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**Project Report**
**ATC-26**

# Technical Assessment of Satellites for CONUS Air Traffic Control Executive Summary

I.G. Stiglitz

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**Lincoln Laboratory**
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
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16. Abstract

A number of satellite system techniques have been suggested as candidates to provide ATC surveillance, communication, and/or navigation service over CONUS. All techniques determine the aircraft positions by multilateration based on the arrival times of signals transmitted between the aircraft and the satellites. The techniques can be categorized as follows: 1) Coordinated Aircraft-to-Satellite Techniques (CAST), 2) Random Access Aircraft-to-Satellite Techniques (RAST), and 3) Satellite-to-Aircraft Techniques (SAT).

This volume summarizes the results of a technical assessment of all three techniques. The detailed assessment is presented in companion volumes.

The assessment has shown that workable systems could be configured using any one of the three techniques without reliance on high risk technology. No one technique has emerged as superior. Rather several viable alternatives have been identified. All techniques appear to require more costly avionics than today's ground-based system.

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# INTRODUCTION

Over the last half decade, a number of satellite system concepts have been advanced as candidates to provide Air Traffic Control (ATC) surveillance, communication, and/or navigation service over the CONtinental United States (CONUS). Each has its advantages and disadvantages. All employ position location service by multilateration using a constellation of satellites. This overview summarizes the highlights of a technical assessment of satellite techniques made by Lincoln Laboratory.[1-9] The work was performed in support of the Transportation Systems Center, Department of Transportation, as part of the Advanced Air Traffic Management System (AATMS) study.

No attempt has been made in the work summarized here to assess the broad spectrum of operational or economic implications of employing these techniques in the National Airspace System. No consideration has been given to such factors as: (1) the cost effectiveness of satellites as an element in the CONUS ATC system, (2) the manner by which any of these satellite techniques might evolve from present-day aircraft surveillance, navigation and/or communication systems, (3) the detailed operational requirements on such a system, or (4) the implications of sharing system resources with other non-ATC functions. Instead the work has focused entirely on technical issues.

The results of this assessment of the key technical issues have verified that satellite-based techniques for CONUS ATC could be developed without reliance on high risk technology. No one particular technique has emerged as optimum; rather several viable alternatives have been identified.

## FOCUS OF THE PROGRAM

The objective of the Lincoln Laboratory work has been to make technical assessments of several possible techniques for utilizing satellites in air traffic control. These techniques can be categorized as follows:

Coordinated Aircraft-to-Satellite Techniques (CAST)

Aircraft respond to discretely addressed interrogation by satellite. Aircraft responses are repeated by the visible satellites to a central facility for processing.

Random Access Aircraft-to-Satellite Techniques (RAST)

Aircraft transmit periodically in an independent uncoordinated fashion. These signals are repeated by the visible satellites to a central facility for processing.

Satellite-to-Aircraft Technique (SAT)

Transmitted signals from the visible satellites are used by aircraft to compute their position. This position data is displayed to the pilot and can be transmitted over a line-of-sight link to the ground.

The method used to assess the foregoing techniques was to select and analyze a "baseline configuration" for each. It was not the intent of the baseline to be a "best possible" implementation of the techniques. Instead the intent was to insure that all major technical issues were addressed.

One of the primary attractive attributes of satellites is their inherent ability to provide broad coverage of low altitude airspace. General aviation aircraft are predominant users of low altitude airspace. Hence, a central issue throughout this study has been the complexity of general aviation avionics required for satellite operation.

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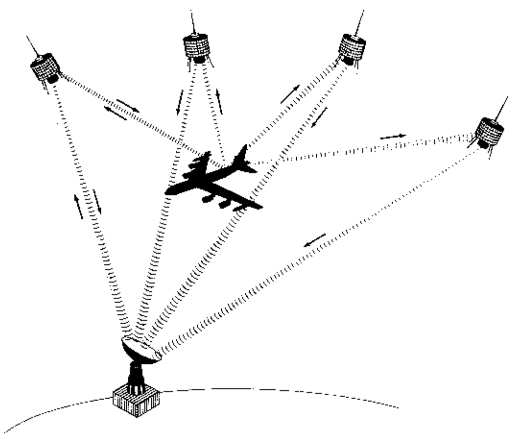
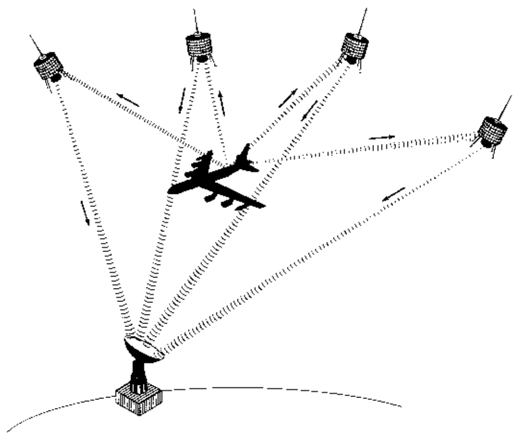
CAST



