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The Application of Ranging Techniques to Navigation and Traffic Control

Philip M. Diamond
Associate General Manager, Office for Development Planning, The Aerospace Corporation,

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ABSTRACT

During the last decade a variety of ground- and air-based radio aids have been implemented in efforts to solve major military problems in navigation and guidance, and command, control and communications. Because of significant advances in space technology and avionics, satellite-based systems to provide position-fixing data by means of ranging and range-differencing techniques, and to provide communications capability, have been shown to be feasible and attractive, and to have unique technical and operational advantages. World-wide coverage, essentially instantaneously availability, and three-dimensional position-fixing accuracy of a few tens of feet seem feasible. In the civil area, demand for improved communications over the oceans, and for improved air traffic control over both the U.S. and the oceans, may be met by space-based systems. Indeed, the Office of Telecommunications Policy has recently called for a satellite telecommunications service for over-ocean aeronautical operations. A developing view supports the use of satellite-ranging techniques and satellite communications to provide for certain fundamental air traffic control functions over the U.S. in the period through the 1990s. From a satellite and data processing point of view, it appears feasible to implement in the early 1980s a system which could provide surveillance data to the order of 100 feet in three dimensions; an emergency communications capability corresponding to the operational notion of intermittent positive control; data for accurate autonomous navigation and for terminal approach and blind landing. These capabilities would be available to aircraft to an extent depending on its investment in avionics. To accomplish the implied objectives requires the establishment of organized and systematic R&D programs, including a well conceived evaluation methodology.

I. INTRODUCTION

The development of aircraft during and since World War II has contributed to enormous progress in a number of fields related to navigation and air traffic control. In turn, the utilization of these developments has created new requirements which are increasingly difficult and expensive to satisfy. In the military context, the development of close air support techniques, the use of air mobility, and the need for execution of operations involving the intimate combination of otherwise autonomous ground, sea, and air forces have resulted in new and exceedingly complex requirements for command and control capabilities. Prime among the ingredients of command and control are knowledge by each autonomous element of its specific position, and a similar knowledge by the centralized command/control authority. Thus, it is possible to distinguish between two functions: (a) autonomous navigation, in which a navigator (e.g., a user of a radio navigation system) determines his position from various sensory inputs and operates upon that information in carrying out his mission, and (b) traffic control in which a centralized facility determines (or has knowledge of) the navigator’s (user) position and operates upon that information to achieve some objective involving many users. Air weapon delivery to a distant target requires autonomous navigation; transit of many such aircraft through combat zones requires traffic control.

Similarly, a civil carrier aircraft carrying out its flight plan requires autonomous navigation. However, to assure flight safety in crowded airspace, the implementation of air traffic control among the many aircraft is required. These concepts merge at some points and may become indistinguishable. The instrument landing system is a case in point.

These notions of navigation and traffic control are also applicable to a lesser degree to other operating circumstances than flight, most notably maritime operations. The requirements imposed by these operations have caused the technical community to inquire into the feasibility of space systems providing necessary solutions. The rapid development during the 1960s of launch vehicles, communications satellites, satellite-tracking techniques, miniaturized and reliable components (especially computers), and the operation of geodetic satellites and the Navy Navigation Satellite System (TRANSIT) have generated a technology base from which new solutions have appeared. The prospects are very bright that the required new capability can be provided by the utilization of space systems.

II. REQUIREMENTS

Statements of requirements generally stem, at least initially, from an intuitive blending of experience and recognition of deficiencies, and are combined with a view of the potential performance offered by technologically advanced systems. The cases of concern herein are dominated by such origins. In consideration of the separation of
functions alluded to in the Introduction, Tables 1 and 2 present postulated requirements for autonomous navigation and for traffic control. These data are assembled from a variety of sources, including study groups, experienced opinions, analyses, and individual inquiries. They are rationalized, however, not only on the basis of what seems operationally desirable in a future time period, but also on the basis of what satellite systems can provide. The requirements goals are tempered by consideration of the economic feasibility of the systems alternatives available. In these cases satellite systems utilizing ranging and range-differencing techniques have been postulated as the systems of choice.

Examination of Table 1 indicates basic similarity of classes of requirements for position-fixing accuracy among the several air and sea operations. However, the reasons for these requirements are somewhat different and reflect the nature of the function as well as the nature of the implementation of the system apparatus. For example, the military need for extreme accuracy is predicated upon the obvious benefits occurring when conventional munitions with destructive radii of several tens of feet are delivered to the target with comparable accuracy. By contrast, the civil need for extreme accuracy for air and sea traffic occurs due to safety considerations in dense terminal regions with severe maneuvering restraints and where the vehicles must operate in tightly specified corridors. On the other hand, landing and docking operations specify requirements which are fundamentally the same throughout, and, of course, military aircraft operating in civil airspace must conform to the same procedures as civil aircraft. The measurement interval or frequency of fix is highly dependent upon the speed of the user and the specific mission function. While the role of velocity (vector) information is reasonably well understood for the case of air-delivered munitions and for landing and for docking operations, it is less well understood for enroute (cruise) operations, where velocity, as such, is only weakly coupled. Clearly, the distinction between navigation and traffic control is blurred, as the requirement statement stems from strong dynamic and geometric relationships to other users and installations. It is also clear that differences between systems implementation techniques (e.g., ranging vs. range differencing, one-way vs. two-way, etc.) will depend less upon the numerical values characterizing their performance than upon operating circumstances and philosophies. For example, the military will tend to desire a high degree of signal privacy and security by comparison to their civil counterparts. This consideration leads to the selection of user receive-only techniques.

