A Candidate Near-Term Satellite System for Domestic Air Traffic Control?

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Abstract:

Air traffic control is important for safety of aviation and for its contribution to the economy. Near-100% safety can be assured by keeping the airplanes on the ground. This problem was tackled over several years by the Air Traffic Control Panel of the President's Science Advisory Committee (PSAC) with a resulting report in 1971 providing considerable detail on the solution of choice-- an all-satellite system for providing the three components of ATC, navigation, communication, and independent monitoring of position and velocity.

Despite delay in implementing the system, largely caused by reluctance to do so, it is worth comparing the proposed approach to what could and should be done now. The talk will be enlivened by some of the other experiences of the speaker in fields related to civil and military aviation.

The three elements of ATC are commonly taken as:

- NAVIGATION to know where one is and also where relevant destinations and obstacles are to be found;

- MONITORING so that the overall system knows where each aircraft is, in order to help with collision avoidance, safety of flight, and the like. Collisions to be avoided include those with stationary objects and with other aircraft in flight and with vehicles, including aircraft, on the air fields;

- COMMUNICATION including the transfer of information from the ATC system to the aircraft, with acknowledgement and also provision of information from the cockpit to the ATC system. For instance, declaring an emergency is an urgent piece of communication.

The ATC system has all of the characteristics of a multi-user concoction built and operated by a federal bureaucracy. The task is difficult; the rewards go to private industry; and the penalties for failure are large. All of which indicates the need for a good deal of redundancy and conservatism.

Any such system needs the ability to evolve as technology, usage and the characteristics of the vehicles change, and clearly there can be no instantaneous, simultaneous changeover for flight systems and ground systems in parallel.

Here I want to open a window on a candidate solution to the ATC problem proposed by the Air Traffic Control Panel of the President's Science Advisory Committee (PSAC) in 1971. PSAC was an 18-member panel established by President Dwight D. Eisenhower in 1957 with Dr. James E. Killian as its first chair. It met two days each month in the Old Executive Office Building and had a staff of one—David Z. Beckler—throughout its history from 1955-1973. Members had

4-year terms, and I was honored to serve from 1962 through 1965 and again 1969 through 1972.

The PSAC work was greatly aided by a large number of panels, either standing or *ad hoc*. Among the latter were one on insecticides and pesticides; the former included several military-oriented panels such as the Antisubmarine Warfare Panel, the Limited War Panel, the Military Aircraft Panel, and the Naval Warfare Panel. The Military Aircraft Panel morphed into the Aircraft Panel, thus including civil aviation, and split off an Air Traffic Control Panel. I chaired the aircraft-related panels and the Navy-related panels and was a member of the Strategic Military Panel from the 1950s until PSAC was dissolved in February 1973. The PSAC panels were supported by excellent and hard-working staff of the Office of Science and Technology, also led under another hat by the President's Science Advisor.

President’s Science Advisory Committee
Ad Hoc Air Traffic Control Panel

Chairman

Richard L. Garwin, IBM Thomas J. Watson Research Center

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By the time PSAC took up the air traffic control problem, I had had a good deal of relevant experience:

- In 1951 I provided for Edward Teller at Los Alamos the broad design of the first thermonuclear weapon, tested November 1, 1952 at a yield of 11 megatons, together with flyable models of this liquid deuterium monster, that were actually built and available for use.
- In 1953-54 I worked 3 days a week on Project Lamp Light, to extend the Canadian-US continental air defense to the sea lines of approach of Soviet nuclear-armed bombers.
- In early1959, after I had served for six weeks on the U.S. government team for the international negotiations on Prevention of Surprise Attack, I met with T. Keith Glennan, first head of NASA, to request consideration of the deployment of special-purpose geosynchronous satellites that would serve to relay teletype-data rate signals from American watchers of Soviet missile silos and airfields, in support of a

mission to prevent surprise attack. Advised to request this of the military, I met with Herb York, first head of DARPA, to present my proposal for such a satellite that would relay 1-W VHF 200-baud signals. The satellite was to have dynamic solar power, with a graphite thermal store to tide it through the maximum 45-minute of eclipse by the shadow of the Earth.