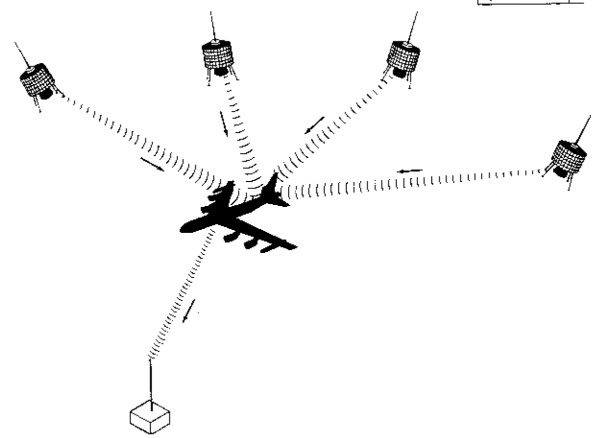
COORDINATED AIRCRAFT-TO-SATELLITE TECHNIQUE

RAST



RANDOM ACCESS AIRCRAFT-TO-SATELLITE TECHNIQUE

SAT



SATELLITE-TO-AIRCRAFT TECHNIQUE

## PRINCIPAL CONCLUSIONS

No significant technological advances are essential for developing a system employing any one of the techniques.

Both CAST and RAST provide surveillance as a primary service. Two way digital communication is especially easy to accommodate with CAST. Both techniques can be configured to support tens of thousands of aircraft at an average surveillance update rate of once every ten seconds. Navigation is the natural service with SAT. Surveillance (dependent on the navigation data) could employ the DABS transponder for line-of-sight digital communications with ground stations.

Because signals between satellites and aircraft travel tens of thousands of miles, they are severely attenuated when they arrive at their destination. A combination of techniques are needed to combat this power loss. On the satellite large antennas are required both to collect a useful fraction of the power transmitted by the aircraft and also to transmit focused signals to them. In addition special avionics designs, with coherent high power transmitters and sensitive receivers with high signal processing gain should be employed. The required avionics for satellite service is expected to be several times more costly than today's ATCRBS transponders.

Systems employing either CAST or RAST would be vulnerable to disruption by hostile groups. In particular, both techniques rely upon an aircraft-to-satellite uplink which could be disrupted by several inexpensive, easily transportable, low power jammers. In addition both techniques require a large centralized computing facility, the disruption of which would disable all service.

Regardless of which technique is employed, at least ten satellites are required for realistic "down to the ground" CONUS satellite service. In contrast, today's ground-based system employs hundreds of ground sites and does not provide this "down to the ground" coverage everywhere. However, satellite-based systems also require the support of extensive ground facilities. Both CAST and RAST require a large central processing facility considerably more complex than today's NAS Stage A system. SAT has no such requirement; rather, it employs a network of relatively simple ground sites for line-of-sight aircraft-ground digital communications.

Although there are no major technical obstacles to the development of systems employing any one of these techniques, the associated cost to the government will be considerable. For example, estimates of engineering, development, facilities and equipment cost range from a few hundred million dollars for SAT to nearly a billion dollars for CAST and RAST.

## TECHNICAL AREAS FOR POSSIBLE FUTURE EFFORT

If a decision is made to pursue a CONUS satellite development program, then the following technical areas merit early program attention.

### Satellite Experimentation

Experiments can be performed with L-band satellites such as ATS-F and AEROSAT to characterize the L-band aircraft-satellite channel. These should emphasize quantification of both channel noise and the ionospheric effects with influence on position accuracy. This information is a prerequisite to a detailed system design.

### Ground Processing Requirement Sizing

Both CAST and RAST require a large complex centralized facility to process the signals for each aircraft. This facility is expected to represent a major system element. A careful assessment of the required hardware and software is expected to be pivotal in selecting between alternative satellite techniques. Special purpose hardware and novel computer architectures that reduce complexity and improve reliability require special attention.