Table 2 indicates air traffic control requirements which are shown principally as postulated characteristics of civil air operations. With only minor alterations, these are also applicable to marine operations. Note that military air tactical command and control appear to have requirements which are very similar to civil requirements. It is of interest to note that the North Atlantic position-fix requirement for traffic control is the most substantially supported of these requirements. Through the use of collision probability analyses for the anticipated traffic densities requiring narrower flight lanes, it has been shown that improved ATC position fixing is required for superimposition on on-board navigation.

Table 3 presents some of the factors which characterize other pertinent requirements issues and which may have a very strong influence on the nature of the satellite (or any) system implementation. Note especially the immediate need for worldwide coverage for military applications, the dynamic character of tactical aircraft as contrasted with civil aircraft, military security, and survivability characteristics, and autonomous navigation signal non-saturability (extremely high user density). Note, further, that certain requirements appearing dissimilar are not necessarily so. For example, consider that the possibility of accidental or test nuclear explosions in space during peacetime presents a common problem of satellite hardening. Also, resistance against ground-based interference to the satellite receiver is similar, if it is supposed that harassment of civil air operations is a real possibility (cf., hijacking).

III. SATELLITE SYSTEMS

The requirements discussed above can be met with a variety of systems and/or combinations of systems. From a technical point of view, satellite systems utilizing multiple satellite ranging and/or range differencing are attractive possibilities for satisfying the requirements. Two major questions arise: (a) Is it economically feasible to implement satellite systems for these purposes vis-a-vis consideration of all the feasible alternatives, the "true" demand for improved services, the development still required, and the costs to the user communities?; and (b) What specific configuration(s) of systems is (are) best and what specific roles should the satellite system(s) play in satisfying the entire operational problem? The answers to these questions are dependent upon further analyses, development, experiments, and demonstrations, and evaluation of the results with regard to not yet existing thoroughly determined methodologies and criteria. The present environment, therefore, appears to be one of support for subsystem development and system test, pre-operational demonstration, and evaluation. It is not likely that systems of an operational nature will come into being for any portion of these requirements much before 1980. The remainder of this paper will be devoted to the illustration of system concepts regarded as having potential sufficient to justify the implied expenditures over the next decade.

A. Autonomous Navigation

Analysis of military requirements indicates that only systems based on measuring the ranges between satellites and the user, or the range differences between links to pairs of satellites, can meet the accuracy requirements while being available to users in high-speed aircraft. Furthermore, the desire to accommodate high-speed users requires all of the measurements needed to establish a navigation fix to be made essentially simultaneously.
Measurement of range can be accomplished by comparing the time of arrival of a signal as determined by a clock at the user synchronized to a clock at the satellite. To maintain clock synchronization with any clock presently feasible for inclusion in all user's equipment, one additional measurement must be made. Since a three-dimensional fix is required, signals from four satellites need to be received. By measuring the time of arrival of the four signals relative to the user's clock, the position coordinates and a clock correction can thus be determined. In addition, the frequency shift is measured, the three-component velocity vector of the user can be found. Since a clock correction is calculated, the user effectively has an extremely accurate time standard, and frequency standard, available to him.

Geosynchronous orbits (generally not circular or equatorial) are preferred from the standpoint of providing global coverage and the ability to deploy less than a full global system. A particularly attractive configuration employs one satellite in a synchronous, near-circular, near-equatorial orbit in conjunction with three or four satellites in inclined, elliptical, carefully phased orbits, having the property that their ground traces follow a common near-circular path around the trace of the first (center) satellite. Such a constellation provides continuous regional geographic coverage with high redundancy. The satellite configuration which has just been described is shown from two points of view in Figure 1. On the left, the satellites are shown in orbit as viewed by an observer in space who rotates with the earth. In this set of coordinates, the satellites do not appear to be in their orbital planes. In the right-hand view, the same series of satellites for an inertially-fixed observer are seen to be inclined elliptical orbits. This constellation array is also highly compatible with traffic control requirements in that the central satellite of each constellation can be designed to provide the requisite communications capability and one such constellation provides nearly Western Hemisphere coverage. Four such satellites appear as a rotating "Y" in the sky, and five as an "X".

A system using the measurement technique just described is termed a one-way pseudo-range and pseudo-range rate system. Such a system makes measurements equivalent to one-way range and range rate measurements made by the use of a synchronized user clock. It is also equivalent to a hyperbolic system in which three range differences are measured to four satellites.

A conceptual diagram of a system based on the above considerations as deployed for regional coverage is shown in Figure 2.

Since the satellite positions form the reference from which navigation is performed, it is essential that their positions be accurately determined in geodetic coordinates. A master tracking station containing a tracking antenna sequentially acquires the four satellites and, for a period of several minutes, measures range and range rate using the two-way path from the master station to the satellite. From these data and a model of the earth's gravitational potential, the satellite ephemerides are determined.

Figure 2 illustrates the process by which the user obtains a position and velocity fix. An arbitrary set of coordinates, X, Y, and Z, are introduced in which the satellite positions are assumed to be known and in which the user wishes to obtain his position and velocity. Each satellite transmits a signal to the user. These signals contain identifiable range codes modulated upon the carrier, typically by biphase modulation. The signals also contain the equivalent of satellite ephemerides modulated at a low data rate. The signals are either at different carrier frequencies or are modulated by orthogonal codes in order that the signals may be distinguished by the user. The preferred modulation for military applications appears to be that of a pseudo-random code which maximizes interference protection and signal privacy, while achieving high accuracy and resistance to multipath interference.

