BROADCAST CONTROL OF AIR TRAFFIC

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In comparing our oldest form of long range transportation, ships at sea, with aviation, we note several interesting facts. The marine concepts of traffic control are essentially almost all self-contained on the ship with little central control authority from the shore being accepted. This marine concept stems probably from the fact that shipping as a form of transportation has been successfully employed for hundreds of years, reinforcing the early concept of the full authority of "master of the ship" in all matters, including avoiding collisions with other ships and objects.

Aviation, however, being only about sixty years old, and then perhaps only significant in the last thirty years, has accepted many innovations and technologies rejected by the marine experts. Consequently, aviation is in many respects far more advanced. The current marine collision rates are appalling, so much so that the alarm has been sounded in the science of marine navigation and traffic control attempts are being made to establish some new means of reducing the obviously excessive losses in collisions and groundings, particularly in restricted waters such as harbors (reference 1).

Aviation, of course, has the third dimension, vertical separation, which has probably done more to hold its accident rates to lower values than marine rates; say, air carriers compared to major ships. The third dimension for navigation and control by its nature saves many cases that are otherwise collisions.
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in two dimensions. Anyone who suggests that ATC gets all the credit is unwilling to admit this pure chance advantage of aviation. That is to say, if ATC were all conducted at the exact same elevation, it is possible that air collision rates (collisions with other aircraft and objects) would equal or exceed the appalling marine rates. Psychological factors, (fear of flying) and the higher probability of fatalities in any aviation accident further stress the differences.

Consequently, aviation has become mostly a system of highly centralized ground control with "radar vectoring" being the major tool in any dense traffic region. Of course, radar vectoring also exploits vertical separation to the maximum, using an air pressure gauge known as the barometric "altimeter" to achieve height differentials. This traffic concept has tended to create electronic means for the (ground-based) air controller that are much more accurate than the means used by the pilot for normal navigation of airways. A study of (1) AC 90-45 and (2) AC 91-30, two FAA documents that briefly describe (1) the VORTAC Area-Nav concepts and (2) the radar vectoring concepts using the national SSR (radar system), clearly shows that the ground surveillance data available only to the ground controller of air traffic is about 10 to 20 times more accurate than the pilot's navigation and track information, basically derived from airborne R-NAV, VORTAC instruments and displayed to the pilot in the cockpit.

Thus, we see the pilot being "vectored," that is, continuously steered in many cases through a maze of other traffic by personnel viewing a radar scope on the ground. An increased
emphasis on radar vectoring or its equivalent is proposed by some authorities. An obvious risk exists in several major areas if this trend continues. Failure of the SSR is one. Conflict between the R-NAV displayed track (to the pilot) and the ground SSR track display is another. The pilot and controller may not be viewing the track situation the same way, creating potential violations of separation criteria. "We obviously cannot continue to let one man on the ground navigate more and more aircraft without eventually getting into trouble." (Reference 1) We must find an optimum means to provide the pilot with better information on where he is and where he intends to be than he presently has available. Accuracy, flexibility, economics, coverage, uniformity of data, quality of data all must be considered, optimising each in a total-system approach. VORTAC is deficient in too many of these areas when applied to wide-area navigation concepts.

In the marine case, experts say it is obvious some shore centralized/authority must be added in the dense traffic areas, such as ports and narrow waterways where many ships converge and move on regular schedules including fog conditions. Thus, in both our most ancient form of transportation (marine) and in our most recent form of transportation (air), we find the two generalized concepts of/centralized control (ground or shore), and/captain or on-board control being examined. In the marine case, after centuries we are now considering changing major rules and concepts, including adding extensive electronics guidance and control to achieve a more centralized control.

In the air we have probably over-emphasized centralized control (ground computers, ground radar, radar vectoring).
Consequently, we are now looking at means for bringing the pilot back into more participation in the act of traffic control (such as his own speed, destination, track keeping, separation, etc.). This concept will cause the controller to provide more of a surveillance function, rather than a navigation function, by avoiding extensive radar vectoring. This new balanced concept/herein called "Broadcast" control of air traffic.

The ICAO (International Civil Aviation Organization) recently established a panel on this subject known as the panel on Revision of General Conception of Separation (RGCS panel). A good summary of its activities is to say it will re-examine the relationship of the pilot and controller in navigation, separation, etc., in our modern dense air traffic environments as well as other categories: (1) ocean, (2) medium, (3) high density, and (4) very high density (areas).

Two phrases used herein will be: "Close Control" and "Broadcast Control" to differentiate between the two ATC concepts. "Close Control" assumes the present techniques expanded wherein the ground (computers-controller) will control (closely) each aircraft individually using Radar Vectoring as the primary ATC technique with the pilot employing R-NAV as a minimal secondary need in terminal areas. Broadcast control assumes that a new balance of equality between improved cockpit guidance and control capability and ground control is implemented so that the pilot will be an equal participant in following track (more accurately than at present), maintaining desired track speed, maintaining air-to-air common track separation, and meeting scheduled
destination (time-position), etc., goals far better than the pilot is now capable of achieving in terminal areas because of the VORTAC deficiencies. This in no way downgrades the full radar ground system (SSR) for surveillance, schedule planning, and assuring the pilot that he is safe by being monitored continuously and that he is executing the ATC required conditions in dense traffic—all with more pilot participation than in the past. It is a means of preventing an overload (and potential failure through delays, complexity, etc.) of the use of our surveillance system by placing the navigation and other functions in the air, using a new coordinate system suited for such purposes.

We do not in any way infer "Broadcast Control" to be a "free-lance" operation of the pilot as in the marine case, since the results would be so disastrous as to be obvious. However, we do mean that "Broadcast Control is a new concept of ATC wherein we seek by experience the optimum balance of the ground radar system and the precision, improved coordinate Area-Nav system (LF-VLF). We seek in "Broadcast Control" the optimum balance of authority between the pilot and the controller; we also seek an ATC concept suitable to very high density ATC as well as very low density ATC; We also seek in "Broadcast Control" a means of cost benefits to all users including general aviation, military and air carriers. "Broadcast Control" should offer major improvements in capacity while simultaneously creating major reductions in the cost of ATC.

Some of the fine lines between "Close" and "Broadcast" control of air traffic are not always obvious; however, one purpose of this study is to continue to clarify and refine the definition
of "Broadcast Control". Goals that are significant to aeronautics include increased capacity of our airports and airways, with reduced risk of collision with ground or other aircraft, all more sensitive to the pilot, the aircraft, its use, and pilot displays. A further goal is to take an insurmountable load (that is increasing) off the (centralized, radar-tracking) controller system so that it can survive and serve ATC by doing the ATC jobs it does best, in an improved manner, instead of diverting its capacity to functions, such as navigation of aircraft, that are done better by other means. The ground monitoring and planning of control and separation of dense traffic remains an enormous burden.

Major changes in the pilot's ATC functions, economics, numbers of ground personnel, use of SSR data, etc., are all involved in this change of emphasis from "Close" to "Broadcast" control. These changes that are evolutionary and not revolutionary are compatible with our current national investment in ATC and will be identified in more detail than in the initial "overview" study of this subject in "Aeronautics and Air Traffic Control," NASA CR-1833, Published in August 1971). These ATC involvements of the pilot, his displays, his ability to refine the flight control of his aircraft (better track, altitude, track speed, air-to-air separation controls, etc.) are primarily problems in aeronautics, although electronic sensing of the data is obviously essential.

However, until we really comprehend (1) what "Broadcast Control" means; (2) how the pilot really participates in ATC functions (rather than being a lackey to the controller or computer),
and (3) how the pilot-controller relationship varies in different air traffic densities; we cannot define in the necessary detail an aeronautic program that is required to evolve ATC toward the improvements that are obviously possible. Such obvious improvements as being able to fly curved approach paths precisely defined in three coordinates, at exact track speeds (not airspeed), yet to a tolerance at the runway threshold of about ±5 seconds is but one of many examples of what is primarily an aeronautics constraint on the future of ATC as well as the future value of aviation. Until we can find means to do these and many similar things and at lower costs for such new capabilities with higher safety; then ATC will remain the constraint to the future public value of all of aviation. It is increasingly evident that these constraints are aeronautical and pilot oriented rather than electronic. Since we know electronics can provide the essential inputs once defined, the problem is to define them in terms of "Broadcast Control." However, the electronic inputs to the aircraft and pilot, such as "R-NAV", must be much better than the current VORTAC system can provide.
Recently several investigators and planners of future ATC systems and concepts have suggested more pilot participation in the ATC control loop. For example, the International Civil Aviation Organization publication of August 1971 was devoted to various international views on ATC, one article noting that: "This thinking is in favor of placing more responsibility for the ATC process, particularly separation part of it, in the aircraft cockpit, and in this way relegating ATC (ground control) to traffic directions along ATS routes, at intersections and at airport runways."—"Any look into the future must be based on the reality of today, where we find the greatest difficulty centering on the human controller in the system." An MIT report notes: "By tightening the control loop over aircraft separations through including the pilot as a monitor and active control agent, it would seem to be possible to demonstrate reduced standards at higher levels of safety..." The DOT-ATCAC report (reference ) discusses the use of "Strategic Control" sometime in the future—a concept also involving more pilot and cockpit responsibility in ATC functions.

However, the means for accomplishing these ATC functions in the cockpit varies with different technical proposals. In the concept of an "intermittent positive control"/(IPC), a new data link is essential to provide detailed but standardized messages to the pilot from the ground surveillance system, addressed and transmitted automatically to individual pilots. In another concept,
the SSR system uses a new digital data link (differing from the IPC link) to create a cathode ray display of traffic for the pilot much like the controller's display, but with filtered information. By using the SSR codes, only pertinent traffic need be viewed by the pilot in his display for his maintenance of spacing, etc.

In even another future ATC concept we see the overall, detailed programming of the many traffic movements is planned adequately in advance so that routings, track directions, velocities, etc., are transmitted in one message to the pilot much like a flight plan. The three dimensional and time coordinates are based possibly supplied by a wide base LF/VLF system on a more uniform grid of common coordinates. Such coordinates are sensed directly in each aircraft executing its individual plan.

In this latter case, the pilot may actually file and request the flight plan in these coordinates, and it will be approved (possibly with minor modifications to interface with all other flight plans at that time), so that he knows well in advance his detailed operational ATC plan, and few if any "minute-by-minute" decisions are made by the ground. Essentially, radar vectoring is avoided, but the SSR capacity is applied to monitoring the total ATC scheme leaving detailed ATC functions (speed, spacing, etc.) to each pilot.