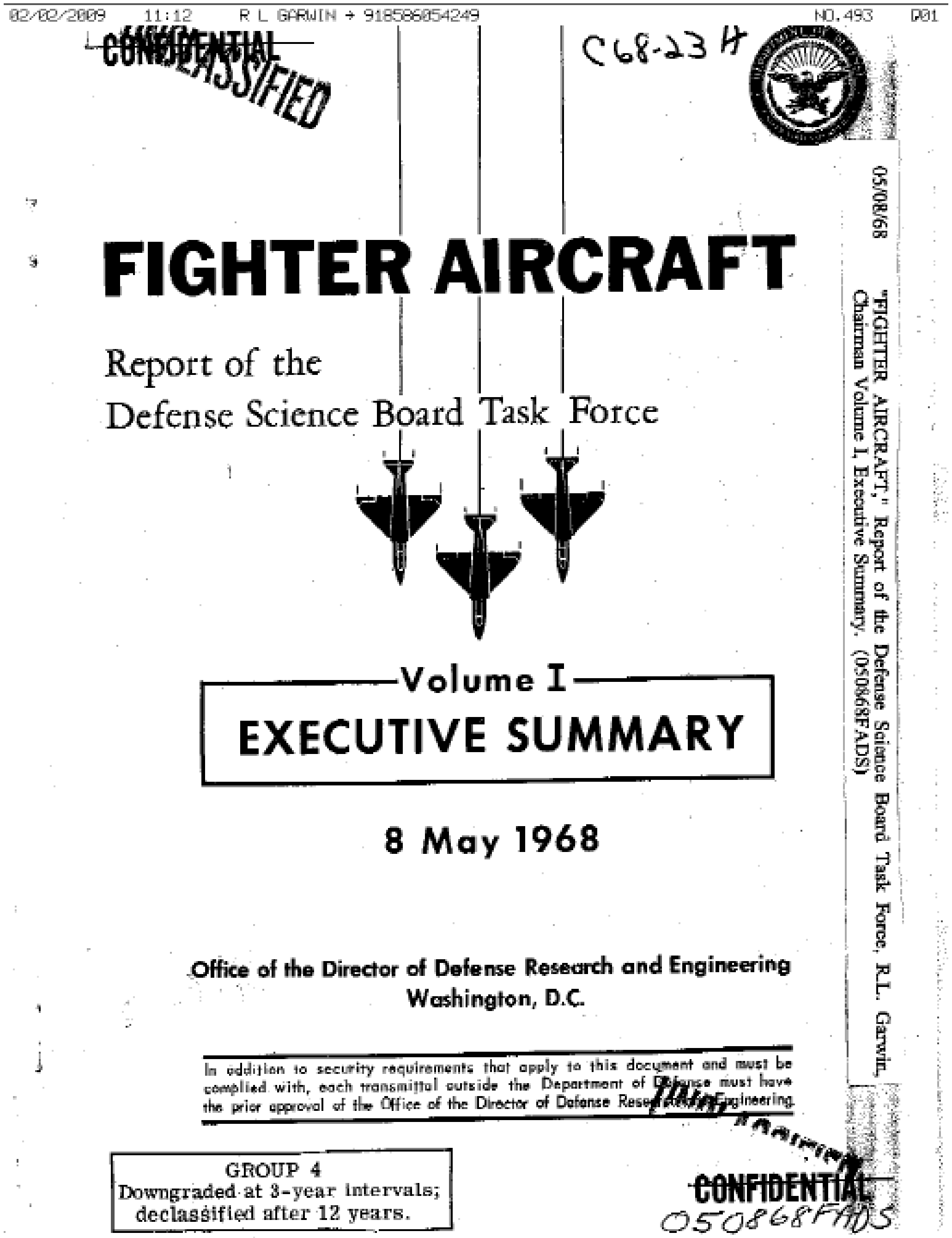
- And from 1960 I worked intensively on both imaging and electronic intelligence satellites, as recognized in the year 2000 in my being named by the NRO one of the ten Founders of National Reconnaissance.
- In 1963 I served as midwife for the introduction of the Cooley-Tukey algorithm (Fast Fourier Transform) that is at the basis of much image processing and compressed communication these days. By reducing the number of multiplications required in a full Fourier transform on N points from N-squared to N ln N, this revolutionized such computation. That is, for N = 1000, the old way would have required 10^6 multiplications, and it now required about 15,000. But for those

willing to consider Fourier analysis for N = 10^7, the amount of computation would go from 10^{14} multiplications to something like 1.8 x 10^8, a reduction by almost a factor 10^6.

- In 1968 I led a Defense Science Board Advanced Tactical Fighter Task Force that reported to the Secretary of Defense in 1968. At this time the PSAC Military Aircraft Panel was advocating the elimination of all displays (gauges and indicators) from the military cockpit, replacing them with a helmet-mounted, dual-resolution TV tube that provided an image in the eye of the pilot or crew, that, sensitive to the positive and orientation of the head, would regenerate a virtual cockpit, complete with old-fashioned gauges and CRTs. Because this would be single-threaded, for reliability an additional miniature TV tube would be available as a replacement. Unfortunately, this is still more talked about than in existence, but it should have been done long ago.
- In 1968, the deceptively named Defense Communication Planning Group (DCPG) deployed in Laos the “air-supported barrier” system of unattended ground sensors, VHF relay to an orbiting aircraft, and

microwave relay to a control center in Thailand, to enable real-time interdiction of military logistic transport through Laos by North Vietnamese forces.

- And, of course, the Apollo program had achieved its goal of putting Americans on the Moon and returning them safely to Earth.



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05/08/68 "FIGHTER AIRCRAFT," Report of the Defense Science Board Task Force, R.L. Garwin, Chairman Volume I, Executive Summary. (050868FADS)

FIGHTER AIRCRAFT

Report of the
Defense Science Board Task Force

Volume I
EXECUTIVE SUMMARY

8 May 1968

Office of the Director of Defense Research and Engineering
Washington, D.C.