### Avionics Considerations

Avionics to work with a satellite system represents a critical system element about which there remains considerable uncertainty. The required sophistication and reliability are in contrast with the desire for low cost avionics. Avionics considerations should focus on the role of new sophisticated, but low cost, components like surface acoustic wave devices and techniques for achieving high reliability, e.g., to achieve the reliability to today's multiple element avionics with a single piece of avionics.

## COORDINATED AIRCRAFT-TO-SATELLITE TECHNIQUES (CAST)

### Operation

Aircraft interrogations originate at a centralized ground facility. These are relayed through a satellite repeater to the aircraft. Interrogations are received using top-mounted aircraft antennas. In general, the interrogation waveform contains aircraft identification and a digital message, e.g., for intermittent positive control, traffic advisories, weather data, vectoring, etc.

Aircraft respond (using the same top-mounted antenna) by the transmission of a timing pulse and a digital message, e.g., confirming receipt of the uplink message, reporting status, requesting new vectors, etc. These signals are received by at least four visible widely separated satellites for relay to a centralized ground facility for processing.

At this facility signal time of arrival is determined for each of these satellites and aircraft position is determined by multilateration. Included messages are decoded and the surveillance data base is updated. Thus CAST can provide both surveillance and digital communications service.

Aircraft are interrogated periodically according to a schedule (continually updated by the ground facility) designed to eliminate mutual interference between aircraft replies. The requirement that aircraft transmissions not interfere is the factor that ultimately limits capacity, i.e., the number of aircraft that can be handled per second. The Astro-DABS[10,11] concept advanced by the MITRE Corporation is an example of CAST.

## Principal Conclusions

- Development of a system employing CAST is not dependent on high risk technology.
- Surveillance and duplex digital communications are the natural ATC services with CAST.
- Large aperture satellite antennas help to reduce the cost of the required avionics.
- Nonetheless, avionics for CAST would be considerably more complex than today's ATCRBS (Air Traffic Control Radar Beacon System) transponder. The principal contributing factor is the transmission of coherent pulses at a power level of several hundred watts.
- A large centralized ground processing facility is required for operation.
- The aircraft-to-satellite uplink is susceptible to disruption by inexpensive, low power, easily transportable jammers.
- A system employing CAST can be designed to provide surveillance (with a three dimensional accuracy of a couple of hundred feet), and digital communication (of a few tens of bits per aircraft) for several thousand aircraft each second.

## RANDOM ACCESS AIRCRAFT-TO-SATELLITE TECHNIQUES (RAST)

### Operation

Aircraft transmissions are initiated by the aircraft itself. Each aircraft employs a top-mounted antenna for periodic transmission of a unique identifying signature waveform consisting of a string of pulses. These signals are received by a constellation of satellites, at least four of which are in view.

The received waveforms are then relayed to a central facility for processing. The signals from each satellite are processed to detect aircraft presence and estimate arrival time. Aircraft position, determined by multilateration, is used to update the surveillance data base.

Since the times at which aircraft transmit are uncoordinated (random), the transmissions from different aircraft can mutually interfere at the receiver. This effect, called multiple access noise, complicates the ground data processing problem, and eventually limits system performance for large numbers of aircraft.

A variety of concepts employing RAST have been advanced. These include: the North American Rockwell AATMS System A concept,[12] the RCA SATAN concept,[13] the Boeing satellite concept[14] and the TRW LIT concept.[15]

## Principal Conclusions

- Development of a system employing RAST is not dependent on high risk technology.
- Surveillance and aircraft-to-ground communications are the natural ATC services with RAST.
- Large aperture satellite antennas help to reduce the avionics cost. They permit improved performance by reducing the multiple access noise and increasing the received signal to noise ratio.
- Avionics with RAST would be considerably more complex than today's ATCRBS transponder. The principal contributing factor is the transmission of coherent, power-controlled pulses at a power level of several hundred watts.
- A large centralized ground processing facility is required for operation.
- The aircraft to satellite uplink is susceptible to disruption by inexpensive, low power easily transportable jammers.
- A system employing RAST can be designed to provide surveillance with a three dimensional accuracy of a couple of hundred feet for several thousand aircraft each second.

## SATELLITE-TO-AIRCRAFT TECHNIQUES (SAT)

### Operation

Timing signals are transmitted by at least four visible widely separated satellites. Periodically each satellite transmits a timing pulse and an accompanying digital message. In general, the message includes satellite identification and location and special broadcast messages, e.g., severe weather advisories.