Thus, we see much of the conceptual thinking about the future of ATC is now turning toward obtaining much needed assistance from the pilot, his displays, and his ability to precisely effect the flight properties of his aircraft in all axes to aid in the ATC process. This should distribute the ATC load, avoiding what
may become an unmanageable controller-computer load if the pilot participation and responsibility is not "engineered" into the ATC system. This is the goal of "Broadcast Control."

One of the ICAO articles raises serious questions and doubts about increased automation of the ATC decision process to a point where even the human ground controller cannot take over if the computerized commands somehow fail or go astray. It would seem that a given degree of ground automation will be essential but that the improved ATC pilot participation and his new relationship to the controller must be considered the direction for the future. The total ATC burden is then borne by the two parties, each carrying the load that he can do the most about, and each with the responsibility of most concern to him.

Although the "IPC" concept is a means to this end, it is but one option with a risk that may not warrant the investment. Essentially, in the "IPC" concept the ground surveillance system is further burdened and relied upon to determine when proximity pair spacings become dangerous and then to use this data (only ground derived) automatically on an automatic "uplink" (or data link) to the specific pilots involved, giving each or both pilots "commands" to which there is no alternative but to blindly obey. Some collision avoidance systems operating independently of the SSR system also adopt this blind pilot command idea, merely "commanding" the pilot (without question) to climb or descend. His judgment often does not enter into this mandatory maneuver.

Neither of these concepts of commanding maneuvers is likely to be accepted when one really understands the pilot and
his responsibilities, both real and legal. Also, a serious question arises when an electronic command occurs that the controller may not concur in that is a false alarm, resulting in traffic disruption or chaos. These concepts are often the solutions of electronic enthusiasts that have little awareness of the contributions the pilot can make and should make. Many electronic enthusiasts are also overly confident as to what electronics can deliver in the "real world" in the form of a safe, high integrity system that can safely control dozens of aircraft each with 400 lives at stake.

"Broadcast Control" Involves Pilot Skills, Judgment, and Responsibility

Herein we will discuss a "Broadcast Control" concept of ATC that essentially provides the desired pilot participation (that now seems to be the direction of the future of ATC), but involves the pilot in a redundant manner, does not overburden the SSR system (as in IPC), but/recognizes SSR as the foundation of ATC surveillance (but not navigation or track guidance). An independent collision avoidance system does not seem necessary as the SSR will supply this function now that it has been relieved of the other functions.

We have the ability, now with modern computers, to plan traffic flow in three dimensions in densely trafficked airspace that will not conflict. The flight path and schedule planning must be done correctly, and the pilot must be given the ability to actually execute his specific plan. Today the anticipatory flight track planning cannot adequately occur for many reasons; one being the deficiencies of the track forming system itself (limitations of coordinates, coverage, and accuracy, etc.). Further, we do not
employ the proper concept of the ground ATC function as basically a planning, monitoring-surveillance function rather than an instant-by-instant decision maker and guidance system. The latter forcibly capacity has been/developed since SSR (radar transponder system) and coordinate is about 20 times better than VORTAC. Given a new track/system equal to SSR quality, we can then plan the flight in these coordinates, approve them for execution by the pilot after a computer has scanned all flights in a given volume of airspace, modified and approved them for use, prior by some time to their actual use. The pilot, having a 20 times improvement, can now execute track and schedule if the proper aeronautics exist in the form of displays, flight controls, maneuverability, etc.

This "Broadcast Control" concept avoids the unexpected overloading of controllers that now occurs, resulting in long delays caused by "ad-hoc" planning and decision making by a controller, usually uncoordinated with other controllers doing the same thing. The planning stage is not adequate and does not include pilot participation in ATC for maintenance of spacing, track speed control, track following, and other functions, he can do far better with much less delay than the ground controllers (or for that matter the ground computers fed by the surveillance data, digested and relayed secondhand to the pilot by data link).

The pilot, upon sensing the track (track deviation displays), then adjusts his speed to provide the rate of track motion as per the plan. The ground essentially monitors these basic pilot ATC functions, carefully notes future intersections for common airspace occupancy to be sure that they will be separated
in time as the flight plan computer had determined. Essentially, the plan is "broadcast" to pilots in advance, and each uses the data and broadcast coordinates broadcasted of his concern to comply with an overall scheme of things. Codification of an area could result in a simple voice message from the ground, establishing the entire sequence since most flight plans are only slight variations of previously used ones.

In the ideal case (not realistic but to exaggerate the impact of "Broadcast Control" on ATC), the pilot would, upon receipt of his validated flight plan, take off and guide his aircraft on a precision, geometrically varying track in three dimensions; at a track speed indicated by the plan in terms of the track coordinates (such as a wide-area, with uniform grid of constant positional accuracy, navigation system). The pilot within time limits could proceed to destination and land without the ground control intervening at all. However, during this scenario of the perfect flight in dense traffic, the ground is monitoring in depth his every action to determine the deviations from track and track or check points speed to assure the other air traffic in the same nearby airspace that no conflicts (and certainly no collisions) will occur, due to a poor pilot execution of the specified and planned flight track schedule parameters. The pilot is now in his own right and contributing to ATC; he is not being "vectored" instant-by-instant in a nearly "open loop" fashion as so often occurs today, resulting in the enormous burden, stress, and overload of air traffic controllers. This "ad-hoc" solution to the peak traffic problems must be abandoned as one cannot predict the impact or
chain reactions that occur from instant to instant (local decisions) in the total system. There is a growing need to organize the traffic flow ahead of time and use pilot functions in ATC in order that the radar controllers can function without the constant risk of being overloaded. One must have an organized flight plan based on a uniform set of coordinates that is uniform and equal in accuracy to the ground surveillance system (VORTAC does not have these required characteristics). An LF/VLF system of uniform coordinates should be seriously considered and tested for a new national ATC-Navigation grid, using perhaps 4 to 6 large transmitting stations in a complementary manner with the VORTAC network, which is then operating at a lesser level but in an active partnership with an LF/VLF system. VORTAC and LF/VLF (wide Area-Nav) complement each other when engineered together for transition to give this new "Broadcast Control" concept. To put this concept in different terms, the pilot cannot participate adequately in the ATC system today without the use of precise/data. Such data is now only available on the ground. The SSR transponder system is providing this, but is already overloaded in support of the ground controller and computers. To relay this ground SSR data to the pilot in place of a direct attack on the real problem is to further dangerously overload the SSR system. A fully complementary, pilot-oriented, guidance system engineered directly for the requirements of the pilot's participation in "Broadcast Control" is now warranted.

Admittedly, much research is needed on many aspects of the "Pilot participation in ATC" concepts that are now becoming
popular. First, the pilot must be catered to in the system design as a knowledgeable and cooperative individual, not a lackey to dive or climb at the whim of some electronic black box. This means the presentation of all ATC-related information to him in a form that builds his confidence in it, and that will give him adequate information to exercise his judgment and decision process within the bounds defined by our concept of "ATC Broadcast Control." In most instances of large aircraft with hundreds of lives at stake, the pilot's judgment, experience, and other qualifications for these ATC functions delegated to him are better than the average qualifications of the controller. What is most significant is that the pilot is where the action is; he has directly at his fingertips the controls for track, spacing, velocity, descent, climb, turn, etc., of his aircraft. Furthermore, he knows what can and cannot be done within the confines of flight dynamics, turn radius, acceleration, deceleration, etc. Controllers only know such flight parameters in generality, and must observe, detect, and transmit corrections to the pilot—a time consuming and partially "open loop" process since variable and long time delays prevent good ATC-rate information. A pilot can observe continuously ATC track speed just as he observes air speed and provide fine adjustments, while a controller has no such data and uses crude, randomly timed changes in gross velocity. ATC must be designed as a massive, complex servo system with dozens of loops, each with adequate rate data to prevent "hunting" in servo language or "overload" or "delays" or "stacking" in ATC language.
MECHANIZING PILOT PARTICIPATION IN ATC

This subject will probably become one of the most controversial ATC subjects of the '70's, as there are so many potential means for giving the pilot the displays he needs in ATC. His position, track, track speed, track deviation, spacing to aircraft behind, spacing to aircraft ahead, above and below his changing position, all typify the data involved. The amount, quality, and utility of this ATC pilot data will vary according to traffic density, locale, and type of aircraft, ranging from a Cessna 150 "shooting" a "400-1 mile" approach at a remote field to a 747 "shooting" a CAT III in dense New York traffic.

One of the simplest concepts is to simply relay the "picture" that the ground controller already has, using a TV system for remoting the picture, to the pilot. This technique has drawbacks and disadvantages as noted by many and summarized in the MIT report (reference  ) and controlled by tests of the idea. MIT suggests that a data link with coded and processed SSR information be used; an airborne computer-processor is employed to select the desired information from undesired SSR information for the selected pilot's display. Such a display is a cathode ray tube in the cockpit with a pilot's "own" position in the center and "others" about him. Synthetic targets created by the computer are used rather than the usual poorly defined "blips" associated with typical radar displays.

In the FAA-DOT ATCAC report (reference  ), another concept known as IPC (Intermittent Positive Control) was conceived of by the "Alexander-Goldmuntz" committee. In IPC an up-link is used to transmit data to aircraft much like the current national down-link of
4096 codes employed in the SSR transponder system. The up-link is a sophisticated data link channel with a sophisticated decoder and processor of the pulse codes required in the air. In such designs the decoding, processing and display of data is often much more complex than the initial "encoding" means. When on the ground such a decoder processor is of little concern and is usually serving many encoders. Here in this proposal we put the complexity in the air, a serious drawback. This IPC up-link of IPC will give "commands" addressed to the specific pilot such as "up," "down," "right turn," "left turn," speed changes, etc., effectively replacing the voice commands now used in ATC. In IPC the pilot would not have an onboard plan position display of other aircraft positions relative to him. A message display of annunciator type shows selectively addressed, pilot oriented and filtered "commands" (of the ground control sensed data that the ground computer generates).

Other competitive concepts prevail, such as in the ATA-CAS (Air Transport Association, Collision Avoidance System), see IEEE March 1968 Transactions on Aerospace and Electronic Systems (AES 4, No. 2). In the ATA/CAS concept the air-to-air sensing of other aircraft can conceivably measure the air-to-air separation (range between) two aircraft and their position relative to ground stations using multilateration (pulse and CW Doppler) techniques.

Another candidate to be discussed herein in depth is the use of a nationally broadcast, precision grid system of uniform granularity and useful at all altitudes by all users at all cost levels for not only creating the onboard position of the specific aircraft, but by using simple time signals relate this to others; both air and ground have equal accuracy.