In addition to security requirements that apply to this document and must be complied with, each transmittal outside the Department of Defense must have the prior approval of the Office of the Director of Defense Research and Engineering.

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As with most PSAC Panels, the organization and mission of the ATC Panel was reviewed and approved by PSAC, especially by the chairman at that time, Dr. Edward E. David of AT&T Bell Telephone Laboratories. The Aircraft Panel and the Air Traffic Control Panel each met two days a month. Members of the ATC Panel visited en-route and terminal area ATC centers, and flew in the cockpits of commercial aircraft, on the jump-seat. Several of the members were private pilots, and several had worked previously with the government to improve the ATC system. They had been chosen for their effectiveness and knowledge in the field.

THEN:

In the late 1960s the U.S. air transport system was in crisis. Aircraft wree launched on schedule and "stacked up" for hours near the destination airport. In response to the Terms of Reference, we soon established that the technology existed to implement an "all-satellite" ATC system, such that the three functions of ATC—navigation, position monitoring, and communication—would all be done via satellite. Especially in those days, with the hope of configuring and deploying the system within the decade, satellite communications was a scarce resource, so efficient utilization was of the essence. For that reason, and others, the primary communication mode was to be digital data, with all of the outgoing and incoming communications to be archived within the aircraft, and displayed as text. Emergency voice communication was also to be available.

The PSAC Military Aircraft Panel had long espoused what was to become NAVSTAR/GPS, and was familiar with the parameters of such a system.

An essential element of ATC is independent monitoring of position of the aircraft, in order to implement a central responsibility for avoiding collision between aircraft or to help avoid collision between aircraft and stationary obstacles, including the ground.

At the midpoint in the Study, the Panel met with PSAC to provide an interim draft report, for which we were criticized (memorably by PSAC member Bill Hewlett, of Hewlett-Packard) for providing inadequate context and comparative evaluation of alternative systems. We had demonstrated the parameters of the all-satellite system, but we had not fleshed out the alternatives. So in the final report, the system of choice is exposed fully only in Appendix 3 (pp. A3-1 through A3-32).

Monitoring of position needed to be independent of the on-board navigation mode, which was to be essentially GPS for commercial and military aircraft, but would be “navigation by surveillance” for small general aviation craft.

In order to put the minimal burden on the aircraft, we chose, in principle, a surveillance system that would have each aircraft emit approximately once each second, a powerful pulse that could be relayed to the ground by bent-pipe satellites, so that it could be processed at the ATC center in conjunction with the reception of that same transmitted pulse via other geosynchronous relay satellites. For a single aircraft, it is clear that the time differences of arrival, just as in the case of GPS, could be used to determine an accurate location for the aircraft, with precision limited by the channel band width and signal-to-noise ratio (S/N). For instance, generating a 400 kW pulse, 0.1 microsecond wide (0.04 J), and radiating it into the upper half space would correspond to a received energy some 30dB over thermal noise.. The satellite receiving antenna area, A, was to be limited in this case so that the geosynchronous satellite would have a view of the entire facing surface of the Earth, which would limit its gain to that portion of the sphere or about 150 over isotropic. The corresponding satellite antenna area for a carrier frequency of 300 MHz (1-m wavelength) would be 15 m, but for the available band near 1500 MHz (0.2 m wavelength) would be only 3 m or less. Pulsers that would deliver 10 kV and 100 amperes, and corresponding vacuum tubes were daunting but not impossible.

Alternatively, one could have a pencil triode capable of pulse power of 1 kW at low duty cycle, so that one could adopt a system using a “compressible pulse,” which, in our case, was chosen as a 500-chip pseudo-random-noise (PRN) train with 0.1-microsecond chip length—hence 50-microsecond duration. The necessary rf energy would remain the same (0.04J) if the PRN train could be processed coherently, and the peak power output of the surveillance transmitter on the aircraft could thus be reduced to less than 1 kW. For reliability one could implement part-redundancy to compensate for the finite life of vacuum tubes, with an automatic changer like the “flash bar” that substituted a new miniature flash bulb when the previous one has been used. Indeed, this could work not only on the aircraft but also in satellite applications. The 500-chip compressible pulse is analogous to the open “code word” used in spread-spectrum communications for efficient use of power and spectrum.

The monitoring satellites (dubbed MONSTAR) were to be essentially bent pipes, with microwave relay of the received band to the central processing station(s). At the receiving station, the common 500-chip PRN pulse would be transparently and linearly compressed, for instance by a delay-line compressor, to the form of a single, physical, 0.1-microsecond pulse.