These signals are received at the aircraft using top-mounted antennas. Aircraft position is determined aboard each aircraft by multilateration using the signal time of arrival data and the satellite location. The calculations are performed using a microprocessing computer (available today for less than a thousand dollars). The computed aircraft position is then displayed to the pilot as navigation information.

This position data could also be relayed over the DABS (Discrete Address Beacon System) data link to the ground for inclusion in the ATC data base. Thus, SAT can provide navigation to the pilot and dependent three dimensional surveillance to the ground. A number of concepts employing SAT previously have been advanced in the military sector. These include the Defense Navigation Satellite System (DNSS), TIMATION, System 621B and the Global Positioning System currently under development.[16,17]

## Principal Conclusions

- Development of a system employing SAT is not dependent on high risk technology.

- Navigation is the natural ATC service provided by SAT. Dependent surveillance using an air-to-ground communications link could provide primary three dimensional surveillance in low density airspace and/or back-up surveillance in high-density airspace.

- Large aperture satellite antennas help to reduce the cost of the required avionics.

- Avionics with SAT would be considerably more complex than today's ATCRBS transponder. The principal contributing factor is the microprocessing computer required for the position determination calculations.

- Workable systems employing SAT can be designed which do not require a large ground-based data processing facility.

- Workable systems employing SAT can be designed to avoid the use of the aircraft-to-satellite uplink with its associated jamming vulnerability.

## AVIONICS FEATURES

The range between an aircraft and a satellite is typically a hundred times larger than that between an aircraft and a line-of-sight ground station (e.g., 22,000 miles versus 220 miles). Consequently, signals for satellite service are attenuated much more severely than those for ground-based systems. As exemplified in the table, avionics for satellite service must satisfy more stringent performance requirements and hence costs more than today's ATCRBS avionics.

The avionics transmitter with CAST and RAST must put out several times more power than today's typical ATCRBS transponder. Moreover, coherent transmitted signal waveforms are required to permit significant receiver processing gain. By contrast, today's ATCRBS transponder employs a simple incoherent cavity oscillator which is pulsed on and off. The transmitters intended for use with RAST must, in addition, be carefully power controlled to minimize multiple access degradation of disadvantaged aircraft due to signal overlap at a satellite repeater.

A frequency drift of several megahertz is permissible with ATCRBS transponders. Frequency drift for satellite avionics must, however, be maintained to within a kilohertz. To realize the full potential of receiver processing gain, coherent matched filter receivers are also required. By way of contrast, ATCRBS transponders employ simple leading edge detectors. Avionics receivers for CAST and SAT must employ low noise front ends; these are also not required for today's ATCRBS service.

The top-mounted antennas must have nearly uniform upper hemispheric coverage. One candidate is a crossed dipole antenna fabricated using inexpensive stripline techniques. Today's ATCRBS antenna is an even simpler bottom-mounted blade.

The small avionics computer required to perform the position-determination computations for SAT could be realized today with a (single circuit board) microprocessing computer at an OEM (original equipment manufacturer) cost under $1000. Even lower costs may be achieved with custom integrated circuits.

The overall cost of the minimum package for RAST, CAST or SAT is estimated to be two to four times that of an ATCRBS transponder.

| | CAST | RAST | SAT | ATCRBS |
|---|---|---|---|---|
| Transmitter | Coherent 500W of rf Power | Coherent 500W of rf Power, Power Control | Not Required | Incoherent 200W of rf Power |
| Frequency Stability | $1:10^6$ | $1:10^6$ | $1:10^6$ | $1:10^3$ |
| Receiver Noise Figure | 11 dB | Not Required | 11 dB | 15-19 dB |
| Receiver Processor | Coherent Matched Filter | Not Required | Coherent Matched Filter | Leading Edge Detector |
| Antenna | Top-mounted Crossed Dipole | Top-mounted Crossed Dipole | Top-mounted Crossed Dipole | Blade |
| Data Processing | Specialized Logic | Not Required | Microprocessing Computer | Minimal |