By comparisons of equal quality in the aircraft and on the ground of the aircraft's position relative to the desired ATC
position, both pilot and controller are now equals in the ATC process. Also, if desired, all aircraft of concern and the ground central ATC system can determine by reception of simple timing marks (not a data link) if the desired spacing, speed, track deviation of the aircraft is occurring. All data is in simple synchronous time markings as a part of and in terms of the signal format of these superior coordinates (reference 11).

This national grid system of high quality coordinates is aimed primarily at the missing half of the ATC control loop, namely, the pilot and his aircraft controls of all types of aircraft (airlines, military and particularly the 200,000 or so general aviation aircraft). Cost and performance must be adequate for all levels of users, even "Cessna" 150 users.

OPTIONS FOR MORE PILOT PARTICIPATION IN ATC FUNCTIONS

It is obvious we must identify several practical options for this new national service of (1) a uniform positioning-guidance grid and (2) SSR surveillance, so adequate validation testing will be completed permitting then some designated government authority to adjudicate the matter on the basis of quantified, measured and tested (1) technical merits, (2) economics, (3) funding levels, (4) savings, and (5) cost benefits to the users of all types of aircraft, all types of airspace, and all densities of traffic.

Until these options have each had perhaps 10 to 20 million dollars spent in many objectively oriented R & D programs averaging about 100 thousand dollars each, there can be no such objective. We are relegated otherwise to determinations. Only the committee reports and committee designs
we are all so familiar with, and which usually contradict each other.

We can develop a matrix of many typical low-cost validation efforts that should be a combined nationally oriented effort of DOT/NASA/DOD to create a total-national plan. We now have a model of how many to create a new national plan. The/microwave landing developments of the years 1961-1968 permitted a 1968-1971 (RTCA) analysis of what a plan for a new national system, costing about one billion dollars, would look like technically and operationally. It is suggested we follow this same political-technical-operational route here/only after the several 1/10 million dollar (100K) projects are completed as adequate/measured, "real world" data on which to base the decision-planner process. Current/data is completely inadequate for such a plan in spite of the many well intentioned committee reports on future ATC concepts.

One of possible three future ATC options should be the concepts herein called "Broadcast Control" of air traffic at all densities whose main objective is to involve the pilot in the ATC loop to a much greater degree in the future. In so doing, we can add to the ATC system more integrity, reduce the controller workloads, prevent "over-dependence" on automation (computer control) of ATC, and, most importantly, meet the cost-benefits criteria of all users. Primarily, users down to the lowest economic strata must be accommodated so they are in no way excluded from the ATC system. They are now probably being discriminated against with plans for costly three-dimensional VORTAC Area-Nav, IPC, CAS, data links, etc.—proposals that could readily run the minimum electronics cost to enter any ATC area (called positive-control areas) to about 50 thousand dollars.
One gets what he pays for in aviation as elsewhere, but the minimum service for the lowest economic strata of aviation should be in the "less than 5 thousand dollar" category for ATC (transponder), PWI, communications (voice-VHF), guidance-navigation (VLF-LF) displays, etc. Assuming that all electronic elements for basic ATC are as widespread in production (and thus cost reduction) as the current ATC transponders that sell now for 500 dollars, yet meet FAA/RTCA/ICAO specifications. In about 600-dollar steps we would have a "minimum operating characteristic (MOC) so that each function would cost between 400 dollars and 1000 dollars, giving a total of about 6 to 8 major functions for full ATC within a 5 thousand dollar limit.

THE DESIGN OF ATC SYSTEM FOR PILOT USAGE

Since the discussion is oriented toward design of ATC for the pilot rather than the controller, a short historic analogy might clarify this philosophy. The critical aspects of the pilot in any new aeronautical venture is best dramatized by the unintentional competition between the Smithsonian Institute and the Wright Brothers — the goal of each being the first to discover a man-carrying powered aircraft. The Wright Brothers were both the designers and the pilots of the research aircraft. They appreciated the non-mathematical aspects of the human pilot requirements to such an extent as to spend two years in preparation for their powered flight by building gliders, teaching themselves to fly them in a safe environment (over sand dunes), and, most importantly, means for their control (elevators, rudders and wing warping).
Although powered models had flown before in calm air with pitch and yaw controls, apparently only the Wright Brothers appreciated the full significance of roll control as being essential to the pilot. This they gained from studying the piloting problems firsthand, inventing roll controls about 1899 and building it into gliders for pilot tests preceding the design of a powered, man-carrying aircraft.

The Smithsonian program to develop the first aircraft was on a grander scale and resulted in an aircraft, engine and pilot to be launched from a ramp built on a large houseboat, anchored in the Potomac River. The pilot was simply expected to ride down the elevated catapult track and fly out over the water, having never piloted such a device in the air before. This seems to imply the Smithsonian scientist believed that piloting was a minimal matter, perhaps as simple as riding a bicycle. Of course, aviation history notes the immediate crash of the aircraft in the river.

Years later it was argued the Smithsonian aircraft could have been successfully flown in all environments, but this proved false in an actual analysis, as roll control was not part of the design (see F. C. Kelly, "The Wright Brothers").

However, the main point to be emphasized is that the very invention of the airplane itself was only possible by the direct involvement of the pilot in the process. The Wright Brothers succeeded where others failed since they comprehended the piloting problems as well as the aeronautic problems. Although ATC engineers cannot combine both disciplines of pilot-engineer, it behooves the ATC engineer to fully comprehend the pilot-aircraft aspects before proposing changes to our aging ATC system.
Today pilots and engineers know how to control aircraft to keep them aloft and to land them. However, the new era of aircraft in the 70's and 80's control is one of precision, three-dimensional control in a defined airspace environment along with many other aircraft and in nearly zero visibility.

To avoid collisions with others, safe, efficient passage through airspace filled with unseen aircraft and to land without seeing the runway is something again demanding the full involvement of the pilot before it is solved. The electronic specialist who, like some early aircraft inventors, ignores the pilot and does not study and fully understand how to include him as an integral part of the design of new ATC systems, will meet the same fate as those who did not appreciate the pilot involvement as the Wright Brothers did. The Wright Brothers were proficient designers of wind tunnels, engines, propellers, control surfaces, structures, and total systems, but every aspect of the design considered the pilot as the control element, and each aspect of the system design was tailored to his needs and survival; so it is with the design of ATC for pilots.

From foregoing views of future ATC systems, it is important to analyze each step of the many competing concepts. It will be argued that the Broadcast Control concepts not only should be realized for less costs to all users as well as to the government, but that added integrity will make the system safer, will have greater capacity, etc. The rationale for such views is complex and will be presented in variations to attempt to clearly state this major issue that will determine the success or failure of our ATC modernization efforts in the coming decade. Clearly, when we enter the domain of the pilot, his psychology, abilities, and limitations, the aircraft
pilot displays, pilot responses, aircraft responses, etc., we are depending upon a clear understanding of all of these functions separately and in combinations under an ATC environment. These considerations cannot be left only to electronic engineers, controllers, or installers of electronics. Such pilot-ATC responsibilities must be determined by engineers with interdisciplinary training and experience in aeronautics, flight dynamics, pilot psychology, pilot response, and the coupling of the pilot and aircraft into a cohesive unit when reacting in a given ATC environment. Neither can we leave this problem to a mathematician who writes a formula for the pilot control loops and leaves it there. We must now learn to provide the full communications essential between the aeronautical and electronic aspects of ATC, even though at present and in a bad state/need repairing; if we hope to actually move forward in ATC technology.

SOME SPECIFIC PILOT-ORIENTED ASPECTS OF ATC

Probably most important in ATC planning is to establish what the pilot participation should be in ATC. The first step is make a list of the future ATC areas he will potentially participate in, making sure the list is comprehensive. Then we will examine means to validate his participation in each area and compare it to the ground control portion to assure that the pilot-controller complement each other and are interfaced optiminally. Then we can trade-off the ground-oriented ATC functions against the pilot-oriented ATC functions, creating what redundancy is needed from a total system viewpoint. We then create a more balanced concept of
ATC and future trends than now exists. What is currently lacking is this understanding of the pilot and tools to do his job. At present we are heading toward more and more ground dominations either in the control process or in over-burdening the ground electronics or controller. Added traffic loads of the 70's will overload such ground control concepts beyond what can be done safely and is economically justified. Enormous new capacity is needed in ATC for the ten times growth indicated for 1990.

In order to cite a specific example illuminating the last point, let us note how the SSR "L" band radar-ATC surveillance system operates for data to the ground controller and how it compares to the pilot data. According to FAA reports (see description of SSR "EAIR" facility in FAA report NA 70-3(RD 69-53), this system used as a measurement tool, is shown to be accurate to less than 0.1 degree in angle (out of 360°) and with less than 200 feet error in range (out of 200 NM).

This does not imply all SSR data supplied to the ground controller is this accurate, but even if degraded, we would have a 0.2 degree and 300 feet granularity in the surveillance system. At 60 miles from the SSR, 0.2 degree represents about 1/300, or about ±1/5 NM. Compare this to the pilot's VORTAC data. The end product of aircraft position via VORTAC-R-NAV is about ±4.5 degrees for 2 sigma (95 percent probability) or ±4/2 NM at 60 miles. About 20 times degradation of pilot data over controller data is clear. VORTAC ATC errors include the VORTAC ground station, airborne receiver, and piloting display errors. Although the electrical errors of VORTAC total only about ±3 degrees, the inability of the pilot to use the VORTAC information any more accurately is determined
to be about ±2.5 degrees according to ICAO reports and the FAA reports. AC 90-45, an FAA report entitled "Approval of Area Navigation Systems for Use in the U.S. Airspace System," clearly states this limitation and large discrepancy of 20 to 1 between controller ATC inputs and pilot ATC inputs.

The interrelationships between what is called "Flight Technical Errors" and the (electrical) station, VHF propagation, and receiver errors is very direct. A pilot cannot be expected to fly a course whose indication of center is in error, "wanders," and has "bends," to anywhere near the accuracy that he can fly a course that has minimal errors, bends or perturbations using a stable display of optimum sensitivity.

Thus, a system with poor accuracy and course disturbances not caused by aircraft displacement causes the pilot to amplify the total track deviation and thus ATC error. The final aircraft position and guidance efficiency of VOR-DME created flight path perturbations that are caused by this 20 to 1 deficiency of pilot data as viewed by the controller's ground displays. Such track errors are greater than the merely electrical errors of the system. So aircraft must be separated greater distances for this reason, lowering ATC system capacity.