Figure 3 illustrates the method by which a position fix is determined from these signals. A typical signal from one satellite is shown together with the same signal as generated by the user's unsynchronized clock. This clock typically would be a high-quality quartz crystal oscillator of the type commonly incorporated in high-grade field equipment. By means of a correlation detector, the time shift between a satellite signal and the user clock is determined. This time shift ("T" in Figure 3) consists of the speed of light transit delay from the satellite to the user and the lag of the user's time reference relative to system time. Four T's as measured from the four satellites together with the positions of the four satellites can be expressed as a set of four non-linear algebraic equations in four unknowns (three components of user position and clock bias). Since the signals from the four satellites are synchronized as one of the ground station functions, the user clock bias is the same in each of these equations. The equations can then be solved for the user position and the clock bias.

If, at the same time as the pseudo-ranges are measured, the rate of change is measured by normal Doppler extraction techniques, four equations with user velocity as unknown may be written and solved for user velocity in three dimensions. The computation of user position and velocity would normally be made in a digital computer of the sort used in an integrated avionics system. If less than full accuracy is required, many simplifications are possible which result in more modest user equipment.

The error performance of the concept discussed above has been analyzed considering the error sources listed in Figure 4. The results as presented herein are based on the use of the four satellites with the highest elevation angles of a representative five-satellite constellation; better accuracy may be achieved with more satellites from all five satellites of the five-satellite constellation (at the expense of some geographic coverage).
Satellite tracking accuracy is determined primarily by the number and location of ground stations taking measurements, the degree of complexity and sophistication of the algorithm used to transform tracking measurements into satellite ephemeris estimates, and the interval of time over which the satellite ephemerides are predicted. In general, satellite position errors are smallest in the radial direction and largest in the in-track direction; errors in the cross-track direction typically lie between these two extremes. To facilitate a more general description of the effect of satellite tracking accuracy on navigation accuracy, a typical satellite error ellipsoid shape is assumed: the principal axes of the ellipsoid are in the radial, in-track, and cross-track directions and have relative magnitudes of 1.0, 8.0, and 4.0, respectively; an inter-satellite radial correlation of 0.6 is also assumed. A representative set of values are (1σ), 50 ft, 400 ft, and 200 ft, respectively.

Of particular concern is the area of error sources due to propagation delays because of ionospheric and tropospheric uncertainties. This follows because of the unique association these factors have with frequency choice. There is clearly another major factor involved, that of satellite RF power, which for natural noise limited designs is obviously a strong function of frequency (f^2), considering Doppler tracking requirements as a function of frequency. However, for designs in which a substantial amount of artificial radio interference is the dominant constraint, the RF power level required is very nearly the same over a wide frequency range from a few hundred MHz to a few GHz. This range includes the most desirable frequencies for navigation. These effects are illustrated parametrically in Figure 5.

Propagation delay errors are those associated with prediction or measurement of the signal delay during its passage through the ionosphere and the troposphere. The range increment due to ionospheric delay, for frequencies above approximately 200 MHz, is inversely proportional to the square of the frequency and a direct function of the propagation path total electron content, as shown in Figure 6. For frequencies below C-band it is characterized by several tens of nanoseconds uncertainty. The geographical variation of velocity is also similar in form with smaller variation and can be characterized by 0.25 to 0.5 ft/sec. Time synchronization variation is also similar and can be characterized by several tens of nanoseconds uncertainty.

B. Traffic Control

For purposes of presentation herein, and to illustrate a feasible and potentially attractive system concept, some key elements of satellite ATC capability will be described. The scheme as a whole is based upon some of the notions discussed in the previous section.

As noted earlier, the basic performance capabilities desired for traffic control are that of developing within a central facility the position data associated with each of the autonomous elements in the vehicle fleet and of operating upon this data to assure safe and efficient passage and/or execution of the mission function. The first capability is easily recognized to be that of surveillance, traditionally performed by means of radar, and the second requires a computational capability mechanized with suitable algorithms and ground-to-user communications facility. These capabilities can also provide for a form of navigation since the communications link can be utilized to transmit the individual vehicle's position to that vehicle for on-board utilization. A system concept combining autonomous navigation with surveillance and communications becomes highly flexible and powerful, and will be discussed later.

1. Surveillance

Figure 9 illustrates a surveillance concept based upon the notion of a user active system. To minimize user equipment costs and complexity, a one-way pseudo-ranging concept is postulated. In this approach, a unique ranging signal is radiated by the satellite is penalized since both channels re-

...
each user which also establishes user identity. Since the user signal is not synchronized to the system, four relative-time-of-arrival measurements accomplished at the ground computation center are required to establish user position. The signal radiated by each user is received at four (or more) transponder-equipped satellites, deployed in a manner similar to that previously discussed, which re-transmit it to the ground station associated with central control facility. Here, the relative-time-of-arrival is determined by subtracting the time of travel from the satellites to the control point through the use of the known satellite positions. The corrected times of arrival, when multiplied by the speed of light, are referred to as pseudo-ranges (they would be ranges if the exact time of the user transmission were known). The only additional data needed at the ground computation center in order to perform the position determination function are the satellite ephemerides.

There are three general mathematical techniques for accomplishing the position determination function -- exact, approximate, and iterative. Each technique in some form will utilize the satellite ephemerides. The selection of an appropriate technique to determine each user's position (simple in principle) is strongly dependent upon the accuracy required, the frequency with which the position determination is needed, and the number of users. These parameters determine the quantitative size of the computation, a factor of significance in establishing that feasible computers can, indeed, handle the traffic.