REPRESENTATIVE AVIONICS CHARACTERISTICS

## SATELLITE ANTENNA

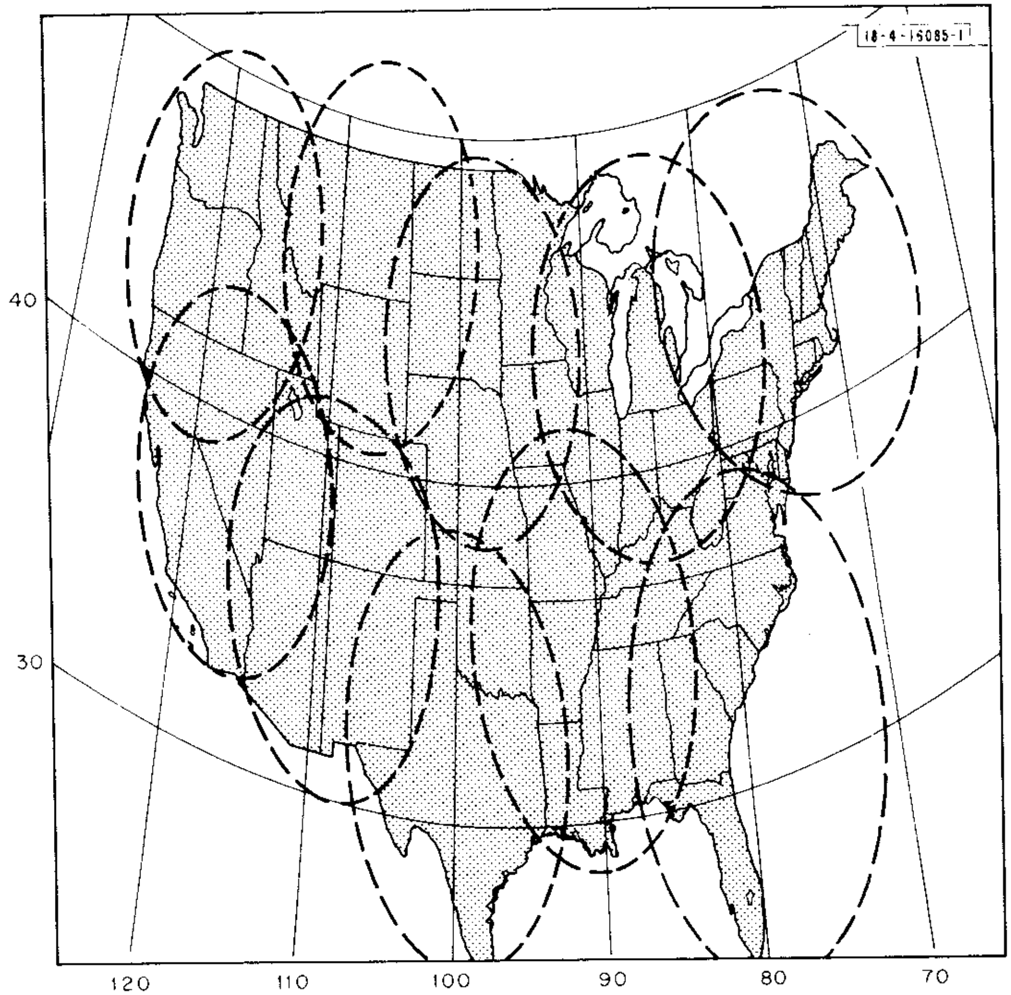
The high attenuation that signals experience in traveling between satellites and aircraft can partially be offset by use of large-aperture, high gain, multi-beam antennas at the satellites. Use of such antennas significantly reduces the requirements on transmitter power and receiver sensitivity, and therefore reduces avionics costs.

In the assumed 1535-1660 MHz aeronautical radio navigation band, the use of a 30 ft antenna (e.g., like that to be deployed on ATS-F) could provide coverage zones of hundreds of miles (as illustrated). For the indicated 10 beams, a 10 dB power saving results (relative to a single CONUS coverage antenna). With such an antenna, a 1 kW satellite power amplifier operating with an avionics receiver having an 11 dB noise figure front end would perform as well as a 5 kW satellite power amplifier and a CONUS coverage antenna working with an 8 dB noise figure avionics receiver. Similarly a 500 watt aircraft transmitter would suffice with a high gain satellite antenna while 5 kW would be required for a CONUS coverage antenna.

With CAST an added benefit to CONUS interrogation efficiency accompanies the use of a multibeam antenna. It is evident that the interrogation algorithms for non-overlapping coverage zones can be made largely independent, hence, permitting high surveillance update rates.

With RAST a similar benefit derives from the ability of aircraft within different beams to operate with little mutual interference.

With SAT, the use of a large aperture satellite antenna permits use of impulse like signals and a relatively simple avionics receiver for time of arrival estimation.