On the other hand, an ATC guidance-track-navigation system that does not create these piloting problems can be flown with far less electrical error which in turn means far less "flight technical errors." These improvements are interdependent, adding to the total useful system accuracy and thus ATC capacity-safety. The piloting aspect of "Flight-Technical error" noted in our standard is very
complex and seldom measured scientifically. We will outline some of the interrelationships that require analysis from the views of (1) the pilot and his displays, (2) the pilot and his "coupling" to the aircraft, and (3) the direct automatic coupling of the aircraft to the guidance system. All three of these generalized cockpit problems have their own peculiarities and must be fully understood before any of the many "future ATC" systems now being proposed for improved pilot participation in ATC will ever become a reality.

Although dozens of reports exist on electrical errors of VORTAC, only one or two exist on the impact of these errors on the pilot and the controller who sees the pilot as deficient through the superior "eyes" of the SSR in an angular system 20 times as precise as VORTAC.

**SURVEILLANCE VS PILOT NAVIGATIONAL ACCURACY**

Let us now compare the surveillance accuracy of ±0.2 degree and 300 feet to the Area-Nav accuracy of 4.5 degrees and about 2,000 feet. Angle data is the critical comparison since the VORTAC angle is proportionately much worse than range accuracy, both being polar coordinate systems. Range error is usually a linear function not differing too much with increased distance from the emitter. Obviously, in a polar coordinate system, the angle errors, measured in linear terms such as miles, increase with distance from the source. They also vary in orientation relative to the flight track orientation.

The SSR error of ±0.2 degree is displayed to the ground controller as a positional error of 60/300 or only 0.2 NM at a range of 60 NM, while the pilot's VOR total flight track error is ±4.5 degrees,
or 60/13, or about ±4.5 NM. This difference of about 4.5/0.2 or in excess of twenty times is of major concern in any ATC system planning for the future where the pilot will be asked to become a more active element in the ATC process and must be able to do a better job than now possible with VORTAC. In fact, identical accuracies of pilot displayed position-track and controller displayed position-track seem essential before any real progress can be made.

It plainly is not fair to the pilot and the aircraft control systems to compare the performance of an SSR ground display that is twenty times more precise than the basic information given to and executed by the pilot. Merely relaying the precise ground derived data to the pilot (after computing-processing, etc.) is also unfair to the assessment of pilot ATC participation since the pilot is then at the mercy of the same system as the controller, and any failures wipe out both parties and safety levels are decreased. Furthermore, SSR was not developed for pilots; only controllers were considered and all system decisions optimize the controller aspects of SSR, making its basically a poor second choice for aircraft pilot usage via data link or other means.

Thus, although one praises SSR for its ground derived data, it is already working at full capacity and should not be further modified for both pilot and controller but only be modernized to work better as a surveillance "only" system and specifically not attempt to make it into a navigational system by remote control means. It is dangerous planning and quite unfair to the pilot to assume he will not be given directly a new coordinate system but only second-hand SSR ground derived data. There are many shortcomings a massive
electronic ATC system on the ground can cope with or a controller can modify by switching computers, codes, displays, radar inputs, etc., that the pilot cannot do as all such controls are on the ground. To give to the pilot the degree of sophistication that the controller has with his many inputs, multiple-redundant displays, computer backups, etc., would be prohibitive. It is essential to safety in a central ATC surveillance concept as anyone can witness by touring an ATC center, such as New York, and then going through the basement areas viewing some 40 million/electronic facilities and/technical staffs that create the "pictures" for the controllers' benefit.

Such enormous redundancy and complexity can be justified in a large building with 100 to 200 employees on duty at all times, representing perhaps 10,000 lives since an ATC center serves up to 200 or more aircraft at a time.

A modern, high-density tower is somewhat less complex but still a major display electronics marvel. Since an aircraft of SSR remoted data would have none of this back-up capability, the pilot would be at the end of a long line of complex electronics with so many intervening elements that any one with an added one, data link, could create chaos.

There seems to be little the pilot can do to become a more active participant in ATC, as many ATC experts/seem to be suggesting, without giving him a new system that is equally suited to his peculiar needs and ATC responsibilities of track, schedules and separation. Yet, any new facility for the pilot must be fully harmonious with the rest of the ATC system. By going to the appropriate rectilinear coordinates of a wide based LF/VLF navigational system, we can give the pilot at low airborne costs a means (using a new national
network of 4 to 6 stations), an excellent track system. On the average, the quality, accuracy/coverage, equal to or better than the SSR system.

While the SSR surveillance accuracy varies with range, being useful to 200 miles, where we must recognize that 10.2 degree is a spread of error of about a mile, while in the parallel oblique coordinates of a specifically designed LF/VLF system for ATC in the United States the errors should be about 1,000 to 2,000 feet. Obviously, engineering precautions are used in the design of such an LF/VLF system using such features as automatic diurnal corrections, higher station sampling rates, localized differential data, etc.

Each of these elements of a new ATC LF/VLF system does not increase the complexity of local usage of LF/VLF (or even Omega as it is) since the number of pilot adjustments, selections, etc., will be equal to or less than the number of pilot actions required for a VORTAC station to cover the same volume of airspace (say, 150 X 150 NM from the surface to 40 thousand feet). Thus, in comparing the actual "real world" usage of the surveillance (ground) ATC functions of displays, computers, etc., with the airborne on-board derived data from LF/VLF coordinates, we will find on the average that pilots' LF/VLF data will equal or exceed in many cases the SSR data due to the limit of, say, 1,000 SSR stations in the United States. Meeting surveillance accuracy on its own grounds means equality of total area accuracy / a national granularity average/is possible with LF/VLF systems. A 20 to 1 degradation (as in VORTAC) is also avoided as well as its similar line of site limitations. In fact, LF/VLF will be shown to provide many services to thousands of remote
fields that would otherwise not receive any service from ATC.

This VLF/LF capability can be realized for as little an investment as 2,000 dollars or less for airborne units designed for general aviation, yet suited for selection of way-points from a few miles apart up to hundreds of miles apart, with linear track deviation displayed to the pilot, as noted in a recent flight demonstration by a manufacturer. More sophisticated receivers, "course and way-point" selectors, displays, etc., could cost in an airline version perhaps as much as 10 thousand dollars. In both the quality levels the airborne units should still be lower in cost than a comparable wide Area-Nav service with way-points, etc., inertial, from any other source, such as VORTAC, Doppler, etc.

NATIONAL PLANNING FOR NEW ATC CAPACITY FOR ALL USERS

What is lacking in planning for a future national ATC system is something that obviously must be evolutionary in nature, but evolves toward more pilot participation. What is now needed is a series of tests and analytical treatments of the various candidate ideas. They are in the general classes of:

I. DOT/ATCAC; IPC "up-link" on Transponder

II. Telemetering and processing of SSR digital data from the ground controller's display inputs giving a cockpit pilot's display (using a cathode ray tube)

III. Area-Nav using VORTAC with 3-dimensional corrections and with its constraints of degrading angular errors

IV. Wide Area-Nav using a (LF/VLF system derived from Omega), creating a nearly rectilinear national
grid whose average and uniform accuracy is 20 times better than the VORTAC (in the worst cases) and about 5 times better in the average cases. With simplified time sharing signals the coordinates can be used in roll call for a low density, low cost surveillance, separation system as well.

V. Air-derived collision avoidance systems.

Each of these cases need not be examined too much in their electronic aspects except for No. IV where not much data exists on aviation applications. Considerable data exists on the others.

What is needed is a means to evaluate the proposed methods for increased pilot participation in the ATC process. What the pilot can do with the new information, whether it increases his work load, whether it works in both low and high density traffic, at major hubs and remote strips, and certainly whether the redundancy and integrity are increased, leading to greater safety. The so-called "flight-technical" aspects of the five solutions to pilot participation in ATC must be stressed in evaluations much more than in the past. We will discuss some of the possible means of introducing in the engineering of a system/flight technical aspects, not just some pilot opinion poll as has often been done in the past.

The total national planning for advances in ATC technology must assume that both the pilot and his aeronautic counterparts are as well represented in the decision process as the electronic experts and the ground controller authorities. The latter now seem to dominate the national ATC decision processes.
WHAT IS MEANT BY THE "FLIGHT-TECHNICAL" ASPECTS OF ATC

The phrase, "flight-technical," originated with the early post-war IATA and ICAO technical committees that were purposely balanced, giving the pilots and aeronautic engineers the "flight-technical" problems and the electronic engineers and the controllers the "radio or electronic" technical committee assignments. As noted previously, one of the best ways to introduce this subject is to cite a specific example.

In a system such as VOR which has a total of ±4.5 degrees of error, of which the r.m.s. value is composed of 3 or 4 sources—one being the pilot response to his VOR display at a value of about 2.5 degrees—it is often thought that this pilot or flight technical error component can be reduced relative to the other values. This is usually not true since the noise perturbations, multipath degradation, course bends, etc., often determine how high the flight track deviation indicator sensitivity can set. This is a figure often empirically arrived at, based on estimates of pilots and with few scientific measurements. For example, if the flight track is a line in space, represented by a wavy, curved line due to multipath, low space pattern sensitivity, etc., the pilot will attempt to follow some of these undesired perturbations to the indicated VORTAC track, be it "raw" VOR or computed Area-Nav. The pilot in following a centered track indication, such as a zero-centered meter, must blindly assume that a given deviation indication represents a certain track error in space measurable in a given number of feet. He then turns his aircraft in response to the displayed deviation with his horizontal course indicator or other steering device that
mixes heading and track. Such combinations of track and heading are required to intercept the track and drop on it "dead-beat" without passing through it and then bracketing it to lesser amounts, requiring two or three damped cycles of track oscillation as recorded on the usual chart recorders.

If a rapid wind shear or other atmospheric turbulence occurs, this can shift the aircraft off course even with the same heading or if the heading is caused to shift in turbulence, results in pilot action (or autopilot action) to return to the center of the course. Even a perfect electronic path in space will see these maneuvers in rough air to cause the aircraft to stick to its earth-referenced course and track in space. These can be quite small changes requiring small deviations (corrections).