There is no particular problem in performing exact computations for up to several thousand users. However, since, in this example, the system is to provide ATC surveillance for all CONUS aircraft, an approximate calculation approach was developed which is capable of handling 100,000 simultaneous users with a one-second cycle time, a number which might be expected by the 1990s. This approximate position determination algorithm utilizes precomputed auxiliary data (which includes the satellite ephemeris information) which are common to more than one user. In this fashion the "average" amount of computation for a position fix is relatively minimal. Each set of precomputed auxiliary data is associated with one of 50,000 10x10x10nm cells which cover the CONUS. The technique for recognizing which cell contains the user requires an initial evaluation of the measured range differences and a comparison of these with precomputed values characterizing each cell.

The position fix error capability achievable by the above method is 130 ft (average, 1σ) with a maximum error of the order of 500 ft. With increased capability to perform an exact computation, which might be necessary and/or desirable for a small portion of the total flight population, the error performance could be reduced to that shown in Figure 10.

2. Collision Avoidance

A complete ATC system includes activities of conflict determination and resolution, traffic scheduling, flight plan processing, and interface processing with terminal ground control systems. Compatible with the initial ATC approach considered here are the surveillance of airspace for all equipped aircraft (discussed earlier), the identification and resolution of all potential conflicts, and a communication channel (discussed later) for positive or negative (intermittent positive control - IPC) commands to avoid collisions, advisory ATC messages and/or position fix data. If applied to all aircraft, an important portion of a complete ATC system would be provided.

For computational feasibility reasons it is important to consider conflict resolution. For present purposes, the identification of "aircraft conflict" is defined as that part of the collision-avoidance function which involves recognizing that it is physically possible for two aircraft to approach each other within some minimum miss distance (different in horizontal and vertical planes) during a projected time interval. If an extrapolation of current velocities and intentions within the projected interval shows a closest approach to be less than the specified minimum, then a positive command to change course will be given. Since there is no "intent" information for visual flight rule (VFR) aircraft which have not filed flight plans, aircraft must never be allowed to come so close that they could maneuver to within the specified minimum distance of each other during the projected interval. This is the primary function of the negative IPC commands which would seldom conflict with the interests of the pilots.

A possible concept to identify aircraft conflict situations is basically comprised of a three-level serial filter and is illustrated in Figure 11. The filters are designed to require a minimum of computation per aircraft pair for each filter level. The smallest number of computer instructions per aircraft pair will occur in the earlier filters, thus eliminating the aircraft pairs which do not provide conflict situations early in the computational cycle. The first filter essentially eliminates those aircraft pairs of the total airborne population which are farther apart than approximately 21 n mi horizontally and 0.9 n mi vertically. The remaining aircraft pairs pass to the second filter where the aircraft velocity is considered constant and the approach geometry is solved. In the second filter, the aircraft pair relative range, range rate, and miss distance are tested in a sequential manner. Those aircraft pairs that pass all three tests enter the third filter where the most detailed of the conflict calculations are performed. In the third filter, the aircraft pair relative trajectory is predicted and compared during the projection interval with worst-case potential deviations from the predicted relationship. If it is possible that the safe-passage criteria are violated, then a conflict situation has been identified.

Computational algorithms were designed which utilize inputs of range difference measurements obtained from ranging signals transmitted by 100,000 aircraft via a satellite constellation of at least four synchronous satellites with a computational
cycle time of one second. These algorithms were estimated to require a computer instruction rate (not including redundancy) of $40 \times 10^6$ instructions/sec. This can be accomplished by one or two large 1975 general purpose computers with a total mass storage and fast storage of $25 \times 10^6$ and $300 \times 10^3$, 32 bit words, respectively.

3. Communications

The above technique was examined with respect to a "gas model" aircraft environment from which it follows that the number of "actionable" aircraft pair interactions depends on the permissible interaction distance of aircraft. The study indicates that an upperbound of 200 and 400 interactions/sec can be associated with interaction distances of 5000 and 10,000 ft, respectively. If one assumes a warning time of 30 sec and a turning rate capability of 3.0 deg/sec a conservative upperbound on required actions (commands) for 100,000 aircraft may be as high as 1000/sec.

The uniqueness of the spatial position of each aircraft with respect to the participating satellites can provide both the required address codes and secure digital communications. This is illustrated in Figure 12. With a satellite average power of 50 W (2kW peak), zero dB aircraft antenna, and directive satellite antenna (31 dB), the system can adequately handle a data rate of $5 \times 10^8$ bps. This corresponds to 1000/sec - 6.0 bit ATC command messages plus 550/sec - 41 bit navigation data messages (3.0 min fleet update) plus 450/sec - 30 bit general ATC messages (3.6 min fleet update).

C. A Unified Approach

There are a large number of factors which must be considered in the introduction of a satellite system, especially when such a system might be anticipated to have an extremely large potential impact on the nature of operations and procedures. Indeed, it is very likely that the principal benefits to be achieved through the introduction of a satellite system are not likely to be fully identified until after such a system has been put to the test of experimental evaluation. Figure 13 shows some of the factors which must be considered.

Above all, the new system must inherently have the performance capabilities to accommodate the anticipated nature of the traffic, and have the geographic coverage properties which enable that performance capability to be implemented in an economically practical manner. Furthermore, it would be desirable to provide independent navigation and surveillance functions. It might be noted here that traffic forecasts indicate rapid growth of the number and extent of high density areas.

Under these circumstances, local disturbances of airspace utilization, such as those caused by bad weather at a terminal, will propagate more quickly and extend over a larger geographical area than ever before. It will become necessary for the airspace system to adapt itself on a national scale. Thus, the unique advantage of a satellite system in providing a common positional and time reference source over a very wide coverage area will be of extreme significance.