TYPICAL COVERAGE ZONES FOR LARGE APERTURE SATELLITE ANTENNA

## COMPUTATIONAL REQUIREMENTS

In CAST and RAST the aircraft positions are computed in a large centralized data processing facility located on the ground. By contrast in SAT the aircraft positions are calculated in a distributed manner - each aircraft calculates its own position. The key data processing requirements are summarized in the table. While all tasks have not been sized, it has been estimated that the computations required for position determination alone substantially exceed that for NAS Stage A. In the case of CAST, the computation problem is complicated by the need to schedule aircraft interrogations. In the case of RAST, the problem is complicated by the need to sort the incoming pulses (which become interleaved due to the random transmission times). The remaining tasks further contribute to the computational load.

The data processing requirement for CAST and RAST is evidently huge. Because of the "iceberg" nature of large automated systems, it is difficult to assess the true scope of this development; hence, the ground data processing facility presently is rated as an area of significant technical uncertainty for CAST and RAST.

| | CAST | RAST | SAT |
|---|---|---|---|
| Multiple Matched Filtering | | X | |
| Arrival Time Estimation | X | X | |
| Position Determination | X | X | |
| Interrogation Scheduling | X | | |
| Message Scheduling | X | | |
| Aircraft Tracking | X | X | X |
| Satellite Tracking | X | X | X |

REQUIRED COMPUTATIONAL FUNCTIONS

## VULNERABILITY TO INTENTIONAL DISRUPTION

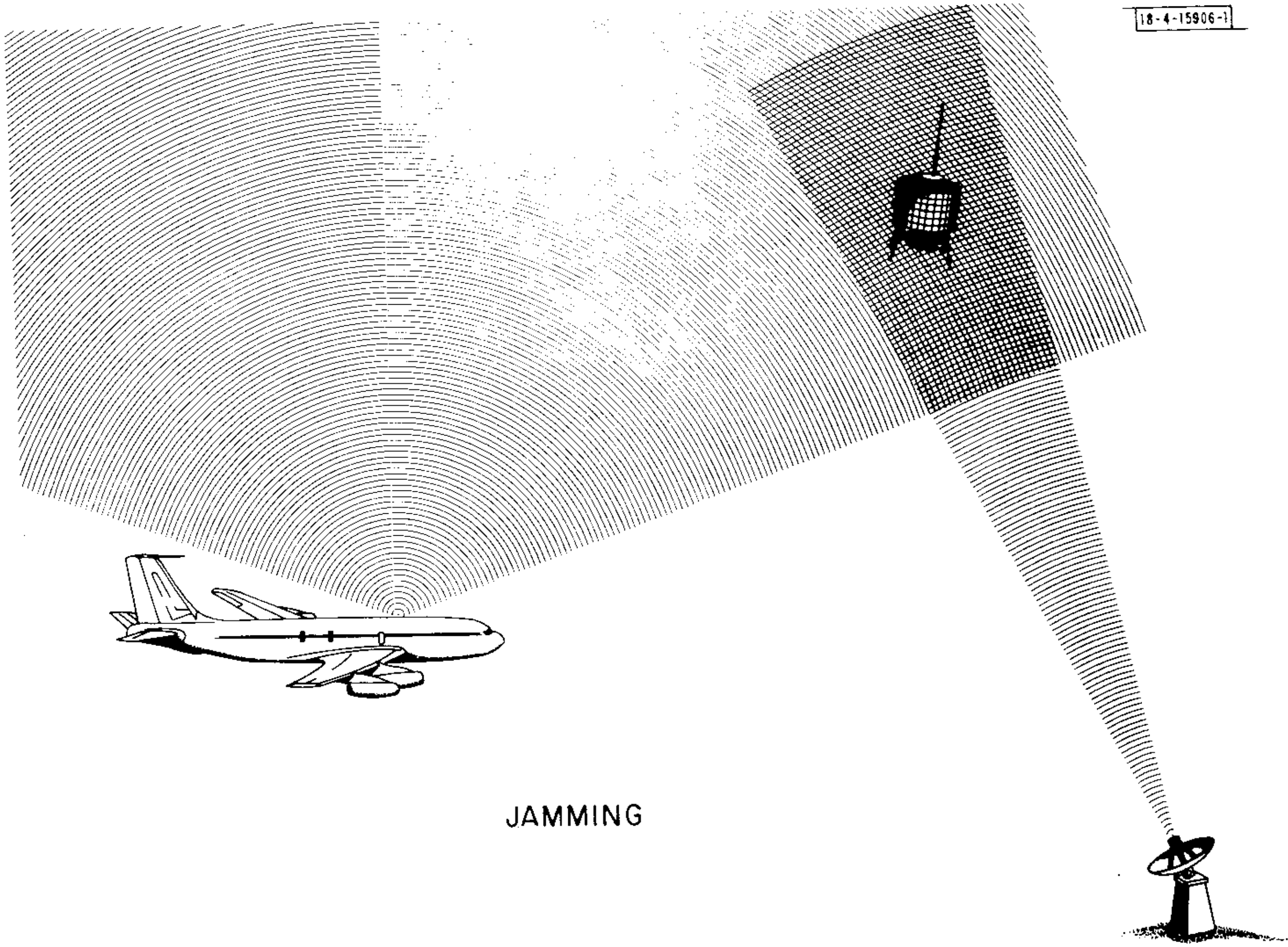
A system that employs CAST or RAST depends upon the aircraft-to-satellite uplink for proper operation. The high mobility of aircraft precludes use of an antenna which must be pointed toward each of the satellites. Hence, the aircraft antenna must be nondirectional; i.e., it must cover nearly the entire upper hemisphere. By contrast, a jammer fixed on the ground can focus a highly directional antenna toward each satellite. Thus a "toaster powered" jammer can "swamp out" signals transmitted from aircraft to a particular satellite.