For navigation, the problem in the 1970s was not to conceive of sufficient accuracy of GPS, including ionospheric compensation, but to know where the surface of the Earth was. Obviously, considering the 40-km difference between equatorial and polar Earth diameter, a spherical approximation to the Earth’s surface is clearly wrong not only because of the altitude variations—mountains and such—but because of the first-order error due to Earth oblateness. At that time, it was nigh inconceivable to have the detailed maps of today, although for specific approaches of cruise missiles to their targets, our Military Aircraft Panel had earlier advocated terrain-clearance by navigation, making use of previously determined terrain maps, so that 3-D navigation in radio coordinates could be teamed with the digital terrain maps to provide terrain-following commands. Both to limit the necessary data storage and to ensure significant and unambiguous terrain variation for navigation, specific approach paths and corresponding patches of terrain data were to be defined.

For terminal aircraft navigation, small GPS transmitters at the airfields were called out in our 1971 Report to provide higher signal strength (and immunity to jamming) so that the navigation function would be clearly adequate for blind landing and thus provide a cost-avoided stream for funding the overall ATC system by eliminating the proposed Microwave Landing Systems (MLS) and, incidentally, also emergency locator beacons. With every aircraft being tracked every second to 10-m accuracy, the precise location of a crash would be available.

Digital communications have happened by themselves, and although I might add something to the knowledge of GPS history, I can't contribute significantly to the digital communications story.

But surveillance is the big problem with ATC.

In our Report, we distinguish the much simpler problem of oceanic ATC from domestic ATC, with some 500 aircraft in flight over the oceans compared with an expected 50,000 aircraft over the continental U.S. Furthermore, greater separation can be enforced over the oceans without hobbling the system. And greater time delays in position fixing and navigation are acceptable—one minute vs. one second, as stated in the 1971 Report.

When the FAA and contractors consider satellite-based position monitoring, they soon encounter the critical problem of intentional jamming. Unlike GPS, where jamming is important for the individual receiver, particularly if it is an airplane or a weapon with the mission to destroy something nearby and soon, thus motivating the potential destroyee to purchase GPS jammers and the world market to provide them, it is essential that the ATC system not be disrupted by jamming the sensitive receivers on a few ATC monitoring satellites.

Why is jamming potentially such a problem? After all, each aircraft puts out 1 kw during its 500-chip, 50 microsecond pulse, which is the equivalent of 0.5 MW during the compressed 0.1 microsecond pulse. So if a noise jammer is to fill each 0.1 microsecond chip interval with a signal comparable with that from an aircraft, it would need to radiate 1.5 MW. But this is doubly and fatally wrong. First, because the monitoring system depends on good S/N, so interference at the 20-dB down level would be serious, thus reducing the required jammer noise output to 15 kW. More importantly, in the search for low-cost configurations for the on-board equipment, a choice was made to have a near-isotropic antenna pattern so that the aircraft need not track the satellite positions. Since the ground-based jammer knows perfectly well the position of the satellite, it could deploy a large directional antenna to jam a specific satellite (or an antenna with multiple feeds to jam a few satellites in its hemisphere). For instance, a 5-m diameter dish with an area of 20 sq m would at a wavelength of 0.20 m (1500 MHz) have a gain of 500, so that troublesome jamming could be carried out with a radiated power level of 15kW/500 = 30 W.

Surely the nations of the world could make such interference with a civil ATC system illegal, but that wouldn't prevent it from happening. In fact, even the threat of jamming is enough, properly, to dismiss such systems from consideration because of the single-point failure thus introduced.

One could design the surveillance satellites to set a narrow null on the jammer, but it would be trivial to proliferate jammers. A modern system could, of course, use directional antennas on large commercial aircraft to increase the signal at the satellites, but that would have eliminated much of the value of the system as regards the more numerous private aircraft. TRW, and in particular David D. Otten provided the parts-count design and cost for the General-Aviation equipment.[1]

The context for our ATC Panel was given by its terms of reference, but included not only an ATC system for arbitrary flight of expected commercial aviation, general aviation, and military aircraft, but also the possibility of limitation of that flight to make it more controllable under ordinary circumstances. Hence the idea of “strategic control” (Page ES-5) as opposed to tactical control. A tactical control approach would demand central dictation of aircraft maneuver, whereas the strategic control would allow aircraft to file arbitrary flight plans, with a commitment to following them in 3-D and at times in 4-D (position and time), to enable the essential monitoring element of an ATC system to determine whether the deconflicted flight plan was being followed.

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[1] I later worked with him on his proposed system for satellite-based domestic personal communications service (PCS—cellular) that had a very large antenna at GEO which provided hundreds of spot beams to cover the United States. Such technologies would be very helpful in reducing vulnerability to jamming.

This would be implemented via Intermittent Positive Control—IPC— so that there would be ATC intervention with command and advisory messages only when there was a deviation from the flight plan, or to warn of potential collisions.

We considered also the great potential contribution of vertical and short takeoff and landing transport aircraft in the air transportation system of the future, and indeed devoted Appendix 1 to that. Essential to a productive V/STOL System (more precisely a STOVL System—short takeoff/vertical landing), is automatic takeoff and landing (ATOL). Military aircraft capable of vertical landing for decades had been saddled with the requirement of a 5-minute hover on landing, whereas a PSAC Aircraft Panel Report considered what would be achieved by an automatic maneuver limited to 1.4 g that would bring the aircraft to rest on a landing pad from an on-wing speed of 200 kt. The time required for that maneuver is 11 seconds, making it possible to consider productive use of pure jet-lift systems with a specific impulse of one pound of thrust per pound of fuel per hour. A more passenger friendly 0.2 g longitudinal deceleration (1.02 g total) would correspond to less than one minute of hover, using 1.6% of the fuel load but permitting comparable savings in landing-gear weight.

