic two-way digital communication merely because a minority of the aircraft requires these devices. One of the advantages of APT is its compatibility with all sorts of navigation techniques including contact flying, VOR and other air-derived navigation systems, deadreckoners corrected manually or automatically from ground-derived data, and advanced inertial systems.

There are many design problems in the APT system which remain to be attacked, so it is too early to predict success. However, the investigations and tests to date indicate that the system is feasible and has several strong points. Some of the more important advantages are: simplicity of airborne equipment, flexibility of parameter choice, minimization of pilot attention, and perhaps most important of all is the independence of position-measuring accuracy with respect to malfunctions or misadjustments in the airborne unit.

Discussion

Mr. Bhippel (U. S. Signal Corps): Wouldn't three ground stations be sufficient for position determination?

Mr. Ross: Assuming that accuracy of the order given in the paper is required, then one must acknowledge that the final results depend on variation in three dimensions and, therefore, three independent time differences are required. The number of independent time differences is one less than the number of TOA receivers.

D. C. Friedman (National Bureau of Standards, Washington, D.C.): What provision would be made for control when there is a plane transmitter outage, possibly unknown to the pilot? Or a plane with no transmitter?

Mr. Ross: In any future air traffic control system, two-way radio would continue to be employed; thus any outage of the APT transmitter could be overridden by reverting to voice transmission of estimated times of arrival over various fixes as determined by airborne navigation equipment. Aircraft not outfitted with APT would, of course, be required to file position reports by voice radio at all times while flying under instrument conditions.

Mr. Friedman: How many computers would be required for current airways? How many ground stations? What would be the cost for the ground and aircraft installations?

Mr. Ross: One coordinate conversion computer and four TOA receivers are required for each major airport. Throughout most of the United States, the enroute area would be adequately covered by the installations at the terminals. In the areas where the terminal installations do not provide sufficient enroute coverage, one has the alternative of installing supplementary APT nets or requiring the use of voice radio for position reports while flying through these areas. It is too early to state cost estimates for either ground or the aircraft installations.

T. Kampe (Librascope, Glendale, Calif.): How many ground stations are envisioned across the country?

Mr. Ross: The number of APT installations depends entirely on the number of terminal areas requiring automation of the position-reporting function. The determination of the traffic level needed to justify such service would have to be made by the Civil Aeronautics Administration in the case of civil airports and the cognizant military service in the case of military airports. Further technical development and product engineering work should be carried out before these questions of system economics can be answered intelligently.

Mr. Kampe: How are aircraft with malfunctioning sets to be detected, and how handled?

Mr. Ross: It is important to note that malfunction of the APT transmitter does not produce erroneous position measurements. However, there are two important malfunctions to consider. First, a complete absence of the UHF pulse would be detected at the ATC data processing center in the form of a missing position report in some particular time slot. If this situation continued, the pilot of the offending aircraft would be notified by voice radio to revert to voice position reporting over certain fixes. An outage of the framing pulse would result in a very slow drift in the aircraft identification number—a difficulty which is easily resolved either by automatic or manual "identification tracking" at the air traffic control center.

Mr. Kampe: How are transmissions between different sets of ground stations, for a specific aircraft, to be integrated into a coordinated picture of aircraft?

Mr. Ross: The output of the coordinate conversion computer associated with each APT ground installation would be transmitted automatically over ground-to-ground communication facilities to the terminal air traffic control facility and also to the air route traffic control center covering enroute operations in the area. Thus, each air traffic control facility receives position data on all aircraft within its area of responsibility. Digital data transmission techniques presently available are entirely satisfactory for the APT application. The necessary data processing and display equipment at the air traffic control centers would be designed to include data from APT along with data from other sources.

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