For purposes of illustration assume that the aircraft transmits a 500 watt, 500 TW (time-bandwidth) product pulse through a top-mounted, crossed dipole (2.5 dB gain) aircraft antenna and that adequate performance requires a 10 dB signal-to-noise ratio. If the jammer uses a 6 ft (8° beamwidth, 26.5 dB gain) antenna, then the jammer need only transmit* 100 watts of rf power into the antenna in order to be a threat. To disrupt normal operation the jammer would have to point beams towards several different satellites. Because of the multiple satellite beams covering CONUS, several different locations (most probably in regions with multiple beam overlap) would have to be used to completely disrupt CAST and RAST service.

CAST and RAST also require the use of a large central facility (for processing aircraft replies) whose disruption could have serious consequences. An independent on line backup facility might be employed for guaranteed performance.

By contrast, SAT is comparatively jam proof due to the absence of an aircraft-to-satellite uplink. Vulnerability of the dependent surveillance is comparable to that of the present ATC system; i.e., local jamming for short time periods.

*27 dBW + 27 dB + 2.5 dB - 10 dB - 26.5 dB = 20 dBW




JAMMING

## IMPROVING ACCURACY

The so-called Geometric Dilution of Precision (GDOP) conventionally has been used to assess the accuracy afforded by a multilateration system. In effect GDOP is an error magnification factor that specifies how much the basic ranging error is magnified by a particular transmitter-receiver geometry. Clearly the smaller the GDOP, the better.

A new procedure for determining GDOP was developed at Lincoln Laboratory as part of the AATMS study.[1,2] The new procedure differs from previous methods in that it provides considerable insight for the selection of good geometries. Basically, the method reduces the problem of calculating GDOP to that of determining the moments of inertia of a mass configuration easily obtained from the satellite-aircraft geometry.

The insight provided by the method indicated that satellite constellations with significantly improved GDOP's could be designed. Accordingly, a family of new constellations was designed to determine the practical extent to which GDOP could be improved or equivalently the required number of satellites could be reduced. The constellations include large (15 satellite), medium (10 satellite) and small (7 satellite) constellations. The table compares the performance of one of the resulting constellations, LL-10,[4] with that of the previous RCA-8[13] and NAR-15[14] constellations. The entries are based upon GDOP calculations over a 119 point CONUS grid. Evidently, the performance of the ten satellite constellation (LL-10) is comparable to that of the fifteen satellite constellation (NAR-15) and significantly better than that of the eight satellite constellation (RCA-8).

The work also showed that while small (seven satellite) constellations can produce reasonably low values of GDOP during level flight, the GDOP's are highly sensitive to satellite failure and aircraft maneuvers. Thus, if high accuracy is to be maintained following a satellite failure, and during maneuvers, larger constellations are necessary. Analyses of a variety of constellations indicated that ten satellites should suffice.

| CONSTELLATION | NOMINAL LEVEL FLIGHT | | SINGLE SATELLITE FAILURE | | $30^{o}$ AIRCRAFT BANK | |
|---|---|---|---|---|---|---|
| | AVERAGE GDOP | RMS DEVIATION | PERCENT GDOP > 10 | AVERAGE GDOP < 10 | PERCENT GDOP > 5 | PERCENT GDOP > 10 |
| RCA-8 | 3.8 | 0.38 | 42 | 7.6 | 38 | 17 |
| LL-10 | 2.4 | 0.42 | 0.8 | 2.7 | 13 | 9.5 |
| NAR-15 | 2.4 | 0.35 | 0 | 2.8 | 11 | 0.3 |

## LINCOLN LABORATORY REPORTS FOR THIS PROGRAM


1. H.B. Lee, "Accuracy Limitations of Hyperbolic Multilateration Systems," Technical Note 1973-11, Lincoln Laboratory, M.I.T. (22 March 1973), DOT/TSC-241-3.