The significance of STOVL is increased airfield utilization capacity because any pre-planned azimuth could be used for approach to any landing pad, just so that it was deconflicted in advance.

Our Report considered the transition to an all-satellite ATC system, with initial deployment to handle oceanic traffic, which was easier because the number of aircraft in flight was expected to be smaller by a factor 100, and the allowable position accuracy similarly looser by a factor ten or more.

The transition to an all-satellite domestic system was to include ground-based supplementary transmitters, especially at airfields to allow automatic approach and landing with better position accuracy and assured reliability than could be promised from the satellite navigation system.

For small aircraft, the idea was to offer “navigation by surveillance” in that a simple transmitter on the aircraft would provide an inverse-GPS position determination when that signal was relayed by bent-pipe satellites to a ground processing station, which could then communicate with the aircraft by the HF data link.

Page 3-19 of the Report identifies three problems with an all-satellite system—

1. Jamming that could eliminate the surveillance capability from the whole-Earth observing antennas on the satellites;
2. A problem of cold start of the surveillance system, which would need to disambiguate the highly efficient signals on which we were relying; and
3. Technical complexity in codes and signals that would allow the navigation, surveillance, and communication function with then-

achievable power, hemispherical antenna patterns on the aircraft, and 50,000 aircraft in flight at one time over the United States.

Our Report was really only a qualitative scoping of the technical requirements and crude estimates of the cost and schedule. It proposed urgent and parallel development of a more conventional ATC radar beacon system (ATCRBS) and the all-satellite system, with a choice made as the systems were demonstrated.

At that time, FAA was proposing widespread deployment of the Microwave Landing System (MLS) based at airports for approach and landing, but it was clear that the Defense Navigation Satellite System (DNSS), which I call here “GPS” for short, was fully capable and would provide better performance with a system that would be invaluable for en-route navigation.

We estimated that in 1970 technology an on-board receiver/computer would $50,000 (p. 3-34) whereas a $1000 box on the aircraft could provide navigation-by-surveillance capability.

Precision navigation would then enable strategic control ("free flight") that would depend on filing of 3-D and even 4-D flight plans and navigation.

The early GPS predecessor of the day was Air Force 621B, and we did call out in our Report for placing pseudolites at air fields, where even one such transmitter would refine the navigation solution to better than 10-ft cross-track accuracy, and thus enable Category 3 landings. We wanted to go further than that and to depend on automatic takeoff and landing (ATOL) in which the aircraft would do its job in taking off and making the transition to terminal and en route travel without the necessity of human intervention. The same for landing.

But in order that aircraft be able to do this (especially in the 1970s) and in order for pilots to do that safely, there would need to be structure to the traffic flow and to the environment. The traffic flow structure was to be provided by a free-flight regime, achieved by the pilot filing a 3-D flight plan and sticking to it, except when circumstances intervened (strategic control, supplemented by intermittent positive control (IPC).

As for structure of the environment, there would need to be assurance on the ground that the runway was clear except for aircraft that were equipped to be monitored by the system, so that there should be no conflict, and if there were a conflict it would be apparent in a timely fashion to the ATC system.