For example, in an ILS approach the full-scale pilot indication at threshold is ±150 microamperes for ±350 feet, shown in a display about 12 inches in dimension. The pilot is expected to control to a threshold condition, so with a flight technical error of no more than about 20 feet, according to the tentative ICAO and FAA guidelines on CAT II and III operations. This means the pilot-displayed error must not exceed about ¼ inch. However, if this sensitivity (±350 feet) were used in a Area-Nav display, based on VOR inputs, the indication would be so unstable as to not be usable. Usually sensitivities of about ±2 NM (±12,000 feet rather than ±350 feet) for full-scale indication are used. With an indicated course width of 4 NM or about 25 thousand feet vs the 700 feet at the runway threshold for ILS, pilots must be adaptable, but the spatial guidance stability in feet must be high in the latter case.
ILS simply has much more antenna sensitivity in db per degree and is at closer range so that this difference of about 25 times in the pilot deviation indication is necessary to provide stability in VOR displays. Thus, the pilot must fly with widely varying "gains" in his responses to these indications. Certainly a 50-degree heading change on a VORTAC at 50 NM will create a slowly changing deviation to correct an error back to center. However, if this 50-degree intercept angle were used in an ILS approach near the airport to correct a % scale deviation, the pilot would overshoot the course and into a maximum deviation in the other direction in a few seconds. Pilots are apparently extremely adaptable to this type of display variation and do the best jobs they can. However, as noted, we are now giving the pilot the ability to only position his aircraft with approximately something much less stable and accurate by/as much as 20 times worse than the ground controller's data. If we now say to ourselves, how do we have the pilot fly a track in space so that he will be within much smaller error limits as the controller's display indicates than we have in the past, we will see the quality of guidance must be higher, approaching ILS quality rather than VOR quality. If this pilot response occurs, many things accrue automatically to the benefit of an ATC system, the controller and the pilot.

First, the communications load is reduced since pilot errors are reduced and he is where ATC desires him rather than up to a few miles off course that can be attributable to a poor VOR station (each VOR has an error characteristic differing from the next VOR). Secondly, we can ask the pilot to adhere more closely
to his track, thus increasing the separation between adjacent tracks. Next, since the LF/VLF track is created by a rectilinear type grid system—equally accurate longitudinally as well as transversely to the track—we will now ask him to observe track speed and separation in dense traffic greatly smoothing traffic flow. This track velocity is equivalent to the ground speed indication often used with DME when it is known the track is on an absolute radial to the station. Such a case is a DME on the localizer course, where the aircraft is always on a radial-only path. In Area-VORTAC-Nav, this track speed is not available since the VOR rate is 20 times worse than DME and the geometrics of the R-NAV track will encounter these large track speed errors.

In LF/VLF techniques this ground speed feature, admired by many pilots but only available in a very limited way in VORTAC, is available on all tracks in all directions, with uniform track velocity outputs. Admittedly, the U.S.-only LF/VLF complex must update about once every 3 to 4 seconds. This essential pilot ATC function cannot be realized with any useful accuracy with VORTAC inputs since the angular perturbations, station to station registry, height corrections, slant range errors, etc., all create a track velocity that is also unpredictably up to 25 times worse than the ATC track velocity as computed in the ground computers for the projection of conflicts and avoidance of collisions. The present position of the aircraft is extended electronically for a given time into the future as are all other aircraft to detect obvious conflicts or potential collisions and informing the controller so he can anticipate before the occurrence as to what is the best maneuver to avoid the case.
Thus, we can envision that the pilot with the uniform navigational grid system can observe a cockpit display, much like an airspeed display, using standard cockpit instrumentation (not "pictures" or cathode ray tubes), the actual track speed. If all aircraft have an assigned track speed as well as three-dimensional tracks in space, that are coordinated initially in a flight plan integration (via a flight planning computer program), then we have a system that can run with little controller intervention.

For example, it would be quite possible to test pilots under synthetic conditions, using the two methods of maintaining spacing between aircraft (air derived and SSR telemetered from the ground computer). At the same time the displays must assume that the track speed is correct (in addition to spacing fore and aft with respect to other common track aircraft at the same altitude). When the aircraft is alone without immediate spacing needs, the track speed may be just as significant since an airway juncture is ahead, forcing the single aircraft into a track containing a stream of aircraft. The aircraft's spatial "slot" of time and moving position must be accurately filled, by achieving both track speed and positional accuracy in three dimensions, on the path prior to the intersection with the other traffic.

It is believed that the pilot will prefer a standard instrument indication for this with a "bug" that is set by the pilot or by ATC communications to the desired track speed, just as an airspeed "bug" is now set. Such features are hard to add to a cathode ray display that is a relay of the ground controller's ATC displays with selected data. The intent here is not to modify
the principles of pilot displays but to suggest new pilot displays. These new displays are needed for ATC reasons. They should be consistent with what the pilot now accepts, which is 90 percent electro-mechanical rather than cathode ray displays. One reason the relaying of ground sensed data is probably a poor technique is that to obtain track velocity the SSR system would have to repeatedly compute it for each aircraft and transmit the separately addressed data continuously to every aircraft—an enormous burden for ground computers, data link transmission systems, airborne data link receivers, processors, and annunciator displays. A major part of the complexity of track speed measurement is avoided by direct on-board measurement of the traversal of the grid coordinates in space, using a rectilinear type, national grid.

**INTRODUCTION OF RATE FEEDBACK INTO ATC**

Any modern servo system uses two basic signals: one is displacement, and the other is rate (of change of displacement). The rate is often measured in mechanical servos with a separate rate type generator in addition to the usual displacement synchro-repeater that provides only displacement. Without rate in a servo system we have oscillations. If the oscillations are reduced by lowering the displacement sensitivity then we have delays, errors, etc., due to the sticking of the gears, etc. Consequently, neither solution is adequate with displacement-only systems, and some 30 to 40 years ago "rate" was added to mechanical servos (particularly in central fire-control systems for Navy ships).

However, in aviation ATC systems we are still working
with an old fashioned displacement system as far as the pilot is concerned. He essentially gets only the crudest of rate information such as arbitrarily assigned airspeed limits in terminal areas. These corrections are in large steps, with long periods between sensing and results (feedback is poor). They are of little value when spacings of, say, 3 miles or less are desired on a common ATC track. In visual "station-keeping", where the ATC tells the pilot to "follow the aircraft ahead," the pilot, by visually judging the direction, distance to the other aircraft using its image size/etc., is able to maintain remarkably accurate spacings. The controllers also assist with radar vectoring where instant-by-instant changes are commanded by voice.

However, as the system becomes more loaded we must provide this ATC "rate function" in some other way as the need for it will increase astronomically with the traffic density, making these current practices inadequate. Since the pilot has at his fingertips the actual rate controls—the throttles, drag elements, etc.—he should be given an instrument with a direct display of his track velocity and then permitted to adjust the aircraft according to its own peculiar needs/only he is aware of, such as weight, and any unique problems, such as partial power, so as to maintain this track speed to within perhaps 2 to 3 knots rather than wide limits of 10 to 20 knots, now possibly the best available by the pilot and controller estimating the conditions of winds aloft. Often a common terminal area track speed for all aircraft is used, and this assists greatly as one of the worst problems in ATC is variation in track speed of different aircraft in a mixed air traffic pattern. However,
this implies variable airspeeds depending upon direction of flight, wind direction, altitude, etc.

NON-PRECISION APPROACHES TO THOUSANDS OF SMALL FIELDS

Any future ATC plans should also accommodate the tens of thousands of airspace users that operate in low density areas. Namely, avoiding collision with high obstructions and providing a universal let-down procedure would solve the major problems. As we will see, LF/VLF coordinates are ideally suited for these applications, and with VHF communications and a transponder, a very low-cost Area-Nav approach system is possible.

In addition to meeting some of the dense ATC environmental problems, it is essential that the pilot participation also be involved in those geographical areas where medium and low density air traffic exists. Here, the mid-air collision is not such a risk as collision with the ground as noted in an ICAO survey. Collisions with the ground are the most prevalent, fatal accident in aviation, be it landing, approach, enroute, blundering into mountains, altimeter errors, etc. The solution to this low density problem is as much a part of our national ATC system as solutions to dense traffic problems.

It could be that we solve the ATC problem of a few high density areas with an abundance of everything, raising the participation costs and driving much aviation into the country and remote areas where essentially no facilities exist. This would create added traffic that would be exposed to higher risks due to lack of facilities to avoid collisions with the ground (and with others), since
no adequate means exist to provide coverage of the thousands of possible areas for small airports.

The IPC concepts would not work in such environments as the enormous amount of ground equipment and computation would not exist for it. The cost of the airborne receiver, decoding, etc., is beyond the reach of general aviation. This does not infer, however, that the basic SSR system will not spread its coverage throughout the nation to perhaps a 1,000-station network of the contiguous 48 states, since a basic station may now cost markedly less with modern digital designs (about 400 such simplified SSR ground stations are being purchased by DOT/DOD).

Thus, we will have surveillance functions covering the nation, using the estimated 100,000 transponders operating in aircraft in 1975. The sophisticated computers, displays, etc., will be only at major centers and airports that "net" many radars, etc. The high cost of an IPC site, such as a complex cylindrical phased array (see ATCAC report, reference ), will cost many times more than the simple stations using a small rotating SSR antenna. Thus, basic SSR will be quite prevalent in low density areas, but not IPC. It is argued here that the LF/VLF grid will cover all areas with equally good coverage whether they are low density or high density traffic areas, and thus we should base the use of the future ATC system on elements that meet both criteria.

A typical example is a so-called VOR "Let-Down" procedure which is widely used in low density areas and has contributed to many recent airline and general aviation accidents. This is a procedure where a pilot selects a VOR radial that may or may not
emanate from a VOR on or near the desired airport. It may be a radial to a remotely located VOR, as most of them are. The pilot then starts down the VOR radial from some navigation fix crossing the radial, perhaps another VOR radial or a marker. This initial point of descent on a non-precision approach is such that the pilot is from 5 to 10 miles away from threshold of the runway at a given altitude and descending at a given sink rate. The pilots have charts giving the sink rate for each VOR let-down. Sink rate is measured by rate of change of air pressure and has many limitations as does the barometric altimeter, both being pressure gauges of slightly different design but not inherently related to the physical height above the runway elevation.

These approaches are often to such limits as "400 and a mile," meaning that the pilot descends without seeing the surface until he is at 400 feet elevation above the airport and has one at and below 400 feet mile of horizontal visibility. Both of these values are poorly determined at most small airports as ceiling and visibility measurement instruments are costly. A typical VOR let-down is shown in Figure . To understand the method now used for establishing these criteria one must study in some detail the "TERPS" manual (Terminal Instrument Procedures) describing authorization of these non-precision let-downs. If a favorable case exists with a VOR actually on the airport, low ceiling visibility values may be assigned. The lower the limits can be established, obviously, the fewer the cancellations due to weather. Airport operations occurring on an annual basis/for most economic analyses/makes an airport with low limits a more commercially viable operation. Many small feeder
Of course, if one wants to go to ILS (glide slope, localizer, markers), lights, transmissometers, etc.—about a 500,000 dollar investment beyond the typical VOR let-down (non-precision authorization);—then a 200 and ½ mile or even a 200/6 mile precision approach criteria might be authorized at good approach locations. The cost for lowered ceilings probably goes as some inverse power of the MDA height, being possibly one unit for a "1,000-foot and 2 NM" MDA limit, and ten times that for, say, a 350-foot MDA limit, then rising to perhaps 25 to 50 times that for a precision approach to a 200-foot Decision Height (DH is a phrase used with precision glide path, localizer, approach limits, markers, etc.).