2. H.B. Lee, "Accuracy Limitations of Range-Range (Spherical) Multilateration Systems," Technical Note 1973-43, Lincoln Laboratory, M.I.T. (11 October 1973), DOT/TSC-RA-3-8-1.

3. H.B. Lee and B.B. Goode, "Technical Assessment of Satellites for CONUS Air Traffic Control, Vol. III: Satellite-to-Aircraft Techniques," Project Report ATC-26, Vol. III, Lincoln Laboratory, M.I.T. (February 1974), DOT/TSC-RA-3-8-3.

4. H.B. Lee and A.E. Wade, "Improved Satellite Constellations for CONUS ATC Coverage," Project Report ATC-23, Lincoln Laboratory, M.I.T. (to be published), DOT/TSC-RA-3-8-4.

5. R.S. Orr and K.S. Schneider, "Technical Assessment of Satellites for CONUS Air Traffic Control, Vol. I: Coordinated Aircraft-to-Satellite Techniques," Project Report ATC-26, Vol. I, Lincoln Laboratory, M.I.T. (31 January 1974), DOT/TSC-241-4.

6. K.S. Schneider and R.S. Orr, "Technical Assessment of Satellites for CONUS Air Traffic Control, Vol. II: Random Access Aircraft-to-Satellite Techniques," Project Report ATC-26, Vol. II, Lincoln Laboratory, M.I.T. (February 1974), DOT/TSC-RA-3-8-2.

7. K.S. Schneider, I.G. Stiglitz and A.E. Eckberg, "Surveillance Aspects of the Advanced Air Traffic Management System," Project Report ATC-10, Lincoln Laboratory, M.I.T. (22 June 1972), DOT/TSC-241-2.

8. I.G. Stiglitz, J.U. Beusch, A.E. Eckberg and K.S. Schneider, "Concept Formulation Studies of the Surveillance Aspects of the Fourth Generation Air Traffic Control System," Project Report ATC-7, Lincoln Laboratory, M.I.T. (21 September 1971), DOT/TSC-241-1.

9. R.S. Orr and R.D. Yates, "On the Estimation of the Arrival Time of Pulse Signals in Gaussian Noise," Technical Note 1974-13, Lincoln Laboratory, M.I.T. (to be published), DOT/TSC-RA-3-8-6.

## RELATED REFERENCES

10. "Advanced Air Traffic Management - System B Summary Report," MTR-6419 Series 1, MITRE Corporation, McLean, Virginia (June 1973), FAA-EM-73-10.

11. L. Schuchman, "The ASTRO-DABS Concept," Technical Report MTR-6287, MITRE Corporation, McLean, Virginia (November 1972).

12. "Final Report - Advanced Air Traffic Management System," Report C72-1206/201. Rockwell International Corporation, Anaheim, California (April 1973).

13. "Fourth Generation Air Traffic Control Study," Volumes I-IV, Report DOT-TSC-304-1, North American Rockwell Corp., Anaheim, California (November 1971).

14. "Study and Concept Formulation of a Fourth Generation Air Traffic Control System," Volumes I-V, Report DOT-TSC-3601-1, Boeing Company, Renton, Washington (April 1972).

15. D.D. Otten, "Study of a Navigation and Traffic Control Technique Employing Satellites," Volumes I-IV, Group Report No. 08710-6012-12000, TRW Systems, Redondo Beach, California (December 1967).

16. K.D. McDonald, "A Survey of Satellite-Based Systems for Navigation, Position Surveillance, Traffic Control, and Collision Avoidance," Journal of the Institute of Navigation, Vol. 20, No. 4, pp. 301-320, (Winter 1973-4).

17. P.M. Diamond, "The Potential of a System of Satellites as a Part of an Air Traffic Control System," AGARD Conference Proceedings No. 105, pp. 20-1 (June 1972).