It must be recognized, also, that the vast majority of aircraft will belong to the category of general aviation. These aircraft (or perhaps their owners) will not be economically capable of supporting costly equipment and will not necessarily be desirous of being serviced to the same degree as, say, commercial airline aircraft. Even within the general aviation category there exist a number of uniquely different types which may be easily identified by their differences in performance envelope, size, and cost. As a consequence of this large variation in the user fleet it is necessary that both the service offered and the corresponding user equipment be tailored to the spectrum of user aircraft. In addition, the airspace structure utilized should be rationally designed, allowing the greatest possible freedom of action, and not be dominated by the ATC system.

Of course, in order not to disrupt the present evolving system and to avoid undue economic constraints to system growth, a new system must be evolutionary in nature. Although a satellite system is commonly thought to be revolutionary, this is not necessarily so. Indeed, many of the major subsystems and procedures accompanying the satellite system have their roots in procedures and systems currently in being or planned. These include the concept of area navigation (which is just coming into use), the present plan to automate the ATC centers, the planned use of the Super Beacon and its data link/data processing subsystems, the FAA Oakland Oceanic ATC experiment on data display and human interpretation, and the experiments and plans on ranging (time-frequency) collision avoidance systems. The evolutionary approach will also provide a number of redundant and backup modes of operation which might be necessary to assure the absolute safety of the system. It is also economically desirable that older, and ineffective, system components be phased out as the system components become fully operational.

Clearly, the satellite system must have acceptable implementation cost and must be functionally acceptable to the aviation community. Since the aviation community is comprised of a large number of institutions, each of which has a unique requirement to fulfill, this factor is far from insignificant and implies that the new system must have a high degree of functional flexibility. Furthermore, although the military have their own unique requirements which have, in the past, been frequently satisfied by unique solutions, military aircraft do operate in civil airspace. Thus the satellite system must be compatible with military operations. In addition, because of the growing cost of high-performance systems which depend increasingly upon advanced technology, such as that represented by satellites, it may be more than mere compatibility that is required. Joint program sponsorship may be necessary to enable a national commitment to a new program of the extent suggested.

Figure 14 indicates an example of the matrix of user functions and user types which represent needs.
and capabilities with regard to the satellite system approach outlined to this point. The chart is predicated on the airspace being divided into three regions: (a) Controlled airspace in which a full surveillance and communications capability is required, (b) mixed airspace in which certain minimum equipment is necessary in order to enter into the ATC system, and (c) an uncontrolled airspace region in which operators do not necessarily participate in the ATC system. Extended communications and terminal navigation, including Category IIIIB or IIIIC landing capability, are growth directions for the satellite system.

Figure 15 shows some of the characteristics of the user equipment and satellites, and the typical performance which might be achievable for each of the functions indicated. To add the surveillance function and the emergency communication function to the satellite which provides the autonomous navigation capability requires only an additional 100 lb (approximately) of equipment on the satellite and may be achieved for user costs of several hundred dollars. Terminal navigation capabilities would be achieved through the use of one of the satellites plus runway-located cooperative transmitters. Extended communications would require an enlargement of the satellite capabilities and major cost increments in the user equipment.

Figure 16 summarizes the major functional characteristics of a Unified Satellite System: providing military unique autonomous navigation, general autonomous navigation, surveillance data acquisition, emergency communications, and having the potential to support terminal navigation and ILS.

**IV. CONCLUDING REMARKS**

Throughout this discussion, it may have been implied that satellite systems can be the ATC system, i.e., that satellite systems are the ultimate solution. This is far from the actual circumstance. It does not yet seem viable to provide the total communications required, nor the backup or redundant capability necessary for confident use of the system. Landing and terminal region aids independent of any satellite aid may also be required. Furthermore, the ground-based data processing/decision-making facilities are still required. Thus, it must be clearly understood that satellite systems seem able to play an important role but are to be considered only as providing specific elements, albeit important and powerful, of the services required. Figure 17 graphically illustrates these points.

The discussion has focussed on the viable limits of the contribution satellites can make and has featured complex, multiple satellite concepts. By virtue of National Policy statements recently issued by the Office for Telecommunications Policy, it is likely that the first satellite systems related to these objectives will be implemented to serve the Pacific Ocean region in the 1973 - 1974 time period and the Atlantic Ocean region in the 1975 - 1976 time period on pre-operational bases. The principal purpose of these systems will be to provide over-ocean communications to and from enroute civil carrier aircraft and will explore the feasibility of surveillance ranging for ATC. As illustrated in Figure 18, it is envisioned that for each ocean region two geostationary satellites will be deployed. Utilizing two-way ranging mechanized with a simple signal structure coupled with altimeter data read-out, position-fix capability of the order 0.25 - 0.5 nm is expected. The link would be closed at L-band frequency. These oceanic coverage systems are relatively straightforward. Systems designed for CONUS ATC or military navigation are far more complex and require more extensive development and evaluation programs.

Table 1. Postulated Advanced Navigation Performance Requirements.

Table 2. Postulated Air Traffic Control Requirements.

Table 3A. General Requirements.

Table 3B. General Requirements.

Table 3C. General Requirements.
POSTULATED ADVANCED NAVIGATION PERFORMANCE REQUIREMENTS

<table>
<thead>
<tr>
<th>CIVIL</th>
<th>POSTULATED NAVIGATION PERFORMANCE REQUIREMENTS</th>
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<tr>
<td>MARINE</td>
<td>TERMINAL &amp; SCIENTIFIC CONFLUENCE ZONES</td>
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<td>AIR</td>
<td>SPACE SYSTEM TRAJECTORY DETERMINATION</td>
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<td>AIR</td>
<td>AIR MISSION ENROUTE NAVIGATION, COUNTERAIR, RENDEZVOUS</td>
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<td>AIR</td>
<td>GENERAL ENROUTE NAVIGATION</td>
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TABLE 1.