It is obvious that with up to ten thousand or more small airports and fields in operation by 1990 that facilities cannot cost 500,000 dollars for precision and approach capability. Nor can we tolerate having the MDA limits so restrictively high as to make the airport facilities, hangars, runways, fuel, radio communications, real estate, low cost lights, etc., a losing proposition. No one will operate these much needed, small airports.

A CRITICAL COMPARISON OF VLF/LF APPROACHES TO VOR/ADF APPROACHES

An analysis of the TERPS manual indicates one of the major decision points on MDA is the location of the VOR or ADF facility. Since VOR is far more likely to be used, we will continue the comments on this facility for the purpose of analyzing the operating and safety benefits of LF/VLF approaches in place of the current non-precision approach procedures and systems. Probably the key criterion for MDA is that the VOR must be within 6 NM or less of
the airport, or on the airport, to qualify for a low-visibility authorization, such as "400 and a mile." This specific value is picked as being somewhere in the middle of the dozens of MDA/DH authorizations ranging over 10 to 1 from 1,000 feet of altitude to 100 feet of height, and from a horizontal visibility (also ranging over 10 to 1) of 2 NM (12,000 feet) to only 1,200 feet for CAT II ILS.

If such an authorization as "400 and a mile" were available on a national basis nearly for free to all airports, regardless of size or location, this would be a major benefit to all airspace users, airlines, general aviation, VSTOL services, air taxi operations, private flying, business aircraft, etc. In fact, this ATC capability alone could set into being a chain reaction wherein the small aircraft no longer will be attracted to operate and depend on the large airport facilities, such as VORTAC, SSR, primary radar, extensive lighting, DME, glide slopes, localizers, surface detection nationally available radars, etc. A/(400-1) authorization could create a suitable reason for attracting many operations to more remote areas. Industrial parks are now very common, some states installing up to 50 such small airports, each as a heart of an industrial park, so that the 400/1NM authorization would allow good reliability in most places and enhance the safety of all operations. If growth occurs, then most importantly ILS could be added, but the dispersion of aviation would take place, something essential to sound planning of any future ATC concepts, as well as to the users of corporate and general aviation aircraft. Effectively, services with many options are offered with the cost benefits of a given aircraft usage, being the determining factor.
If, however, we must have at least a VOR on each small airport to obtain this 400/1NM authorization, we will not succeed since the cost of the VOR is still about 50,000 dollars when properly installed and monitored. Even if this cost and the continuous inspection maintenance costs could be met, there are few new radio channels available for adding, say, 3,000 VOR stations to small airports (one in three out of the projected total 10,000 population by 1990). The 6 NM TERPS criteria eliminates nearly all cases of a single VOR serving two airports. We must therefore seek another means of providing this major step in ATC technology.

As will be seen, it will be the use of the same concepts of LF/VLF sensors that permit the pilot to become more a part of the "ATC loop," using on-board, low-cost equipment. Another serious VOR constraint worth mentioning is the fact that the VOR let-down must be along a line of position in space from or to the VOR that crosses the runway centerline at angles no greater than 30 degrees. This criterion again severely limits the VOR authorization of a low MDA at many airports. Thus, the 30-degree and 6-mile rules of TERPS would force at least another 2 to 3 thousand VOR stations on the air or possibly "300 - ¼" to give a broad national use of "400-1 mile" criterion. (See Figure 1.)

To re-emphasize the unsuitability of such a VOR expansion, it would require radio channels that do not exist, cost probably over 100 million dollars for installation and about 5 to 10 times that amount for the "life-cycle" cost of modernization, maintenance, adjustment, monitoring, flight inspection, etc. A total national cost for a life cycle of 15 years for a national 400 -1NM capability using VOR would be about a billion dollars. For VOR this would be
VOR STATIONS IN SECTORS X-Y (240°) CANNOT BE USED

TERPS LIMITS ON USE OF VOR FOR NON-PRECISION APPROACHES TO A 400 FT MDA

FIG 1
added onto the current need to modernize the VORTAC network with "super VOR's" such as the Doppler VOR, increasing the total life cycle cost to perhaps 1.5 billion dollars. With knowledge and experience gained from 20 years of LF/VLF guidance and navigation development, testing, and operation of such systems as Loran-C and Omega, we could readily engineer and install for about 50 million dollars an entirely new network of 5 or 6 stations designed solely for the future ATC need to add "Broadcast Control" and to serve all economic levels. Life cycle costs would be much lower for technical reasons.

It is with such a view that inevitably major investments will be made. At least a few million dollars (20 or 30 of the 100 K validation and tests and studies) should be expended on LF/VLF by DOT/NASA/DOD before any decision is made. With such validated information, good economic studies, operational tests, and a truly scientific source of validation data exists from outside qualified sources to assure objectivity in the decision process. In other words, don't just extend VOR endlessly since that is all the FAA has early in inventory and the urgency requires it—but provide an option that may be far superior.

If, say, a case can be made for another 1,000 VOR stations, we would then have a total national investment in 2,000 VOR stations, many with double costs if DME is added in the so-called VORTAC versions. This would become a major cost burden to the FAA budget. Aside from that, the new channelization scheme of 25 kHz VHF channel spacing would be mandatory in an attempt to find enough channels for 2,000 VOR's. This subsequent, forced change would shortly
require the replacement of over 100,000 private VOR/VHF receiving units with more expensive units probably, each costing at least a thousand dollars (so-called NAVCOM units). Without expanding VOR we would avoid this total additional cost and channelization chaos, leaving VOR as is for many years since it complements the LF-VLF equipment in usage.

**APPROACH GEOMETRICS**

It can be seen from Figure 2 that a VOR must almost always be associated with every airport if there is any hope for a national usage of a 400/1 NM criterion meeting all criteria of safety, etc. Many collisions with mountains could be eliminated since LF/VLF is two dimensional and VOR is one dimensional. We must remember that the pilot will be dead-reckoning in the vertical plane, using the error-prone, barometric altimeter as no checks along the VOR approach are available except the outer check point that may be in error by a mile, since it may be an intersection of two VOR radials. However, the pilot will usually not be heading along the direction of the runway when he obtains his first visual contact and this is such a wide area, ±30 degrees, that it could be very dangerous with VOR. (Figure 3)

Furthermore, the vertical descent plane could be in error with an error in the outer check point and the next point, say, where the descent from a typical 1500-foot altitude (above the airport starts). If a typical 3-degree slope is assumed (in the sink rate), dead reckoning then will occur along the descent path. This operation of estimated actual height is along a path 1500 X 20 or 30 thousand feet long (or about 5 NM). Typically, head winds,
VOR TOLERANCES FOR TERPS NON-PRECISION APPROACH TO A 400-1 MILE MDA

**FIG 2**
AIR SPEED OR WIND ERROR IN DEAD-RECKONED DISTANCE FROM FIX.

NOT TO SCALE

RADIAL UP TO 30° TO 6 NM VOR WITH 4.5° ERRORS

HIGH RISK AREAS (SHADE)

EXTENDED RW CENTERLINE

AIM POINT FOR MDA OF 400'

OTHER 30° LIMIT OF 6 MILE DISTANT VOR

8,000 FT TO 400° MDA

TAIL WIND

HEAD WIND

SOME OUTER LIMITS OF VOR LET DOWN ERRORS AT AN MDA OF 400 FT. AIRCRAFT CAN ARRIVE WITH FIRST VISUAL REFERENCE IN SHADED AREAS THAT MAY CONTAIN OBSTRUCTIONS.

FIG---3---
wind shear, barometric error in setting or use, and the horizontal variables (up to 30 degrees off-axis) make VOR let-down a very unattractive future concept even though acceptable up until now.

Several accidents in the years 1969-1971, including some airline accidents in the Northeastern part of the United States, can be traced to poor VOR let-down procedures, wherein the total procedure has so few checks and balances that its use is hazardous, even for the highly trained airline pilot.

**VLF/LF LETDOWN PROCEDURES CAN CREATE A CENTERLINE TRACK WITH RANGE CHECKS**

With the use of the nearly rectilinear grid system of LF/VLF coordinates, several of these serious (VOR letdown) limitations are overcome. (See Figure 4.)

1. The "waypoint selection" is a waypoint to the end of the runway using LF/VLF.

2. No DME is added either to the ground or the aircraft, but

3. We will have effectively a DME (along centerline) capability, giving continuous longitudinal checks of position so altitude corrections can be made rather than only one vague initial altitude check at the time of the beginning of the descent.

4. Probably most importantly, the non-precision approach flight-track is parallel to and on the checkline of the runway, avoiding a 130-degree heading change and track error at MDA up to 4,000 feet.

5. Approaches can be made to any runway. Since many such small fields have cross wind runways that are useless in low ceiling weather as they do not meet anything but the circling criterion,
LF/VLF offers continuous height check during descent.

Outer fix can be selected not requiring an actual unit.

Distance: 400' MDA

Longitudinal error: Small on visual contact

Wind and/or air speed errors: During dead reckoned flight of 4-6 NM

Only a visual check after the fact.

Single outer fix site must be found.

Lack of longitudinal checks on altitude on VOR non precision approach is possible cause of many recent fatal accidents.

Fig 4
a criterion even more hazardous and with higher limits than our 30-degree, 6 NM criterion. At cross wind runways using LF/VLF, straight, centerline approaches can be made to four thresholds with an equivalency of DME on each, greatly reducing the approach minimums at that airport since the positional breakout "scatter" at MDA will be reduced by a factor of as much as 10 times, permitting a continuation to land under visual conditions.

6. Simple computations can be set up, by the pilot turning two knobs or so to create a path in space something like a crude glide slope using one of the many VLF/LF LOP's that cut across the flight track (localizer track) to the runway. This can give a distance to go to threshold to an accuracy of about 1,000 feet or perhaps even 600 feet (according to Navy "Rendezvous" tests with Omega), since the runway coordinate values are derived by an LF/VLF receiver in the local area referenced to the end of the runway. This difference in value is continuously supplied with barometric altimeter data to avoid any diurnal errors or pilot errors. (See Figure 4.)