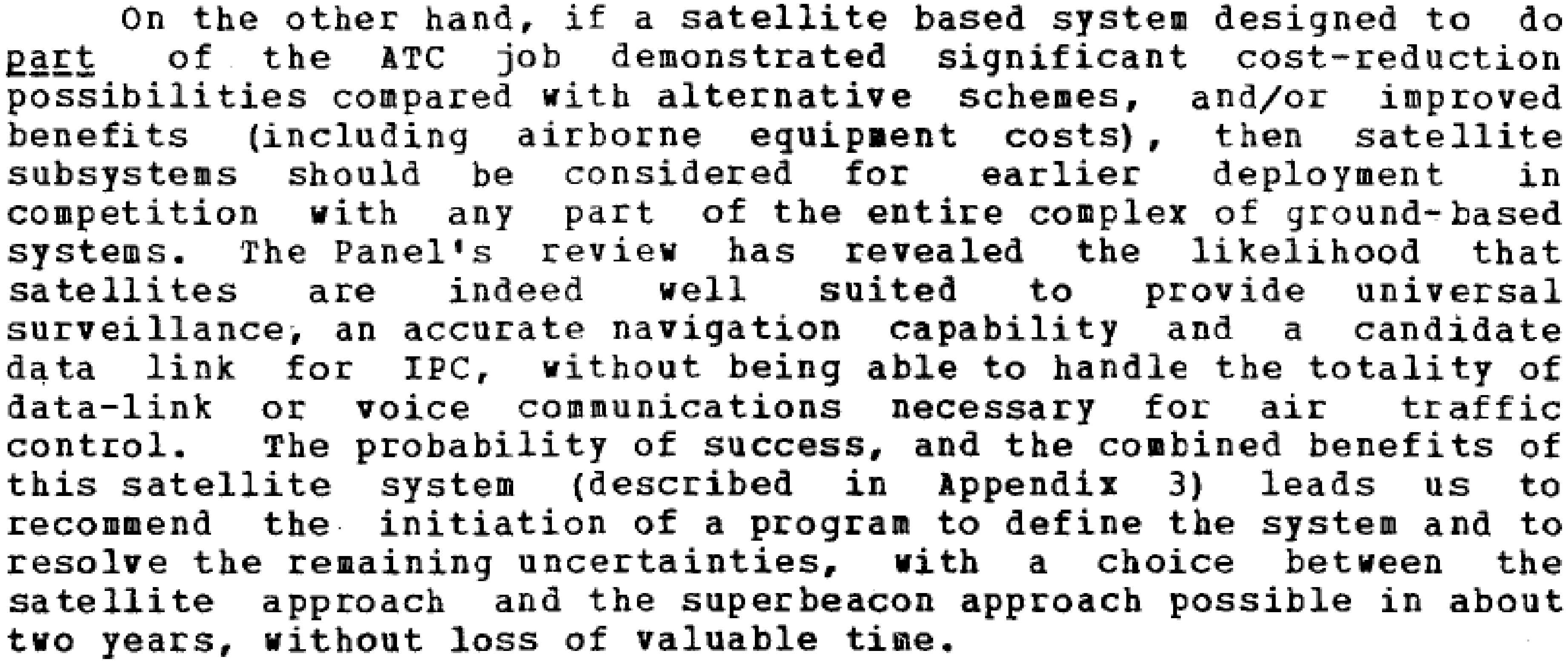
The shortage of memory and computing power also drove some of the specific communication means sketched in the Report, including “addressing by position.” Instead of the Discrete-address mode of the advanced Air Traffic Control Radar Beacon System (ATCRBS) which would have used a 78-bit address, we proposed to have the aircraft respond to commands and information that were provided to it in near time coincidence from two satellites (or three), which would not occur for any other of the 50,000 aircraft assumed to be aloft in the United States at one time.

A4-6

The two most promising approaches to development of new data acquisition and air-ground data-link systems for the future are:

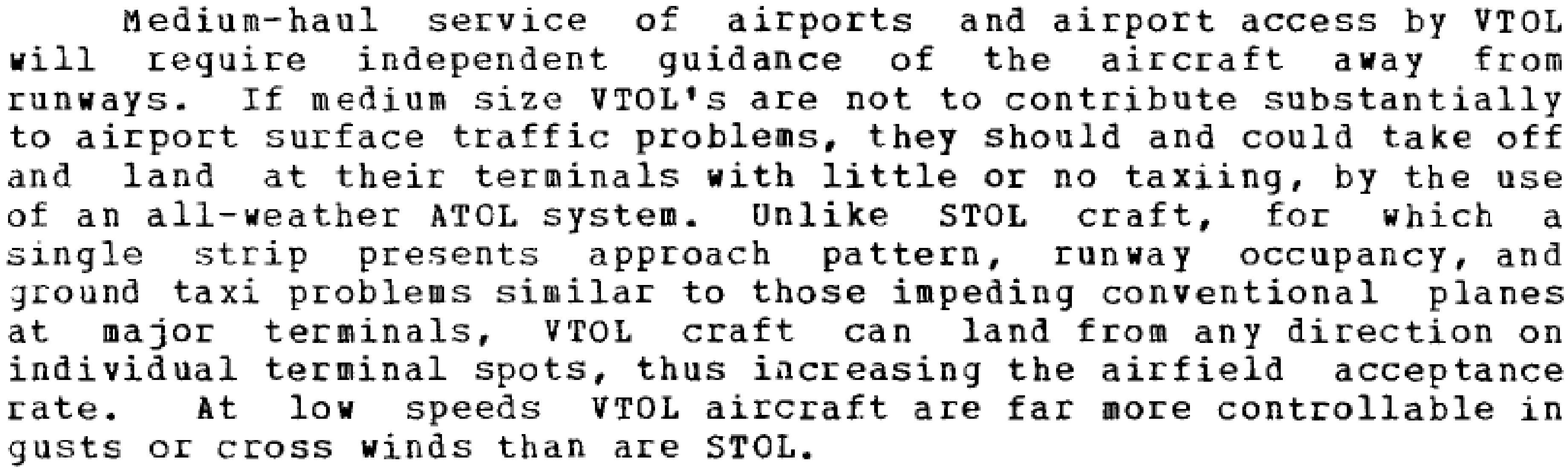
1. **A new discrete-address ATCRBS which may or may not be compatible with present airborne transponders and present interrogators and has an air-ground data-link function**
2. **A new satellite-based system, which provides a surveillance capability for all aircraft together with an independent VHF air-ground data-link, maintains the present ACTRBS airborne transponders until the satellite system is phased into service, but improves the ground-based interrogators as described in Section 3.2.2.2A, “Near-Term Improvements.”**