POSTULATED AIR TRAFFIC CONTROL REQUIREMENTS

<table>
<thead>
<tr>
<th>SERVICE REGION</th>
<th>EXAMPLE</th>
<th>AIRCRAFT TYPE</th>
<th>LARGEST ACCEPTABLE ERRORS (ft)</th>
<th>MEASUREMENT INTERVAL SECOND</th>
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<td>HIGH ALTITUDE, HIGH DENSITY</td>
<td>NORTHEAST CORRIDOR</td>
<td>TRANSPORT CLASS BUSINESS JETS</td>
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<td>MILITARY OBJECTIVE AREA OPNS (UCNI)</td>
<td>WORLD-WIDE TACTICAL AREAS</td>
<td>ALL MILITARY TACTICAL A/C</td>
<td>~1000 (100 ALT)</td>
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<td>TERMINAL AREA, HIGH DENSITY</td>
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<td>ALL, INCLUDING LIGHT SINGLE ENGINE</td>
<td>100</td>
<td>1</td>
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<td>AIRPORT APPROACH, LANDING, AND ROLL OUT</td>
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<td>IFR EQUIPPED</td>
<td>10</td>
<td>1</td>
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<td>OTHER AREAS WITHIN CONUS</td>
<td>AREAS BETWEEN HIGH REGIONS DENSITY</td>
<td>ALL</td>
<td>5000 (200 ALT)</td>
<td>3-10</td>
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<td>TRANS-OCEAN</td>
<td>NORTH ATLANTIC</td>
<td>TRANSPORT</td>
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<td>1-3 Min</td>
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TABLE 2.
# GENERAL REQUIREMENTS

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<tr>
<th>ITEM</th>
<th>CIVIL</th>
<th>MILITARY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MARINE</td>
<td>AIR</td>
</tr>
<tr>
<td>COVERAGE</td>
<td>NORTH ATLANTIC</td>
<td>PACIFIC</td>
</tr>
<tr>
<td></td>
<td>NORTH PACIFIC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>WORLD-WIDE GOAL</td>
<td></td>
</tr>
<tr>
<td>ENVIRONMENT</td>
<td>ALL WEATHER, MINIMAL PROPAGATION ANOMALIES</td>
<td></td>
</tr>
<tr>
<td>AVAILABILITY</td>
<td>PERIODIC ACCEPTABLE</td>
<td>CONTINUOUS, ON DEMAND</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>VERY LOW</td>
<td>LOW</td>
</tr>
<tr>
<td>COST</td>
<td>MODERATE</td>
<td>VERY HIGH</td>
</tr>
<tr>
<td>RELIABILITY</td>
<td>FOREIGN BASES ACCEPTABLE</td>
<td>NO FOREIGN SITES</td>
</tr>
<tr>
<td>GROUND STATIONS</td>
<td>STEADY PLATFORM</td>
<td>RAPIDLY MANEUVERING VEHICLES</td>
</tr>
<tr>
<td>USER TYPE</td>
<td>ACCEPTABLE</td>
<td>USER PASSIVE</td>
</tr>
<tr>
<td>USER RADIATION</td>
<td>DATA AVAILABLE TO ALL</td>
<td>DATA DENIABLE</td>
</tr>
<tr>
<td>SYSTEM SECURITY</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 3A.**

# GENERAL REQUIREMENTS

<table>
<thead>
<tr>
<th>ITEM</th>
<th>CIVIL</th>
<th>MILITARY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MARINE</td>
<td>AIR</td>
</tr>
<tr>
<td>INTERFERENCE</td>
<td>HARASSMENT PROTECTION</td>
<td>AJ, SPOOF PROTECTION</td>
</tr>
<tr>
<td>EQUIPMENT</td>
<td>ADAPTABLE TO ALL USERS</td>
<td></td>
</tr>
<tr>
<td>COMMON GRID</td>
<td>NOT REQUIRED</td>
<td>REQUIRED</td>
</tr>
<tr>
<td>SATURABILITY</td>
<td>ACCEPTABLE AT HIGH LEVEL</td>
<td>NON-SATURABLE</td>
</tr>
<tr>
<td>3-D CAPABILITY</td>
<td>NOT REQUIRED</td>
<td>REQUIRED FOR SPECIAL CASE</td>
</tr>
<tr>
<td>SURVIVABILITY</td>
<td>PEACETIME, INT'L ENVIRONMENT</td>
<td>MILITARY ENVIRONMENT, NUCLEAR HARDENING</td>
</tr>
<tr>
<td>TACTICAL PORTABILITY</td>
<td>NOT REQUIRED</td>
<td>REQUIRED</td>
</tr>
<tr>
<td>FREQUENCY ALLOCATION</td>
<td>BROAD ACCEPTABLE REGION</td>
<td>CRITICAL DESIGN IMPLICATIONS</td>
</tr>
</tbody>
</table>