This VLF "differential" VLF/LF receiver, essential to our concept, may cost about 5,000 dollars as it does not have to "track" precise at a given velocity but merely measure statically the position of the end of a runway in terms of the LF/VLF coordinates. One such receiver might serve a radius of about 50 to 100 miles since the differential corrections from a fixed, surveyed point (receiver location) are highly predictable. When, say, 1,000 such receivers are produced
VOR LET DOWN PROCEDURE IS OPEN LOOP IN DISTANCE FROM DESCENT FIX CAUSING INCREASING ERRORS AT MDA THAT MAY VIOLATE THE OBSTRUCTION CLEARANCES.
Simple geometric analysis and the attached illustrations will show why so many collisions with the ground often occur in such procedures since the pilot is actually descending into the altitude region containing obstructions. With the LF/VLF coordinate system, there are everywhere (any airport in the United States) at least 4 lines of position (LOP's) such that two pairs of LOP's are used to compute a course parallel in direction to the centerline and coincident with the centerline. Another simpler computation determines the distance to the threshold (often called a way-point). This system, using a low-cost receiver, only offers essentially a continuous indication of distance to threshold. That is, a permanent ground-referencing system exists at all airports with no local installation other than a possible reference ground receiver to supply exact coordinates to the pilot. The approach is not "open-loop" as now encountered longitudinally in VOR letdowns.

The/coordinate, let's call it the DME coordinate, is as accurate as the other, which is equivalent to a localizer, both being about 500 to 1,000 feet in accuracy. Thus, we can define the threshold to about 1,000 feet or maybe even ±600 feet according to some data. This terminal condition at threshold or way-point is shown as a distance to touchdown and is employed then with the barometric data to give a safe descent path as compared to VOR (see Figures 4 and 6).

SUMMARY OF A NEW 400 - 1 NM NATIONAL AVIATION SERVICE

Essentially, we can eliminate most of the deficiencies and hazards of the VOR letdown (non-precision approaches) as well as the
costs of hundreds of more VOR stations. The LF/VLF system avoids the angular intercepts; its tracks are all parallel to the extended runway, avoiding a serious turning and psychological orientation problem when breaking out at 400 feet. A DME-type function is realized for free using the same LF/VLF receiver-processor as used for centerline. Outer fixes can be eliminated as well as probably many markers and superfluous VOR stations. The pilot will obtain what is an equivalency combination of DME, VOR, course line, precision altitude correction, etc., with a receiver only. A 2,000-dollar cost seems likely for a general aviation unit based on at least two commercial designs now under test. Low altitude coverage and approaches to all runways of a small field are easily accommodated. A single reference receiver shared with 10 airports would prorate the only airport cost for such a service to about 500 to 1,000 dollars per airport. The total service to 10,000 remote and small city airports of the nation can be provided with about 4 to 6 stations at LF/VLF specifically designed and installed for this purpose. Another 1,000 VOR stations needed for the 10,000 small fields to give a 400 - 1 NM capability nationally would cost through their life cycle about one billion dollars and require new 25 kHz VOR receivers. An LF/VLF net to provide a national minimum of 400-1 NM at all such airports will cost a small fraction of this amount for an equivalent life cycle.

A minimum national safety standard of a simple to use, 400 - 1 NM capability would probably reduce the fatalities in this area of air safety so extensively as to create the savings equal to the cost of such a 4 to 6 station network. Experience may indicate "300 - ¾" is also safe with LF/VLF (see Figures 3, 5, 6-10, 11). It is time general aviation
NOT TO SCALE

COURSE DEVIATION INDICATOR (CDI) HAS CONSTANT DEFLECTION FOR FULL SCALE ERROR MEASURED IN FEET AT ANY POINT ON THE NON-PRECISION APPROACH MAKING PILOTING MUCH EASIER WITH A DIFFERENTIAL LF/VLF APPROACH GRID

DIFFERENTIAL REF. POINT

LF/VLF COORDINATES

CONSTANT DEVIATION SENSITIVITY IN BOTH AXES

PLAN VIEW

WITH A VOR APPROACH THE ANGLE FROM RUNWAY CENTERLINE CAN VARY AS WELL AS THE DISTANCE TO THE VOR STATION; IT MAY BE ON THE AIRPORT SO THE PILOT COURSE DEVIATION INDICATOR WILL HAVE A FULL SCALE DEVIATION SENSITIVITY MEASURED IN FEET THAT CAN VARY BY 20 TIMES OR SO AT THE CRITICAL 400 FT MDA

PLAN VIEW

HIGHLY VARIABLE SENSITIVITY IN THIS AXIS AND OPEN LOOP IN THE OTHER AXIS WITH VOR NON PRECISION APPROACHES.

PILOTING PROBLEMS INCLUDE VARIATION IN SENSITIVITY OF THE COURSE DEVIATION INDICATOR WITH VOR; WHILE IT IS CONSTANT WITH LF/VLF PILOT IS OPEN LOOP LONGITUDINALLY IN VOR, AND CLOSED LOOP WITH LF/VLF

FIG 6

52A
be guaranteed a minimum national approach standard at all airports throughout the nation, regardless of their size. One hundred thousand users are possible.

USE OF AREA-NAV VORTAC

The foregoing relates to the use of a VOR only service such as the VOR letdown procedures in the TERPS. However, modern instrumentation now allows the computation of position in rectangular coordinates from the VORTAC polar coordinate source, using the VOR receiver and a DME. However, this infers the use of all 360 degrees of the VOR bearing data, not some limited and selected/radial as in the past for an airway. For the basis of Area-Nav accuracy, all angles including the worst must be considered.

The worst case accuracy (maximum error at any angle within the 360-degrees of a given VOR) must now be considered for a non-precision R-NAV approach since there is no way to predict the runway displacement and heading from the VORTAC station relative to this poor angle-data sector.

The FAA has fortunately conducted some well documented tests using the "VAC" Area-Nav computing system fed with a good VOR and a good DME airborne equipment. The "VAC" Area-Nav computer costs about 10 to 15 thousand dollars. This cost is in addition to the cost of the VOR/DME equipments (combined being about 3 to 4 thousand dollars more).

In the FAA report RD 70-11, "An Evaluation of the VAC Model 5-A, Area Navigation Equipment," dated May 1970, we have some measurements of these VORTAC Area-Nav errors. If the error is mostly
FAA source

R/W - VORTAC ORIENTATION

ATR VORTAC

R/W 14

![Diagram](image)

LEGEND:
- --- DESIRED TRACK (R/W BEARING)
- ---- PILOT C TRACK
○ DESIRED POSITION AT 378' (400' MSL - 22' FIELD ELEVATION)
× ACTUAL POSITION AT 355'-395' (PILOT INDICATED FAILURE)

FIG. II-3  CAPE MAY 14-ATR ORIENTATION RESULTS  
(VAC 1NM FUNCTION)

FIGURE 7
FAA SOURCE

R/W - VORTAC ORIENTATION

DISTANCE TO THRESHOLD ALONG DESIRED TRACK (nmi)

LATERNAL DEVIATION (nmi)

1.00
0.75
0.50
0.25
0.00
0.25
0.50
0.75
1.00

LEGEND:

--- DESIRED TRACK (R/W BEARING)
Pilot A TRACK
Pilot B TRACK

◊ DESIRED POSITION AT 313° (400' MSL - 87' FIELD ELEVATION)
⊙ ACTUAL POSITION AT 290°-330° (PILOT INDICATED SUCCESS)
× ACTUAL POSITION AT 290°-330° (PILOT INDICATED FAILURE)

FIG. 11-8 MILLVILLE 32-SIE ORIENTATION RESULTS (VAC 1NM FUNCTION)
approach threshold or MDA error is variable for every VOR, at every angle of the VOR, and every geometric disposition of the VOR relative to the runway distance direction, etc. This is to say, there is no uniformity in VORTAC R-NAV errors, and one must consider the worst cases, not the best cases, when considering VORTAC. Since the threshold MDA errors vary by as much as 20 to 30 times in determination of where the pilot actually is when he is at 400-feet altitude, ±1 NM is probably the extreme, according to Figure 9.

The pilot cannot be expected to be aware of the amount and direction of these errors. All he knows is that when he uses a VORTAC R-NAV computer, he is at the mercy of the computer output. Although it may be damped and "smooth" it is impossible to extrapolate the varying errors relative to the amount of radial or cross radial motion with respect to the VOR. The final Area-Nav indication is usually a display like a localizer that is about ±1 NM wide (or a 12,000-foot wide track whose center may be off an equal amount). It is questionable to claim that R-NAV will give an "ILS equivalency" at all non-instrumented runways. It may come close occasionally where a VORTAC is actually on the airport. But when/off the airport VORTAC accuracy is greatly reduced in centerline performance as compared to a centered, standard localizer. It is quite unrealistic and misleading for the sales promoters of R-NAV to make such claims for VORTAC's up to 20 miles distant, or maybe 5 to 10 miles distant, which are the usual cases at small airports.

One cannot use "RMS" or other smoothing criteria normally used to quite VOR accuracy. A 6-degree error, although only appearing in a small sector around the VOR, may be lost in the RMS value, but
TYPICAL VORTAC ERRORS USING AREA NAV COMPUTERS

TAKEN FROM FAA REPORT

FIGURE 9
it is still 6 degrees if it happens to lie along or near a computed Area-Nav track to a runway. The FAA report (noted above) clearly points this out. A combination of a few of the error figures into a single scatter diagram is shown in Figure 9 and gives some idea of the distribution.

As can be expected, one should allow at least ±1 NM for the use of VORTAC with or without R-NAV computers when any of the many thousands of combinations of runways, runway directions, and VORTAC's, all taken on a national basis, are considered. If, for example, it was decided that no airport with a 400 - 1 NM authorization would be greater than 6 miles from a VORTAC, then we would have a VORTAC in every direction spaced about every 12 NM, or a total of nearly 20,000 VORTAC's nationally. Even so, at 6 NM we see that a typical operational error spread is about 5,000 feet, and in worst cases of poor VOR sites, this may be as high as a spread of 7,000 feet. This must be compared to an LF/VLF system that does not have angular errors or angular dilution. With a differential LF/VLF system, a local or national diurnal correction signal can be employed as all coordinates are shifted, not just a few selected ones. This is to say, there is no standard VOR error curve that can be used for correction of specific VOR signals as there is with LF/VLF. With proper engineering of a new national LF/VLF aviation system, probably 600 to 1,000 feet of accuracy. (See Figure 10.)