3-20:



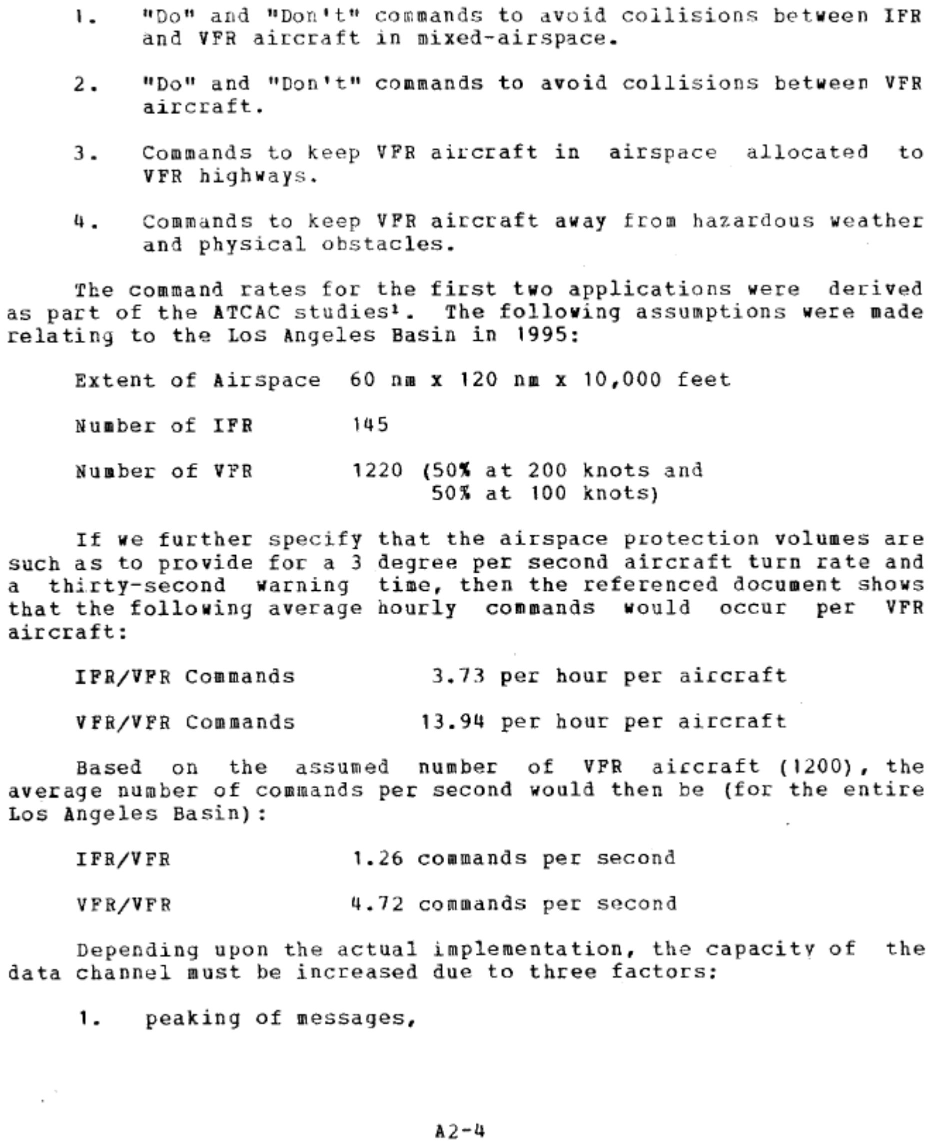
On the other hand, if a satellite based system designed to do *part* of the ATC job demonstrated significant cost-reduction possibilities compared with alternative schemes, and/or improved benefits (including airborne equipment costs), then satellite subsystems should be considered for earlier deployment in competition with any part of the entire complex of ground-based systems. The Panel's review has revealed the likelihood that satellites are indeed well suited to provide universal surveillance, an accurate navigation capability and a candidate data link for IPC, without being able to handle the totality of data-link or voice communications necessary for air traffic control. The probability of success, and the combined benefits of this satellite system (described in Appendix 3) leads us to recommend the initiation of a program to define the system and to resolve the remaining uncertainties, with a choice between the satellite approach and the superbeacon approach possible in about two years, without loss of valuable time.

A1-3 V/STOL in the transportation system of the future.



Medium-haul service of airports and airport access by VTOL will require independent guidance of the aircraft away from runways. If medium size VTOL's are not to contribute substantially to airport surface traffic problems, they should and could take off and land at their terminals with little or no taxiing, by the use of an all-weather ATOL system. Unlike STOL craft, for which a single strip presents approach pattern, runway occupancy, and ground taxi problems similar to those impeding conventional planes at major terminals, VTOL craft can land from any direction on individual terminal spots, thus increasing the airfield acceptance rate. At low speeds VTOL aircraft are far more controllable in gusts or cross winds than are STOL.