**TABLE 3B.**

15-18
<table>
<thead>
<tr>
<th>ITEM</th>
<th>CIVIL</th>
<th>MILITARY</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INTEGRABILITY WITH OTHER SYSTEMS</strong></td>
<td>MINOR</td>
<td>INTEGRATE INTIMATELY</td>
</tr>
<tr>
<td><strong>INSTITUTIONAL ISSUES</strong></td>
<td>MULTILITHIC INSTITUTION</td>
<td>MONOLITHIC INSTITUTION</td>
</tr>
<tr>
<td><strong>COMMITMENTS</strong></td>
<td>INTERNATIONAL STRUCTURE</td>
<td>DEDICATED</td>
</tr>
<tr>
<td><strong>TRAFFIC CONTROL (TC)</strong> (DATA LINK, CENTRAL CONTROL, ETC.)</td>
<td>COMPATIBLE/INTEGRABLE</td>
<td>NOT IMMEDIATELY DESIRED</td>
</tr>
<tr>
<td><strong>TC SECURITY</strong></td>
<td>COMMERCIAL DATA PROTECTION</td>
<td>PROTECTION FROM ENEMY USE</td>
</tr>
<tr>
<td><strong>TC COMMUNICATIONS</strong></td>
<td>WEATHER, COMMERCIAL DATA, ETC.</td>
<td>LIMITED STATUS, COMMAND DATA</td>
</tr>
<tr>
<td><strong>TC PROXIMITY WARNING</strong></td>
<td>REQUIRED</td>
<td></td>
</tr>
<tr>
<td><strong>TC AUTOMATED PROCESSING</strong></td>
<td>REQUIRED</td>
<td></td>
</tr>
</tbody>
</table>

*TABLE 3C.*
Figure 1. Orbital Deployment - Two Views.

Figure 2. Pseudo-Ranging to Four Satellites.

Figure 3. Determination of User Position, Velocity, and Time.

Figure 4. Major Contributions to System Error.

Figure 5. Signal Power Analysis.

Figure 6. Frequency Dependency of Range Error.

Figure 7. Propagation Ranging Error.

Figure 8. Horizontal Position Accuracy (1σ), Coverage Contours, and Satellite Ground Trace for a Five-Satellite Constellation.

Figure 9. Ground Identification and Range Measurement Concept.

Figure 10. System Performance.

Figure 11. Filter Concept for Conflict Determination.

Figure 12. "Space Ordered" Digital Communications System.

Figure 13. Factors for Consideration.

Figure 14. User Spectrum.

Figure 15. Satellite System Spectrum.

Figure 16. Unified Satellite NAV-ATC Concept.

Figure 17. Role of Satellites.

Figure 18. General Scheme of Current Over-Ocean Aero-Services Satellite Concepts.
ORBITAL DEPLOYMENT - TWO VIEWS

FIGURE 1.

PSEUDO-RANGING TO FOUR SATELLITES

FIGURE 2.

16-21
DETERMINATION OF USER POSITION, VELOCITY, AND TIME

SIGNAL FROM Jth SATELLITE

SIGNAL FROM USER CLOCK

- PSEUDO-RANGE = $T_j - C = \sqrt{(X - X_j)^2 + (Y - Y_j)^2 + (Z - Z_j)^2} - T_B \cdot C$

- PSEUDO-RANGE RATE = $\dot{T}_j - C = \frac{(X - X_j)(\dot{X} - \dot{X}_j) + (Y - Y_j)(\dot{Y} - \dot{Y}_j) + (Z - Z_j)(\dot{Z} - \dot{Z}_j)}{\sqrt{(X - X_j)^2 + (Y - Y_j)^2 + (Z - Z_j)^2}} - \dot{T}_B \cdot C$

- Since $X_j, Y_j, Z_j, \dot{X}_j, \dot{Y}_j, \dot{Z}_j$ are known, 4 $T_j$'s and 4 $\dot{T}_j$'s allow solution for user position $(X, Y, Z)$, and velocity $(\dot{X}, \dot{Y}, \dot{Z})$, and time bias $(T_B)$

FIGURE 3

MAJOR CONTRIBUTIONS TO SYSTEM ERROR

- SATELLITE TRACKING, ERRORS, AND GEOMETRIC EFFECTS
  - TRACKING STATION LOCATION
  - GEOPOTENTIAL MODEL
  - SATELLITE-USER/SATELLITE-TRACKING STATION GEOMETRY

- SIGNAL PROPAGATION
  - IONOSPHERE UNCERTAINTIES
  - TROPOSPHERE UNCERTAINTIES
  - MULTIPATH DELAYED SIGNALS

- INSTRUMENTATION ERRORS
  - RECEIVER/TRANSMITTER DELAY
  - RECEIVER RESOLUTION
  - RECEIVER NOISE
  - TRACKING STATION CLOCK DRIFT
  - SATELLITE CLOCK DRIFT

FIGURE 4
SIGNAL POWER ANALYSIS

FIGURE 5.

FREQUENCY DEPENDENCY OF RANGE ERROR

FIGURE 6.
FIGURE 7.
HORIZONTAL POSITION ACCURACY (1σ), COVERAGE CONTOURS, AND SATELLITE GROUND TRACE FOR A FIVE-SATELLITE CONSTELLATION

FIGURE 8.
ACCURACY W/4 SAT. MEAS.

15-24
GROUND IDENTIFICATION AND RANGE MEASUREMENT CONCEPT

SATELLITES WITH ATC TRANSPONDERS

1.6 GHz

1.5 GHz

1.0 GHz

SATELLITE EPHEMERIS DATA

UNIQUE TRANSMITTED SIGNAL FOR EACH USER
- CODED, PHASE MODULATED, PULSE COMPRESSION SIGNAL (52.3 μsec PULSE TRAIN)
- AUTOMATIC & ASYNCHRONOUS (APPROX ONCE/sec)
100 UNIQUE CODES
1000 UNIQUE PRF 100,000 USERS

ATC COMPUTATION CENTER
- EQUIPMENT
  100 MATCHED FILTERS + SPECIAL PURPOSE COMPUTER
- TECHNIQUE
  \[
  \left( \frac{\text{RELATIVE TIME OF ARRIVAL}}{\text{TIME OF TRAVEL FROM SATELLITES}} \right) \times \text{SPEED OF LIGHT} = 3 \text{ RANGE DIFFERENCES}
  \]

FIGURE 9.