The LF/VLF errors are uniformly predictable across the nation, being the same value for an airport 30 miles from a VORTAC as one with a VORTAC on it. It is almost equivalent to say differential LF/VLF is as useful as a VOR on every small airport or strip.
NOT TO SCALE

DIFFERENTIAL - LF/VLF
NATIONAL COORDINATE
SYSTEM

COMPUTED TRACK IS PART OF LF/VLF RECEIVER
NOTE IT IS PARALLEL TO C/L

TRACK ERRORS ALSO PARALLEL TO CENTERLINE

400 FT MDA

POSITION AND FLIGHT VECTOR ERRORS

VOR TRACK IS RARELY PARALLEL TO CENTERLINE

TERPS VOR NON PRECISION APPROACH

30°

400' MDA

NOTE PILOT MUST MAKE A MAJOR
HEADING CHANGE AND SIDE STEP
UPON OBTAINING VISUAL CONTACT AT
400 FT.

PILOT MANEUVERS ARE GREATLY REDUCED IN
LF/VLF APPROACH USING RECEIVER ONLY (2 LOP'S AT LEAST)
AS COMPARED TO A VOR LET-DOWN TO THE SAME LIMITS
(NOTE POSITIONAL AND FLIGHT VECTOR ERRORS)

FIG. 10
The LF/VLF coordinates are wide-based (1,500 to 3,000 NM), hyperbolic lines, lying on a sphere, that converts them to essentially parallel lines crossing at oblique angles for any local area (an area equivalence of a single VORTAC coverage). Essentially, oblique parallel lines exist at any altitude from the surface to well over 20,000 feet, giving a three-dimensional rectilinear system avoiding the R-NAV curvature of a VORTAC station. The aviation LF/VLF system herein discussed can be engineered and installed for about 10 percent of the costs of the current 2,000 stations (about 1,000 VOR's and 1,000 TACAN-DME's).

COST COMPARISONS OF LF/VLF-VORTAC SERVICES FOR A NATIONAL 400-1NM SERVICE

Thus, we see that with the normal TERPS "VOR let-down" (non-precision approach to a 400-foot and 1-mile MDA, very serious constraints exist because of VOR deficiencies. A high risk level is also evident in the accuracy analysis and as witnessed by several recent accidents (in, say, the past 4 years). This type of approach has been identified by ICAO as probably the most critical area of air safety. Next we see that even with costly VORTAC computers, the approach tracks can be computed and displayed along the runways, avoiding the 30-degree legs crossing the runway axis. However, the computed VORTAC displacement errors run as high as nearly 1 NM in any direction from the MDA three-dimensional aiming point. An FAA test of a few VORTAC sites confirms this limitation. The cost to the nation to meet the close-in VORTAC means that stations would have to be within 6 NM or less of the small airport, the STOL airport, etc. To assure full growth and public use potential to general aviation,
a minimum national service should be available. To carry this analogy to the extreme, one can assume that ten thousand small airports of 1980 would cause the need for ten thousand VORTAC's to obtain 6 NM spacing. Channelization changes of VORTAC add costly new airborne units to the total national cost.

This cost is about one to two thousand dollars for an improved VOR receiver, one to two thousand dollars for a DME, and about three thousand dollars for a simplified R-NAV computer, and about another thousand dollars for displays. Since we cannot recover by flying a radial to the VOR station, the regulations will probably require a dual VOR or dual DME. So, installed we have an airborne investment of about seven to eight thousand dollars to provide the minimum ability to approach an airport under conditions of "400 - 1 NM."

This is the cost to each aircraft to provide the minimum IFR capability to a non-equipped airport (without ILS, radar, etc.)

With a two thousand dollar multi-LOP Omega type (L/F/VLF) receiver (using a "U.S.-only" grid with higher accuracy and update rates than Omega), we can insert the threshold coordinates and the lateral and longitudinal initial descent coordinates and provide the pilot both a deviation from a selected approach track (that is aligned with and parallel to the runway centerline). Also the pilot is provided a "distance to go" meter which is a meter movement giving anticipation to the threshold "way-point," or an equivalency of a "DME for free" on every airway in the nation. (See Figure 11.)

From these two simple displays, the pilot could use a simple table (probably actually a part of the display) showing his distance from threshold and the correct barometric height for that
distance. This is similar to a glide path and could be so displayed. It is also strongly suggested that some means be added to calibrate barometric altimeters in the vicinity prior to beginning of the descent as FAA (DOT-ATCAC) reports suggest errors as much as 400 feet exist in general aviation units. This vertical height correction is another subject not covered here but of utmost criticality to the success of all of ATC, not just the approach to land.

The third dimension of ATC requires much more attention. Without a safe means of using the third dimension, ATC will have many difficulties. Solutions using vertical crossed beam radars have been proposed that would give the service to pilots on voice channels at no cost to the pilot.

SUMMARY

In summary, we have in the LF/VLF system a (1) track, (2) distance to threshold, and (3) computed glide path with horizontal accuracies not exceeding 1,000 feet in any direction. With good national system planning, flight test and validation, the use of local differential, or general diurnal corrections, a far superior service to VORTAC is possible. We capitalize on the utilization of the propagation characteristics of LF/VLF, something not possible with line-of-sight, polar coordinate VHF facilities, such as VOR and DME. Added to line-of-sight limits and other errors are such that 1,000 correction curves must be made for 1,000 VOR's—no two being identical.

Thus, a national coordinate system with VOR improved to, say, 1,000 feet at 6 NM would be equivalent, requiring 2,000 to 3,000
more VOR's while LF/VLF can achieve this with less than 10 stations for the nation.
APPENDIX

SELECTIONS FROM RECENT DISCUSSIONS OF NEW ATC CONCEPTS

I. From ION UK, Page 388, Vol. 24, No. 3 (reference 1)

"The commonest single cause of life in civil air transport today (not airframe damage) is the inadvertent collision with the ground in terminal areas. Most of these accidents seem to have had a common factor: a set of circumstances which results in overloading of the flight crew. One of the factors is the considerable crew workload associated with navigating the aircraft when a primary radar is used; for example, the air-ground communications load increases substantially. When it is remembered that on certain short-haul flights, two-thirds of the time is spent in air-ground communications by the crew, and frequently 40 percent of the information conveyed by such communications is misunderstood and has to be verified by other redundant information procedures, it can be seen that a series of diversions, perhaps for weather or ATC requirements, runs the risk of substantially overloading the crew. Readily assimilable information or possible navigational alternatives WITHOUT recourse to air-ground communications or elaborate setting up procedures such as ADF, VORTAC, etc., could considerably reduce the crew workload in these peak conditions." (From the British UK ION, page 388, July 1971)

Comments: The radar vectoring causes excessive pilot load as he attempts to follow the radar controller's navigational instructions; this is minimized if the pilot navigates directly, avoiding communications with the ground.

"Care must be taken to ensure that ATC plans for Area Navigation do not involve the transfer of any additional workload to the flight crew."

"ATC (experts or authorities) must define their objectives vis-à-vis Area Navigation as well as aircraft navigation accuracy requirements."

Meetings will start on these and related subjects in November 1971.

Comments: IATA pilots are asking for a clear definition of VORTAC R-NAV plans as the location of every VORTAC is random with respect to any other VORTAC requiring full three-dimensional coordinate information on each ground station be inserted into the R-NAV computer.

III. From reference 1, Page 389

"In collaboration with the ICAO-RGCSP, one of our first tasks will be to develop a precise, and as far as possible quantified knowledge of current navigation performance. This is a prerequisite to further progress and will lead to criteria for separation in various environments. An increase in the capacity of ATC systems will depend on how long it takes for all or most of the traffic to acquire Area Navigation capability and on the availability of airspace for air transport; and (importantly) on the reorganization of ATC centers for full exploitation of Area Navigational potential."

(Page 389, reference 1)

Comments: This expert clearly notes the impact of Area Navigation on ATC and that Area Navigation will be varied according to the
operational environment. Of course, LF/VLF is Area Navigation just as VORTAC, however, LF/VLF is a contiguous "wide-area" navigation system superior to the randomized coordinates of VORTAC.

IV. From the ICAO publication, reference 3 (article by FAA)

"After examining various methods of implementing the 'IPC' concept, the ATCAC (committee) recommended--transmitting through the upgraded ATC radar beacon." "This would require the addition of a decoder in the aircraft to recognize its coded identity, and the associated message. The avionics also would include an indicator to display some 16 clearance signals to the pilot. The same indicator would present collision resolution clearances and steering commands to keep the aircraft within the confines of the highway lane selected for the particular flight."

Comment: These comments clearly indicate an extension of "close control" ATC concepts to the point of the pilot being commanded by a black box for ATC purposes. This would seem to ignore the pilot's responsibilities and authority to participate more in the process of ATC, rather than less. IPC merely relegates pilots to lackeys in the new concept. (Webster) Command: "To govern authoritatively, without question or opposition."

V. From FAA AC-150/5090-2; 25 June 1971

"The new national airport classification system is based on the concept that all airports in the system have a functional role—this role being reasonably discernable by what the Landing Facility currently does or is projected (to do)/the future as having
Comment: This new FAA view of all airports is based on the landing-approach facilitation of each airport. Some of these views support arguments for the case of having a national minimum landing service at least, of/ say, 400 - 1 NM on every approach to any runway in the nation.

VI. Also in ICAO Bulletin, reference

"The rapid proliferation of tasks (ATC controllers) resulting from the dispersal of (ATC) data reduces the effective contribution everyone can make to the collective task of processing information, and sets off a chain reaction leading to an EVEN FURTHER BREAKDOWN OF THE WORK." "Although automation holds out possibilities for reducing the overall task of the controllers compared with the manual system (of ATC), it must give rise inevitably to a new category of ADDITIONAL TASKS WHICH CAN BE TERMED INDUCED TASKS."

VII. Page 15 of reference 3

"This thinking is in favor of placing more responsibility for the ATC process, paticularly the separation part of it, in the aircraft cockpit and in this way relegating ATC to traffic directions."

VIII. Page 373, reference 1

"The pilot with navigation and communication equipment naturally wants to use them both. Having installed VOR/DME, for instance, he would appreciate coverage down to something like 1500 feet over a much wider area than at present." "Perhaps the main
pilot complaint is that having invested in some quite expensive equipment (VOR type R-NAV) and learned how to operate it, he still cannot use the airways system without a full instrument rating."

Comment: Wide Area-Nav would be used at much lower costs and by even pilots of all skill levels and at all altitudes/below 500 feet, for VFR as well as IFR. A 400 - 1 NM IFR capability should be possible for the least skilled pilot (with an investment of perhaps only 4 or 5 thousand dollars total).
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