We worked out the datalink requirements, for instance for the Los Angeles basin, for which we scoped the system to handle 1365 aircraft airborne at any one time:



1. "Do" and "Don't" commands to avoid collisions between IFR and VFR aircraft in mixed-airspace.
2. "Do" and "Don't" commands to avoid collisions between VFR aircraft.
3. Commands to keep VFR aircraft in airspace allocated to VFR highways.
4. Commands to keep VFR aircraft away from hazardous weather and physical obstacles.

The command rates for the first two applications were derived as part of the ATCAC studies[1]. The following assumptions were made relating to the Los Angeles Basin in 1995:

Extent of Airspace	60 nm x 120 nm x 10,000 feet
Number of IFR	145
Number of VFR	1220 (50% at 200 knots and 50% at 100 knots)

If we further specify that the airspace protection volumes are such as to provide for a 3 degree per second aircraft turn rate and a thirty-second warning time, then the referenced document shows that the following average hourly commands would occur per VFR aircraft:

IFR/VFR Commands	3.73 per hour per aircraft
VFR/VFR Commands	13.94 per hour per aircraft

Based on the assumed number of VFR aircraft (1200), the average number of commands per second would then be (for the entire Los Angeles Basin):

IFR/VFR	1.26 commands per second
VFR/VFR	4.72 commands per second

Depending upon the actual implementation, the capacity of the data channel must be increased due to three factors:

1. peaking of messages,

NOW:

Recycling 40-year old technology is rarely a good idea, in view of both a billion-fold improvements in computing capability and an enormous elevation in the level of sophistication and competence of communication engineers as practiced in local and wide-area networks, spread-spectrum mobile-phone communications, and the like. Still, the tricks that were incorporated in this 1971 proposal may be of interest, although some of them have been employed in rapid-acquisition of GPS-like signals, and the like.

However, it still makes sense to ask the structure of a modern system that makes use of ubiquitous satellite capability for the independent functions of navigation, monitoring (surveillance) and communication. On the navigation side, the question answers itself in view of the demonstrated performance of GPS-aided navigation both for in-flight and terminal operations, including blind landing and even taxi.

Would the all-satellite ATC System recommended by the PSAC ATC Panel in 1971 have been deployed? Would it have worked?

Probably it would have worked, but more probably it should not have been deployed.

It would have been good to have carried out the urgent, competitive development that would have improved both the ACTRBS and the satellite system. Indeed, we suggested a new executive agency of the U.S. government to develop, deploy, and operate the air traffic control system, recognizing that it was unlikely otherwise to be achieved. The all-satellite system was very much a centralized system, with an explicit recommendation that it maintain a path for upgrade and growth, which would probably have needed to be a different technology. The proposal was constrained by the relative resource costs of the day in communication and computing and storage. Thus, it emphasized short messages, even to the point of constraining flight to previously filed plans (except for emergencies) and monitoring exceptions to the plan.

It proposed the use of “addressing by position” as its form of “discrete address” in order to broadcast to particular aircraft out of 50,000 or more, without having to provide the 12-15 bits of address space to select the particular recipient aircraft. It used reasonable insight in solving some of the problems. For instance, at the time, a RAND report had estimated that collision avoidance calculations, repeated every ten seconds for 50,000 aircraft in the domestic United States, would require at least an initial consideration of the 1.25 billion possible pairs of aircraft that might collide, and the determination of their distance, in order to prune them from the rest of the calculation. Instead, the PSAC Panel recognized that by doing the calculation for each of, say, 1000 fixed 2-D boxes in the United States, the average occupancy of a box would be 50 (with boxes tailored to maintain that approximate occupancy), and so the requirement would not be the consideration of 1.25 billion pairs each second but a consideration of 1250 potential pairs per box, multiplied by the 1000 boxes for a potential collision pair number of 1.25 million (rather than billion). It was apparent that an aircraft near the edge of one box might collide with an aircraft near the edge of the adjacent box, so the calculation was to be repeated with a spanning box set, the vertices of which were at the centers of the first set of boxes. Still, a factor of 500 reduction in computation was welcome and brought it within the range of computers of that era.

The substance of the Report was to solve the problem of limited capacity and greatly increasing cost of the U.S. ATC system. Although we estimated that satellites could handle the whole technical job (certainly not the whole job, because there would still be air traffic controllers and human intervention), we understood that there would need to be a period of transition between the existing radar- and VHF-voice-based system, and one with digital communications and satellite navigation and position monitoring.

It is difficult in 2011 to understand the constraints of limited computing power in the 1971 era, but I suppose in NASA, there is a resonance with this difficulty, in view of the tiny memory capacity of the Apollo on-board computers. In our Report, we speak of on-board computers with 5000-word memory, which in modern terms would be stated as 0.02 megabyte. Now, of course, one buys much faster and more reliable memory at $20 per gigabyte, which fits on your thumb nail.

R.I.P.