SYSTEM PERFORMANCE

POSITION ERRORS
MAXIMUM, 1σ FEET

ALTITUDE ERRORS
MAXIMUM, 1σ FEET

COVERAGE
AS A FUNCTION OF ELEVATION ANGLE

FIGURE 10.
FILTER CONCEPT FOR CONFLICT DETERMINATION

1st FILTER
IMPLICIT GEOMETRIC FILTERING
• For each \( R_{ij} \) triple, identify the particular 10 x 10 x 10 nmi local Conus grid containing the user
• Precomputed values of \( S_{ij} \) and \( A \) for each grid
• Map \( R_{ij} \) into appropriate Conus 5 x 5 x 0.2 nmi bins (total of \( 10^7 \) bins)
• Position \( P = P_0 + A \cdot (R_{ij} - S_{ij}) \)
• Identify aircraft sharing common bin
  These aircraft pass the filter

2nd FILTER
SOLUTION OF CONSTANT VELOCITY APPROACH GEOMETRY
• Test each aircraft pair
  a. Relative range: \( R < q \)
  b. Range rate: \( \dot{R} < 0 \)
  c. Miss distance: \( MD < p \)
• Aircraft passing tests also pass through the filter

3rd FILTER
SOLUTION OF WORST CASE DYNAMICS
• Prediction of relative trajectory, \( R(t) \) based upon position history and flight plan
• Estimation of potential relative aircraft displacement \( S(t) \) during projection interval based upon pilot freedom, aircraft dynamics, position errors, and safe passage criteria
• Test \( |R(t)| < S(t) \) over projection interval
• Aircraft pairs passing test require command intervention

FIGURE 11.
"SPACE ORDERED" DIGITAL COMMUNICATION SYSTEM

SATELLITE TERMINALS

ATC CENTER

FIGURE 12.
FACTORS FOR CONSIDERATION

- PERFORMANCE AND COVERAGE
- SERVICE AND EQUIPMENT COMPATIBLE WITH SPECTRUM OF USERS
- EVOLUTIONARY GROWTH
- REDUNDANT AND BACKUP MODES
- ACCEPTABLE SYSTEM COST
- INTERNATIONAL - NATIONAL - INSTITUTIONAL ACCEPTABILITY
- CIVIL - MILITARY COMPATIBILITY

FIGURE 13.

USER SPECTRUM

<table>
<thead>
<tr>
<th>PASSIVE USER NAVIGATION</th>
<th>ACTIVE USER SURVEILLANCE</th>
<th>EMERGENCY COMMUNICATIONS</th>
<th>EXTENDED COMMUNICATIONS</th>
<th>TERMINAL NAVIGATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>MILITARY</td>
<td>GENERAL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GENERAL AVIATION MIN. EQPT.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAX. EQPT.</td>
<td>AREA NAV.</td>
<td>RQ'D</td>
<td>RQ'D</td>
<td>OPTIONAL</td>
</tr>
<tr>
<td>AIR CARRIER OVER OCEAN</td>
<td>AREA NAV.</td>
<td>RQ'D</td>
<td>RQ'D</td>
<td>RQ'D WHEN AVAILABLE</td>
</tr>
<tr>
<td>MILITARY</td>
<td>MISSION UNIQUE</td>
<td>RQ'D FOR OPERATIONS IN CIVIL AIRSPACE</td>
<td>GROWTH TO FULL CBC INTEGRATION</td>
<td>RQ'D WHEN AVAILABLE</td>
</tr>
</tbody>
</table>

FIGURE 14.
<table>
<thead>
<tr>
<th>USER* EQUIPMENT</th>
<th>PASSIVE USER NAVIGATION</th>
<th>ACTIVE USER SURVEILLANCE</th>
<th>EMERGENCY COMMUNICATIONS</th>
<th>EXTENDED COMMUNICATIONS</th>
<th>TERMINAL NAVIGATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>MILITARY</td>
<td>$20-50,000</td>
<td>$1000-$1500</td>
<td>$1000-$3000</td>
<td>$5-25,000</td>
<td>ADD DISPLAY TO PASSIVE EQUIPMENT</td>
</tr>
<tr>
<td>GENERAL</td>
<td>$10-20,000</td>
<td></td>
<td></td>
<td></td>
<td>NO ADDITIONS TO PASSIVE SYSTEM</td>
</tr>
<tr>
<td>SATELLITE WEIGHT</td>
<td>1200 LBS</td>
<td>1300 LBS</td>
<td>1500-2500 LBS</td>
<td></td>
<td>CAT IIIc</td>
</tr>
<tr>
<td>TYPICAL PERFORMANCE</td>
<td>&quot;A FEW TENS OF FEET&quot;</td>
<td>100 FT 3DACCURACY</td>
<td>100 FT 3D ACCURACY</td>
<td>10 BITS IPC MESSAGES</td>
<td>COMPLETE COMMAND AND CONTROL</td>
</tr>
</tbody>
</table>

* COSTS DEPENDENT UPON TYPE OF USER, DEGREE OF SERVICE

**FIGURE 15.**

**UNIFIED SATELLITE NAV-ATC CONCEPT**

**FIGURE 16.**
FIGURE 17.
GENERAL SCHEME OF CURRENT OVER-OCEAN AERO-SERVICES
SATELLITE CONCEPTS

FIGURE 18.